# ORIGIN(S) OF DESIGN IN NATURE

# Cellular Origin, Life in Extreme Habitats and Astrobiology

Volume 23

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Joseph Seckbach
*The Hebrew University of Jerusalem, Jerusalem, Israel*

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# Origin(s) of Design in Nature

## A Fresh, Interdisciplinary Look at How Design Emerges in Complex Systems, Especially Life

*Edited by*

Liz Swan
*Longmont, CO, USA*

Richard Gordon
*Gulf Specimen Marine Laboratory, Panacea, FL, USA*

and

Joseph Seckbach
*The Hebrew University of Jerusalem, Jerusalem, Israel*

Springer

*Editors*
Liz Swan
Longmont, CO, USA

Richard Gordon
Gulf Specimen Marine Laboratory
Panacea, FL, USA

Joseph Seckbach
Hebrew University of Jerusalem
Jerusalem, Israel

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# DEDICATION

For my husband, Eric Swan, and for the little piece of nature we gave origin to, Freeman Jack Swan.

–Liz Swan

Dedicated to my wife Fern, our children, and grandchildren in the Seckbach clan. And in addition, to the late botanical professor, Yaakov Leshem (Bar Ilan University, Ramat Gan, Israel), who guided me on the publication path.

–Joseph Seckbach

For Diana Gordon, artist, on the occasion of her 90th birthday, and her great grandson Luke Hunstad, of as yet undesigned aspirations, on the occasion of his first.

–Richard Gordon

# INTRODUCTION TO ORIGIN(S) OF DESIGN IN NATURE [ODIN]

The origin of life is still a mystery, but the results of design are visible on Earth and in the universe. Design, including the emergence of many evolutionary lines and diverse ecosystems, is familiar to all of us. We recognize design everywhere; interior decorating, garden landscaping, urban planning, and industrial uses are only a few examples. There is also design in social sciences, intelligence, and other manifestations of life.

In this volume, we deal with the *Origin of Design in Nature* (ODIN), with its 42 authors discussing various aspects of this topic. The aim of the authors is to determine whether all phenomena in nature originated spontaneously or under intelligent guidance and creation. One might visualize the wonderful internal structure of atoms, molecules, cells, organs, organisms, and the universe itself and its galaxies and ask, "How did all this come about?" or ask, as stated in the Bible, "Who created all of those?" (Isaiah 40:26). The articles in this book range from a purely scientific approach to the traditional act of creation as seen by religions wherein there is a biblical account for the emergence of life (in the first chapters of Genesis). These statements need not necessarily contradict the scientific approach. Indeed, natural designs can be seen all over, but their origin has led to lively and constructive discussions, as the present book demonstrates. This volume (number 23 of *COLE*) provides an interdisciplinary look at how design emerges in complex systems.

The target audience of this volume is graduate-level students and professional humanists and scientists in philosophy of science, astrobiology, evolution, dynamics, and complex systems.

We acknowledge all the contributors for their chapters and among them the patient "early birds." Special thanks are due to Professor Julian Chela-Flores (ICTP, Trieste, IT) who is always our "right hand" within the new volumes of COLE books and to Fern Seckbach for her constant linguistic and style assistance. Appreciations are due to the reviewers, to external referees who read all the chapters and gave their comments. Last but not least, thanks to Maryse Walsh and Melanie vanOverbeek—the Springer team.

**Joseph Seckbach** The Hebrew University of Jerusalem, Jerusalem, Israel

# FOREWORD

The main theme of *Origin(s) of Design in Nature: A Fresh, Interdisciplinary Look at How Design Emerges in Complex Systems, Especially Life* is especially relevant for the development of the life sciences. Charles Darwin's two theories of evolution remain the cornerstones of our discussion (Mayr, 1991): evolution by natural selection and the common descent of all life on Earth. Indeed, life on Earth is an example of life that can be understood in terms of evolution by means of natural selection. Darwin's second theory is intimately related to the search for the origin of life on this planet.

We should take a closer look several issues that have been discussed for a considerable time in the context of the wider problem: design in nature (Chela-Flores, 2011). This topic has a long history going back to ancient Greece. However, in modern times, we may begin with the work of William Paley (1743–1805), who was an Archdeacon and Doctor of Divinity at Cambridge University. His writings were highly respected in the Anglican order. His *Horae Paulinae* was written in 1790 specifically to prove the historicity of the New Testament. Another famous book was *View of the Evidences of Christianity* (1794), a text that was standard reading among undergraduates during Charles Darwin early university education. However, his best-remembered book is *Natural Theology,* which played an important role in the early stages of the establishment of Darwin's arguments.

Paley presented some observations from nature intending to prove not only the existence of a grand design, but more importantly also, in his book, Paley attempted to prove the existence of an intelligent designer. The famous quotation that follows is at the beginning of his book:

> *Suppose I found a watch upon the ground, and it should be enquired how the watch happened to be in that place…When we come to inspect the watch, we perceive that its several parts are framed and put together for a purpose…the inference, we think, is inevitable, that the watch must have had a maker…*

This argument can be traced back to classical times, but Paley's defense of it in modern times was influential in the nineteenth century dialogue between science, philosophy, and theology. One of the fundamental steps in the ascent on man toward an understanding of his position in the universe has been the realization that natural selection is indeed a creative process that can account for the appearance of genuine novelty within science frontiers, independent of a single act of creation, but more as a gradual accumulation of small successes in the evolution of living organisms. This is a point that has been defended by many of the founders of Darwinism, most recently by others, who refer to an analogy with artistic creation. The creative power of natural selection arises, according to Jacques Monod, as an interaction between chance and necessity (a phrase that became familiar thanks to his very popular book *Chance and Necessity*).

With Francisco Ayala, for instance, we may consider a painter who mixes and distributes pigments over a canvas (Ayala, 1998). The artist does not create the canvas and pigments, but the painting is the creation of the artist. A random mixture of pigments could not have created Leonardo's *Mona Lisa*, or at least the probability is infinitesimally small. This underlines the fact that natural selection is like the painter—it is not a random process. The scientific approach to rationalizing the complexity of the human eye, for instance, has shown us that it is the result of a nonrandom process, namely, natural selection. It is somewhat surprising, however, that what has just been described, Darwin's straightforward (but brilliant) thinking, has led to so much controversy at the frontier of science and the humanities. In the future, unfortunate controversies will gradually disappear, due to recent work, and I am convinced, also, due to many of the chapters that make up the present book.

I would like to end this brief Foreword with some thoughts that may help to turn bitter debates into constructive dialogues helping our culture on both sides of the humanities/science frontier. Two terms from the humanities are relevant for our considerations. Firstly, exegesis is a critical explanation of any text, but more often it is restricted to a critical interpretation of a religious text to discover its intended meaning.

On the other hand, hermeneutics refers to an approach arising from the method of interpretation. When we apply it to religious texts, it is precisely exegesis, but when we apply it elsewhere, it coincides with other approaches to interpretation. For example, when we apply it to literary texts, the interpretative method is known as philology, whereas when it is applied to legal texts, it is known as jurisprudence (Changeux and Ricoeur, 2000). The objective of hermeneutics is not to reach some ultimate truth, but to get deeper insights into thoughts and symbols, to reach within our limitations the best and most exact position possible.

Hermeneutics is in principle relevant to all forms of communication and expression: written, verbal, artistic, physiological, and sociological. But the physical, Earth and life sciences have not been included in this range of disciplines. For a good reason, we may add since science within its frontiers—defined by Galileo—has to be judged by its close adherence to the results of repeatable experiments, or by careful repeatable observations. As scientists, we are not qualified to cross over into the domain of the humanities, as its various branches are, unlike scientific disciplines, not based on theories supported by experimental data or supported by observations shared by a large number of independent scientists. And very often, when the frontier is crossed in the opposite direction, lamentable misinterpretations occur. In general, frontier crossing without the necessary background and respect for the special characteristics of science, as well as for the special characteristics of the humanities, lie at the root of most of the misinterpretation of Charles Darwin's monumental contribution to science, which is the basis for understanding design in the life sciences.

Humanists have an advantage on scientists, in the sense that with the long traditions of exegesis and hermeneutics, going back to the emergence of Western civilization, only misinformed interpretation of the Holy Books of the Abrahamic religions lead to unnecessary defense by the pious in view of a presumed contradictions raised by rational thinking. More damaging still is the vision of a (fortunately) small group of highly prolific scientists—extraordinarily competent in their own special scientific field of expertise—but without a thorough mastering, or even with complete lack of respect for the specific merits and methods of the humanities. Without hesitation, or meditation, sometimes, the scientific frontier has been crossed into areas of the humanities that are best left to the specialists of philosophy and theology, where the scientific method is well beyond its range of validity. Fortunately, excellent clarifications of these extrapolations have appeared in competently written literature by well-qualified humanists (Cornwell, 2007).

With its many chapters by our distinguished authors, the present book is making a genuine attempt to provide arguments related to design in complex systems, including life. We are convinced that these pages will define more sharply the all-important frontier of science and the humanities. This volume is intended to serve as a stepping-stone to fully appreciate, and to interpret correctly, the humanistic implications of one, if not the most, transcendental contribution to science: Darwin's publication in 1859 of his seminal book *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.*

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**Julian Chela-Flores** Salita di Contovello, Trieste, Italy

# PREFACE: ODIN

Design as evidenced by the presence of ordered complexity fills nature. Most especially, but not exclusively, this is manifest in the biosphere. The conundrum we confront in this book is from where did and does this complexity, this functionally effective design, arise, and how does it maintain itself? Does the emergence of design demand that there be a designer? From the finely tuned structure of an atom, through the eloquent molecular biology of a microbe, to the intricacy of a brain with the surprise emergence of consciousness, design is obvious. Just as it is with William Paley's proverbial watch found on a path. But unlike a watch which has no ability to remake and refine itself, nature seems imbued with a drive, a force that pushes it to ever-increasing complexity. This upward direction is so obvious and ubiquitous that we, being one of the products of this drive, may fail to internalize the implications. Nature has a direction.

Though the universe, as it expands outward, races toward its own heart death, in specific, favored locations where abundant sources of energy remain, complexity abounds. The forces of nature cannot defeat increasing entropy on the scale of the universe. This is one of the unyielding laws of nature. But locally, those same forces can out maneuver the drive toward chaos, concentrate the energy, and ultimately give rise to life and brain and mind.

"I don't know who discovered water, but I'm pretty sure it wasn't a fish." So wrote Marshall McLuhan in The Medium is the Massage. Why would not a fish be the first to discover water? Simply because it is their total milieu. We are not so different. We live so totally in a world of complexity and consciousness that only by intellectual effort do we question its origins. Let us do that.

The first step toward sentient life is the creation of existence, the universe. We might ask why there is existence, but of course if there were nothing, we would not be here to ask. So, let the need for existence be a given. An eternal universe (i.e., no creation) presents technical problems such as accounting for the residual useful energy currently present in an infinitely old universe. If the universe is not eternal, then we need a force to produce it. The current best estimate is that a quantum fluctuation in a virtual vacuum brought the universe into being.

Our concept of time begins with the universe. Therefore, the laws of nature, of which quantum phenomena are a part, must predate time, be timeless at least in the human conception of time. This has extraordinary implications. As Ed Tryon, who first proposed this idea almost 40 years ago, recently observed, "If matter and energy are the result of a spontaneous creation [i.e., a quantum fluctuation], then matter and energy are not fundamental. They are manifestations of underlying the laws of nature. Ultimate reality would then be the laws of nature." The world we discover is the product of ethereal eternal forces of creation.

The laws of nature as they act within this world which they created have a plethora of complexity enhancing and ultimately life-enabling traits. To name just two, we have the following: the Pauli Exclusion Principle and de Broglie's revelation of the wave characteristics of matter. Remove these from our milieu and chemistry ceases, stable molecules never form. Together, along with the twist of nature that produced protons and electrons with identical but opposite electrical charges even though the proton has a mass 1,837 times that of an electron, it allowed chemistry to proceed. The fundamental requirements for life were present, not only at the creation, but if Ed Tryon's hypothesis is correct, the needs for eventual life were present even prior to the creation, couched within the laws of nature.

Fourteen billion years had to pass before the expanding universe became amenable to life as we know it. But once the life-friendly platform we call Earth emerged, the right-sized planet located in the narrow habitable zone around the right-size and right-age star, our sun, in the life-friendly region of a spiral galaxy, the Milky Way, life burst forth. On Earth, the oldest rocks that can bear fossils of life have them. And noting that the size and shapes of these primordial fossilized microbes are spot-on matches of their modern descendents, it is likely that their genetic engineering was similar to that found throughout today's biosphere.

DNA, the universal (or at least earthly)-coded blueprint of life seems to have been ubiquitous from the very beginning of life. Now that is surprising because DNA is a totally digitally coded system. Just as dot dot dot dash is meaningless to anyone not familiar with the Morse code (It signifies the letter "v.") and just as dot dot dot dash holds absolutely no similarity to the letter for which it stands, so the four-digit code of DNA, the four nucleotides, bear no physical relationship to any one of the 20 amino acids for which they code by varying their arrangement on the DNA helix. All life is a variation on this theme. And life appears to have gone digital from its inception. With that majestic innovation, the potential for variation became vast.

Darwin was correct when he wrote in the closing lines of The Origin of Species, "… from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved."

But how did it happen? Is all this the work merely of the laws of nature, as Professor Tryon wrote, or is there a more cosmic force at work nudging those laws to facilitate the emergence of forms "most beautiful and most wonderful?"

For this, we might turn to the complete quote of the closing sentence of Darwin's "Origin," as it appears in every edition except the first (including the second edition which appeared a mere 5 weeks after the first edition). "There is a grandeur in this view of life, with its several powers, having been originally breathed by the Creator into a few forms or into one; and whilst this planet has gone cycling on according to the fixed laws of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved."

Has Darwin correctly identified the ultimate origin of design in nature? Would that not be a surprise!

End

**Gerald L. Schroeder** College of Jewish Studies, Jerusalem, Israel

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## LIST OF AUTHORS AND THEIR ADDRESSES

**ADRIAENS, PIETER R.**
INSTITUTE OF PHILOSOPHY, UNIVERSITY OF LEUVEN,
LEUVEN, BELGIUM

**BARBALET, TOM**
NOBLE APE AND BIOTA.ORG, NEW YORK, NY, USA

**BARBIERI, MARCELLO**
DIPARTIMENTO DI MORFOLOGIA ED EMBRIOLOGIA,
FERRARA, ITALY

**BELOUSSOV, LEV V.**
LABORATORY OF DEVELOPMENTAL BIOPHYSICS, FACULTY
OF BIOLOGY, MOSCOW STATE UNIVERSITY, MOSCOW, RUSSIA

**BERGER, DOV**
LIFSHITS ACADEMIC COLLEGE OF EDUCATION,
JERUSALEM, ISRAEL

**BISHOP, CORY D.**
DEPARTMENT OF BIOLOGY, ST. FRANCIS XAVIER UNIVERSITY,
ANTIGONISH, NS, CANADA

**CHEN, NICOLE**
INDUSTRIAL DESIGN DEPARTMENT, ROCHESTER
INSTITUTE OF TECHNOLOGY, ROCHESTER, NY, USA

**CHETLAND, CHRIS**
DEPARTMENT OF EVOLUTIONARY BIOLOGY, SCHOOL
OF THE ENVIRONMENT, GRIFFITH UNIVERSITY,
BRISBANE, QLD, AUSTRALIA

**COOK, STEPHEN P.**
PROJECT WORLDVIEW, WEED, NM, USA
DEPARTMENT OF ASTRONOMY, NEW MEXICO STATE UNIVERSITY,
LAS CRUCES, NM, USA

**DICKSON, MICHAEL**
DEPARTMENT OF PHILOSOPHY AND CENTER FOR HUMANISTIC
STUDY OF SCIENCE, UNIVERSITY OF SOUTH CAROLINA,
COLUMBIA, SC, USA

**EGAN, CHAS A.**
PLANETARY SCIENCE INSTITUTE, RESEARCH SCHOOL
OF ASTRONOMY AND ASTROPHYSICS AND THE RESEARCH
SCHOOL OF EARTH SCIENCES, AUSTRALIAN NATIONAL
UNIVERSITY, CANBERRA, AUSTRALIA

**FALLER, MARK**
LIBERAL STUDIES DEPARTMENT, ALASKA PACIFIC UNIVERSITY,
ANCHORAGE, AK, USA

**FARGE, EMMANUEL**
MECHANICS AND GENETICS OF EMBRYONIC AND TUMORAL
DEVELOPMENT GROUP, UMR168 CNRS, INSTITUT CURIE,
PARIS, FRANCE

**FLEURY, VINCENT**
LABORATOIRE MATIÈRE ET SYSTÈMES COMPLEXES,
UNIVERSITÉ PARIS-DIDEROT, PARIS, FRANCE

**GADOTH, NATAN**
DEPARTMENT OF NEUROLOGY, MAYNEI HAYESHUAH
MEDICAL CENTER, BNEI BRAK, ISRAEL
SACKLER FACULTY OF MEDICINE, TEL AVIV UNIVERSITY,
TEL AVIV, ISRAEL

**GALWAY, MOIRA E.**
DEPARTMENT OF BIOLOGY, ST. FRANCIS XAVIER UNIVERSITY,
ANTIGONISH, NS, CANADA

**GARBARY, DAVID J.**
DEPARTMENT OF BIOLOGY, ST. FRANCIS XAVIER UNIVERSITY,
ANTIGONISH, NS, CANADA

**GILL, ZANN**
M|M FORUM, NASA AMES RESEARCH CENTER,
MOFFETT FIELD, CA, USA

**GLICKSBERG, SHLOMO E.**
EFRATA COLLEGE, JERUSALEM, ISRAEL

**GORDON, RICHARD**
DEPARTMENT OF RADIOLOGY, UNIVERSITY OF MANITOBA,
WINNIPEG, MB, CANADA
GULF SPECIMEN MARINE LABORATORY, PANACEA, FL, USA

**GRAND, STEPHEN**
LONDON, UK

**GRANDPIERRE, ATTILA**
KONKOLY OBSERVATORY OF THE HUNGARIAN
ACADEMY OF SCIENCES, BUDAPEST, HUNGARY

**HARMAN, OREN**
BAR ILAN UNIVERSITY, TEL AVIV, ISRAEL

**ISSAR, ARIE S.**
GEOLOGICAL DEPARTMENT, BEN GURION UNIVERSITY
OF THE NEGEV, BE’ER SHEVA, ISRAEL

**KAK, SUBHASH**
DEPARTMENT OF COMPUTER SCIENCE, OKLAHOMA
STATE UNIVERSITY, STILLWATER, OK, USA

**KAMENIR, YURY**
THE MINA AND EVERARD GOODMAN FACULTY OF LIFE
SCIENCES, BAR-ILAN UNIVERSITY, RAMAT-GAN, ISRAEL

**KLOSTERMAIER, KLAUS KONRAD**
DEPARTMENT OF RELIGION, UNIVERSITY OF MANITOBA,
WINNIPEG, MB, CANADA

**LINEWEAVER, CHARLES H.**
PLANETARY SCIENCE INSTITUTE, RESEARCH SCHOOL
OF ASTRONOMY AND ASTROPHYSICS AND THE RESEARCH
SCHOOL OF EARTH SCIENCES, AUSTRALIAN NATIONAL
UNIVERSITY, CANBERRA, AUSTRALIA

**LUISI, PIER LUIGI**
DEPARTMENT OF BIOLOGY, UNIVERSITY OF ROME 3,
ROME, ITALY

**MASS, ELIYAHU**
THE PEDIATRIC DENTISTRY UNIT, BARZILAI MEDICAL
CENTER, ASHKELON, ISRAEL
THE MAURICE AND GABRIELA GOLDSCHLEGER SCHOOL
OF DENTAL MEDICINE, TEL AVIV UNIVERSITY, TEL AVIV, ISRAEL

**MCGREW, STEVE**
NEW LIGHT INDUSTRIES LTD., SPOKANE, WA, USA

**MIRAN, MICHAEL D.**
DEPARTMENT OF PSYCHOLOGY, ROCHESTER INSTITUTE
OF TECHNOLOGY, ROCHESTER, NY, USA

**MIRAN, D. ESTA**
PROGRAM DEVELOPMENT, ROCHESTER, NY, USA

**NEGROTTI, MASSIMO**
UNIVERSITY OF URBINO “CARLO BO”,
URBINO PESARO E URBINO, ITALY

**POLLAK, MOSHE**
DEPARTMENT OF STATISTICS, THE HEBREW UNIVERSITY
OF JERUSALEM, JERUSALEM, ISRAEL

**REES-DESSAUER, ELISABETH**
HISTORISCHES SEMINAR, ABTEILUNG FÜR JÜDISCHE
GESCHICHTE UND KULTUR, LUDWIG-MAXIMILIANS-
UNIVERSITÄT MÜNCHEN, MUNICH, GERMANY

**ROŠKER, JANA S.**
DEPARTMENT OF ASIAN AND AFRICAN STUDIES,
FACULTY OF ARTS, LJUBLJANA UNIVERSITY OF LJUBLJANA,
LJUBLJANA, SLOVENIA

**RODGERS, DIANE M.**
NORTHERN ILLINOIS UNIVERSITY, DEKALB, IL, USA

**ROZENSON, YISRAEL**
EFRATA COLLEGE, JERUSALEM, ISRAEL

**SCHRADER, MALCOLM E.**
DEPARTMENT OF INORGANIC AND ANALYTICAL CHEMISTRY,
INSTITUTE OF CHEMISTRY, THE HEBREW UNIVERSITY
OF JERUSALEM, JERUSALEM, ISRAEL

**SCHROEDER, GERALD L.**
COLLEGE OF JEWISH STUDIES, JERUSALEM, ISRAEL

**SECKBACK, JOSEPH**
THE HEBREW UNIVERSITY OF JERUSALEM, EFRAT, ISRAEL

**SHOOK, JOHN R.**
UNIVERSITY AT BUFFALO, BUFFALO, NY, USA
GEORGE MASON UNIVERSITY, FAIRFAX, VA, USA

**SOLYMOSI, TIBOR**
DEPARTMENT OF PHILOSOPHY, SOUTHERN ILLINOIS UNIVERSITY,
CARBONDALE, IL, USA

**STILLWAGGON, EILEEN**
DEPARTMENT OF ECONOMICS, GETTYSBURG COLLEGE,
GETTYSBURG, PA, USA

**SVOBODA, JOSEF**
DEPARTMENT OF BIOLOGY, UNIVERSITY OF TORONTO
AT MISSISSAUGA, MISSISSAUGA, ON, CANADA

**SWAN, LIZ STILLWAGGON**
LONGMONT, CO, USA

**WARD, ARTHUR**
DEPARTMENT OF PHILOSOPHY, BOWLING GREEN STATE
UNIVERSITY, BOWLING GREEN, OH, USA

**WINTERS, ANDREW M.**
DEPARTMENT OF PHILOSOPHY, UNIVERSITY
OF SOUTH FLORIDA, TAMPA, FL, USA

**YISRAELI, JOEL K.**
DEPARTMENT OF DEVELOPMENTAL BIOLOGY AND CANCER
RESEARCH, INSTITUTE FOR MEDICAL RESEARCH – ISRAEL-
CANADA, HEBREW UNIVERSITY-HADASSAH MEDICAL SCHOOL,
JERUSALEM, ISRAEL

# PART I:
# ORIGIN OF DESIGN

**Lineweaver**
**Egan**
**Grandpierre**
**McGrew**

Nature and Man – cooperation in design. This photo of a bush shaped like an elephant was taken by Joseph Seckbach at the Utopia Park at Kibbutz Bachan near the city of Netanya (Israel). All rights reserved by the photographer.

Biodata of **Charles H. Lineweaver** and **Chas A. Egan**, authors of "***The Initial Low Gravitational Entropy of the Universe as the Origin of Design in Nature***."

**Dr. Charles H. Lineweaver** is the convener of the Australian National University's Planetary Science Institute and holds a joint appointment as an associate professor in the Research School of Astronomy and Astrophysics and the Research School of Earth Sciences. He obtained an undergraduate degree in physics from Ludwig Maximillians Universitat, Munich, Germany, and a Ph.D. in astrophysics from the University of California at Berkeley. He was a member of the COBE satellite team that discovered the temperature fluctuations in the cosmic microwave background. Before his appointment at ANU, he held postdoctoral positions at Strasbourg Observatory and the University of New South Wales where he taught one of the most popular general studies courses, "Are We Alone?" His research areas include cosmology, exoplanetology and astrobiology.

Personal homepage: **http://www.mso.anu.edu.au/~charley**
E-mail: **charley@mso.anu.edu.au**

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**Dr. Chas A. Egan** is a visiting researcher at Australian National University's Research School of Astronomy and Astrophysics. Following a secondary school education in the Pacific Kingdom of Tonga, he obtained an undergraduate degree in physics at Griffith University, Brisbane, Australia, and a Ph.D. in astrophysics at the University of New South Wales, Sydney, Australia. His research is primarily in cosmology, in particular, dark energy, cosmological thermodynamics and anthropic selection effects.

E-mail: **chas@mso.anu.edu.au**

# THE INITIAL LOW GRAVITATIONAL ENTROPY OF THE UNIVERSE AS THE ORIGIN OF DESIGN IN NATURE

**CHARLES H. LINEWEAVER AND CHAS A. EGAN**
*Planetary Science Institute, Research School of Astronomy*
*and Astrophysics and the Research School of Earth Sciences,*
*Australian National University, Canberra, Australia*

> *Great fleas have little fleas upon their backs to bite 'em,*
> *And little fleas have lesser fleas, and so ad infinitum.*
>
> —Augustus De Morgan
>
> *Big whirls have little whirls that feed on their velocity,*
> *and little whirls have lesser whirls and so on to viscosity.*
>
> —Lewis Fry Richardson

## 1. The Second Law of Thermodynamics: Entropy Increases

Life and other far-from-equilibrium dissipative structures such as galaxies, stars, planets, convecting mantles and hurricanes, increase the entropy of the universe (Lineweaver and Egan, 2008). They need gradients of density, temperature, chemical potential, pressure, humidity or luminosity to form and survive (e.g. Schroedinger, 1944; Schneider and Kay, 1994; Schneider and Sagan, 2005; Kleidon, 2010). Each one of these gradients can be traced back to other larger-scale gradients which are the sources of free energy.

For example, the Sun is hot (~6,000 K) while the Earth is cool (~290 K). Since the Earth is a sphere, the equator receives more sunlight. Equatorial sunshine evaporates the oceans and warms the tropics. Large-scale hemispheric temperature and humidity gradients are set up and maintained by sunlight. These gradients drive winds, thunderheads and hurricanes. Water evaporates, goes up into clouds, gets blown over land and rains down on mountains. We convert the resulting difference in gravitational potential (gravitational gradient) into a voltage gradient using a turbine in a hydroelectric power station. With a windmill, we convert the momentum gradient of the wind into a voltage gradient. Then with heaters, refrigerators and air conditioners, we convert the voltage gradient into conveniently placed small-scale thermal gradients – which then dissipate into waste heat. Each conversion is irreversible in that it is dissipative and produces waste heat. Physicists call the non-existent exceptions to this rule dissipationless, reversible processes.

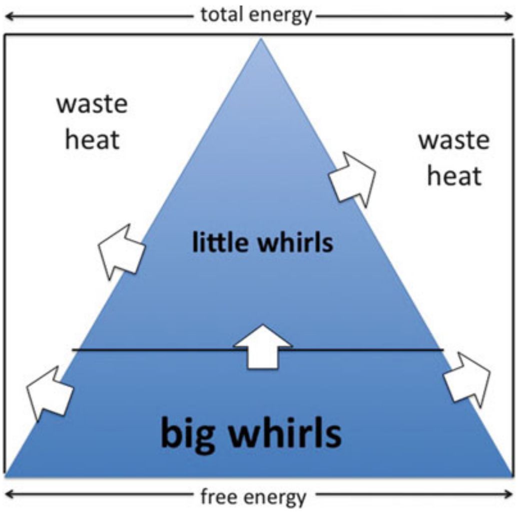

**Figure 1.** The dissipation of free energy. Starting at the bottom, the free energy of a few big whirls gets converted into many more little whirls and dissipated into waste heat. The total energy (= width of figure) is conserved. Big whirls turning into little whirls which turn into waste heat is a simple way to understand the more complicated picture of Fig. 2.

The conversion of free energy into waste heat can be similarly described for all processes (Kleidon, 2010). While Earth-bound climate scientists take the free energy from the Sun as a given, astrophysicists can dig deeper into the origin of free energy. Figure 2 is a more explicit version of Fig. 1 that tries to do that.

Just as big atmospheric whirls on Earth dissipate into little whirls and soon become microscopic waste heat, on a cosmic scale, the energy of the universe – initially stored in a small number of degrees of freedom – dissipates as it spreads out over a larger number of degrees of freedom (Fig. 3). In this way, free energy is converted into waste heat by dissipative structures, and the overall ability to do useful work diminishes. Energy is conserved, but distributing it over a larger number of degrees of freedom makes it less extractable to do work. This is how entropy increases (Jaynes, 1984).

Since there are no net flows of energy between large (>100 Mpc$^3$) comoving volumes of the universe, energy is conserved (first law of thermodynamics). This constant energy is represented by the constant width of (Figs. 1, 2, and 4). The second law of thermodynamics (entropy increase) is represented by the diagonal lines of the pyramid – the boundary between useful free energy and waste heat. The relationship between the Helmholtz free energy $F$, total energy $U$ and waste heat $TS$ ($T$: temperature, $S$: entropy) can be written as

$$F = U - TS, \tag{1}$$

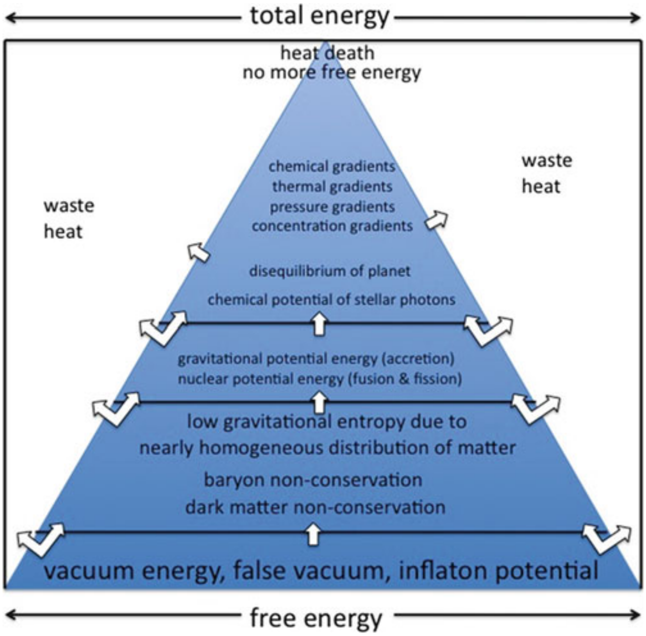

**Figure 2.** Trophic pyramid of free energy production – a more explicit and comprehensive version of Fig. 1. The free energy available at one level comes from the level below it. The width of the pyramid is the amount of free energy available. As free energy spreads into more and more processes at smaller and smaller levels, waste heat is produced as dissipative structures (*white arrows*) feed off the steady state disequilibrium. Dissipative structures can also transfer free energy to other structures. For example, stars provide high-energy photons that power the thermal gradients that make winds blow and evaporate oceans, driving the hydrological cycle, and energy for plants, which produce waste heat but also oxygen and apples (the free energy of chemical redox gradients) for heterotrophs. The lower levels are prerequisites for the life above it. Far-from-equilibrium dissipative structures traditionally classified as life forms (FFEDSTCALFs) are restricted to the top level. The narrowing at the top of the pyramid represents the decreasing amount of free energy available at higher trophic levels (Figure modified from Lineweaver and Egan, 2008).

or in words,

$$\text{Available work} = \text{Internal energy} - \text{Waste heat}.$$

Figure 4 is just a version of Fig. 2 annotated with Eq. 1. Taking the differentials of Eq. 1 for a system in which total energy is conserved and temperatures are not changing (i.e. $T_{\text{Sun}}$ = constant ~ 6,000 K and $T_{\text{Earth}}$ = constant ~ 290 K) yields

$$dF = -T\,dS, \tag{2}$$

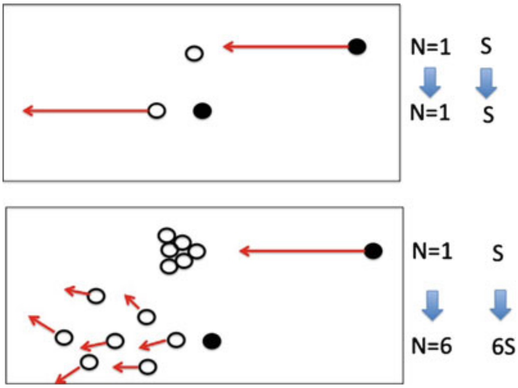

**Figure 3.** Entropy, *S*, increases when the number of degrees of freedom over which the energy is spread increases. In the *top panel*, the kinetic energy of one *black ball* is transferred to the kinetic energy of one *white ball*. The number of degrees of freedom over which the energy is spread (and thus the entropy) is constant. In the *bottom panel*, the kinetic energy of the *black ball* is transferred to six *white balls*. The number of degrees of freedom increases from 1 to 6, and the entropy increases from *S* to 6*S*.

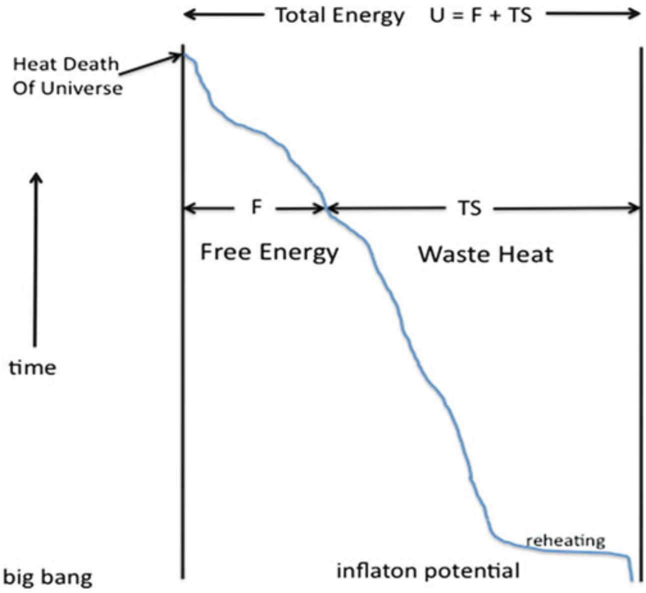

**Figure 4.** We can separate the total energy $U$ into useful free energy $F$ and waste heat $TS$ (since $U = F + TS$). With a constant $U$, starting at the big bang at the bottom of the figure, entropy increases and $F$ decreases. As time goes by, more and more of the initial free energy is converted into waste heat.

which means that in such a system, all extracted free energy d$F$ is eventually converted into waste heat $T$d$S$.

The various forms of free energy are usually written as (Bejan, 2006; Kleidon, 2010)

$$(dF = pdV + \phi dm + \boldsymbol{v} * \boldsymbol{dp} + \Sigma_i \mu_i \, dN_i) \tag{3}$$

where $p$ is pressure, $V$ volume, $\phi$ gravitational or electric potential, $m$ mass or charge, **v** velocity vector, **p** momentum vector, $\mu_i$ chemical or nuclear potential of species $i$, and $N_i$ number of particles of species $i$. For each pair of variables, the first is an intensive quantity, while the differential is of an extensive quantity. The extractable work comes from the gradients of the intensive variables (gradients in pressure, gravity, momentum and chemical potential). Work can be extracted from macroscopic gradients, i.e. gradients of a scale larger than the microscopic particles (atoms, molecules, charges) which get pushed around or fall through the gradients and importantly provide the large number of degrees of freedom for waste heat. A pressure gradient (think pistons of a steam locomotive or internal combustion engine) does "$p$d$V$" work. A gravitational potential gradient can do work when a mass, d$m$, falls (hydroelectric power plant). If the potential is from an electric field, work is done when a charged d$m$ falls from high potential to low potential (inside a kitchen appliance for example). In the presence of a velocity gradient, momentum exchange does work (windmill). Work can be extracted from a chemical potential gradient (concentration gradient) when a particle species does work by going from high concentration to low concentration (lithium batteries, osmotic pressure engines, metazoan digestive tracts). Jaynes (1984) describes the relationship between the Carnot efficiency of a heat engine and the efficiency of muscles and insightfully relates both to work and the number of degrees of freedom.

## 2. Spiegelman's Monster

A differentiated and information-rich terrestrial environment applies selection pressure on whatever is existing or evolving in that environment. If the environment is hot, then molecules and membranes that can withstand the heat survive. On Earth-like planets, temperature, humidity, pH and surface chemistry vary both spatially and temporally. Any life form in these environments has to be able to survive the conditions and maintain enough variability in the population to be able to adapt to the changing condition. Thus, both the phenotypes and the dispersion of the genotypes are selected by the environment. The evolution of the dispersion is known as the evolution of evolvability (Kirschner and Gerhart, 1998).

As an example of how the information in the environment enters the genotype, and to quantify the minimal set of genes necessary to keep something alive, Spiegelman conducted some experiments (Kacian et al., 1972). He created environments that were ideal for a Qb virus. Everything the virus needed to survive and replicate was provided (RNA replicase, some free nucleotides and some salts). After 74 generations, the original viral strand of 4,500 nucleotide bases had evolved into a streamlined 218 nucleotide bases. All the extraneous bases normally used as molecular locks or keys to help the virus obtain what it needed atrophied away. The simplest explanation of these results is that in an information-poor environment where there are no challenges, no selection pressure, and no tricks are needed, the information in the bases of the virus is not selected for and diffuses away. Thus, the amount of information in the genotype reflects the amount of information in the environment. This lazy, streamlined, couch potato of a virus became known as Spiegelman's Monster. Thirty years later, Oehlenschlager and Eigen (1997) showed that Spiegelman's Monster could become even shorter, containing only ~50 nucleotides, which provide the binding sites for the RNA replicase (Mareno and Ruiz-Mirazo, 2009). This relationship between environment and genes is generic. If extraterrestrial life exists, then the information in its inheritable molecules will also reflect the information of its environment.

## 3. The Entropic Paradox: A Low Initial Entropy Seems to Conflict with Observations

There is general agreement that life on Earth (and elsewhere) depends on the non-equilibrium of the universe (Anderson and Stein, 1987; Schneider and Kay, 1994). If stars are shining, if there is any friction, if life of any kind exists in the universe, then the second law of thermodynamics tells us that the entropy of the universe is monotonically increasing. Since the big bang, ~13.7 billion years ago, irreversible dissipative processes have been increasing the entropy of the universe. Thus, the initial entropy had to be much lower than it is today, and in the future, it will be much higher than it is today (Figs. 5 and 6).

The cosmic microwave background (CMB) radiation is almost isotropic. The temperature of this radiation is ~2.7 K in all directions. There is, however, a very low level of anisotropy. The amplitude of the temperature anisotropies are $\Delta T/T \sim 10^{-5}$ (Smoot et al., 1992). This low level of temperature anisotropy after the big bang means that the universe was close to chemical and thermal equilibrium 400,000 years after the big bang. There were no stars or planets, no hurricanes and no luminosity gradients. Density inhomogeneities were comparable to the temperature anisotropies ($\Delta\rho/\rho \sim 10^{-5}$). Thus, according to the standard accounting of entropy (which importantly does not include any term for gravitational entropy), the universe was near equilibrium and therefore near maximum entropy, not minimum entropy. All the entropy terms that we know how to compute were already close to their maximum values. With $S$ at an apparent maximum, in Eq. 1, we would have $F=0$. That is why in Fig. 5, the point labelled "observed in CMB" is in the upper left. If this were the whole story, the universe would have started near maximum entropy and nothing would have happened: no

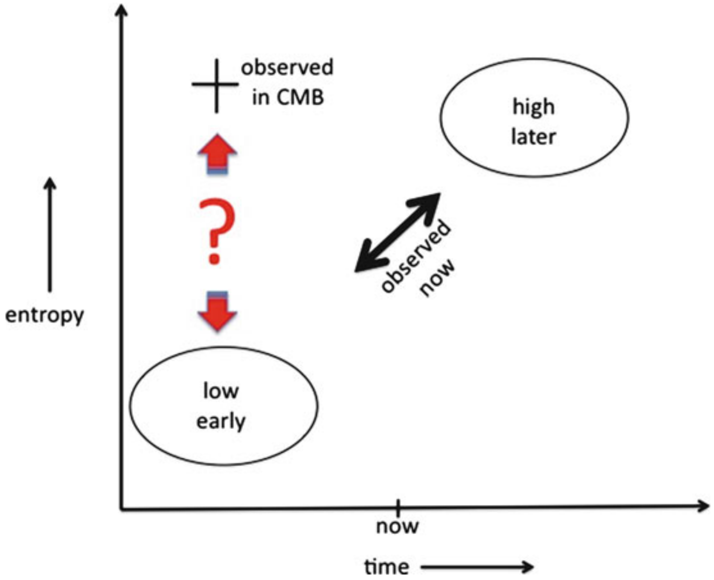

**Figure 5.** The entropic paradox. The entropy of the universe is increasing. Therefore, in the future it will be higher, and in the past it was lower. A telescope is a time machine; as we look further away, we look into the past. When we look as far away as we can, we see the cosmic microwave background (*CMB*) radiation – the afterglow of the big bang (Smoot et al., 1992). By analysing this radiation, we can see that the early universe was close to thermal, chemical and density equilibrium. That is, the entropy of the universe appears high ~400,000 years after the big bang when the CMB was emitted. Thus, a low initial entropy seems to conflict with CMB observations. There must be some component of the early universe that was at low entropy – so low that it dominated the other entropic terms.

stars, no life, no observers. An observable universe has to start in a low entropic state in order to produce structures like observers.

How can a big bang universe, apparently near equilibrium, have a low entropy? There has to be another entropy term responsible for the low initial entropy, and this term has to dominate the entropy budget of the universe because the other terms were already close to their maximum values. This is an important point. It means that all the chemical, thermal and luminosity gradients that now exist in the universe and support life are ultimately due to a poorly understood and unquantified entropic term that was initially low but which still dominated all the other terms that were close to their maximum values. The missing term is the entropy associated with gravity (cf. next section).

Figure 6 illustrates how entropy, starting at some minimal initial value $S_{ini}$, has increased over time and is approaching a maximum $S_{max}$. If $S(t)$ were now at its maximum possible value $S_{max}$, then the universe would be in equilibrium. Thomson (1852) understood this as a heat death since no heat could be exchanged – everything would be at the same temperature. The universe would be isothermal,

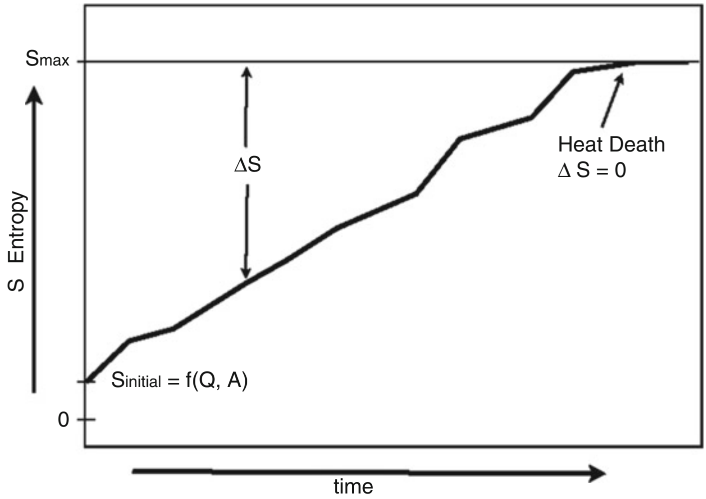

**Figure 6.** Same as Fig. 5, but constructed to show the entropy gap $\Delta S$ (Eq. 4). The second law of thermodynamics tells us that as long as life or any other irreversible dissipative process exists in the universe, the entropy of the universe $S$ will increase. Thus, the entropy of the very early universe had to have some initially low value $S_{\text{initial}}$ where "low" means low enough compared to the maximum possible entropy $S_{\max}$ so that $\Delta S$ is large and can produce and support irreversible processes (including life forms) in the universe. As indicated in the lower left of the figure, the initial entropy is some function of the parameters $Q$ and $A$ which are used to quantify the level of inhomogeneity of the cosmic density distribution (Figure from Lineweaver and Egan, 2008).

isobaric, isodensity – iso-everything. There would be no gradients, no structure, no design and no observers to see all this featurelessness. Equilibrium is a structureless, designless heat death. Since this is not yet the case, there is an entropy gap $\Delta S$ between the maximum possible entropy and the actual entropy of the universe,

$$\Delta S(t) = S_{\max} - S(t). \tag{4}$$

In Lineweaver and Egan (2008), we showed how the entropy gap is the driver of all irreversible processes.

Since $\Delta F = -T\Delta S$ (Eq. 2), solving Eq. 4 for $\Delta{\sim}S$ would yield an estimate of how much free energy is available in the universe to support life or maintain any far-from-equilibrium dissipative structure. To solve Eq. 4, we need to know $S(t)$ and $S_{\max}$. In Egan and Lineweaver (2010), we reviewed previous estimates of $S(t)$. Based on the latest observations of the mass function of supermassive black holes, we found $S(t)$ to be at least 30 times larger than previous estimates. With this new estimate of $S(t)$, $S_{\max}$ is the only important remaining unknown which we address in a paper in preparation (Egan and Lineweaver, 2012). Thus to understand the origin of design in nature, we need to understand the low initial value of the entropy of the universe and the corresponding high initial value of $\Delta S$.

## 4. Gravitational Entropy

The relationship between entropy and gravity is fundamental and poorly understood. Penrose (1979, 1987, 1989, 2004) has been concerned with the relationship between entropy and gravity for more than three decades (see also Barrow and Tipler, 1986, their section 6.15). Penrose (1979) suggested that a low gravitational entropy was responsible for the initially low value for the entropy of the universe. The low gravitational entropy of the nearly homogeneously distributed matter has, through gravitational collapse, evolved gradients in density, temperature, pressure and chemistry that provide the free energy required by life. As seen in the top panel of Fig. 7, when thermal energy dominates the gravitational binding energy, maximum entropy corresponds to an even distribution of matter. In contrast, when gravitational binding energy dominates, maximum entropy corresponds to collapse into black holes and evaporation, through Hawking radiation into photons. In other words, the low initial entropy of the early universe is explained by the even distribution of matter subject to gravitational force, which

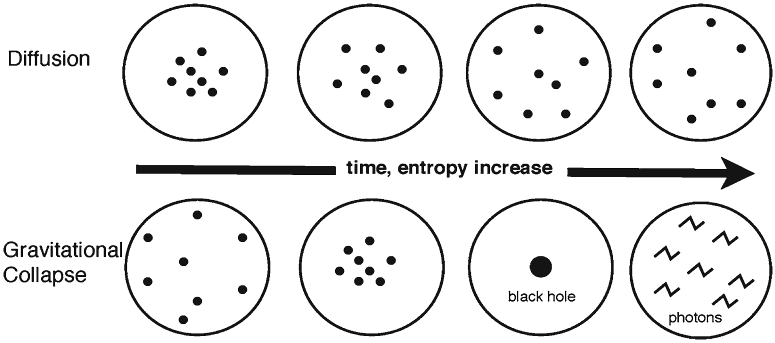

**Figure 7.** Entropy increases during both diffusion (*top*) and gravitational collapse (*bottom*). It is widely appreciated that non-gravitating systems of particles evolve towards homogeneous temperature and density distributions. The corresponding increase in the volume of momentum-position phase space occupied by the particles represents an increase in entropy. If thermal energy dominates the gravitational binding energy (*top*), then entropy will increase as material diffuses and spreads out over the entire volume (think perfume diffusing in a room). We know how to compute this phase-space entropy (e.g. Binney and Tremaine, 2008). If gravitational binding energy dominates thermal energy (*bottom*), then entropy will increase as some material and angular momentum is expelled to allow other matter to have lower angular momentum and gravitationally collapse into galaxies and stars. We do not know how to compute the entropy associated with gravitational collapse. Stars eventually collapse and/or accrete into black holes, whose entropies we do know how to compute (Bekenstein, 1973; Hawking, 1974). If the temperature of the background photons is lower than the temperature of the black hole, the black hole will evaporate to produce the maximum entropy state – a bath of photons spread out over the entire volume (*last circle in lower panel*). We know how to compute the entropy of a photon bath (e.g. Kolb and Turner, 1990). Thus, the only entropy that cannot be computed is the entropy associated with the gravitational collapse in the *left side* of the *lower panel* (which corresponds to the initial state of matter in the universe) (Figure modified from Lineweaver and Egan, 2008 and Fig. 27.10 of Penrose, 2004).

over time resulted in gravitational collapse that created the energy gradients on which life depends.

Gravitational entropy is fundamental to the evolution of the universe. It is responsible for both the low initial entropy of the universe, and it is the dominant contributor today in the form of the entropy of supermassive black holes. Previous authors have looked at the future of life (Dyson, 1979; Barrow and Tipler, 1986) and the future of astrophysical objects (Adams and Laughlin, 1997). But this fundamental concept is only poorly understood. No consensus about the ultimate future of life and dissipative processes has emerged because the relationship between gravity and entropy has remained confused and unquantified.

How can we quantify the entropy associated with density fluctuations and gravitational collapse? There is no accepted mathematical equation that relates entropy with any of the observable parameters of the initial density perturbations. Initial density perturbations in the universe have been measured (Smoot et al., 1992) as the power spectrum of cosmic microwave temperature fluctuations and as galaxy density fluctuations (e.g. Peacock, 2000). $Q \sim 10^{-5}$ is the observed normalization of the initial fluctuations. We have no mathematical formulation of the relation between the initial entropy of the universe and these measures of deviation from a homogeneous distribution of matter. We have no formula of the form

$$S_{\text{initial, grav}} = f(Q). \tag{5}$$

In addition, observational cosmologists measure and model the growth of large-scale cosmic structure as a power spectrum,

$$P(k,t) = g^2(t) A k^n, \tag{6}$$

where $k$ is inverse wavelength, $n$ is the spectral index, $g^2(t)$ is the growth factor, and $A$ is the initial normalization shown in the lower left of Fig. 6. Yet we have no formula relating $A$ to the initial entropy or the growth factor to the growth of entropy.

Much has been made of our current inability to unify general relativity and quantum mechanics to arrive at a theory of everything. Although the murky relationship between gravity and entropy may provide key insights into the theory of everything, it has received much less attention. Gravity is almost universally ignored in thermodynamics textbooks. What is known about the relationship between entropy and gravity is similar to what was known about the relationship between energy and heat 200 years ago when the concept of energy conservation in thermodynamics was being developed. It took many decades for the different forms of energy (e.g. potential, kinetic, heat) to be recognized. It seems to be taking even longer to recognize and define the different forms of entropy. The relationship between information entropy (Shannon, 1950) and thermodynamic entropy has been partially clarified (Dewar, 2003; Brissard, 2005). But we still need to clarify and quantify the relationship between gravitational entropy and the other forms of entropy.

## 5. Inflation, Baryon Non-conservation, and the Homogeneous Distribution of Matter After Reheating, as the Sources of Free Energy

In the last 30 years, to extend the big bang models to earlier times and solve several problems, quantum cosmologists have constructed inflationary scenarios. In these models, the low amplitude initial density fluctuations that have been observed at large scale in the cosmic microwave background radiation, have their origin in irreducible vacuum fluctuations of a false vacuum also known as the inflaton potential (Lineweaver, 2005). Inflation can occur either at the Planck time ($10^{-43}$ s after the big bang) or at the GUT scale ($10^{-35}$ s after the big bang). At the end of inflation is a period called reheating, in which all the energy of the false vacuum is dumped into the universe (Kofman et al., 1994). Matter and anti-matter particles annihilate. However, because of baryon non-conservation and non-equilibrium conditions described by Sakharov (1967), there was a slight excess of baryons over anti-baryons (Dolgov, 1997; Quinn and Nir, 2008). If there were not, all of the matter and anti-matter dumped into the universe at reheating would have annihilated and turned into radiation. Thus, the universe would have started off in a maximum entropy state and stayed that way (Lineweaver and Egan, 2008) – and we would not be here to think about it. However, there was a slight excess of matter over anti-matter, and so the result of reheating in combination with baryon non-conservation was to spread matter more or less homogeneously throughout the universe. Since this corresponds to low gravitational entropy, the universe starts off with a large entropy gap $\Delta S$ and lots of free energy, which, on its way to waste heat, can produce and maintain (for a while) all the complex, differentiated structures in the universe.

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Biodata of **Atilla Grandpierre**, author of "***On the Biological Origin of Design in Nature***."

**Dr. Attila Grandpierre** is currently a senior scientific researcher at the Konkoly Observatory of Hungarian Academy of Sciences. He obtained his degree of university doctor in 1977 from the Eötvös Lóránd University and his academic degree candidate of physical sciences in 1984 from the Hungarian Academy of Sciences, and continued his research at the Konkoly Observatory.

Dr. Grandpierre's scientific interests are in the areas of astrobiology, philosophy of science, origin of solar activity, the Sun as a self-organizing system and as a system showing lifelike activities, non-protein-based life-forms in the universe, and first principles of physics and biology. His pioneering work on the dynamism of the solar core is reported extensively in the New Scientist. He was the organizer of the international conference "Astronomy and Civilization" and a coeditor of the conference proceedings (2011). In 2011, he was a visiting professor at the Chapman University, California for half a year.

E-mail: **grandp@iif.hu**

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# ON THE BIOLOGICAL ORIGIN OF DESIGN IN NATURE

**ATTILA GRANDPIERRE**
*Konkoly Observatory of the Hungarian Academy of Sciences,*
*P.O. Box 67, H-1525 Budapest, Hungary*

## 1. Design and Teleology

As the Oxford English Dictionary indicates, design is "a mental plan" or a "purpose, aim, intention." Therefore, design seems to be closely related to teleology. Perhaps the most transparent version of design is the type that is created by man, like the one that is manifest in machines. In a machine, design is manifest in its structure, namely, in its materially manifest "plan" or "working principle," which controls the function of the machine. Actually, the "working principle" can fulfill the prescribed function only by harnessing the physical laws; that is, machines manifest a dual control—one is exerted by their design, and the other is by the physical laws. Certainly, the design of machines is teleological since machines by their very nature are controlled by human purposes: a car is designed to be suitable for transport, a watch to show the time, etc. What can we know about the nature and origin of the underlying control, the one realized by the physical laws? Physical laws in physics are regarded as the fundamental basis of physical reality. This means that physical laws play an important role in the ontological structure of the universe. Therefore, understanding the origin of control by physical laws requires the exploration of the ontological structure of the universe. Indeed, it is required by the fact that in the concept "design in nature," the teleological aspects of physical reality play a basic role.

We are interested here in the scientific aspects of natural phenomena or man-made facts that are usually referred with the term "design." At present, it seems that from the basic natural sciences, physics, biology, and psychology, only physics is a mature and exact science. Regarding the general view that teleology is widely regarded as being "contrary to the whole orientation of theoretical physics" (Yourgrau and Mandelstam, 1960, 154), the scientific study of "design" in nature seems to be problematical in the usual conceptual framework of physics. Yet our aim is to approach this problem with the most exact tools of science. As a preliminary step, let us consider the question: Is there any scientific basis for the general belief in the "design" of the universe?

"The belief in a purposive power functioning throughout the universe (…) is the inevitable consequence of the opinion that minimum principles with their distinctive properties are signposts towards a deeper understanding of nature and not simply alternative formulations of differential equations in mechanics (…)"

(Yourgrau and Mandelstam, 1960, 154). In the last decades, it is more and more recognized that the least action principle plays a central and comprehensive principle of all the fundamental branches of modern physics (Landau and Lifshitz, 2000, 2–3; Feynman et al., 1964, Vol. 2, 19–4; Moore, 1996, 2004; Brown, 2005, x; Taylor, 2003). Actually, it is well known that all the fundamental physical laws (i.e., the laws of classical mechanics, hydrodynamics, electromagnetism, thermodynamics, theory of gravitation, and quantum physics, including quantum field theories and string theory) are derivatives of one and only one deeper-level law—namely, the *least action principle.* It has been remarked (Taylor, 2003) that the least action principle lies at the foundation of contemporary theoretical physics. "The action principle turns out to be universally applicable in physics. All physical theories established since Newton may be formulated in terms of an action. The action formulation is also elegantly concise. The reader should understand that the entire physical world is described by one single action" (Zee, 1986, 109).

Now, if the action principle is so fundamental, and if its property of being a minimal principle is crucial for the deeper understanding of nature, as Yourgrau and Mandelstam claim, then why is it that teleology is regarded as being "contrary to the whole orientation of theoretical physics"? One point is the appearance that "the action is not always the least, like in the case when the particle may move between two points on the ellipse in either of two paths; the energy is the same in both cases, but both paths cannot have the *least* possible action." On that basis, Yourgrau and Mandelstam were quick to conclude: "Hence the teleological approach in exact science can no longer be a controversial issue; it is not only contrary to the whole orientation of theoretical physics, but presupposes that the variational principles themselves have mathematical characteristics which they *de facto* do not possess. It would be almost absurd to imagine a system guided by a principle of purpose in such a manner that sometimes, not always, the action is a minimum" (ibid., 155). Yet we point out that the action principle in its usual form considered by Yourgrau and Mandelstam is restricted to holonomic systems, that is, systems whose geometrical constraints (if any) involve only the coordinates and *not the velocities*; therefore, the conclusion of Yourgrau and Mandelstam does not apply to the case they refer to. After all, it is a simple thing to see that a particle with any given initial velocity cannot start in the opposite direction; therefore, there is no such case "when the particle may move between two points on the ellipse in either of two paths," assumed by Yourgrau and Mandelstam (ibid.). If this is the crucial argument underlying the widespread opinion against teleology in physics, then it does not follow that teleology must be exiled from physics. Therefore, we have to reconsider the problem.

It is true that teleology is not visible at the level of observable phenomena or of physical laws. Indeed, the fundamental differential equations are time symmetric, and so they avoid teleology. Yet at the level of the action principle, teleology is explicitly manifest. In the usual formulation of classical action principles, the initial and final states of the system are fixed and are formulated as follows: Given that the particle begins at position $x_1$ at time $t_1$ and ends at position $x_2$ at time $t_2$, the physical trajectory that connects these two endpoints is the one that makes the action stationary. "The method does not mean anything unless you consider paths which all begin and end at the same two points. So the deviations have to be zero at each end. With that condition, we have specified our mathematical problem" (Feynman et al., 1964, Vol. 2, 19–4).

For our present purposes, it is enough to realize that teleology (see the entry "teleology" in the Encyclopedia Britannica) is defined as "explanation by reference to some purpose or end." Definitely, the least action principle is based on a relation between some initial and final state; therefore, reference to some end (attention: not necessarily to a purpose)—namely, to a subsequent, final physical state—is already explicitly present. Variational principles are "the contemporary descendants of final cause" (Brown, 2005, x). We can observe that Yourgrau and Mandelstam misinterpreted physical teleology as "purpose" (these are widely different concepts!) and were wrong when claiming that the action principle does not possess teleology. Now, if a kind of teleology is present already in physics, the general opinion that its companion, design, must be "naturalized" (explained in terms of physical forces as effective causes) in order to become scientifically acceptable is also based on a wrong premise.

## 1.1. MECHANISM AS A WORLDVIEW AND THE RELATED CAUSAL LEVELS OF NATURE

In the last centuries, science as well as philosophy of science has been dominated by the idea of *mechanism*. Apparently, the "mechanism worldview" was formulated as a bedrock of scientific method by Henry Oldenburg, the first secretary of the influential Royal Society, who claimed that all phenomena can be explained exhaustively by the mechanical operation of physicochemical forces (Oldenburg, 1661; Henry, 1988). Physical forces can arise as effects of causes arising at two basic levels: (1) due to interactions between physical objects (which are, of course, mediated by physical laws) and (2) interactions between physical objects directly with the physical laws. A third element is also allowed: (3) "random," "spontaneous," or "acausal" phenomena. Examples are collision of physical objects (1), free fall (2), and radioactive decay or spontaneous emission (3).[1]

Indeed, "almost all physicists who work on fundamental problems" accept that "the laws of physics stand at the base of a rational explanatory chain, in the same way that the axioms of Euclid stand at the base of the logical scheme we call geometry" (Davies, 2004). Yet to take into account the action principle in our explanatory scheme requires an extension of the above-cited, two-leveled

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[1] In quantum electrodynamics, radioactive decay as well as spontaneous emission and similar processes are elicited by virtual interactions. In that way, class (3) causes become involved into class (1).

explanatory scheme, and to indicate whether the action principle offers us a deeper understanding of nature or not.

## 1.2. DESIGN OF THE UNIVERSE AND ITS APPARENTLY NECESSARY NATURALIZATION

A significant attempt of modern physics seeks answers to the origin of physical laws trying to "naturalize" the possible answers (Wheeler, 1994; Hartle, 1991; Davies, 2006), explaining them in terms of "randomness" (Davies, 2011) or by such a highly speculative idea as the "multiverse" (e.g., Hawking and Mlodinow, 2010). Now "a strong motivation for introducing the multiverse concept is to get rid of the need for design, this bid is only partially successful. Like the proverbial bump in the carpet, the popular multiverse models merely shift the problem elsewhere – up a level from universe to multiverse" (Davies, 2011).

We point out that the aim of science, since at least Plato, is to find the minimal number of ultimate principles which are able explain observable phenomena. In this chapter, we carry out this program and explore this road in two steps, obtaining a new, more deeply penetrating and more completely comprehensive explanatory scheme than the one in which "the laws of physics stand at the base of a rational explanatory chain." In our essentially complete explanatory scheme of nature, the first principles of physics, biology, and psychology stand at the base of a rational explanatory chain.

## 1.3. THE ESSENTIAL SURPLUS OF THE ACTION PRINCIPLE OVER THE PHYSICAL LAWS

It is a widespread opinion that the least action principle is strictly equivalent with the differential equations derivable from it (Yourgrau and Mandelstam, 1960, 156). At variance with this unsubstantiated claim, we point out that the at-present best explanation of the least action principle, Feynman's sum-over-histories approach (Feynman et al., 1964, Vol. 2, 19–4; Feynman and Hibbs, 1965; Brown, 2005), contains definite surplus beyond the differential equations derivable from it. "There is quite a difference in the characteristic of a law which says a certain integral from one place to another is a minimum – which tells something about the whole path – and of a law which says that as you go along, there is a force that makes it accelerate" (Feynman et al., 1964, Vol. 2, 19–8). "It isn't that the particle takes the path of the least action but that it smells all the paths in the neighborhood and chooses the one that has the least action by a method analogous to the one by which light chose the shortest time" (ibid., 19–9). The essential surplus elements are the following: One is the selection of the endpoint corresponding to the least action principle in the given situation, another is exploring all possible paths in the universe[2] (Taylor, 2003), and the third one is the activity of summing up the probability amplitudes of each explored path.

It seems that reality is even more surprising than the presence of an automatic, physical teleology: How is a quantum able to explore all paths in the universe? How is it able to select its endpoint from the gigantic zoo of all possibilities? And how is it able to execute any activity, especially such characteristically intellectual activity like summing up the obtained gigantic amount of information? The answers lead to infinite dimensional Hilbert spaces, where the wave functions exist, and to virtual particles of the quantum vacuum, the physical manifestations of the action principle (Grandpierre, 2007). In our more complete explanatory scheme, a new class of possible physical causes seems to be also available: class (4), containing the first principles, namely, the least action principle of physics, the Bauer principle of biology, and the first principle of psychology.

## 1.4. SCIENTIFIC EXPLANATION BY FIRST PRINCIPLES: THE ONTOLOGICAL STRUCTURE OF NATURE

We indicate here that the "mechanism" view gives a partial picture of nature, and as such, it can be misleading. We present here the first essentially complete scientific picture of nature, improving what has been considered till now as the "best model of human knowledge," built up on the basis of the Aristotelian model of scientific induction and empiricism by Kepler, Galilei, Bacon, and Newton (Hooker, 1996). Acknowledging about the fundamental significance of the first principle of physics, we allow it to represent a third and ultimate explanatory level of physical reality. Instead of physical laws, as in the explanatory scheme of the mechanism view, we recognize the least action principle as the natural end of any physical explanation since all the fundamental laws arise from it. In our new, broader picture, the universe consists of three fundamental ontological layers: the levels of phenomena, of the laws of nature, and of first principles, representing the surface, depth, and core of nature, respectively.

## 1.5. ON THE NECESSITY TO INTRODUCE THE BIOLOGICAL PRINCIPLE INTO SCIENCE

It is not generally known that the behavior of biological organisms is governed also by a "first principle," which is the Bauer principle (Bauer, 1967; Grandpierre, 2007).

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[2] In the double-slit experiment, Feynman's ideas mean the particles take paths that go through only one slit or only the other; paths that thread through the first slit, back out through the second slit, and then through the first again; paths that visit the restaurant that serves that great curried shrimp, and then circle Jupiter a few times before heading home; and even paths that go across the universe and back. Feynman's formulation has proved more useful than the original one (Hawking and Mlodinow, 2010, 45–46).

The Bauer principle is the first principle of biology since it is mathematically formulated, giving quantitative account of all basic phenomena of life, including metabolism, regeneration, growth and death (Bauer, 1967, 119–132), reproduction (ibid., 133–158), adaptation, and response to stimuli, substantiated by experimentally determined basic relations (ibid., 159–183)—as well as determining the basic law of evolution (ibid., 184–198). The Bauer principle tells that "The living and only the living systems are never in equilibrium; they unceasingly invest work on the debit of their free energy budget against that equilibration which should occur for the given the initial conditions of the system on the basis of the physical and physico-chemical laws" (Bauer, 1967, 51; Grandpierre, 2008a). Its introduction is necessary since no physical theory explains the basic life phenomena as well as biological behavior at the level of the organism, including such observables as the gross behavior of a living bird dropped from a height (Grandpierre, 2007), or the simple action of bending a finger. The complexity of the living organisms, as it is widely acknowledged, is intractably large in the bottom-up approach of physics. A still bigger problem is that this complexity is not static. It changes from time step to time step. Such structural changes are regarded as random in thermodynamics. Yet in biology, these structural changes are not random, but change systematically and consequently and sum up in a complex way which is governed by the Bauer principle. It was shown that this fundamental biological principle can be formulated in terms of physics as the greatest action principle (Grandpierre, 2007). Therefore, biology shows the same explanatory structure as physics: Phenomena can be explained by laws, and all basic biological laws can be derived from the first principle of biology. Based on the newly found fundamental explanatory structure of physics and biology, we postulate that the ontological structure of the universe represents a hierarchical order: Observable phenomena are governed by laws, and laws by first principles. If so, psychology must also have a first principle.

## 1.6. ON THE NECESSITY TO INTRODUCE THE PSYCHOLOGICAL PRINCIPLE INTO SCIENCE

Let us consider a simple example to shed light on the nature of physical, biological, and psychological causes of natural processes. Why did I jump into the air? Let us approach this problem in two steps. (1) A physicist can claim that I jumped into the air because a physical force had arisen between my foot and the ground. Yet this explanation indicates a further question: Why did these physical forces arise? The answer can be given by the biologist: because biological processes like induction of biocurrents or neural voltage (excitations, action potentials, electric gradients) have been generated and form a system of stimuli extending from the neurons through the nerves to the muscles, making them contract. But then a further question arises: Why did the neurons become excited? The answer a psychologist (a scientist of self-conscious decisions) would likely give is that the neurons were agitated because a willing, self-conscious agent made a decision—in this case, to jump in the air. Apparently, this simple example indicates that the physical explanation by mechanism does not exhaust the problem nor does it exclude the need for a biological or psychological explanation.[3] (2) Of course, the physicist can point out that the generation of the neural voltages and their propagation towards the muscles corresponds to material processes (like ion transfer) which are determined by physical laws. But this claim is only partially true; the generation and coordination of an immense number of elementary biocurrents into a biologically meaningful system of neural processes cannot be *explained* by physics; physical equations do not allow to *predict* them, simply because they serve a *biological* aim, and that aim governs the whole process from its generation to its final manifestations. If so, how are the first neural voltages generated? This is a crucial problem: How can our allegedly immaterial, unobservable decisions elicit material, observable consequences?

## 1.7. SPONTANEOUS PROCESSES ARE TRIGGERED BY VACUUM FLUCTUATIONS

Answering that crucial problem, we note that we found apparently unnoticed loopholes in physical determinism regarding the significance of spontaneous processes. For example, in spontaneous radioactive decay, it is impossible to determine which atom will be the "next" to decay. By our best present understanding given by quantum field electrodynamics, spontaneous emission and similar processes are due to vacuum fluctuations, that is, virtual interactions (Milonni, 1994), and are not determined at the level of differential equations. In our understanding, such virtual interactions act on a deeper level than the laws of nature, at the generative, principal level of nature, where the action principle acts, and it acts through virtual interactions.

We found that the biological principle, the natural extension of the least action principle, works in a similar manner: by virtual interactions. These virtual interactions represent the interface between "nothing" and "matter"; they can trigger physically spontaneous, that is, physically undetermined, phenomena, such as the spontaneous emission of photons, whereby photons activate biomolecules, triggering spontaneous couplings between endergonic and exergonic processes (Grandpierre, 2008a). Certainly, the biological principle can organize physical

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[3] It is easy to observe that the different kinds of explanation of "why did the frog jump into the water?" given by Rose (1997, 10–13, 85–97) missed the target of obtaining a clear and complete picture regarding the nature of causation in nature. At variance of his five types of explanations, all the three causes we indicated here are actual causes, and all of them correspond to a generative principle of reality, which form an essentially complete system of nature.

conditions, the input elements for physical laws, into suitable sequences for successfully fulfilling biological needs and ends. The suitably organized input conditions can lead with the help of physical laws to biologically useful output, like in the case when we bend our little finger. We are led to the insight that biology is the control theory of physics.

## 1.8. THE EXAMPLE OF THE DROPPED BIRD

Let us illustrate this point with the following example. A live bird dropped from the Pisa tower manifests a characteristically different trajectory than other physical objects dropped from the same location. It is customary to think that the reason for this difference lies in the extreme, intractable complexity of the living bird relative to that of the sorts of objects dropped by Galileo—stones, cannonballs, compacted feathers, etc. Such objects fall uniformly, in "free fall."

Yet the case is different with the complex, living bird. For it can accomplish the feat of regaining its height to the point where it was originally dropped from the Pisa tower, and it can do so without changing its own vital, *specific complexity* during the process. Although all the vital aspects of the bird's complexity prevail, some other aspects of the bird's complexity must change, like the position and shape of its wings or tail. This process unfolds in a highly specific, time-dependent manner. Though the bird is not changing its "vital complexity," it invests work to change the position of its wings and tail in each instant in a way which, instead of being random or sporadic, is continuous and above all consequent. One change comes after another, in such a way that they quickly sum up to an increasing deterioration from the path expected on the basis of physical laws, given the same initial conditions. We must also take into consideration the given initial conditions of the bird: There is a biological principle generating and governing the internally initiated modifications of the physical conditions on which the physical laws exert their influence. The bird harnesses the physical laws and evidently does so with the utmost ease.

The question is: How is this possible? To answer, we are led back to the first principles. How do the first principles exert their physical role? And how does the biological principle act, if all living organisms consist of material particles, and all of these are governed by the physical laws? It seems that "there is simply no 'room at the bottom' for the deployment of additional 'downwardly mobile' forces if the physical system is already causally closed. Thus a typical closed and isolated Newtonian system is already completely determined in its evolution once the initial conditions are specified. To start adding top-down forces would make the system over-determined. This causal straightjacket presupposes the orthodox idealized view of the nature of physical law, in which the dynamical evolution of a physical system is determined by a set of differential equations" (Clayton and Davies, 2006, 46).

## 1.9. IS THERE A ROOM AT THE BOTTOM?

We indicate that the two-leveled mechanism view of the nature of physical world would not allow "room" even for the activity of the least action principle, which, as we suggest here, is the very bedrock of all fundamental physical laws themselves. In contrast, we point out that there exists an immense realm of physically not completely determined possibilities—for example, spontaneous emission or absorption, fluctuations, instabilities, chaotic phenomena, or spontaneous energy focusing (Martinás and Grandpierre, 2007). We propose that these "holes" in physical determinism allow the generation of significant changes in the observable behavior of living organisms, which are extremely complex systems far from thermodynamic equilibrium. Extreme complexity is necessary in order that the "hole" in physical determinism be sufficiently large, so that spontaneous reactions can dominate the system. Being far from thermodynamic equilibrium is necessary in order for spontaneous processes to lead to macroscopic changes. In suitably organized, complex and far-from-equilibrium systems, an immense number of couplings are possible between quantum states having a large nonequilibrium energy, by spontaneous emission and spontaneous absorption processes between an immense number of spontaneous exergonic (energy-liberating) and endergonic (energy-consuming) reactions; these latter ones require activational energy.

With the help of an illustrative example, biological couplings are like the performance of acrobats in a circus. One *acrobat jumps down onto one end of a seesaw, and another performer standing on the other end of the seesaw gets launched into the air*, and so the otherwise fast equilibration process of the exergonic process that should set up within the individually given initial conditions plus the physical laws will be postponed in the presence of the coupling. In a living organism, an immense number of "acrobats," that is, spontaneous processes triggered by virtual interactions, are coupled by an immense number of "seesaws" (seesaws are simple mechanical machines; living organisms can apply complex nonmechanical "machines" as well) to thermodynamically uphill, biologically useful processes, to realize biological endpoints.

Therefore, although the "bottom-up" view simply regards that biological behavior is "obscured" by the "untractable" complexity of living beings (Vogel and Angermann, 1984, 1), it is possible to shed more light to these depths of complexity. We found that this time-variable complexity is governed by the biological principle.

## 1.10. THE SOLUTION OF THE MIND-BODY PROBLEM AND THE NATURE OF BIOLOGICAL CAUSES

We note that quantum electrodynamics (QED) is able to give account of the generation of "matter" in quantum processes: QED is able to describe quantitatively the generation and annihilation of particles and antiparticles from the vacuum, which is a "sea" of spontaneously generated virtual particles (e.g., Davies, 1984, 104–106; Milonni, 1994, xv). Therefore, the solution of the mind-body problem—namely, the generation of biocurrents by means of decisions—has a plausible solution: Biocurrents can be generated through virtual particles, through quantum-vacuum interactions (Grandpierre, 1995) that serve biological aims. This is not forbidden but, instead, explicitly allowed by the physical laws. The term "spontaneous" means something not completely determined by physics.

We found not only that biology is an autonomous science having its own first principle but also that this biological principle acts in the same way as the least action principle, namely, through virtual interactions mediating between the biological principle and the material world. Spontaneous processes provide scope for the biological principle to act upon physically not completely determined, spontaneously arising possibilities, so to serve biological ends such as well-being, happiness, survival, as well as routine tasks like biological functions.

## 1.11. HOLES IN DETERMINISM: CONCRETE EXAMPLES

Now let us offer some more concrete insights into the nature of "holes in determinism." For example, Jacob and Monod (1961) discovered that *there is no chemical necessity about which inducers regulate which genes* (Monod, 1974, 78). "The result—and this is the essential point—is that so far as regulation through allosteric interaction[4] is concerned, everything is possible. An allosteric protein should be seen as a specialized product of molecular "engineering" enabling an interaction, positive or negative, to take place between compounds without chemical affinity, and thereby eventually subordinating any reaction to the intervention of compounds that are chemically foreign and indifferent to this reaction. The way hence in which allosteric interactions work permits a complete freedom in the "choice" of controls (ibid., 78–79). On such a basis, it becomes possible for us to grasp how in a very real sense the organism effectively transcends physical laws—even while obeying them—thus achieving at once the pursuit and fulfillment of its own purpose" (ibid., 81). This means that the *functional* properties of proteins are determined by nonphysical, that is, *physically arbitrary*, processes. It is this arbitrary nature of molecular biology that Monod calls "gratuity."

The basic importance of physically arbitrary processes is frequently acknowledged (e.g., Hunter, 1996; Barbieri, 2002; Yockey, 2005, 6). Maynard Smith (2000) emphasizes the profundity of Monod's idea. He proposes to call the terms for

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[4] In biochemistry, allosteric regulation is the regulation of an enzyme or other protein by binding an effector molecule at the protein's allosteric site (i.e., a site other than the protein's active site).

inducers and repressors “symbolic” since there is no physicochemically necessary connection between their form (chemical composition) and meaning (genes switched on and off), just as in semiotics, where there is no necessary connection between the forms of the symbols and their meaning. For example, histidine is coded by the triplet CAC (C stands for cytosine) in the DNA. Maynard Smith calls attention to the fact that *there is no chemical reason* why CAC should not code for glycine instead of histidine. Maynard Smith argues that it is the symbolic nature of molecular biology that makes possible an indefinitely large number of biological forms.

We found that there is a room “at the bottom,” and the biological principle can act on matter, making the existence of organismic order, teleology, and design plausible. Now let us evaluate some relations between phenomena, laws, and first principles.

## 1.12. RELATION BETWEEN PHENOMENA, LAWS, AND FIRST PRINCIPLES

The whole presently observable universe is generated into material existence by deeper-level laws of nature. “Given the laws of physics, the universe can create itself. Or, stated more correctly, the existence of a universe without an external first cause need no longer be regarded as conflicting with the laws of physics.… This makes it seem as if the laws of physics act as the ‘ground of being’ of the universe. Certainly, as far as most scientists are concerned, the bedrock of reality can be traced back to these laws” (Davies, 1992, 73). Such general views underpin our argument above, which states that all physical phenomena are rooted in laws and, ultimately, in first principles.

Now let us consider the relation between the physical and biological principle. Here we can only indicate that the greatest action principle of biology can fulfill its role only when, after selecting the endpoint according to the greatest action, this endpoint is realized by the least action principle. Illustrating it with an example, a bridge-constructing company wanting to reach the maximum output in a year (corresponding to the greatest action principle), after deciding about the concrete bridges, must build them with the least cost (corresponding to the least action principle), in order that it can reach the maximal output. We can observe that there is a possibility to interpret the relation between the biological and physical one as being such that in a logical sense, the biological principle precedes the physical one. If so, it can be the most ultimate principle of the universe, from which the physical principle arises. “Bauer’s dream of theoretical biology was similar to Einstein’s goal in physics to create a single equation that encompasses the ‘Essence of Nature,’ from which all physical phenomena can be derived” (Tokin, 1988). The above argument seems to underpin that Bauer’s dream can be realized.

## 2. Natural Classes of Teleology

### 2.1. DIFFERENT CLASSES OF NATURAL TELEOLOGY

Teleology has played a significant role in the history of physics (Barrow and Tipler, 1986) and philosophy. Physico-teleology was considered by Leibniz and Kant. *Physical teleology is independent of physical objects*, not only because the endpoint of the trajectory is not selected by the physical object itself, but also because the physical object does not contribute actively to the selection of its trajectory. Indeed, mathematically, different trajectories can have the same endpoints. In biology, the endpoint is characteristically selected by the greatest action principle; therefore, at first sight it may seem that biological teleology is also independent of the system considered. Yet, even if this is true, living organisms actively participate in the realization of their trajectory. First of all, usually the endpoint is not unequivocally determinable, since an immense number of processes occur in a living organism in many timescales simultaneously. Therefore, it is necessary that the living organism itself selects the processes requiring endpoint selection. Moreover, the organism can select the timescale on which the action should be maximized. Additionally, there is a possibility that the organism can select the context of maximization, with respect to its individual or communal life. Moreover, the commitment to the biological principle is not as strict as in physics. While all physical objects must obey the physical laws as secured by the coercive physical forces, there are no such coercive forces in biology. And so living organisms can manifest different degrees in their commitments to the biological principle. At the one end of the scale, they can live their life with almost full vitality; at the other end, they can commit suicide like lemmings. Even in cases when the commitment to the biological principle is strong, as is usually the case, living organisms must contribute to the selection and realization of their trajectory because in biology, many different, biologically possible trajectories can lead to the same endpoint. For example, a bird dropped from a height has many degrees of freedom to select the direction and the form of its trajectory, even when the endpoint is already selected. The biological principle prescribes only one requirement: “Regain your vitality!” All the other parameters, for example, whether the dropped bird selects a trajectory towards north or south, are indifferent for the biological principle and are determined by the organism itself. Therefore, considering biological behavior from different angles, we can find biological teleology either dependent or independent from the considered living organism. This circumstance goes far to explain why viewpoints regarding biological teleology are so controversial.

### 2.2. OBJECTIONS AGAINST TELEOLOGY

Now let us see somewhat more concretely the objections against teleology based on Mayr (1988, 40), who summed up the traditional objections against teleology in four reasons, namely, (1) teleology is based on vitalism, which is an unverifiable theological or metaphysical doctrine in science; (2) final causation is incompatible with the mechanistic explanation by physical laws; (3) final causation represents a backwards causation; and (4) teleology is a form of mentalism.

## 2.3. DEFENSE OF TELEOLOGY

Regarding (1), the argument against neovitalism is summed up by Hempel (1966, 72) in the following form. The doctrine of entelechy is not definite enough to permit the derivation of specific implications concerning the phenomena that the theory is to explain. It does not indicate under what circumstances entelechy will go into action and, specifically, in what way it will direct biological processes. This becomes clear when we contrast it with the explanation of the regularities of planetary and lunar motions by means of the Newtonian theory. Notwithstanding, instead of unscientific concepts like "entelechy" or mystic "God," we worked out exact scientific concepts like the greatest action principle, formulated it in mathematical form, and applied it to yet unexplained phenomena (Grandpierre, 2007). Regarding (2), we have shown above that final causation is not only compatible with the mechanistic explanation but is the only means to explain biological behavior at the whole organism level. Regarding (3), already Nagel (1979, 278) pointed out that the agent's wanting a goal acts contemporaneously with the initiation of biological behavior; therefore, it does not represent "backwards causation." Regarding (4), we argue in this chapter that mentalism corresponds to a type of teleology that is not present in physics. This last point requires a suitable classification of teleologies occurring in nature.

## 2.4. A NEW CLASSIFICATION OF TELEOLOGICAL TYPES BASED ON THE PHYSICAL APPROACH

Appreciating the achievements of physics in becoming the first exact natural science, and aspiring to a similar achievement regarding biology and teleology, we will categorize teleology on the basis of theoretical physics, but, as necessary, expanded by a minimal step allowing endpoint selection corresponding to the greatest action principle. Therefore, as a starting point, we consider the fact that the two fundamental factors governing physical processes are (a) the input (i.e., initial and boundary) conditions and (b) the physical laws. On this exact physical basis, natural behavior can be categorized into the following classes:

(A) The simplest case: The input data are few and fixed, corresponding only to the initial state $t = t_0$. This is the usual case in physical problems. Since the input conditions are simple, the relative complexity of the physical laws is large, and therefore the arising behavior is considered as determined by the physical laws (A1). (A2): The input data can be many and variable in time but simple in a sense that they average out to the arising physical behavior. This is the statistical case.

(B) The input conditions are complex but fixed and do not average out. The simplest case is (B1) in which the input conditions are built in into the physical object in a form of a prefixed scheme, like in the structure of machines or in programs of robots. The behavior of these machines is continuously determined by this basically fixed input (structure, blueprint, or design) plus the physical laws. Even learning robots are always governed by external inputs plus physical laws. Machines are artifacts representing a fixed human purpose to solve a task. Similarly, biological organisms regularly meet in their normal life with the same type of tasks to be solved, such as respiration, digestion, moving the body, etc. These routine biological tasks are solved by functions (B2) of lungs, stomach, muscle, etc. Biological functions significantly modified in their history by natural selection can contribute to the development of adapted features. Biological functions and adapted features represent natural design.

(C) The input conditions to the physical laws are not prefixed but variable in time and contribute to the arising nonphysical behavior. The system continuously changes the internally generated input conditions of the physical laws in order that the output serving varying biological needs can change in a manner corresponding to the greatest action principle. Serving biological needs within changing conditions requires a capability to solve newly arisen problems—in other words, creativity. Type (C1) of biological behavior corresponds to the case when the endpoint of the trajectory is determined by the biological principle. In such cases, the distance of the organism as a whole from thermodynamic equilibrium, which decreases due to the continuously occurring physical processes, is regained, due to biological processes. In the prototype case of a dropped bird, (C1) corresponds to the fact that the bird regains its original height. Teleology of the class (C2) of biological behavior is an aspect of biological behavior which is determined by the autonomous decisions of living organisms. In the case of a dropped living bird, (C2) corresponds to parameters forming other points of the trajectory besides the endpoint, which are determined by the bird itself. Instead of one parameter, the distance of the endpoint of the given process from equilibrium, class (C2) corresponds to other degrees of freedom. The difference between (B2) and (C2) can be illustrated when one considers different aspects of the same biological behavior: the nonautonomous in case (B2) and the autonomous in case (C2). Class (C3) biological behavior corresponds to cases in which the organism can autonomously select, not only the special trajectory corresponding to the given endpoint, but also can contribute to decisions respecting the context and timescales in which its distance from equilibrium can be regained. That is, although the endpoint in a sense is determined by the biological principle (in our example, the dropped bird striving to regain its height above the equilibrium), living beings also have a certain autonomy in selecting the important processes and timescales involved in maximizing distance from equilibrium. Autonomous interpretation of the different contexts (short- and long-term, individual and communal) of the biological principle enables determination of the controllable aspects of autonomous behavior, which in turn can lead to the development of systematically self-conscious behavior to self-conscious goals. The same biological behavior seen in the bending of a finger can be classified as (C2) if it occurs without self-conscious control, "instinctively" or consciously, but it belongs to (C3) if it is a result of a self-conscious decision. In the language of teleology, physical laws refer to "ends," biological ones to "aims," and psychological ones to "goals." The common term comprehending all three together is "telos." Isolated from its system, the heart seems not to have a goal nor an aim, yet as an integrated part of the whole system, it corresponds to an overarching, fundamental biological aim—its function, pumping blood, corresponds to a biological aim of the organism as a whole.

One can see that this new classification is logically systematic and extends to all types of possible behaviors: physical, biological, and psychological. If so, it can be regarded as the first complete scientific classification of behaviors and teleologies. Yet in science, a suitable quantitative measure is inevitable.

## 2.5. THE MEASURE OF TELEOLOGY: ALGORITHMIC COMPLEXITY

Now let us look for a suitable measure of complexity on the basis of which one can distinguish easily between classes of teleology (A), (B), and (C). Behavior belonging to class (A) is usually regarded as simple, without notable complexity. Yet if we compare the complexity of the physical laws when they are the dominant factors in the governance of behavior, with the complexity of the simple input (i.e., initial conditions), we recognize the complexity of the physical laws can be assessed in terms of algorithmic complexity. Acknowledging the control of physical laws over natural phenomena, we noted above (Sect. 1.3) that in comparison to the mathematical laws, physical laws represent a measure of control, and now we add that this control represents a complexity that can be measured in terms of algorithmic complexity and expressed in measuring units of bits.

In general, the solution of a task requires two kinds of procedures: one leading towards the end step by step, involving a finite number of steps, and one which requires an infinite number of steps. In computable cases, the problem can be formalized and solved in a finite number of steps. The minimum number of steps is a good measure of the complexity of the problem. Indeed, Kolmogorov (1965) and Chaitin (1966) suggested defining the information content of an object as the length of the shortest program computing a representation of it. *The algorithmic complexity* of a mathematically described entity is defined as the length of the shortest program computing a representation of this entity. Since algorithmic complexity is a measure of the complexity of solving a task, which is definitely an end-directed process, teleology is an ineliminable property of algorithmic complexity. Chaitin (1985) determined that the laws of physics have very low information content since their algorithmic complexity can be characterized by a computer program less than a 1,000 characters long. His programs were solved numerically, taking into account Newton's laws, Maxwell's laws, the Schrödinger equation, and Einstein's field equations for curved space-time near a black hole. All were about half a page long—which is amazingly simple. Now we can estimate the complexity of a page as approximately $2 \times 10^3$ bits since the average rate of information processing in reading is about 50 bits $s^{-1}$, and so at a reading rate of 1.5 pages per minute, the information content of a page is about $10^3$ bits. Taking a page from Chaitin, we thus found that the algorithmic complexity of physical equations is surprisingly low, being around $10^3$ bits.

The distinguishing mark of class (A) is a simple input without complexity; at the same time, physical behavior corresponds to the algorithmic complexity of the physical laws. Class (B) can be characterized by the algorithmic complexity present in the fixed input conditions of machines or adapted features. Remarkably, class (C) has a fundamentally different complexity measure since it corresponds to the solution of continuously surfacing new problems. As a result, the complexity representing class (C) is measured not in bits but in bits $s^{-1}$. It follows that this kind of complexity can be termed generative complexity (Grandpierre, 2008b). Since generative principles represent a deeper concept than laws of nature, generative complexity represents a deeper level of complexity than algorithmic complexity. We obtained a useful result: The three different kinds of behavior correspond to three different kinds of teleology, design, and complexity, and these can be easily distinguished with the help of quantitative complexity measures.

## 2.6. COMPARISON OF THE NEW AND OLD CLASSIFICATIONS OF TELEOLOGY

As a test of our new classification of teleologies, we now compare it to that of Mayr (2004). He defined five classes: (1) teleomatic, (2) teleonomic, (3) purposive behavior, (4) adapted features, and (5) cosmic teleology. It is straightforward that Mayr's first teleomatic class (1) corresponds to cases when physical laws determine the output "automatically." His teleonomic class (2) corresponds to cases when the behavior is determined by programs. "All teleonomic behavior is characterized by two components. It is guided by 'a program' and it depends on the existence of some endpoint, goal, or terminus that is 'foreseen' in the program that regulates the behavior or process. This endpoint might be a structure (in development), a physiological function, the attainment of a geographic position (in migration), or a 'consummatory act' in behavior" Mayr (2004, 51). He also includes the behavior of human artifacts like machines into this class. With the recognition that tortoises have short stocky legs adapted for a certain function (namely, climbing, crawling, and walking), and as such represent behavioral programs, we can classify the legs of tortoises as corresponding to our class (B). It is easy to see that physiological functions like the heart pumping blood, migration of birds, or consummatory acts, as well as the complexity of machines, can be characterized by algorithmic complexity, which can be measured in bits, confirming the classification of teleonomic behavior into our class (B).

Mayr's category (3) is that of purposeful behavior. We classified purposeful behavior into class (C) and gave it a somewhat definite meaning. His fourth category "adapted features" is classified into our class (B). This classification is confirmed by the fact that the complexity of adapted features can be characterized by algorithmic complexity and can be measured in bits. Mayr refutes his own fifth class, (5) "cosmic teleology," with the following argument: "Natural selection provides a satisfactory explanation for the course of organic evolution and makes an invoking of supernatural teleological forces unnecessary. The removal of the mentioned four material processes from the formerly so heterogeneous category 'teleological' leaves no residue. This proves the nonexistence of cosmic teleology" (Mayr, 2004, 61). We note that in biology the universal principle of all biological behavior is more basic than the study of some historical aspects of one specific form of life, which is present on Earth. Moreover, instead of supernatural forces, in this chapter, we argued the case for cosmic teleology on the basis that biology has its own autonomous principle which is an exact analogue to the least action principle already established in physics, and so, similarly as the physical principle, it is valid in the whole universe. This means that the biological principle permeates the quantum vacuum, and so it can govern virtual interactions. If so, then the quantum vacuum fulfills the criterion of life, and thus it represents a cosmic life form. Indeed, a detailed consideration of the criteria of life within cosmic conditions (Grandpierre, 2008a) has shown that different cosmic life forms extend to the whole of the universe. This conclusion is confirmed by the simple quantitative fact that algorithmic complexity increases in the universe (e.g., in the protosolar cloud, in solar activity [quantitative study in Grandpierre, 2004, 2008b]) and in the biosphere (Grandpierre, 2008b). Therefore, nature can be characterized by generative complexity corresponding to our class (C). This means that Mayr's "cosmic teleology" actually exists in nature and it belongs to our class (C). This completes our comparison.

## 2.7. SOME USEFUL EXAMPLES

Now let us look some other useful examples elucidating the differences between these types of natural design.

### *2.7.1. Homo sapiens from Cosmic Cloud*

Definitely, the contraction of the protosolar cloud, from the onset of contraction until the development of the Earth and *Homo sapiens* on it, is conceived today as describable by physical laws. Yet our results indicate (see also Ellis, 2005) that this assumption contradicts the fact that *Homo sapiens* appeared on the Earth, since the physical laws have a fixed and relatively low algorithmic complexity that is measured in bits ($10^3$ bits), while *Homo sapiens* is a creative being having a much larger algorithmic complexity ($10^{15}$–$10^{17}$ bits) and having also a generative complexity that is measured in bits $s^{-1}$.

### *2.7.2. Physical "Self-organization" Corresponds to Phenomenological Complexity*

Physical "self-organizing" processes are frequently regarded as the basis of extremely complex, biological organization (e.g., Kurakin, 2010). Yet we point out that all physical "self-organizing" processes are, at least in comparison to biological organization, *very simple, having a relatively very low algorithmic complexity*. The crucial difference is that physical "self-organizing" processes are governed by the physical laws and manifest characteristically physical behavior. Biological processes differ from physical ones with respect to their governance. Biological organization is governed by the biological principle, while physical self-organization is governed by the physical principle. This is why the latter is much simpler.

### *2.7.3. Control of Physical Laws: The Dual Control of Organisms*

Although physical laws prevail within organisms, their behavior is governed by a dual control, in which the biological control harnesses physics. Mayr (2004, 29) assumes that the dual control is due completely to the genes: "In contrast to purely physical processes, these biological ones are controlled not only by natural laws but also by genetic programs. This duality fully provides a clear demarcation between inanimate and living processes. The dual causality, however, … is perhaps the most important diagnostic characteristic of biology…." We point out that the relation between the two controls, the physical and the biological, is not symmetric, since it is the biological control that determines the characteristically biological behavior, and the physical control is subservient. It is the biological control that regulates the input of physical laws and harnesses the physical laws, not vice versa. The crucial element of transcending physical laws is that virtual interactions are able to induce spontaneous, physically undetermined processes, couple them together in an extremely specific manner, in a way that the biological control can become manifest, observable, as in the trajectory of a living bird.

We add that genetic complexity corresponds to the sequence of the amino acids, and so, it is static and can be measured in bits. Since the solution of new tasks is an inevitable part of life, generation of algorithmic complexity is also inevitable. Generative complexity, measurable in bits/s, is more fundamental than any algorithmic complexity which is already generated. Therefore, if genetic programs play an important part in governing dynamic biological behavior, they must be suitable tools for the activity of the biological principle that continuously generates the algorithmic complexity of biological behavior.

Since man-made control is applied at the input of physical laws, it can harness the physical laws, and it can "govern" the physical laws, similarly to a sailor who changes the inner condition of his ship by trimming its sails in a way to most efficiently harness the physical power of the wind. It is the control of behavior through the control of input of the physical laws that determines the observable gross behavior of organisms, and not the physical laws themselves.

### *2.7.4. The Mathematical Science of Intentional Behavior*

Certainly, modifying systematically and time-variably the input of the physical laws in a way to obtain an outcome corresponding to certain kinds of goals, (C)-type behavior must generate especially complex conditions in order to be manifested. Such especially complex conditions can be made accessible with the help of especially complex internal structures having an especially sensitive and rich set of different internal conditions. The task to produce certain favorable time-dependent output with the help of a suitable selection of time-dependent input variables is investigated in control theory. Control theory is an interdisciplinary branch of engineering and science that deals with the behavior of dynamical systems. The desired output of a system can be generated by the suitable selection of changing input conditions. The description of this type of problem requires the introduction of an extra degree of freedom in problems such as creating the design of a rocket capable of reaching a target governed by a living being (Pontryagin maximum problem). Pontryagin (1978) found that the most important element of such a problem is that the governed system can change all its coordinates at any moment by exerting governmental forces. To take these governmental forces into account, one has to introduce additional degrees of freedom that the living bird has, which the dead bird no longer has. This means that life and its related governmental forces are what elicit the exerted physical forces, and these are the most important elements determining the bird's trajectory. That being the case, one cannot ignore them without missing the main point of the whole problem. In mathematical psychology, the introduction of such an additional variable corresponds to the decisions made by a subject, which can be described with the help of the Reflexive-Intentional Model of the Subject (RIMS, Lefebvre, 2001). The RIMS is a mathematical model that predicts the probabilities of two alternatives a subject will choose, and *it allows us to deduce theoretically the main patterns of animal behavior* in experiments with two alternatives (Lefebvre, 2003).

## 2.8. THE POWER OF TELEOLOGICAL EXPLANATION

It is usual to assume that teleology is not useful in science. In contrast to this view, we argue here that such an anti-teleological assumption presents a conceptual obstacle to a more complete understanding of nature. The biological principle allows us to introduce biological ends, which in turn represents natural teleology. Such an approach opens up vistas for a new scientific revolution since it makes it possible to understand the behavior of whole organisms in mathematical details, elevating biology to the rank of a quantitative, exact science. At present, the situation is characterized by the following quotation: “Today, by contrast with descriptions of the physical world, the understanding of biological systems is most often represented by natural-language stories codified in natural-language papers and textbooks. This level of understanding is adequate for many purposes (including medicine and agriculture) and is being extended by contemporary biologists with great panache. But insofar as biologists wish to attain deeper understanding (for example, to predict the quantitative behaviour of biological systems), they will need to produce biological knowledge and operate on it in ways that natural language does not allow” (Brent and Bruck, 2006, 416). Our results make observable biological behavior calculable at the level of the organism (Grandpierre, 2007).

## 3. Is There a Design in Nature?

Contemporary attributions of function recognize two sources of design, one in the intention of agents and one in the action of natural selection (Kitcher, 1999). It is usual to deny the existence of the ontological “design” in the universe. For example, Dawkins (2006, 157–158) acknowledged that (1) one of the greatest challenges to the human intellect, over the centuries, has been to explain how the complex, improbable appearance of design in the universe arises. The apparent design is so spectacular that (2) the natural temptation is to attribute it to actual design itself. In the case of a man-made artifact such as a watch, the designer was an intelligent engineer. It is tempting to apply the same logic to an eye or a wing, a spider or a person. But according to Dawkins, “the temptation is a false one, because the designer hypothesis immediately raises the larger problem of who designed the designer.” If so, this “designer problem” raised by Dawkins is solved here. In our picture, the universe is a biologically governed system, governed by the biological principle. Regarding that the first principles exist in all time and space, life is eternal and ultimate. Dawkins continues: “It is obviously no solution to postulate something even more improbable.” In contrast, we were able to show that the nature of scientific explanation leads in two steps from phenomena to laws and, ultimately, to the first principles. The existence of these first principles is validated by all our empirical and theoretical knowledge; therefore they are not improbable but, on the contrary, the most probable, actually, universally reliable facts from all science facts. (4) “Darwinian evolution by natural selection offers the greatest, most powerful explanatory scope so far discovered in the biological sciences.” Dawkins quickly concludes: “We can now safely say that the illusion of design in living creatures is just that – an illusion.”

In contrast, we argued that the theory of Darwin is not fundamental, as it is clear from its contrast with the theoretical biology of Ervin Bauer, which is capable to give the mathematically formulated universal principle of biology. Indeed, Dawkins claims: “We don’t yet have an equivalent well-grounded, explanatory model for physics. Some kind of multiverse theory could in principle do for physics the same explanatory work as Darwinism does for biology." In contrast, we think that Dawkins ignores the present situation of biology, as it is shown from reports like the one cited by us above (Brent and Bruck, 2006), indicating the basic fact that at present the only exact science is physics, and biology seems to suffer from missing the knowledge of similarly exact laws and principles. Yet we argued that it is a false opinion since there is an exact formulation of theoretical biology (Bauer, 1967; Grandpierre, 2007). Regarding the multiverse theory, it is based on a superficial understanding of physics, expressing the opinion that physical laws can be awkward. In contrast, we pointed out that the essence of physics is the least action principle, and all physical laws must obey this fundamental principle and should be derived from it. Therefore, a kind of "grand design" of nature—which is revealed here in the three-leveled, "vertical" structure of the universe (phenomena-laws-first principles), plus the "horizontal" structure characterized by physical-biological-psychological behavior—exists, and this ontological structure of the universe is proved by a scientific analysis. The "grand design" we found is represented in the hierarchical architecture of the universe, which has an ontological, explanatory, and causal significance as well.

Hawking and Mlodinow (2010) argued that the material universe can be explained by the M-theory, which predicts that a great many universes were created out of nothing. "Their creation does not require the intervention of some supernatural being or god. Rather, these multiple universes arise naturally from physical law. They are a prediction of science" (ibid., 12). They added: "The fact that we human beings…have been able to come this close to an understanding of the laws governing us and our universe is a great triumph…If the theory is confirmed by observation, it will be the successful conclusion of a search going back more than 3,000 years. We will have found the grand design" (ibid., 102). We point out that the "prediction" of the M-theory, namely, the multiverse theory, does not explain why do the laws of physics take their specific form we observe. Instead, it assumes that since an infinite variety of physical laws exist in the multiverse, therefore every improbable cases have a certain probability, and the specific form of physical laws that are so favorable for life can occur as well with a finite probability. In contrast of this highly speculative and uneconomic assumption, we point out that the existence of physical laws is explained scientifically by the least action principle. Instead of the speculative assumption of the "multiverse," we presented here a scientific explanation for the origin of the physical laws from an exact and already established physical principle: the least action principle.

We found that the universe is permeated by a biological principle capable of controlling the physical principle. This indicates that we are living in a fundamentally living universe, which allows the presence of "design" in nature. Yet we note that the presence of "design" depends sensitively on what we mean on this term. If we mean "order" by the term "design," then already the existence of the laws of physics presents a design in nature. If we mean by "design" teleological behavior in general, we found such teleology present in nature, in biological processes governed by biological aims. If one means by "design in nature" purposeful planning, processes governed by human intentions show their existence.

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# PART II: PHILOSOPHICAL ASPECTS OF DESIGN

**Faller**
**Harman**
**Schrader**
**Chetland**
**Solymosi**
**Shook**

A colorful picture of *Zinia zowie* (yellow flame) taken by Glen Mendels.

Biodata of **Steve McGrew**, author of "***Creativity in Nature***."

**Steve McGrew** earned a master's degree in physics at the University of Washington in Seattle in 1970 and later did graduate studies in optics, electrical engineering, and biology. He is founder and currently president of New Light Industries, Ltd., a company that develops and licenses technologies in the field of optics, holography, and document security. McGrew received the Saxby Award from the Royal Photographic Society in London for his contributions to 3D photography and the Lifetime Achievement Award and Brian Monaghan Award from the International Hologram Manufacturers' Association for his contributions to the field of holography and business innovation. He has approximately 30 issued patents in optics, holography, document security, heat pumps, and solar power. In 1992, McGrew developed a genetic algorithm software package ("Generator") that is still used by Fortune 500 companies for optimizing financial management strategies and by researchers developing ecological models, optical system designs, and numerous other diverse applications. The software harnesses Darwinian evolutionary principles. At New Light Industries, McGrew is currently involved in developing near-eye displays, electrically variable lenses, and advanced direct-write hologram origination systems. In his spare time, he is an artist-blacksmith (www.incandescent-iron.com).

E-mail: **stevem@nli-ltd.com**

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# CREATIVITY IN NATURE

**STEVE MCGREW**
*New Light Industries Ltd., 9715 W. Sunset Highway,*
*Spokane, WA 99224, USA*

## 1. Introduction

Many people have difficulty with the idea that design can come from nowhere. Some deny it as absurd. The "It's absurd therefore it's impossible" argument against evolution is common today. That was Paley's argument (Paley, 1802), and the argument has been echoed in one form or another for nearly as long as people have thought about the origins of life.

Even many who consider themselves to be scientists have a similar difficulty with the idea that all the incredibly beautiful dancing patterns in nature could have emerged on their own, without a choreographer.

But beautiful patterns emerge all the time, essentially from nowhere. Snowflakes (every one different), landscapes, crystals, sunsets, galaxies, rivers, clay concretions, cloud formations, water waves, and a vast number of other nonliving but highly structured systems spontaneously emerge from an unstructured background – or at least from a background that certainly does not contain blueprints for those marvels.

Living things seem to differ dramatically from nonliving natural objects in one crucial respect: they actually *are* built from blueprints. Well, not from blueprints exactly, but certainly from plans. Even though cows and people are constructed from essentially the same components – essentially the same proteins, sugars, lipids, etc. – cows and people differ because their components are assembled in a different arrangement during embryo development. The plan that determines the arrangement is encoded primarily in the DNA present in each fertilized ovum.

So where did that plan come from? Design – the plan – is something we can easily imagine to be evidence of an intelligent, creative Planner.

## 2. What Is Design?

What do we mean when we say "design?" According to Webster's Dictionary, as a noun, "design" normally means:

(a) A mental plan or scheme for accomplishing a goal
(b) An underlying scheme that governs functioning, developing, or unfolding: pattern and motif <the general design of the epic>

(c) A plan or protocol for carrying out or accomplishing something (as a scientific experiment); *also* the process of preparing this
(d) The arrangement of elements or details in a product or work of art

As a verb, it means:

(a) To create, fashion, execute, or construct according to plan: devise, contrive
(b) To conceive and plan out in the mind <he design*ed* the perfect crime>
(c) To have as a purpose: intend <she design*ed* to excel in her studies>
(d) To devise for a specific function or end <a book design*ed* primarily as a college textbook>
(e) To make a drawing, pattern, or sketch of
(f) To draw the plans for <design a building>

Taking Webster's Dictionary as a guide, it is clear that the ordinary meaning of the word "design" is intimately entangled with the ideas of intention, creativity, mind, and intelligence. When we refer to "design in nature," the phrase itself carries that semantic entanglement, and the arguments begin again. How can there be intention without Someone to do the intending? How can there be a plan without a Planner to create it?

A traditional hard-line scientist, stuck with having to use the phrase, *design in nature*, might try to redefine "design" to mean something really bland, like "any pattern that is potentially interesting to a human being in order to shed the connotations of intention, creativity, mind, and intelligence."

## 3. Nature as an Information Processor

So how does design emerge in nature? Just for fun, let us see if there is anything other than a God or gods that might exhibit intention, creativity, mind, and intelligence and might be responsible for some of the design we see in nature. First, let us take a look at what we are:

We are each a society of cells.

You are to each of your cells, what a beehive is to its individual bees. You are a complex of interacting, communicating, quasi-autonomous subunits. Most of the components of our cells are present in yeasts and fungi. What distinguishes us – multicellular organisms – from fungi and yeasts is the complex network of communication between our cells, and the range of responses our cells have to signals they receive.

Just as two different brick houses are different because of the arrangement of their bricks rather than the composition of their bricks, different animal species are different because of the arrangement of their cells rather than the composition of their cells. An individual cell from a cow is nearly indistinguishable from a homologous cell in a person. During embryo development, cells exchange mechanical, electrical, and chemical messages that guide cell division, differentiation, and migration. The timing, sequence, location, and content of those messages determine whether a particular embryo develops into a human being or a cow.

Brains are societies of cells that exchange electrical and chemical signals at a pace millions of times faster than the signals passed between cells in a developing embryo. Our thoughts and perceptions are comprised of the timing, sequence, and locations of the signals.

Where else do we find societies of elements, whose essence is in the temporal and spatial patterns of the communication between elements? Ecosystems, certainly, where millions upon millions of species ranging from bacteria to bison, perch to petrels, and hydras to hyacinths, are constantly exchanging information in the form of calls, pheromones, head butts, predation, competition, dances, and genes.

It is especially worth noting that the genomes of all of the organisms on the planet are constantly exchanging genetic information via sexual recombination, retroviral infections, and other mechanisms. It has been estimated recently that 8% of the human genome is derived from retroviral fragments (de Parseval, 2003).

The main driver of evolution is communication, both direct and indirect, between genomes. Genetic information exchanged via sexual reproduction is arguably the largest source of genetic variation driving evolution.

Consider the volume of DNA exchange between organisms. The earth has roughly $5\times 10^{30}$ microbes living on it at any given moment, of which, say, one in a hundred million is undergoing some sort of transfer of genetic information with other microbes. The replication cycle of microbes ranges from about 20 min to days or months, so let us say the average replication cycle is 5 days. That means that there are something like $10^{18}$ genetic signals exchanged per second around the planet. Those signals are not on-off bits like the signals processed by computers; they are chunks of DNA often containing thousands of nucleotides organized into genes and control sequences. So, the genetic signal-processing activity of the earth's biome is on the order of $10^{23}$ bits per second.

A human brain, or the fastest supercomputer we have built, processes at the very most about a thousand trillion – $10^{15}$ – bits per second. So, nature processes information at least hundred million times faster than a human brain or a supercomputer.

## 4. Nature as a Goal-Driven System

All that signal exchange does nothing useful unless it is organized. Is nature's processing power organized? You bet! All of it is aimed at adaptation – generating alternative phenotypes and testing them through natural selection.

All of evolution is guided by natural selection. Natural selection is not really "survival of the fittest"; it is all about continuity of lines of descent. If a line of descent stops, natural selection has selected against the genomes represented by the last individuals in that line of descent. It is difficult to define a really good measure of evolutionary success because if circumstances were right, a nearly extinct population could produce an explosion of new species, some of which could outlast all of their competitors. However, differential replication rates within an interbreeding population or between species that compete for the same resources provide a useful if inexact measure of evolutionary dynamics in any relatively short time interval. All of the hundred million supercomputers' worth of genetic information exchange going on in nature is, one way or another, involved in creating new genetic combinations resulting in new phenotypes, which are then tested by natural selection.

I like to think of *intelligence* as information processing directed toward a goal. It does not have to be a specific long-term goal; it can just as well be a goal, like surviving another day, or even a cluster of goals like staying well-fed, mating whenever possible, avoiding pain, and so on.

An individual social insect like an ant, bee, or termite, responding to chemical signals and other cues by picking small objects up or setting them down, turning or continuing, laying down new chemical signals, regurgitating, etc., is not necessarily intelligent by this definition. But a termite *colony* is intelligent by this definition. Through the interactions between its members, it responds intelligently to threats and opportunities. Its goal (whether or not it has a *mind* to conceive of the goal) is to continue its line of descent.

So, it is not unreasonable to think of nature as an intelligent system with the processing power of a hundred million supercomputers and the goal of exploring the universe of genetically defined phenotypes and ecosystems and testing them via natural selection.

## 5. Creativity in Nature

When we mention *design*, we generally think in terms of some mix of artistic and engineering creativity. According to Webster's Dictionary, *to create* is to produce through imaginative skill, or to bring into existence through a course of action. A *design* is usually thought of as the product of goal-directed intelligent, creative effort.

So, when we mention evolution (canonically, an undirected, mindless process) and "*design* (a directed, creative, intelligent process) *in nature*" in the same breath, we have already set an argument in motion. Or have we?

Let us consider what we mean by creativity. For the moment, we will set aside the unarguably creative process undergone by an inventor or artist and focus instead on processes that *are not* unarguably creative.

One of my favorite stories about creativity was first told 30 or 40 years ago. I read in a newspaper that a workman had found a scrap of sheet metal that vaguely resembled a cat. He and his coworkers conspired to enter it into an art competition, and it won a prize. When it was revealed that the scrap metal cat was the product of chance rather than intentional effort, a debate ensued. Did the piece deserve a prize? Was it art? Who was the artist? The judges defused the debate by declaring in essence that art is in the eye of the beholder, and it was the workmen who first recognized the artistic value of the scrap metal. By declaring it to be a cat, the workmen committed an act of artistic creation.

I like that story because, in a way, it contradicts a statement my art teacher in middle school repeated often: "Art is not a mistake!" That statement, boiled down, is equivalent to the creationist's axiom that design requires intent.

On one hand, the scrap metal cat was a mistake: a chance occurrence of unrelated cuts in a sheet of steel, followed by a construction worker's finding the discarded chunk and (somewhat by chance) seeing it as resembling a cat. On the other hand, it was not a mistake at all. The construction worker evidently had an artist's eye. He and his eye turned the random scrap metal pattern into an artistic representation of a cat simply by calling it that.

It is a mistake to think that randomness does not play a large role in every act of creativity. If something is new, it stems from a kernel of randomness surrounded by a matrix of preexisting structure. An artist who deliberately splashes paint on a series of canvases, then keeps only those that meet his artistic criteria, provides the preexisting structure (his criteria) and harnesses the novelty inherent in his random splashing. A sculptor who adapts his vision to uncontrollable (random) nonuniformities as they are revealed in a block of stone is harnessing the random variation in the stone's properties while providing the structure of his artistic criteria.

But what of pure imagination and inspiration? What of the artist who constructs a detailed image in his mind before committing it to paint on canvas? What of the composer who imagines a whole symphony before writing a single note on paper? What role, if any, does randomness play in is kind of creativity?

Randomness plays exactly the same role in mental creativity as it does in the paint-splashing artist's creativity. Randomness is exploration.

I cannot prove it, of course, because mental creativity has not been dissected down to the level of detail that would reveal a source of the little kernels of novelty that grow into a full-blown concerto or a painting in an artist's mind. But I can demonstrate without a doubt that a computer using randomness in a matrix of structure can generate inventions *de novo* that the US Patent Office would recognize as novel.

This, too, is one of my favorite stories. Twenty years ago, I designed my own version of a *genetic algorithm or "GA,"* a computer program that mimics Darwinian evolution to solve complex problems. A GA represents potential solutions to a problem as strings of numbers, with each number determining some aspect of the solution. For example, the problem might be to design an improved forklift mechanism, and the individual numbers might represent possible lengths of the components, sizes of gears, diameters and lengths of hydraulic cylinders, and so on. The task of the GA could to be find a compact mechanism that has maximal lifting force while keeping all the mechanical stresses within practical limits.

In order to search for optimal designs, the GA first creates a population of random designs, each represented simply by a string of randomly selected numbers. The designs are compared by calculating their performance. A new generation of designs is created by recombining designs. This is done by selecting a pair of strings, cutting each member of the pair at the same random place, and switching segments between the two members. Better-performing designs are selected more frequently than worse-performing designs for this pairing operation, so higher-performing designs contribute more information to the next generation than worse-performing designs. A few random mutations – shifts in the values of the numbers – are thrown in for good measure. The result of all this is that the designs represented by the members of the population get better and better. A GA is not guaranteed to find the best possible design, but it is very likely to find an excellent design.

In my case, the problem was to design a good lens system with four elements or less that could fit into a 10-in. cube. I handed the task to my GA and let it run overnight. It is important to note that the only information I provided to the genetic algorithm was the goal and a method to determine the quality of a solution. The goal was to find four-element lens systems shorter than 10 in. that form the highest quality image. I gave the genetic algorithm no limitations or advice at all about lens positions, diameters, or powers.

By the next morning, my genetic algorithm had reinvented most of the four-element lens systems ever invented and patented by human inventors. When a human scientist designs a lens system, we consider it to be a creative act. All the connotations of "design" and "creativity" relating to intention and intelligence are clearly appropriate. Is there really any reason the same product (a lens system design) should not be called a design, regardless of whether it was brought into existence by a man or a machine? Is there really any reason the same process should not be called intelligent or creative regardless of whether it was performed by a man or a machine? I think not.

Nature has the original genetic algorithm, which we call *Darwinian evolution*. It operates on strings of nucleotides rather than strings of numbers. Nature's genetic algorithm is far more powerful than my poor imitation. My GA used a population of 20. Nature's populations range from a handful to billions. My GA can only estimate the performance of a design; nature calculates the performance of each design exactly. My GA ran on a computer whose capacity was limited to testing about one design per second. Nature's GA runs in the real world, testing something on the order of $10^{23}$ designs per second.

By any reasonable and nonchauvinistic standard, nature has the means to create designs ten thousand billion billion times faster or more intricate than we can. Nature certainly has the capacity to be creative.

## 6. A Natural Mind

To me, a mind is simply the hierarchy of goals that drive an intelligent system.[1] That is not very far from the common meaning of “mind.” Your hierarchy of goals, working in the context of experience and available information, determines the way you feel and the way you act. To “change your mind” is to change your immediate or distant goals. But in its common usage, “mind” hints at something supernatural. We tend to deny the possibility that a computer can have a mind, for example. However, if we define mind as the hierarchy of goals that drive an intelligent system, we can step aside from any supernatural connotations.

Does nature have a hierarchy of goals? Does it have any goals at all? I do not mean teleological end goals imposed by a supernatural entity. I mean goals of the sort that human beings have, like filling an empty belly, finding a mate, or storing food for the winter.

Yes, nature has a hierarchy of goals. We see squirrels, bees, ants, and birds storing food for the winter, at the cost of expending extra effort in the summer and fall. Birds build nests in advance so that they will have a safe place to lay eggs and incubate them. Geese and ducks migrate thousands of miles twice a year to raise their families safely.

Nature also “plans ahead” in ways less apparent than migrations, nest building, and food storage. It is no accident that the mechanisms of reproduction are structured at the subcellular level to maximize random genetic variation while ensuring that a majority of the variations produce viable individuals. Similarly, it is no accident that we are born with the ability to heal when wounded and mount an immune defense when bacteria invade. Even if we were never wounded or exposed to bacteria, we would still have those abilities in reserve.

If I programmed a robot to take note of the locations of electrical outlets it sees, so that when its batteries ran low it could scurry to the nearest outlet, there would obviously be some sort of intention at work. Most people would attribute the intention to me, though – the robot’s programmer. *But what if nobody wrote the robot’s program*?

A genetic algorithm can design a computer program as easily as it can design a lens system. A computer program is a string of 1 and 0 s, just like the 1 and 0 s in a computer’s representation of a fork lift mechanism or a lens system. So, a GA could be given the task of designing a computer program that directs a robot to remember locations of electrical outlets in case of future need. And it would succeed.

The forward-looking behaviors observable in nature are programs encoded in DNA. They are programs that were designed by nature’s GA.

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[1] This is similar to Csikszentmihalyi’s definition of self: “The self represents the hierarchy of goals that we have built up, bit by bit, over the years” (Csikszentmihalyi, 1990; Csíkszentmihályi and Csikszentmihalyi, 1988).

It is easy to explain these forward-looking behaviors and abilities in Darwinian terms. After all, practically every one of our millions of ancestors was wounded or sick at some point in life before having the opportunity to produce offspring, so nature has selected against organisms without appropriate defenses. To an evolutionary theorist, it is very straightforward – all that remains is to find a plausible way for those defenses and behavioral programs to have emerged through a series of acceptably small, usually beneficial, steps that involve random variation and fitness-based natural selection.

But I would like to offer an alternative suggestion.

I would like to suggest that, through the usual process of Darwinian evolution, genetic machinery *per se* has become (in effect) a forward-looking adaptive system. A shelf full of books could be written to lay the foundation for arguments in favor of this idea, but since there is not room here for that, I will offer a few plausibility arguments instead.

In a changing environment, there should be a definite selective advantage to organisms whose reproductive machinery is structured at the cellular level in a way that makes them more likely to produce offspring that have genomes as varied as possible while having a high likelihood of being viable.

In effect, all eukaryotic genomes are structured this way because the arrangement of genes in multiple chromosomes ensures that *genetic modules having proven fitness* are combined in novel ways during practically every instance of sexual reproduction. In human reproduction, for example, with our 23 chromosome pairs, each new individual is formed from one of $4^{23}$ (over 70 trillion) possible combinations of chromosomes – practically every one of which is sure to be viable. Crossover (random exchange of DNA segments between homologous chromosomes) is another mechanism that creates new genetic. The number of possible crossovers between two parent genomes is vastly larger than the number of possible chromosome combinations, but the vast majority of combinations resulting from crossover will be viable.

In other words, DNA and its associated molecular machinery is organized in such a way that it evolves rapidly in response to changing selective pressures. I would suggest that it is organized that way because it *needs* to be organized that way. Natural selection works against organisms that cannot evolve quickly enough to keep up with environmental change. More importantly though, natural selection works against organisms lacking the ability to compete effectively with those that evolve quickly – because an organism's competitors are, themselves, powerful agents of natural selection.

So, evolution has not only given life its existence, but has also given life both the means and an imperative to evolve rapidly. The means to evolve rapidly are hardwired into the very structure of our cells at the genetic level. The imperative to evolve is inherent in the nature of natural selection.

Without any idea of end goals, nature is driven to proceed as quickly as possible, on all fronts, in all accessible directions. The drive is encoded in the combination of evolved DNA structures and in the very process of evolution.

To nature, any inheritable change that sustains a line of descent is progress. Like water, whose gravitational imperative is to flow downhill rather than to reach the ocean *per se*, nature's evolutionary imperative is to continue lines of descent rather than to develop any specific, predetermined forms. However, the same could be said of termites, each of which responds only to signals it comes directly in contact with. Any individual termite acts only locally, with no understanding that its acts contribute to long-range processes such as building a 4-m-high air-conditioned nest.

Nature does have a mind, if mind is the hierarchy of goals that drive an intelligent system.

## 7. Emergence of Design

Now, we can return to the question of how design emerges in nature.

It is clear that the set of local rules governing acts of individual termites causes a whole termite colony to act in concert to construct a nest. It is clear that the set of local rules governing the behaviors of individual cells in a developing human embryo act in concert to cause the collection of cells to construct a baby. In a very real sense, the termites' behavioral rules or the embryonic cells' behavioral rules have goals built into them: they exist for a purpose. Evolution is a learning process, and it has learned that termite colonies composed of individual termites whose genes encode rules that result in collective nest-building behavior are more likely to have unbroken lines of descent. Similarly, evolution has learned that colonies composed of human cells whose genes encode rules that result in collective baby building are more likely to have unbroken lines of descent.

From that perspective, there seems to be a fundamental difference between the rules governing behavior of living organisms like termites and human cells and the rules governing behavior of water molecules. That is, the rules governing insect behavior and embryonic cell behavior have been shaped by evolution, and the rules governing water molecules have not. Oceans, lakes, raindrops, and rivers are natural consequences of water molecule physics, but are not the *purpose* of the rules.

We have a pretty good grasp of the rules that govern evolution at the molecular, cellular, species, group, and ecological levels. In scientific circles, it is effectively taboo to speculate on the purpose of those rules because we usually think of "purpose" as connoting intention, which we habitually attribute only to human beings or at most only to "higher" animals. However, I think it is worth asking, "To what extent have the rules that govern evolution been constructed by evolution?"

The answer can only be that very little of what governs evolution *is not* itself a product of evolution! Meiosis and mitosis are evolved processes. Predator/prey interactions are evolved processes. Mate selection behaviors are evolved processes. Competition for resources is a process dependent on evolved organisms and evolved behaviors.

Evolution may not proceed toward a preordained *end* goal, but it certainly is composed of processes that include at least "immediate" goals like nest building, baby building, homeostasis, and maintaining the ability to adapt.

In a separate book, I have proposed a new definition for *design*. The definition is constructed to shed the supernatural aspects of the ordinary definition.

> Design is the property common to useful structures discovered during intelligent exploration guided by a hierarchy of goals.

By "useful structure," I mean a structure that makes a task easier or more efficient; by "intelligent exploration," I mean exploration guided by a complex information processing system; and by "goals," I mean rule sets that have evolved through variation and selection.

Practically anything we think of as a design fits that definition: music, architecture, paintings, computers, and contracts. Even the scrap metal cat was "discovered" by an alert workman and useful for goals conceived by the workman and his coworkers.

More to the point, practically everything we find in nature fits that definition. Nature is undeniably a complex information processing system. It is replete with goals. Practically every feature of living organisms that persists for a significant number of generations is useful to the propagation of a line of descent; if it were not, it would be subject to deletion by natural selection.

Let us briefly consider two examples of design in nature, through the lens of this definition: the shape of a cutthroat trout and the structure of a fly's eye.

The usefulness of a trout's shape to the trout is obvious: it allows the trout to move through the water with minimal turbulence and propel itself with minimal expenditure of energy. The shape emerges from the collective action of individual embryonic trout cells, each of which acts according to the same set of rules in response to local circumstances. The rules evolved over some billions of years as a result of highly structured genetic exploration constrained by natural selection and the laws of physics.

A fly's eye is useful to the fly. It helps the fly detect and locate food sources, predators, and potential mates. Its shape emerges through the collective action of fly embryonic cells, individually following rules written into the cells' DNA over billions of years via variation and selection performed by a genetic algorithm operating in a parallel processor enormously more powerful than anything built by people.

We look at fish, flies, flowers, and firs, and we see design. We think we see signs of intelligence, creativity, and purpose. Of course we do!

Nature *is* intelligent: it processes gigantic amounts of information in a highly complex, highly structured way. Nature *is* creative: it has structured itself into an enormously powerful engine of innovation. Nature *is* purposeful: it has evolved numerous mechanisms and behaviors to help it pursue its goals of adapting to selective pressure and maintaining its myriads of lines of descent.

Nature's intelligence, creativity, and purpose are not illusions, but neither are they supernatural.

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Biodata of **Mark Faller**, author of "***Plato's Pythagorean Cosmos: Order and Chaos in the Intelligence of Natural Design***."

**Mark Faller** is currently a professor of philosophy and former chair of the Liberal Studies Department at Alaska Pacific University of Anchorage, AK, USA. He obtained his Ph.D. from the University of Georgia in 2000, where he wrote his dissertation on Plato's use of geometrical reasoning under Edward Halper. Professor Faller's interests are in ancient philosophy, the philosophy of mathematics, and the philosophies of physics and biology. He wrote his undergraduate thesis on the second law of thermodynamics under the supervision of Hilary Putnam and David Layzer

E-mail: **mfaller@alaskapacific.edu**

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# PLATO'S PYTHAGOREAN COSMOS: ORDER AND CHAOS IN THE INTELLIGENCE OF NATURAL DESIGN

**MARK FALLER**
*Liberal Studies Department, Alaska Pacific University,*
*4101 University Dr., Anchorage, AK 99508, USA*

## 1. Introduction

The origin of the difficulty in determining a model for order or chaos in the natural world lies in the elusive relativity of the concepts themselves. The grass that breaks up your neatly laid out concrete sidewalk to you represents the ominously encroaching second law inevitably drawing your tiny refuge of improbable life into the universal pool of increasing entropy. But it is more accurately the highly ordered force of nature reclaiming its organizational priority over *your* less than natural chaos.

This dialectical relativism is further complicated by the diverse poles around which such orders can be "designed." Just with reference to space and time, we have multiple oppositions (part/whole, future/past) from which to consider untangling the complexities of order and its competitors.

The notion that order and chaos somehow contend directly is a further muddling of the issue. Proclus, in his great treatise on the nature of evil, points out that if the good is order, as identified by ultimate unity, then evil, as disorder, is a very poor contender. Any phenomenon with no order at all has absolutely no power or "being" at all. Pure evil just "is not."

Instead, what we mean by chaos is the "power" and "disposition" of one organization to disorder another. It is competition between highly "ordered beings" that is the "effective" chaos.

In one dialogue (*Timaeus*), Plato directly confronts this issue of order and chaos in the evolution of the cosmos. His answer, while predictably Pythagorean, is surprisingly subtle and complex in the way he sorts out this triply confusing set or organizational polarities.

In this chapter, I will make the case that Plato anticipated almost all of the *fundamental* issues in thermodynamics, chaos theory, complexity theory, and evolution in his own organizational approach to cosmology. And the warp and woof which he develops to disentangle this conceptual web is a model of parts and wholes.

My method will be to show that Plato has a typology of four kinds of *forms* that represent the complete extensional spectrum of possible relationships between the ways in which parts and wholes can interact. I will try to demonstrate that within this set of matrices, he further develops four wonderfully rich metaphors from which to examine each level of hierarchical interaction. Within the elaboration of these metaphors, we can begin to parse the multifaceted aspects of what Plato means by the concepts of design and intelligence. I contend that modern science could sort out many of its present conceptual entanglements by working out these figurative devices in terms of the empirical details now within our command.

## 1.1. THE RELATIVITY OF ORDER: THE DESIGN OF DESIGN[1]

Human beings are creatures of obsessive orderliness; we are *homo temperator* – man the organizer.

There are two direct consequences of this neurosis. First, we are fascinated with chaos. Disorder represents a kind of freedom and relief from the omnipresent cascades of control and manipulation it takes just to survive as a human. Chaos is liberty, the most precious of the civic virtues.

Just as queerly, humans conveniently see chaos everywhere. Our obsession with our own, parochial structures seduces us that any change, or alien structure, is a species of threatening *entropy*, contrived by God's sense of humor to disrupt our otherwise stable existence.

Perhaps these two predilections are God's blessings. It is not clear that the human psyche could comfortably accept a world as intricately structured and ordered, with as little room for true discretion, as the one we live in.

> The law that entropy always increases-the second law of thermodynamics-holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations-then so much the worse for Maxwell's equations. If it is found to be contradicted by observation-well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation (Eddington, 1928 (1933, reprint), pp. 74–75).

The most glaring fracture in the foundation of thermodynamics is the anthropocentric perspective of science. An experimenter creates an ordered structure in her lab, modeled after some regular mathematical pattern. After the structure is exposed to an unprotected environment, it is eventually reduced to a state of disorder. Whether it is separated ideal gases which are allowed to mix, or an ordered deck of cards which is shuffled, there always are more probable states of chaos than order. The difficulty is in comprehending that such manufactured orders are totally artificial and therefore have no validity as orders of the "real" world.

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[1] The following arguments are also reviewed in a paper that will be part of a CAS Conference in October 2011.

They were not designed to be physically competitive and therefore can stake no claim to any durable stability. That civilization has to continually struggle to fight back the encroaching jungle, even in this day of high-tech miracles, is no sign of impending chaos. It is rather a competing branch of nature's order letting us know the race may not yet be over. The infinitely adaptable virus and the communal bee waste not their time commiserating over laws of doom.

It is perhaps significant that we have established entropy rather than its converse, order or information, as the measure of thermodynamics. Certainly, it is easier to gauge the relative disordering of a structure than it is to formulate some absolute standard of hierarchical complexity. If we are to make sense of what order and chaos might objectively imply, we must search for a norm outside our own relative perspective.

## 2. The Good, the Bad, and the Ugly: The Trinitarian Design of Nature

In the *Timaeus*, Plato actually lays out his ordinal relativity in a tripartite set of formal perspectives, expressed in his three separate "starts." Each perspective is hierarchical to some degree and is therefore framed by Plato's polar causal imperatives of reason and necessity. At each level, however, reason and necessity have a qualitatively different balance, and therefore, each level is framed by a distinct vocabulary of order and its own peculiar mathematics.

One of the ways Plato avoids some of the unfruitful discussions which might haunt this dialectic of reason versus necessity is by framing the appropriate categories of opposition. This battle between the gods and giants is not cast as the direct dualisms of mind versus matter or the immaterial against the physical. Rather, he stakes out the intermediately opposed patterns of systemic wholes as contrasted to their discrete parts. Since wholes (species/humans) are often more universal than their parts (individuals/Socrates), and therefore more "mind-like," within this war, those other battles may be turned.

### 2.1. THE OPTIMAL ORDER OF THE HEAVENS

In the heavens, the macrocosm, reason rules absolutely as the unity of heavenly motion orders the cosmos in mathematically dictated, harmonic patterns. For millennia men have looked to the heavens as the stable calendar by which they could regulate their erratic, "sublunar" lives. Plato puts rigor behind such beliefs by establishing a mathematical basis for the great astronomical movements. In order to better grasp the significance of Plato's ordering the heavens to the harmonic ratios of reason, it may be of some help to enlist the aid of the platonic founders of modern mathematics and science.

Contrary to popular belief, the rationalists of the early scientific revolution, rather than usurping this view of an intelligent nature, worked to quantify it.

Kepler utilized Plato's *Timaeus* as an abductive roadmap from which he derived the three laws of planetary motion.

There was also in the Renaissance a great interest in principles such as Snell's law, which predicted that light could "find" the shortest path from source to receptor. Fermat corrected Descartes' proof of Snell's law and speculated as to the implications that light always follows a minimum path. Such a proof begged further metaphysical assumptions, as noted by his Cartesian critic, Claude Clersilier:

> The principle upon which you build your proof, namely that nature always acts by the shortest and simplest ways, is but a moral principle, not a physical one, which is not and cannot be the cause of any effect of nature. It is not, for it is not by this principle that it acts, but by the secret force and virtue which lies in every thing; the latter not being determined by that principle, but by the force that lies in all causes that concur to a single action, and by the disposition which is found in all bodies on which that force acts. And it cannot be otherwise we would be assuming some kind of awareness in nature; and by nature, we mean here only that order and that law which are established in the world as it is, and act without forethought, without choice, and by a necessary determination.[2]

Yet living under the dual inquisitions of early humanism and aging church, Fermat deemed it wise to remain explicitly agnostic on the significance of his find, "do not worry about the meaning".

In the generations of mathematical geniuses that followed, there developed a growing consensus that the "least action principle" (PLA), as formulated by Maupertuis and developed by Euler, was the mathematical expression of a metaphysical model for the reemergence of mind in nature: "since the constitution of the universe is perfect, and completed by an all-wise creator, absolutely nothing happens in this world which cannot be explained by some argument of maximum or minimum; this is why there is no doubt at all that all effects observed in the world can be explained from final causes, with the method of maxima and minima, with the same success as from efficient causes (Euler)."[3] This shared vision by the greatest mathematical minds of modernity was opposed vehemently by the empirical mechanists who religiously refused to re-allow metaphysics back into any interpretation of nature. All the attempts to disarm the implications of this principle have merely pushed scientific explanation more radically toward the opaque position that science does not explain, it only describes.

Although this early generation of PLA proponents may have taken metaphysical flight in their romantic exuberance about "nature's intelligence," a latter generation of physicists and mathematicians (Hilbert, Planck, Helmholtz)

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[2] Ivar Ekeland, *The Best of All Possible Worlds, Mathematics and Destiny* (Chicago, 2007), p. 55.

[3] p 73.

became equally enamored with the promise of PLA, only to retreat in cautious equivocation.[4] At the dawn of the twentieth century, in the blissful naiveté before Einstein or quantum, physicists were beginning to think that the great quests of their field were mostly behind them. One of the few areas of theoretical excitement was how exactly to reconcile the PLA with the well-described theory of Newtonian mechanics.

In this theoretical discussion almost all of the great minds were uniform in accepting the significant position of the PLA with regard to its status as a fundamental principle of nature. Planck himself interpreted this principle as one of final causality with regard to dynamic systems: "This represents a rational order of the world, to which both nature and man are subjected."[5]

Mach, however, the giant philosophical voice of theoretical physics, rebelled against such metaphysical interpretations as anti-empirical. He proscribed the view that the PLA "represented merely an economic reformulation of the differential equations of motion."[6] This understanding melded well with the Kantian philosophy that such "regulative" principles of nature were merely principle of the reflective judgment, with no determinative contribution to the constitutive reality. Mach, like Kant before him understood the threat of overdetermination posed by a teleological principle, with regard to the completeness and uniqueness of the mechanical model of explanation.

But could the creative power of two distinct generations of geniuses have been so totally mistaken in their understanding of this one principle?

We get a better feel as to how the PLA, as a mathematical principle of optimality, can still operate causally in nature, if we compare it to the way in which conservation principles such as the second law of thermodynamics express their dominant influence.

The science of thermodynamics has for some 200 years offered us a model of final causation that cannot be reduced to the mechanism of merely microstate dynamics. A closed, nonequilibrium system will always and lawfully move toward a state of equilibrium.

This lawful process does not uniquely depend upon the given initial conditions (positions, velocities) of its constituent particles. It is fully determined instead by its boundary conditions (temperature, pressure, volume). This "disengaging" of a system from the determination of initial conditions is precisely what we mean by a nonmechanical or end-state driven process. The final equilibrium state is "equipotential" attractor for an infinite number of initial states within the same boundary conditions. For this reason there is no unambiguous way to claim that some particular state of a set of particles mechanically or efficiently "caused" the final state to develop.

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[4] Michael Stoltzner, "The Principle of Least Action as the Logical Empiricist's Shibboleth," *Studies in the History and Philosophy of Modern Physics 34* (2003), pp. 285–318.

[5] Ibid., p 294.

[6] p 289.

This disengagement of the final state from the initial conditions does not mean that there isn't some particular efficiently causal path that the system follows. Rather it is that any particular set of initial conditions is *underdetermined* by the parameters of the final state. Although the precise conditions of a uniquely determined microstate will completely determine all further successive microstates, the macro end state is not so determined.

There are three complaints that the mechanists might reasonably advance against this analysis. The first is to note that this kind of end-driven state is not the kind of teleology that the proponent of efficient causality is adverse to. The "weak" sense of teleology represented by stochastic systems must be absolutely disassociated from the kinds of "strong" teleological causes represented by immaterial forces like God or mind.

Weak or strong it is evident that such influences persist in nature, and to the degree and respect that they may organizationally ingress through evolutionary processes, we cannot fully dismiss the possibility of such top-down mathematical design within even the organic world.

A more subtle attack on the above approach would be to just subsume the boundary conditions under the guise of an expanded set of initial conditions. Indeed, this is what most biologists do when they incorporate the survival pressure of natural selection as part of the mechanistic model of how functional relationships develop. But such "stretching" of concepts in order to incorporate substantially distinct functional phenomena eviscerates the meaning of the concepts themselves.

First, although these kinds of conditions are regularly distinguished in scientific experimentation, it is not perfectly clear how we can draw an absolutely clear line between where an initial condition ends and a boundary condition begins. In an experimental example of efficient causation, boundary conditions are eliminated in order to maximize the predictability of outcome from the giveness of the initial state in concert with the initial stimulus. The final outcome in a determinate, mechanical process is uniquely and sufficiently determined from these initial conditions, *assuming a vanishing degree of influence from variable boundaries.*

With the final cause, just the reverse is the case. Stochastic systems are adequate examples of this kind of causality. A thermodynamic system maintained under a strict set of boundary conditions (temperature and pressure) will eventually attain a predictable final state. The initial conditions for attaining this final state are relatively inconsequential. Significantly contrary to the mechanical situation, multiple distinct initial states will achieve the exact final stochastic description under the same boundary conditions. Here the *initial conditionality* is minimized with respect to the boundary conditionality.

An associated claim to the ambiguity of subsuming the boundary conditions is the type of claim made by Mach and Kant that such "laws" were merely mathematical principles of economy and not "causal" with respect to the determination of the final micro-state configuration.

Again this would seem to be a kind of obfuscation. Conservation laws are causal in the truest sense of the concept: They lawfully predict the final state of a system. That they are blind to equivalent micro-state parameters merely qualifies their causal influence with respect to the ontology of wholes, where in such systems it is precisely the wholes that regulate their parts.

These boundary conditions, whether static or dynamic, compete against the influence of the initial conditions or efficient causality. This is the paradigm of nurture vs. nature. While the influence of dynamic interactions tends to be chaotic in behavior, conservation laws tend to lead systems to some kind of uniformity. They cull or "tame" the dynamic influences. This influence is accounted as Plato's reason or order "persuading" necessity to do it bidding.

A final objection might appeal to the fact that the kind of final cause we are appealing to is one toward a final state of chaos. A closed thermodynamic system under a strict set of boundary conditions (temperature, pressure, and volume) will eventually attain the predictable end state of equilibrium. This kind of final state seems completely inconsistent with what traditional natural philosophies have associated with "telos." It is certainly not Aristotle's *entelechy* or Leibniz' "best of all possible worlds."

But an example of how continuous dynamic systems *actually* transition to chaos will illustrate the misunderstanding that science continues to harbor toward the nature of conservation principles in general and the PLA in particular.

### *2.1.1. The Thermodynamic Origins of Harmony*[7]

One of the ways in which to interpret the second law is to understand it as the principle describing the destruction of gradients. To the degree and respect that some system maintains an energy differential with regard to its environment, that gradient differential will continuously dissipate.

On the path to gradient elimination, systems continuously reconfigure themselves into every available canonical state that maximizes probability. These intermediate states of energy conservation are harmonically ordered, i.e., they form a bifurcated overtone series that internally reinforces the repetition of small whole number patterns. To the degree that such highly ordered intermediate states are *repetitively* echoed in subsequent generations of canonical alignments, the order tends to *resist* dissolution. The flow of energy toward equilibrium proceeds toward a minimization of activity and consequentially a maximum production of intermediately ordered patterns of energy distribution.

When a constrained string is plucked, energy dissipates in a lawfully ordered progression. Since the disturbance is to a continuous medium, the string, the number of possible intermediary states approaches the indefinite. Not all intermediary states, however, are equally probable. Those states that attain an equal

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[7] The hypothesis in this section has been presented in greater detail in a paper, "The Optimal and the Necessary in Leibniz' Mathematical Framing of the Compossible," presently in publication.

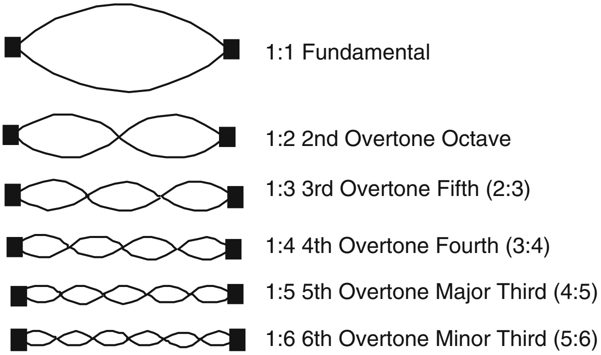

**Figure 1.** The overtone series.

distribution of the system's parts will attract the motion of the string as being the states of maximum possible distribution. Since equality can only attain where there are an integer number of divisions: 2, 3, 4, etc., the successive intermediary states of the string returning to its rest state will be through the series of integer divisions – the harmonic series.

This overtone series is the mathematical basis of all the diverse systems of scaling – diatonic, just and equal temperament – and therefore cannot in any absolute way determine which "musical" system is "better". Diatonic scales are fully determined from the priority of the higher consonances (3:2, 4:3) and favor their purity. Equal temperament scales, reflected in the twelfth overtone, opt for the convenience of equal size notes in compromising the exactitude of the higher consonances.

All scale "cutting" shares certain objective characteristics. The octave (2:1) and the higher harmonies, the fifth (3:2) and the fourth (4:3) are essential to both the "sweetness" and the ordering capacity of the overtone series. The lesser harmonies and the sizes of the whole and half notes have only a "normative" or cultural hold on diverse tastes. The arithmetic pattern itself determines all the relationships of harmony (Fig. 1).

The derivation of the laws of harmony via the principle of gradient dissipation from the second law brings us full circle on the way in which "conservation" laws are causally determinate. By a principle of *continuity* (Leibniz), as the high gradient or "ordered" state of the plucked string is allowed to dissipate, every possible intermediate state of order is attracted by the series. This progression elegantly illustrates the underlying *ordering* power of the law of disorder. Plato's harmonic heavens are reasonable by being the most beautiful by the least effort – a perfect illustration of why it is not his "sinews and bones" that constrain Socrates to his Athenian captivity.

Of equal significance is the way in which harmonically degenerating systems differ from more general thermodynamic transitions. The overtones of a plucked string actually retain the "echo" of their original, fundamental tone. The final state dynamic determination truly preserves the "memory" of the initial state conditions.

## 3. Order Out of Chaos: Why the Best Is Most Likely

When we make our second Timaean start, the works of necessity, from within the locally situated receptacle, we are thrown into the violent convolutions of microcosmic, bodily mechanisms. It seems strange that mechanical necessity should produce total disorder rather than lawfulness. In this world of atomistic, microcosmic interactions, the composite interactions of lawful individual necessities add up to a soup of stochastic disorder.

This is not, however, a world totally devoid of reason. The triangular forms which the receptacle's "vestiges" now reflect are within the intelligible genus of "mathematicals." The microcosm is a world of parts and wholes, ruled by a kind of Darwinian selection. We are told, in the description of chaos, that the vestiges are moved around by the chaotic motion of the receptacle and are yet "sorted out" into graduated levels like wheat from a sieve. This reflects the strangest kind of anomaly, in that while we earlier had witnessed pure reason's incipient fall into disorder, we are now to understand that the purely chaotic motion of necessity results in an unusual striation of order.

In the fall of 1697, Leibniz wrote, "On the Radical Origination of Things", an essay in which he attempted to elaborate the multiply complex levels of necessity and possibility that determined the compossible order of nature. His concern in this essay was to "explain how temporal, contingent, or physical truths arise out of truths that are eternal and essential, or if you like, metaphysical…."[8]

Leibniz attempted to explain how those forms which are most likely to emerge into reality are precisely those which have some priority of metaphysical perfection in possibility. He shows that in the drawing of an unspecified triangle, that figure which will be most easily constructed with a compass will be also the "best" one - the equilateral triangle, "From this it is obvious that of the infinite combinations of possibilities and possible series, the one that exists is the one through which the most essence or possibility is brought into existence."[9] He concludes that this is affirmation that the actual world is the best of all possibilities in that it is "the maximum effect at the minimum cost."[10] Paul Schrecker, in a commentary on this essay has contended that this effort by Leibniz is an attempt to illustrate how order arises out of chaos in Plato's *Timaean* receptacle."[11]

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[8] Gottfried Leibniz, *Philosophical Papers and* Letters (Netherlands, 1989), ed. L. Loemker, p. 487.

[9] G. W. Leibniz, Philosophical Essays, (Indianapolis, 1989), p. 150.

[10] Ibid.

[11] Paul Schrecker, "Leibniz and the *Timaeus,*" *Review of Metaphysics,* 4: 495–505.

Paul Schrecker has noted that this effort by Leibniz is in fact an explanation of how order arises out of chaos in Plato's *Timaean* receptacle (Schrecker, 1951). Plato implies that his elemental triangles are the result of the interplay between likelihood (symmetry) and necessity (dynamic stability). There is a thermodynamic rational for why the triangular, mechanical vectors rule the microdynamics of atomism.

## 3.1. ORGANIC EVOLUTION: SURVIVAL OF THE PERSUASIVELY INFORMED

Plato models the organizational structure of his third start, the interaction between reason and necessity, on the organic. The organic form is that which mediates between the rectilinear microcosm and the harmonic heavens. What is more striking in this presentation is the causal principle under which this mediation takes place: "Reason overruled Necessity by persuading her to guide the greatest part of the things that become towards what is best (*Timaeus 48a)*." If we are to make sense at how these three distinct species of form or information interact, we will need to unpack Plato's provocation on the rhetorical force of organic nature. We will have to inquire as to how it could be that life developed out of the causal interaction that is persuasion.

Life is a species of information. This intuition has been increasingly inspiring bioscientists to formulate new ways to investigate the apparently self-ordering biocosm in an attempt to understand the emergence and evolution of life's diverse forms as a lawful, necessary progression of nature.

But what do we even mean to say that life is information? Are we not just replacing a loose scientific metaphor with a highly equivocal concept? A survey of the way scientists from various disciplines utilize the term information would do little to help us clarify just what we mean by the term.

Broadly speaking, information has something to do with order or organization within a system of elements. The thermodynamic concept of entropy is also associated with such systems, although in an inverse relationship. When we attempt to put these two apparently coordinated schemas of order and disorder together, all kinds of difficulties arise.

The most serious problem in trying to synthesize talk about entropy and information is to develop a coherent, conceptual model. There have been two approaches which have predominated in this effort, each with limited success.

The one, following a thermodynamic approach, has just accepted the original hypothesis by Shannon that entropy simply is negative information or negentropy. Since the equations determining the probability of are formally similar, it is intuitively attractive to understand one quantity in terms of the other.

This approach has some distinct advantages for the task of understanding the nature of biological systems. Thermodynamic relations can better model the energy flows that are increasingly being utilized to understand the self-ordering complexity of evolutionary dynamics as well as the developmental progress of individual maturation. As the life sciences grow toward conceiving biological systems as unified, holistic orders, channeling and conserving energy from the sun, thermodynamic concepts of order and entropy will become increasingly ascendant.

And biological macromolecules are equally banks of information. The crystalline structure of proteins and genetic molecules readily model the ordered arrangements typical of informational systems. The informational content of a DNA molecule can be reasonably approximated using the standard approach of communication theory [$S = k \log W$].

But there are serious difficulties with such easy agreement.

For one, there is an equivocation between the ways in which we designate the entropy of a "message" (Seife, 2006, p. 73). The string of symbols "000000" has an extremely low entropy, yet it carries no information at all. I can transform this string into a generic message such as "101001" to greatly increase the informational content without lowering the entropy. In fact, the entropy of the message has increased.

There are assorted reasons for this apparent disjunction between information and negative order. There is a difference in "dimensionality" between information and thermodynamic order. From a functional perspective, entropy has the dimension of energy divided by temperature. Information, on the other hand, has no such dimensional residue. It is a merely abstract measure with no relationship to a "minimum energy flow" or any principle of conservation. In many ways, information can be considered energy and therefore entropy neutral.

There may also be an equivocation nested within the definition of information itself. There is an information of a "sender" and one of a "receiver," and then there is the added complication of an "interpretive system." Entropy on the other hand is well defined and measureable within the contexts of thermodynamical systems.

A second approach is more conservative. Scientists from the fields of cybernetics and information theory are confident that they are developing the tools to mimic life in all its self-organizing complexity. They are more cautious about importing conceptual framework from the less determinate model of thermodynamics. They trouble more deeply about the paradoxes encumbered by the equivocal use of words like order and information and believe that there is little to gain for the quickly expanding and well-founded field of information theory.

But such an approach lacks much promise for biology. Information theory is oriented toward the microstate causal model of mechanical determinism. It is intrinsically linear.

Biology most effectively studies systems as functional and holistic. If biology is to construct a model that bridges mechanical and systemic models of organization, it must allow for an alternate causal pattern than that offered by microstate physics.

Life is a hybrid with two distinct species of parent.

At one extreme, life is a process, more akin to a fire than a physical object. A controlled, metabolic burn, life is not its physically structured mass but rather continuously consumes it. The fact that the flame of life is locally contained and thermodynamically stable within a couple of degrees does not contravene its nature as a continuous transformation of matter into energy.

But life can equally be described as offspring of crystalline matter. DNA, the structural heart and essence of the living cell, has effectively been described as an organic, aperiodic crystal. Like a crystalline formation, each discrete DNA molecule has its own, electromagnetic resonant frequency by which it "informs" its immediate environment. Igor Svent-Gyorgui hypothesized that it was this field, stimulated by the pi-meson molecular flow on the perimeter of the structure, that "guided" the appropriate nucleic acids to "conform" in the process of molecular replication.

In both models, there are processes and structures, but each has its causal priorities inverted. The crystalline model sees the electrodynamic field of the macromolecule as a property determined specifically by the discrete structure of the molecule. It is a property and function *of* that structure.

The thermodynamic model envisions the structure as an evolutionary product of and a developmental phase in the energetic and informational flows through the environment, temporarily stored and stabilized within discrete colonies of discrete molecular formations.

In order to capture both of these perspectives on the nature of life and subsequently, intelligence, we will need to synthesize the vocabulary of order and information in a way that does not prejudice the further formulation of these models.

This task begins with the problem of what we mean when we use the term information. Clearly, there has developed a technical meaning for the term, following the use since Shannon in the fields of communication and computer science.

Any communication of "order" or "form" is in some sense informative. In this respect, we can separate a "technical" use of the term information from a more general or intuitive use. It is then incumbent on us to develop a coherent and clear vocabulary around the concepts of order and disorder that, if not easily conformable to, at least do not contradict those usages in thermodynamics and information theory. If we are to understand the structure and process of life under a single coherent model, it will be necessary to bring into sync the ways we talk about information and order.

## 4. Death Thou Shalt Die: Entropy Reconsidered

It is widely believed that the modern dilemma concerning the conflicting arrows of time, the thermodynamic and the evolutionary, has been adequately reconciled through the contemporary models of nonlinear dynamics and the energetics of evolution. This easy truce belies persistent problems within the synthesis that remain substantially unsettled.

Most generally, the reconciliation between the second law of thermodynamics and the possibility of evolutionary progress is explained via models of open and closed systems. Closed systems, such as the universe as a whole, are absolutely constrained to follow the parameters of the second law. The universe as a whole is moving to a state of maximum randomness or disorder. Of course this simple generalization does not begin to explain from what kind of "original order" the universe could be descending.

Evolution can take place within the localities of isolated systems because such neighborhoods are inherently "open" with respect to the flow of energy. The order of the evolutionary progress on our planet is "paid" for by the expenditure of solar energy from the sun.

This overly general story of reconciliation has been more recently supplemented by more sophisticated models. Illya Prigogine in his *Order Out of Chaos* updates the narrative of how order can be spawned from out of entropy's bowels. He leaves to the tyranny of the second law those processes which take place in the inanimate world in closed systems. He claims a second arrow of time working within the first for those processes within the biosphere which demand an open flow of energy to maintain order. Living organisms can locally decrease environmental entropy because they have an unlimited supply of energy, the sun, and an open sink for waste heat, space. These far from equilibrium systems he labels "dissipative structures" in a self-fulfilling prediction of what function they must inevitably serve: "to emphasize the close association, at first paradoxical, in such situations between structure and order on the one side, and dissipation and waste on the other" (Prigogine, 1984, p. 143).

There are numerous problems with this model of reconciliation, in both its simple and more intricate forms. Intelligent Design theorists garner increasing support, not so much for their compelling alternative models, as for their negative critique that the modern synthesis remains deficient of some fundamental axiom. I will briefly present an analysis of the most serious difficulties and then move on to Plato's more adequate resolution.

## 4.1. THE AUTONOMY OF ORDER FROM ENERGY

Maxwell, with the creation of his hypothetical demon, intrinsically tied energy flow to an ordering of system. This was a logical, though ambitious, extension of Clausius's expression of entropy as the limiting usage of heat energy. If a system could spontaneously organize itself to separate out differentially energized particles, then it would be able to create extreme temperatures from an initial state of equilibrium. This implies a heat flow from cold to hot, which is thermodynamically taboo, i.e., the second law evolves to a statement of systems which necessarily move to states of greater disorder.

The logical flaw in this development is that even if the flow of energy is order dependent, *order is not energy flow dependent*. Scientists posit with a kind of moral certainty that life, as a self-organizing structure, can only exist in nature because it pays for its order by utilizing energy it takes from its environment. *Energy causes order*. The same scientists will immediately reverse their logic to assert, with equal confidence, that the spontaneous crystallization of a winter's snow fall is only possible because the order it creates is paid for by the released energy of crystallization which contributes to increased environmental chaos. *Energy causes chaos*. The scientific view clearly equivocates between whether energy causes order or destroys it.

Clearly, the right type of energy received into just the precise kind of structure can be utilized to increase order. But this is the thermodynamic exception. We cannot utilize photosynthesis *as* an explanation for the thermodynamic basis of life: It is the thermodynamic origin of photosynthesis we have to explain.

Considering the third possible ordering state, that of a protein reraveling itself into its fourth-degree confirmation, there is no energy absorbed or released. It is apparent from the consideration of these three energy states of self-ordering systems that the process of order growth can be substantially *disassociated* from any strict energy determination. This leaves us where I assume Maxwell intended with his hypothetical demon. While energy flow can never determine the direction of order, microscopic ordering might well affect the level and direction of energy fluctuations.

Even if we are to accept that the nonlinear dissipative systems as modeled by Prigogine and others could account for the preservation of biological order through the continuous expenditure of energy, this model ignores the greater problem. How can such systems arise in the first place? The very energy-rich environments that are needed for their sustenance are equally predictors of the unlikelihood of their emergence. Energy disrupts and disorders stable structures and equilibria. The more energy-rich the environment, the less likely the evolvement of a stable structure or system.

It is not sufficient to invoke the naturalistic fallacy that since solar energy does accompany the development of ordered life, therefore it must. It is to understand and predict precisely how and why such lawful, self-ordering occurs that must be the task of both biology and physics.

Such objections are usually evaded by bringing in the possibility of overcoming the low probability of such events by having an exceptionally long period of time. Such arguments do not explain how evolution must happen but rather merely show that under the present synthesis, evolution is not impossible.

While it is true that when I drop a lead ball there is a minute probability, according to quantum mechanics, that it might push upward rather than fall, it cannot be good science to found major explanatory axioms on such highly improbable accidents. To the degree that inanimate order is tied to the flow of energy, greater energy *lessens* the possibility of self-ordering. We are now becoming more aware that life is not an infinitely exceptional accident that the scientist of the mechanical age predicted. To rely so fundamentally on accident contravening known science cannot be any more adequate than postulating a divine intervention.

## 4.2. THE MISIDENTIFICATION OF EQUILIBRIUM WITH DISORDER

A closely related fallacy of the received models of order and thermodynamics is that the inevitable flow of systems toward a state of energy equilibrium is just a move to maximal disorder. This conclusion is drawn from the misleading condition that the state of maximum disorder would in fact be one of equilibrium. Although the state of maximal disorder is one of equilibrium, the *converse* is by no means necessarily true. There are an unlimited number of possible states configured at equilibrium that are less than maximally disordered, and some particular subset could reasonably be adjudicated as maximally ordered, i.e., Hegel's or Aristotle's fully evolved, universal deity in self-conscious contemplation.

There are no probabilistic grounds for asserting that of all of the possible near-equilibrium states, the one that is maximally disordered would have preferential viability over any that are maximally ordered. In fact, there appears to be good reason to assume the opposite.

There are numerous conservation laws that determine that systems order themselves to move to equilibrium in the most orderly fashion, i.e., one that maximally resists the rate of change. Fourier showed that cooling solids automatically configures the distribution of heat into a harmonic pattern to maximally conserve heat loss. I have shown earlier how the second law itself determines that all dissipating energy sources necessarily conform to a maximally conservative harmonic pattern. All variations of the minimum action principle are manifestations of this greater tendency. These harmonic self-ordering fields are more than merely conservative of order; they actively attract or "cascade" orderly behavior. It is precisely the inevitable march toward minimum free energy that culls, nurtures, and programs nature's drive toward order.

The disassociation of energy flow from the degree and quantity of order, in addition to recognition of the inverse path toward a resistance insuring that this change happens in the slowest way possible with the least amount of action, leads us to formulate a radically revised version of the second law:

**Revised Second Law of Thermodynamics (Energy Version)**

*All systems move toward a local equalization of energy gradients.* (1)

In this continuous adjustment to minimize local gradients, there is an attraction to those discrete states with the greatest distributive probability. These states are conformed to minimize the total loss of energy from the system and make up a harmonic series with self-ordering conformity. When we interpret this revised law with respect to this least action principle, Maxwell's demon begins to develop a definite "shape":

**Revised Second Law of Thermodynamics (Order Version)**
**(First Law of Evolution (Principle of Plenitude and Pulchritude)**
**Leibniz's Law)**

*Coherent Systems move towards equilibrium through every possible ordered state and ordered states are mutually consonant – they tendto persevere.* (2)

## 4.3. FUNDAMENTAL INCONSISTENCY BETWEEN THE SECOND LAW AND ITS CLASSICAL PREDICTIONS

There are yet more direct problems with the modern synthesis. There is an inherent inconsistency between the second and third laws which may be proved with no more than a consistent application of the classic principles of thermodynamics. Given the prevailing model of the Big Bang cosmology, the universe is a finite, expanding continuum of matter and energy. By definition, no heat may enter from "outside" the universe, therefore the expansion is adiabatic. In all adiabatic expansions, the temperature uniformly decreases as the (square) of the rate of radial growth. In any closed system, and this is the only case we may safely so signify, with a decrease in temperature, the entropy must either decrease or remain the same. Universal entropy cannot increase.

David Layzer of Harvard University has recognized the insufficiency of contemporary accounts, and he makes an interesting attempt reconstruct our understanding of the problem. Layzer, in his *Cosmogenesis,* attempts to reconcile the growth of order within evolution with the increasing entropy of the second law by hypothesizing the concept of $R_{\max}$, the maximum possible entropy in the universe (Layzer, 1990, p. 138). He then speculates that as the universe expands, both the potential maximum and the actual measures of entropy increase, but the second quantity less than the first. Information, or order, can be calculated as:

$$I = R_{\max} - R \qquad (3)$$

The growth of information and entropy has been reconciled.

There would appear to be two problems with this reasoning. First, it based on the misconception that with the expansion of the universe, actual entropy must increase. We have shown that such a supposition is both inconsistent with the second law and an unnecessary consequence of the relationship between energy and order.

But perhaps just as problematic is his creating a concept, the maximum potential entropy, that is preponderantly explanatory, therefore ad hoc, to account for an ontological or causal phenomenon. If there is some quantity that grows with universal expansion, it should be formulated as an actual, causally effective phenomenon.

The approach of J. S. Nicolis in his treatise the *Dynamics of Hierarchical Systems* is somewhat closer to recognizing the hurdles to be overcome but still hits short (Nicolis, 1983). Nicolis recognizes the problem that we have put forward that in an expanding, adiabatic system, the temperature necessarily falls and the entropy must remain at least invariant.

His approach to explaining the increase in entropy that he feels he must justify is to speculate that since the expansion of the primordial mass is *asymmetric*, entropy is enabled to increase. This approach seems doubly flawed. First, the parameters of the second law, as applied to an expanding adiabatic system, are blind to any particular configuration of subsystems. Entropy must decrease or remain the same.

Just as importantly, there is something counterintuitive about his supposition. Surely, an ideal gas, expanding with perfect symmetry, would represent a maximally random configuration for the given conditions. Any asymmetric fracturing would open the possibility for aggregation and self-ordering. It is precisely the asymmetric distribution of mass that allows for a decreasing of universal entropy.

In point of fact, there are no perfectly open or close systems in the universe. To the degree that the solar system is a unity encompassed by its own gravitational field, it remains partially closed. And to the degree that the universe is expanding, it needs to be considered as a partially open system.

## 5. Plato's Rational Deduction of the Conservation of Information

Without the benefit of telescopes, optical radio, or orbiting, Plato constructed a conjecture about the cycle of the cosmos which, on close inspection, turns out to be on surprisingly firm ground. At *Statesman* 268e, Plato has his main character in the dialogue, the Stranger, introduce the Myth of the Reversed Cosmos. In this tale, Plato relates that the craftsman or *demiurgos*, who controls the motion of the universe, alternates periods of directly ordering the universe and then allowing it to naturally fall into disorder. How exactly this is brought about is not made completely explicit, but a steersman is invoked as the image of the model. In that Plato's paradigm for the universe was that of a sphere (*Timaeus*), it follows that the reversal of orders involved a reversal of direction of rotation for the sphere, "to twist itself around (268e)." Along with this, Plato imagines this action like that from a pilot, as the winding and unwinding of some sort of steering apparatus – the very modern image of an Archimedean spiral contracting and expanding with the change of direction.

In order to appreciate the full significance of this model, it is helpful to first understand the context within which it is raised. The Stranger, Plato's narrator for the dialogue, has recognized a basic paradox in the nature of the political science: The true knower of the science of kingship will be a potential outlaw in his own land.

The original lawgiver does not fit well into the society whose laws he has fashioned. The true statesman is a knower of the science of justice. He does not need to refer to the arbitrary canons to know what the most just action is in any circumstances. He must merely apply that science for which he is most expert. Laws may not always "foresee" circumstance, but his science can be perfectly applied by him.

The people, however, are obligated to the law. They will never accept that a science can better guide them to justice than the laws which have parented the sense of justice within their own souls. The lawgiver can only seem like an arbitrary usurper of the laws on returning home. The poignancy of this inherent tension is brought home in the haunting vision of Moses watching as his people pass on without him into the land of promise. They are the future – the fulfillers of the promise, the law followers. Moses is from a very different cloth. He is the last of the ancient ones who still have a "memory" of the original order: He had a direct conversation with God. The law itself will from hereafter be in the hands of the people (of its judges), not in those of its prophet. The laws will begin to take on an existence or life of their own. Moses's priority under the law which he will deliver will end with its deliverance.

What we have in these ancient tales is a *tragic* sense about the way of progress. Something is inevitably given up as the cost of advancement. It is the complex interaction of a reciprocal tradeoff between a gain and a loss. Both stories are about the advancing of a culture *through* the decline of greatness among its individuals. The future of the Hebrews will see fewer and fewer prophets and miracles as the laws and rabbis ascend to prominence. The people will have less need to converse directly with God, the more conversant they become with His law. The priority of the lawgiver is displaced by the effectiveness of his laws.

The Stranger first describes the period when the *demiurgos* has tight control over the motion of the cosmos, the reign of Chronos. Under the reign of Chronos, the cosmos moves with the perfect unity of a well-shepherded flock, "there was neither anything savage nor any act of feeding on one another, and there was no war at all or sedition either (271d)." But the Stranger shows that this orderly period can only be the time of the contrary direction, when "the white hair of elders was getting black, and the cheeks of those with beards were, in growing smooth, becoming what they were in their previous period of bloom (270e)."

The time of our present world is that of the overthrow of Chronos, the age of Zeus, when, "after the entire earthly genus had been used up, when each soul had rendered back all it generations, once it had let fall into the earth as many seeds as had been prescribed for each, it was precisely at that moment that the helmsman of the all, just as if he had let go of the handle of the rudder, stood apart and withdrew to his own surveying-post, and a fated and inborn desire reversed once more the cosmos (272e)."

We live in the time of the unruled and expanding cosmos, where disorder, at the cosmic level, is growing. Yet, it is equally the time of man's growth in freedom and the development of self-rule and philosophy. The Stranger's clear response to his own earlier query is that life has more value under the rein of Zeus. Plato interprets the ancient myths with a thermodynamic eye. It is interesting to note that Plato's myth is actually a synthesis of three distinct mythic narratives (Castoriades, 2002, p. 91):

(a) Conflict between Atreus and Thyestes – story about Zeus reversing the course of the sun because of him catching Thyestes cheating
(b) Reign of Cronus – story of the Golden Age under the reign of Cronus.
(c) Earth-born humans – alternative story of how humans originally were produced.

Each of these distinct narratives contributes an important element in Plato's attempt to mine rational principles from this ancient wisdom.

I will attempt to capture Plato's deduction of the Conservation of Information (COI) by paraphrasing the rational principles he explicitly utilizes. In this process, I shall distinguish the methodological principles as common notions [CN] and the theoretical principles as theorems [THM] and corollaries [COR]. I will also try to show that his choice to synthesize the three distinct narratives into a single, coherent story specifically details the necessary conditions for understanding the derivation of his principles.

The reasons given for the necessity of this cosmic reversal are threefold. They are given as three fundamental principles:

**CN1**: *It is impossible that the cosmos should turn itself forever*. (4)

Although the Stranger does not give us the basis of these this principle, it can be made fairly transparent to critically guided intuitions. That the cosmos cannot turn itself forever is obvious from any intuitive grasp of some form of the conservation of energy. A finite cosmos will eventually settle into the state of minimal activity.

The next set of principles Plato draws from the apparent conflict within time:

**CN2**: *Where there are opposing forces or activities*, *there must be opposing principles of order*. (5)

Plato develops these antiposed principles under the imagery of the strife between Atreus and Thyestes. The *mythos* shows the eternal and inherent conflict within the world and that this conflict implies the existence of two fundamental and opposed organizing principles.

Plato's narrative of change sees the two opposing forces of order necessarily bound to each other's genesis. But such a conflict could not be accounted for within a uniformly moving cosmos. So this conflict is acted out in the changing of the movements of the heavens. Can the demiurge be responsible for turning the cosmos in alternating directions? No. Being "always the same and in the same state, and in the same respects (269d)," it is "not sanctioned for him to set in motion anything at one time in a different way, and again in a contrary way (269e)." These competing processes are the subject of his second methodological principle:

> **CN3**: *Where there are two opposing principles which do not either neutralize or dominate each other, each must have its own term or period of expression.* (6)

Essential conflict must be parented by two distinct and competing orders of movement. And two conflicting movements cannot be caused by a single deity [or principle of order]. So the inherent conflict present in the world must be the consequence of a controlled "winding up" and a liberating "winding down." The necessity for the complementary phases of the world's playing out its conflicting organizing principles is represented by the second part of the Atreus myth: Zeus reverses the direction of time by reversing the rotation of the heavens.

As noted before, this "winding up" and "winding down" are direct references to an alternating "contraction" and "expansion" in the model of a ship's steering mechanism. As the helmsman turns hard in one direction, the rope mechanism "winds up" and tightens into a compact ball. On releasing the helm, there is a freeing "expansion" of the knotted rope which returns the wheel to its tensionless position.

This second common notion (5) elucidates how Plato's model of freedom goes beyond the romantic model of modernity. Schiller and Schelling celebrated a vision of freedom based on a triadic principle of balance or equilibrium. In the *Letters on the Aesthetic Education of Man*, Schiller trumpets that the balance with equal measures is exactly like the balance with no weights at all. Balance means lack of constraints.

But here, Buridan's ass weighs in. Equilibrium means stasis, not freedom. Plato's principle of alternating periods enables him to capture a dynamic balance, in which freedom occurs only in the release phase. And in a brilliant, yet subtle, insight, the Stranger relates that this period of freedom does not degenerate into immediate and complete chaos. Rather, the cosmos retains a slowly retreating "memory" of the previous regime of order within which freedom and order can maintain a progressively delicate marriage.

It is at this point in the myth that Plato's Stranger begins to draw some of his most peculiar conclusions. He analyzes that during the reversed cycle:

> The fact that elders go into the nature of a child and, on the other hand, it's from the dead, who lie in the earth, that they get put together there once more and live again, the connection between them is that they accompany the turn in the direction of generation that occurs along with the reversal of circular motion. (271a)
>
> This is the theme of the second myth within his meta-narrative. It is only a physicist who could foresee the necessity of this particular inclusion. How could we tell if time were reversed? In a perfectly Laplacian world, a reversal in the direction of motion of the cosmos might be completely indistinguishable from the original motion. There is no directionality of time in a mechanical world.

Plato's capturing of this myth within his story accomplishes a hypothetical reconciliation between the two traditionally opposed models of time. The fact that there is a differentiable process of generation proves that time *has* a direction precisely because its series can be contextualized within a particular direction of revolution. What is just as significant is that those within time have an epistemological basis for knowing which cycle they are in: Only within the cycle of degenerating order do the beings have memory. Yet within this model of asymmetric, directional clocks, the requirement of the laws of dynamics for microcosmic reversibility is conserved. In the reversed cycle, there is a complete and perfect reversal of time. Whether this is a detail of the *mythos* that we should hold on to is yet a matter of speculation.

It is with the third part of the myth that the Stranger's substantial theme rests. The sole purpose of the thought experiment was to determine under which regime man has the most happiness. Now since in the reversed cycle the cosmos is under the complete and direct control of Cronus, it is the time of perfect "order." It represents a cosmos ruled by the "good herdsman" and is representative of the state under the ideal statesman. There is no strife for man, nor memory, nor freedom.

The present cycle of the world is clearly not so ruled. Plato's Stranger concludes that we are in the cycle of the unmanned helm. We are in the temporal cycle of increasing disorder. Plato, 2,000 years before Claussius, Carnot, and Maxwell, has formulated the second law and tied it strictly to the decrease in order and information within the cosmos.

But the case of entropy is not so simple for Plato. The present cycle is that of the growth of the civilization and education of the ethical citizen, as well as the biological development of the cosmos [*Timaeus*]. This confusion is captured in the Stranger's observation that "it [cosmos] used to partake of a lot of disorder prior to its arrival at the order it now has (273c)." But at the start of the release, it should have had more order, due to the "memory" from the previous cycle. We are somehow using order in an equivocal fashion.

This confusion can only be sorted out with our "memory" back to the previous examination of parts and wholes (263c). The order of the parts is not identical to that of the whole. Plato's thermodynamic thought experiment is an attempt to show that it is in fact antithetical.

This model appropriately recalls the ancient war between the Athenians and Atlanteans (*Timaeus*). In that conflict, Atlantis was presented as the perfectly ordered state, ruled by a single king with complete top-down order. Athens on the other hand was a poorly ordered tribal democracy. Their bottom-up order was in complete contrast to that of the Atlanteans, but it served them well in the chaos of total war.

The present relaxed cycle spells doom for cosmic order, but it is what is required for the nurturing of the philosophical soul. The perfectly shepherded flock under the god's helm is not the womb for moral autonomy. The whole question of Western theodicy is tied to the implicit answer to the Stranger's question about under which reign is man happiest: We are the true children of Zeus.

Within this model of conflicting orders, Plato is developing the limits and conditions for the possibility of recognizing those orders. Order is always relative to what "is" [*Parmenides*]. If one is to theorize about the ordering or disordering of a system or any of its constituent parts, one must have a robust theory capable of certifying what constitutes an ordered system or its ordered constituents.

Plato's insight was to recognize that there are two fundamental kinds of "beings" with regard to which order must be defined. There is the universal system as a whole, and there are the multiple, partially organized systems and entities contending for survival within the whole.

Plato's further insight was to recognize that these two different levels of entity have opposing organizational conditions and constraints. The order of the whole is the tightly turned cycle of the steersman winding up. Under this condition, the whole is strongly unitary. The parts, however, are necessarily limited to the most fundamental simplicity possible in the heat and pressures of the collapsed universe. *Universal order is equivalent to local chaos.*

We can better visualize this reciprocal relationship if we think through the implications of the received "Big Bang" model. In the present cycle, the helm is let go by the steersman. The unitary order of the universal system gradually begins to dissipate. But in exact concordance and reciprocity, as the universal order is degenerating, or cooling, the energy conditions of the partitive localities begins to allow aggregation and coalescence of material bodies (stars, planets, etc.). Eventually, the rhythmic patterning of this energy flow cultivates successive levels of material bodies with greater dispositions to retain and conserve the dissipating energies. One form of this order is life.

It may be objected that it is misleading to refer to these two distinct patterns of order as somehow comparable. Even using the word order for both organizational frameworks would appear fatally equivocal. The local order of mechanical structure and atomistic determinism seems radically distinct from and conceptually opposed to the model of system order implied by the unity of the whole cosmos.

This equivocation within the meanings of "order" has been a major source of confusion between physicists and biologists as well as between scientists and philosophers. The confusion parallels that between the "causal" frameworks of the mechanical and conservational models. This conflict has led many scientists to refer to thermodynamic parameters as "noncausal" determinants in contrast to their mechanical, efficient conditions. But such a resolution belies the strong sense in which we are forced to understand conservation laws as causally efficacious.

For both models of ordering are systems of constraint by which particles and their aggregates are limited with respect to both each other and their unifying systems. As such, they both can be interpreted as kinds of informational parameters. And to the degree that they in fact interact, there needs to be some translational ground by which their influences may be brought into common measure – much like we have adapted to the necessary reciprocity of kinetic and potential energy.

This model of the relationship between the two ordering parameters of the cosmos implicitly suggests Plato’s first theoretical principle:

**Fourth Law of Thermodynamics**
**(Second Law of Evolution (Law of Conservation of Information) Plato’s Law)**

**THM1**: *There is an absolute conservation of the amount of order/ information in the universe. As one kind of order/information increases, the other decreases in exact reciprocity, and vice versa.* (7)

As a direct corollary of this principle, we can state what would be Plato’s definition of the arrow of time:

**COR1**: *There are two directions of time, each with two contrary and reciprocally dependent arrows: one from universal unity and microcosmic chaos toward universal dispersal and mesocosmic complexity, and the other in complete reverse.* (8)

What Plato presents is a slide-step model of evolution where a gain of function at one level is traded off against a loss of structural integrity at another. This device of connected reciprocity, or “entropy pump,” enables these more complex stories to deal with the narrative of evolution within the reign of thermodynamics rather than ignoring or emphasizing one in relation to the other. The second law determines the gradual and certain degradation of the global system while driving the ordered patterning of local, complex systems: Universal expansion directly influences the local decrease in entropy due to cooling.

What is so elegant with this ancient view of progress is that evolution happens, not despite of or in isolation from an overall process of decline (second law), but rather because of the same. The degeneration of the individual does not mean absolute retrogression. Weak individuals are dependent individuals. The degraded prokaryote necessarily begins to seek those relationships which will develop it toward the eukaryote. The whole dispute over the arrows of time is derived from a poorly developed and oversimplified framework for the concept of order.

What makes the sociopolitical models of development we find in the *Statesman* and *Exodus* so interesting is that they are not the gradual, creeping improvements of Darwin and Dawkins, nor the mysterious punctuated leaps of Gould. Modern explanations are unidirectionally simple. We understand evolutionary “progress” as a single, monolithic drive toward a more environmentally conditioned future niche.

It has become a happy revision of earlier thermodynamic and evolutionary thinking to now see the world as inevitably moving toward greater complexity. But what do we even mean by this concept? The algorithmic approaches to defining complexity just concede a simplistic and reducible model of atomistic relationships.

Our thermodynamic analysis allows us to bring some clarity to what complexity must more precisely be within the context of an expanding cosmos. Stochastic systems can be uniquely described by their tendency toward irreversibility, the loss of "memory" for their initial microstate configurations. But within an expanding, dissipative "system," this loss of memory is progressively resisted.

As embedded layers of the gravitationally organized cosmos successively iterate their harmonic patterns through ever more determinate levels, the system of the whole begins to have an increased ability to hierarchically "control" its microstate elements. Evolution is precisely that penetration of causal control from a memory-less, irreversibly conservative unity toward a fully reversible and systemically influenced organic whole, with memory "restored" as the cosmos is fully awakened into self-consciousness: The demon will have a face, and it is us:

### Fifth Law of Thermodynamics (Third Law of Evolution – DeChardin's Omega Point – Hegel's Law)

*Evolution within the present epoch is toward a direction of time in which the universe becomes completely reversible, i.e., the macrocosm "remembers" the microcosm* (9)

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Biodata of **Oren Harman**, author of "***War or Peace? Huxley and Kropotkin's Battle Over the Design of Virtue***."

**Oren Harman** is the chair of the Graduate Program in Science, Technology and Society at Bar Ilan University. He was trained in history and biology at the Hebrew University, Oxford, and Harvard and is a historian of biology and a writer. He teaches evolutionary theory; the interplay between scientific, social, and philosophical thought; and writing. His books include *The Man Who Invented the Chromosome* (Harvard, 2004), *Rebels, Mavericks and Heretics in Biology* [with Michael Dietrich] (Yale, 2008), and *The Price of Altruism* (W.W. Norton, 2010) (Bodley Head/Random House, 2010 which won the 2010 Los Angeles Times Book Prize). He is a frequent contributor to The New Republic, and the cocreator of the Israeli Oscar-nominated documentary series "Did Herzl Really Say That?" His work has been featured in The New York Times, The London Times, Nature, Science, The Economist, Forbes, New Scientist, Times Higher Education, Discover, The Huffington Post, and many others. He grew up in Jerusalem and now lives in Tel Aviv.

E-mail: **oren.harman@gmail.com**

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# WAR OR PEACE? HUXLEY AND KROPOTKIN'S BATTLE OVER THE DESIGN OF VIRTUE

**OREN HARMAN**
*Bar Ilan University, Tel Aviv, Israel*

He would wait until dusk. That would be the best time to slip away, unnoticed. As he packed a small valise, memories of his animated talk on the glacial formations of Finland and Russia at the Geographical Society the previous evening still lingered in his mind. It had gone well, he thought. The country's leading geologist, Barbot-de-Marny, had spoken up in his favor. It was even proposed that he be nominated president of the Physical Geography section of the society. Years of journeying to the frozen hearts of faraway places had finally paid off. But now he must concentrate. Now he must flee. "You had better go by the service staircase" one of the servant girls whispered (Kropotkin, 1978, 232).[1]

A horse-drawn carriage stood at the gate. He jumped in. The cabby whipped the horse and turned onto Nevsky Prospekt, the majestic avenue planned by Peter the Great in the city that called itself by his name. It was a short ride to the rail station, and from there, please the spirits, to freedom. Russia was a vast land, and in the remoteness of its eastern expanses, it was his intention to start a land league, like the ones that would become so powerful in Ireland in the years just ahead. It was the beginning of spring 1874.

Suddenly, a second cab galloped by. To his great surprise, there in its carriage was one of the two weavers who had been arrested the week before, waving his hand at him. Perhaps he has been released, he thought, and has an important communication to make to me. Duly he ordered the cabby to stop, but before he could greet the weaver, a second man, sitting beside him, appeared. Two years of clandestine meetings, disguises, and sleeping in other people's beds had come to an end. Jumping into his carriage, the second man, a detective, cried out: "Mr. Borodin, Prince Kropotkin, I arrest you!" Later that night, in the bowels of the infamous Third Section, a gendarme colonel solemnly read the charge: "You are accused of having belonged to a secret society which has for its object the overthrow of the existing form of government, and of conspiracy against the sacred person of his Imperial Majesty." For Prince Pyotr Alekseyevich Kropotkin, alias Borodin, the game was finally up (Kropotkin, 1978, 232–234).

Across the Baltic and North seas at the very same time, Thomas Henry Huxley was fastening his bowtie in preparation to open, together with the

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[1] This article is a revised extract from Oren Harman, *The Price of Altruism: George Price and the Search for the Origins of Kindness* (New York: W.W. Norton, 2010).

President Sir Joseph Dalton Hooker, the Thursday meeting of the Royal Society in Burlington House, Piccadilly, London.

Pictures of his carriage ride that afternoon flashed like fiery moths in his mind: Magsmen, cracksmen, shofulmen and prostitutes, child fences, religious fakes, and grimy boxers and promoters. This was the Victorian underworld, lying on his route to England's *sanctum sanctorum* of science. He knew the gutters and fever nests well. He had come from them. As he settled into the velvet-cushioned oak chair, he stole a nervous glance across the room.

Born in 1825 above a butcher shop in Ealing, a small village 12 miles west of London, he was forced at 10 to abandon school to earn the pittance his unemployed father could not provide him. At 13, he was apprenticed to a "beer-swilling, opium-chewing" medical man of a brother-in-law in Coventry before being fastened to a lowlife mesmeric doctor back in town. At times, the young Huxley thought he might drown in what a later biographer would call the "ocean stream of life" that was London – teeming with "whores, pandars, crimps, bullies." He found refuge in the dreary apothecary shop, grinding drugs in solitude. Steadily, a rage grew within him. How could the middle class remain so coldly indifferent, he wondered in his diary and in countless letters to friends, to such unabashedly, squalid suffering? (Desmond, 1997, 9, 11; Huxley, 1935).

With hard work and determination, he gained a scholarship to Charing Cross Hospital and later won the gold medal for anatomy and physiology at the University of London. At 20, to pay back debts, he joined the Royal Navy as assistant surgeon on board the *H.M.S. Rattlesnake*, surveying the coasts and innards of Papua New Guinea and Australia and dissecting otherwordly invertebrates from the wild southern seas. The specimens and papers he sent back home quickly made a name for him, an authority on the oceanic hydrozoa. At 25, he was elected to the Royal Society. Before long, he was the professor of Natural History at the Royal School of Mines, Fullerian professor at the Royal Institution, Hunterian professor at the Royal College of Surgeons, and president of the British Association for the Advancement of Science.

He shuffled the papers in front of him. The seat of Britain's most learned men of science for more than 300 years, the Royal Society, was undergoing dramatic change, mirroring the very face of the nation. Gone were the courtly days of yesteryear, the unchallenged loyalties to Crown and Church. As doctors, capitalists, and even those strange birds, "academics," began ringing at the bell, a fresh spirit was being ushered in. The new patrons were merchants and builders of empires abroad, not "blue-blooded dilettantes" and "spider-stuffing clergy." For Britain itself, as for its August Royal Society, the new gods became "utility and service to state; its new priests, the technocrats and specialists." Men, that is, just like Huxley (Chesney, 1970; Huxley, 1888, 161–180; Desmond, 1997, 11; 84).

Earlier that week, he had been hosted by the radical caucus of Birmingham. A statue of the chemist Joseph Priestley was being unveiled and Huxley seemed just the man to do the talking. With the city fathers hanging on his every word, he painted the town folk a vision of "rational freedom" sanctioned by a science-driven state. The post, the telegraph, the railway; vaccination, sanitation, road building – all would be well served if run by government. Improving life for British citizens in this way was the only way to stave off the bloody revolutionary rage scourging the rest of Europe (Desmond, 1997, 443–444; Bowler, 1989).

Clearing his throat to open the meeting, Huxley had calmed. It was the spring of 1874, and he was secretary of the Royal Society. The imperial botanist, Hooker, sitting beside him, had just declined a knighthood as beneath the dignity of science. Huxley smiled to himself. If a little boy from Ealing could make it, the system must be true and just after all. In a cutthroat world of competition, he had clawed his way from the gutter to the very heights of Victorian living. Brimming with fiery spirit – "cutting up monkeys was his forte, and cutting up men was his foible" the *Pall Mall Gazette* observed of him – he was the unblinkered professional public servant at the service of the modern, benevolent state (Desmond, 1997, 361).

"My fellows, I call this meeting to order…."

When the four-wheeled carriage crossed the Palace Bridge over the Neva some days and interrogations later, notwithstanding the silence of the stout Circassian accompanying officer, Kropotkin knew he was being taken to the terrible fortress of St. Peter and St. Paul.

Here Peter the Great had allegedly tortured and killed his son Alexis with his own hands; here Princess Tarakanova was kept in a water-filled cell, "the rats climbing upon her to save themselves from drowning"; here Catherine buried political prisoners alive. And here, too, great men of letters had recently been chained: Ryleyev and Shevchenko, Dostoevsky, Pisarev. The revolutionary, Mikhail Bakunin, too, had spent 8 hard years there before the Czar offered him the choice of banishment to Siberia, which he gladly accepted.

Immediately, he was ordered to strip and handed a green flannel dressing gown and gigantic woolen stockings of "an incredible thickness." Boat-shaped yellow slippers were thrown at his feet, so big that they fell off when he tried to walk. The prince was to be treated like any other inmate. Still, the military commander of the fortress, General Korsakov, a thin and tired old man, betrayed enfeebled vestiges of the tug of stature in czarist Russia, seeming visibly embarrassed by the occasion. "I am a soldier, and only do my duty," he said, not quite looking the prince in the eye. Kropotkin was paraded through a dark passageway guarded by shadowed sentries. A heavy oak door was closed behind him and a key turned in its lock.

The room was a casemate, "destined for a big gun," Kropotkin later wrote in his memoirs, with an iron bed and a small oak table and stool. The sole window, a long, narrow opening cut in a wall 5 ft deep and protected by an iron grating and a double iron window frame, was so high that he could hardly reach it with his outstretched fingers. Defiant, he began to sing "have I then to say farewell to love forever?" from his favorite Glinka opera, *Russlan and Ludmilla*, but was soon silenced by the basso reproach of an invisible guard.

The cell was half dark and humid. Absolute silence reigned all around. Scoping his surroundings, the prince determined to keep his body fit. There were ten steps from one corner to the other. If he paced them 150 times, he would have walked one verst – two-thirds of a mile. Then and there, he decided to walk seven versts every day: two in the morning, two before dinner, two after dinner, and one before going to sleep. And so he did, day in and day out, month in and month out. And he let his mind roam… (Kropotkin, 1978, 237–240).

Darwin called him "my good and kind agent for the propagation of the Gospel," though good and kind were perhaps not quite the words for the slashing rapier of "Darwin's bulldog." For Huxley, the alternative was "to lie still and let the Devil have his own way," for the resistance to the logic of materialism and evolution seemed to him nothing short of the workings of Satan. Darwin's nemesis, Britain's leading anatomist Richard Owen, had called Huxley a pervert with "some, perhaps congenital, defect of mind" for denying Divine will in nature, but this sort of thing only stoked his internal fires. Finally, from the heights of the Royal Society, Huxley, known to his enemies as "the Devil's disciple," could begin to bring about the revolution (Desmond, 1997, xv).

The first blow was struck from Russia. Vladimir Kovalevskii had come to London to work on hippopotamus evolution and was soon befriended by Huxley. Darwin's philosophy of descent with modification by the merciless hand of nature's blind selector had been fought over with rancor on the pages of popular newspapers and debated with disdain in the halls of museums. But evolution still remained at the margins of true scientific discourse. More than a decade following the publication of the *Origin of Species*, the *Philosophical Transactions* of the Royal Society had yet to print one article related to Darwinism, stubbornly clinging to "facts" and avoiding "theory," and keeping as far from controversy as its blue bloodedness could afford. But Huxley and his X-Club friends were now the new masters (MacLeod, 1970). When the secretary read Kovalevskii's paper to the society, George Gabriel Stokes complained that it was an abomination that a nihilist known to the Russian secret police be allowed to air such folly. Comparing Darwinian speculations with the axioms of Newton was a blow to the very foundations of knowledge. For Stokes, Cambridge's Lucasian professor of Mathematics, the "continuous curve" connecting the Creative Acts was a piece of "divine geometry," the very considered opposite of "Creation by Caprice." Yet Huxley arranged for sympathetic reviewers, and "On the Osteology of the Hyopotamidae" soon appeared in the pages of *Transactions*. It took the hippopotami and a nihilist Russian, but the fiery lad from Ealing had finally traversed the Royal Society's impasse. A flood of "free thinking" was about to violently burst open the pearly gates of England's scientific holy of holies (Kovalevskii, 1873; Desmond, 1989).

Kropotkin was born in Moscow in the winter of 1842. His maternal grandfather had been a Cossack army officer – some said of note – but his father's side provided the truly important pedigree. The Kropotkins were scions of the great Rurik dynasty, first rulers of Russia before the Romanovs (Woodcock and Avakumovich, 1950; Miller, 1976). At a time when family wealth was measured in numbers of serfs, the family owned nearly 1,200 souls in three different provinces. There were 50 servants in the Moscow home and another 75 at the Nikol'skoe country estate. Four coachman attended the horses, five cooks prepared the meals, and a dozen men served dinner every evening. It was a world of birch trees, governesses, samovars, sailor suits, and sleigh rides that young Peter was born into, "the taste of tea and jam sharpened and sweetened by the sense of the vast empty steppes beyond the garden and imminent end of it all" (Kropotkin, 1978; Avrich, 1967).

Not all was idyllic. Like other famous sons of Russian landed nobility – Herzen, Bakunin, Tolstoy – Peter would come to despise the particular flavor of Oriental despotism baked in the juices of Prussian militarism and overlaid with a foreign veneer of French culture. Ivan Turgenev's short story, "*Mumu*," describing the misfortunes of the serfs came as a startling revelation to an apathetic nation: "They love just as we do; is it possible?" was the reaction of sentimental urban ladies who "could not read a French novel without shedding tears over the troubles of the noble heroes and heroines" (Kropotkin, 1978, 56; Turgenev, 1959). Images etched themselves on young Peter's mind: the old man who had gone gray in his master's service and chose to hang himself under his master's window, the cruel laying waste of entire villages when a loaf of bread went missing, the young girl who found her only salvation from a landlord-arranged marriage in drowning herself. Increasingly, thinking and caring sons of the ruling elites of Imperial Russia witnessed up close the meanness and sterility of the feudal world into which they were born and fretted over the future of their beloved Russia. Many wondered: *What is to be done*?

Aleksei Petrovich Kropotkin, a retired army officer who had seen little real action but nevertheless lived entirely according to military custom, thought he knew very well what his son needed to do: Little Peter's artistically inclined mother died of consumption when he was just 4, and thereafter, he would be groomed for the life of a soldier. When a serendipitous opportunity presented itself to showcase his son at a gala costume party in honor of Czar Nicholas I's 25th anniversary, 8-year-old Peter's uniform was prepared with particular attention. And there he was, dressed as a Persian page with a belt covered with jewels, and hoisted by his uncle, Prince Gagarin, to the platform, when the Czar himself beheld him. Taking the young boy by the arm, Nicholas I led him to Maria Alexandrovna, the pregnant wife of the heir to the throne, saying: "That is the sort of boy you must bring me" (Kropotkin, 1978, 35).

The Czar would not live to regret his words, but his heir would. The Corps of Pages in St. Petersburg was the training ground for Russia's future military elite; only 150 boys, mainly sons of the courtly nobility, were admitted to the privileged corps and, upon graduation, could join any regiment they chose. The top 16 would be even luckier: *pages de chambre* to members of the imperial family – *the* card of entry to a life of influence and prestige. When Peter was sent there by his father at 15, he already considered it a misfortune. But despite himself, he graduated at the top of the class and was made personal liege to Alexander II, Nicholas having died some years earlier. It was 1861, and insurrections were growing more violent and expensive, opposition more damagingly vocal. The new Czar was coming under increasing pressure to grant freedom to his serfs. When he finally signed the Edict of Liberty on March 5 (according to the old Russian calendar), Alexander seemed, to Peter, transcendent. The sentiment was fleeting. The glamour of richly decorated drawing rooms flanked by chamberlains in gold-embroidered uniforms took his breath away at first, but soon he saw that such trifles absorbed the court at the expense of matters of true importance. Power, he was learning, was corrupting.

As he shadowed the Czar at a distance, with the requisite combination of "presence with absence," the aureole he once imagined over the imperial ruler's person gradually, gloomily eroded. The Czar was unreliable, detached, and vindictive, and many of the men around him were worse. With the Corps of Pages, Kropotkin had learned to March and fence and build bridges and fortifications, but his true interests, he already knew, lay elsewhere. Secretly, he began to read Herzen's London review, *The Polar Star*, and even to edit a revolutionary paper. When the time came to pick a commission, he determined to travel to the far expanses of eastern Siberia, to the recently annexed Afar region. His father and fellow cadets were shocked – after all, as Sergeant of the Corps, the entire army was open to him. "Are you not afraid to go so far?" Czar Alexander II asked him before he was to leave, surprised. "No. I want to work. There must be much to do in Siberia to apply the great reforms which are going to be made." "Well, go; one can be useful everywhere," the Czar replied, but with such an expression of fatigue and complete surrender that Kropotkin thought at once, "He is a used up man" (Kropotkin, 1978, 111; 80; 126).

Thirty years before Kropotkin set out for the Afar, Charles Darwin set sail on the *HMS Beagle*. En route to Buenos Aires in October 1832, Darwin noticed swarms of phosphorescent zoophytes, each smaller than the dot above this i. They illuminated the waves surrounding the ship with the glow of a pale green light as it sailed into the dark unknown ocean. Darwin was aware of the prevalent explanation: The tiny marine creatures had been put there by God to help sailors avoid shipwreck on gloomy nights at sea. This was the doctrine of finalism, or teleology, the very backbone of a tradition of natural theology on which Darwin's generation had been reared (Darwin, 1997).

But the young lad from Shrewsbury would not have God's benevolence stand as a proxy for scientific explanation. The glow ordained to direct lost sailors, he was certain, was simply phosphorescence caused by the decomposing bodies of the millions of dead zoophytes caught among the live ones – a process by which the ocean purified itself. This was purpose enough, God's benevolence notwithstanding. The true beauty of nature could be unmasked only by uncovering her own laws, not God's divinations. The Reverend William Paley figured natural design to be proof of godly design – how else to explain the excellence of the crystalline lens of the eye of the trout or the aerodynamic perfection of the wing of the eagle? But the answers in his *Natural Theology* now seemed to Darwin like questions: If God were bracketed, and natural laws sought out in his stead, how could the seamless fit between organisms' forms and functions be explained? How did nature come to seem so perfect? (Paley, 1830).

One way to look at the problem would be to study nature's imperfections, long recognized as a puzzle and unsuccessfully explained away by the argument for design. Why on earth do flightless kiwis have vestiges of wings, snakes relics of leg bones, or moles traces of once-busy eyes? The mysteries of biogeography kept tugging at his mind, too: Why are there fewer endemic species on islands than on the mainland? Where did these species come from? Why are they so similar to mainland species if their natural surroundings are so different? A fixity-of-species man upon embarkation, Darwin returned to England in October 1836 leaning toward a more dynamic view of nature and her ways. Still unsure of the physical law to explain away all conundrums, he nevertheless arrived, after nearly 5 years at sea, with "such facts [that] would undermine the stability of species" (Darwin, 1835).

And then something momentous happened (Schweber, 1977; Young, 1985). In October 1838, Darwin read *An Essay on the Principle of Population* by the clergyman and former professor of political economy Thomas Malthus. The idea that population increases geometrically while food supply increases arithmetically was meant by Malthus to prove that starvation, wars, death, and suffering were never the consequence of the defects of one political system or another but rather the necessary results of a natural law. A Whig and a supporter of Poor Law action to ameliorate the condition of the destitute, Darwin was not sympathetic to Malthus's reactionary politics, but applying the clergyman's law to nature was different. Immediately, he realized that given the struggle for existence everywhere, "favorable variations would tend to be preserved, and unfavorable ones to be destroyed. The result of this would be the formation of new species. Here, then," he wrote, "I had at last got a theory by which to work." Evolution by natural selection was nothing more and nothing less than "the doctrine of Malthus, applied to the whole animal and vegetable kingdoms" (Darwin, 1993, 120; 1996, 6).

After all, if one great lesson had been gleaned from the journey, it was the awesome abundance of life on the planet. On the massive vines of "wonderful" kelp off the coast of Tierra del Fuego, plummeting 45 fathoms into the darkness, Darwin found patelliform shells, troche, mollusks, bivalves, and innumerable crustacea. When he shook, out came "small fish, shells, cuttle-fish, crabs of all orders, sea-eggs, star-fish, beautiful holuthuriae, planariae, and crawling nereidous animals of a multitude of forms." The "great entangled roots" reminded Darwin of tropical forests, swarming with every imaginable species of ant and beetle rustling beneath the feet of giant capybaras and slit-eyed lizards, under the watchful gaze of carrion hawks. The splendor and variation were endless. "The form of the orange tree, the coconut, the palm, the mango, the tree-fern, the banana," Darwin wrote nostalgically, surveying the tropical panorama at Bahia as the *Beagle* pushed for home, "will remain clear and separate; but the 1,000 beauties which unite these into one perfect scene must fade away; yet they will leave, like a tale heard in childhood, a picture full of indistinct, but most beautiful figures" (Darwin, 1997, 228–9; 471).

In truth, Darwin knew, nature was one grand cacophonous battle – brutal, unyielding, and cruel. For if populations in the wild have such high rates of fertility that their size would increase exponentially if not constrained; if it is known that, excepting seasonal fluctuations, the size of populations remains stable over time; if Malthus was right, as he surely was, that the resources available to a species are limited, then it follows that there must be intense competition, or a *struggle for existence*, among the members of a species. And if no two members of a population are identical, and some of these differences render the life chances, or *fitness*, of some greater than others – *and are inherited* – then it follows that the selection of the fitter over the less fit will lead, over time, to evolution. The consequences were unthinkable, yet Darwin's logic was spotless. From the "war of nature, from famine and death," the most exalted creatures had been created. Malthus had brought about in him a complete "conversion," one which, he wrote to his trusted friend Joseph Hooker in 1844, was "like confessing a murder" (Darwin, 1996, 396; Burkhardt, 1987, 2).

Prisons to reform, schools to build, tribunals to assemble – the great administrative apparatus of the state was waiting to be marshaled. Wide-eyed, Kropotkin had joined the Cossack regiment, eager to bring justice to faraway districts. Gradually, he saw his considered recommendations all dying a silent death on the gallows of bureaucracy and official corruption. When a Polish insurrection broke out in the summer of 1863, Alexander II unleashed a terrible reaction, all reforms and their spirit long forgotten. Disillusioned, Kropotkin gradually turned to nature. Fifty thousand miles he traveled – in carts, on board steamers, in boats, but chiefly on horseback, with a few pounds of bread and a few ounces of tea in a leather bag, a kettle, and a hatchet hanging at the side of his saddle. Trekking to Manchuria on a geographical survey, he slept under open skies, read Mill's *On Liberty*, and beheld with astonishment "man's oneness with nature" (Kropotkin, 1978, 94).

Kropotkin's primary concern now became working out a theory of mountain chains and high plateaus, but he was keen, too, to find evidence for Darwin's great theory. He had read *The Origin of Species* at the Corps of Pages, and in a way, this was his polar voyage of the *Beagle*. What he saw, then, came as a great surprise: Darwin spoke of a fierce struggle between members of the same species, but everywhere he looked, Kropotkin found collaboration: horses forming protective rings to guard against predators, wolves coming together to hunt in packs, birds helping each other at the nest, fallow deer marching in unison to cross a river. Mutual aid and cooperation were everywhere.

Like Darwin upon return from his journey, after 5 years of adventure, Kropotkin had yet to develop a full-blown theory of nature. But if Darwin's belief in the fixity of species had been shaken on the *Beagle*, Kropotkin's assurance of the struggle for existence was completely shattered on the Afar. By the time he arrived in St. Petersburg in April 1867, he wrote, "the poetry of nature" had become the philosophy of his life. At the same time, he had lost all faith in the state: Once a constitutionalist who believed, like Huxley, in the promise of benevolent administration, Kropotkin emerged from the great Russian expanses fully "prepared to become an anarchist" (Kropotkin, 1978, 157; Avrich, 1967).

It was in Switzerland some years later that he became a full-fledged revolutionary. The death of his father finally setting him free, news of the Paris Commune drew Kropotkin to Europe. In Zurich, he joined the International, gaining a taste for revolutionary politics. But it was in Sonvilliers, a little valley in the Jura hills, that something really moved him. In the midst of a heavy snowstorm that "blinded us and froze the blood in our veins," 50 isolated watchmakers, most of them old men, braved the weather in order to discuss their no-government philosophy of living. This was not a mass being led and made subservient to the political ends of a few apparatchiks. It was a union of independents, a federation of equals, setting standards by fraternal consensus. He was touched and deeply impressed by their wisdom. "When I came away from the mountains," Kropotkin wrote, "my views upon socialism were settled. I was an anarchist" (Kropotkin, 1978, 201; 202).

Back in St. Petersburg, he joined the Chaikovsky Circle, an underground outfit working to spread revolutionary ideas. For 2 years, between learned debates at the Geographical Society and lavish imperial soirees, Kropotkin became "Borodin." Disguised as this peasant, he ducked into shady apartments to lecture on everything from Proudhon to reading and arithmetic, slipping away again like a phantom. Communalism and fraternity were the anarchist response to the state, order without Order. Here was the creed: Left to his own devices, man would cooperate in egalitarian communes, property and coercion replaced by liberty and consent. Progress was being made, uniting the workers in revolt against the Czar when the police began taking serious counteraction. A group of agitating weavers had been arrested, and a raid on a student apartment produced a revolutionary manifesto authored by one P.A. Kropotkin. It was then that he knew that he would have to leave without delay. Now, pacing in his prison cell, Kropotkin could not help but grimace: if only he had forgone that last talk on glacial formations….

If competition between individuals was, scandalously, nature's way – she had forgotten to whisper the news to some of her smaller creatures. Many an ant species, Darwin knew, was divided into fixed, unbreachable castes. The honeypot ant of the American deserts has workers whose sole job is to hang upside down, motionless, like great big pots of sugared water, so that they may be tapped when the queen and her brood are thirsty. Members of another caste in the same species have gigantic heads with which, Cerberus-like, they block the nest entrance before intruders. The leaf-cutter ants of South America sport castes that differ in weight up to 300-fold, from miniature serene fungus gardeners to giant ferocious soldiers. In the ant world, some tend to the queen, others to the nest, others to food, others to battle – each to his caste and each to his fate. What Darwin found amazing was that besides the queen and a few lucky males, all the rest of the ants are effectively neuters. This made no sense if success in the battle for survival was measured by production of offspring (Cronin, 1991).

For Darwin, the mystery lay in trying to explain how such different behavior and morphology arose in a single species, for since all the workers had no offspring, natural selection could hardly be fashioning their traits through their own direct kin. What this meant was that the queen and her mate were somehow passing on qualities through their own progeny – massive heads, gardening scissor teeth, and mysterious altruistic behavior – that they themselves did not possess, an obscurity that Darwin found "by far the most serious special difficulty, which my theory has encountered" (Darwin, 1996, 197). This was a problem of heredity: how could traits, both of form and of behavior, perform such Houdini acts in their journey from generation to generation?

It was also a glaring exception to "nature red in tooth and claw." If evolution by natural selection was the doctrine of Malthus applied to the whole of living creation, little ants and bees and termites were islands of chivalry in a sea of conflagration. Why, how – this anomalous sanctuary of "goodness"? (Dixon, 2008). To solve the mystery, Darwin asked a simple question: Who benefits? The answer, he thought, was the "community," for those who could forage or fight would surely free others to partake in procreation, on the very same principle that rendered the division of labor "useful to civilised man." If selection sometimes worked at a level higher than the individual, even the ultimate sacrifice of the stinging bee or ant centurion could evolve. This was quite an idea, for the very essence of Darwin's theory, as he declared in *The Origin of Species*, was that "every complex structure and instinct" should be "useful to the possessor." Natural selection could "never produce in a being anything injurious to itself, for natural selection acts solely by and for the good of each" (Darwin, 1996, 196; 392). And yet it did.

Darwin was impressed. It was the strongest evidence yet, he thought, for the incredible power of natural selection. In truth, he would come to believe, it was actually entirely much bigger. "The social instincts," he wrote in *The Descent of Man*, "which no doubt were acquired by man, as by the lower animals, the good of the community, will from the first have given him some wish to aid his fellows, and some feeling of sympathy" (Darwin, 1871, 103). Evolution was the key to the beginnings of morality in humans (Sober, 2010).

Rheumatism had almost killed Kropotkin. With the help of family connections and a friendly doctor's note, he was transferred after 21 months to the Detention House and from there to the Military Hospital. Finally, even though he was sickly and frail, there was a glimmer of hope: The hospital was not nearly as well guarded as the fortress. The day of the escape was fixed. It was to be June 29, Old Style, the day of St. Peter and Paul – his friends having decided to throw, he later wrote, "a touch of sentimentalism into their enterprise" (Kropotkin, 1978, 254). A red balloon climbing into the blue sky would be the signal to make a dash for the gate, where a carriage would whisk him to freedom. But the impossible happened that day: No red balloons could be found in all of St. Petersburg, and when one was finally discovered and snatched from the hand of a howling boy, it would not fly, nor would the apparatus for making hydrogen hurriedly bought from an optician's shop revive it. The woman who finally strung the flaccid balloon to an umbrella, walking up and down behind the hospital wall, did not help either: The wall was too high and the woman too short, and the signal never reached poor Kropotkin.

The next morning, a relative came to visit at the hospital carrying a watch that she asked that he be given. Unsuspected, it was passed to him, though the timepiece was far from innocent. Hidden inside was a cipher, detailing the new plans for escape that very day. At 4 P.M. Kropotkin went out to the garden for his afternoon stroll. When he heard the cue of an excited violin mazurka, he made a desperate dash for the gate. "He runs! Stop him! Catch him!" – a sentry and three soldiers were in hot pursuit, so close that he could feel the wind of the bayonet thrust toward him (Kropotkin, 1978, 258).

That evening, they clinked glasses at Donon's, St. Petersburg's finest restaurant. The secret police would never think of looking there. The escape was a feat of true altruism: Untold accomplices had selflessly braved grave danger – one signaling with handkerchiefs, a second by means of synchronized cherry eating, a third distracting the guard, a fourth playing the violin, a fifth commanding the carriage.… Kropotkin was aglow with pride. But he would have to leave. Soon, he crossed the Finnish border and was on a steamer headed for London.

Mady Huxley died of pneumonia on November 20, 1887. The great neurologist Jean-Martin Charcot had come to England to examine her – the loss of vision and voice having led her father to fear "the worst of all ends – dementia." She was to him a "brilliant creature," his fair and beloved third child. A specialist on "hysteria" and teacher to the young Sigmund Freud, Charcot determined that Mady suffered from a grave mental illness and invited her to Paris for hypnosis. It was too late. Arriving at the Salpêtrière Hospital, exhausted, she succumbed before the treatment could remove her emotional "conflicts" (Desmond, 1997, 557; Clarck, 1968, 109).

Staggering, in pain, Huxley traveled to Manchester for a talk he felt honor-bound to give. As the train sped north through the West Midlands – Coventry, Birmingham, Wolverhampton, Stock-on-Trent… – he glanced at England passing by. For more than 4 years now, he was president of the Royal Society, the winner of medals, and very soon of the scientific *orbis terrarum*. But if Huxley had come a long way from above the butcher's shop in Ealing, so too had England from its affluent "Age of Equipoise." Dissenters and Nonconformists had waged a battle for meritocracy against Church and Crown in the 1850s, 1860s, and 1870s, but this was long yesterday's triumph. Great boring machines were now miraculously digging the Channel Tunnel deep beneath the sea, yet millions in the cities and countryside took to bed hungry. The "interminable Depression" had coincided with "a specialist age"; at its finest hour, technology was failing the masses (Desmond, 1997, 572–3).

And the masses were swelling. Britain's population had reached 36 million and was adding nearly 350,000 hungry mouths every year. As growth rates had surged, a new phrase made its way from France and Germany. English Darwinians had, by tradition, few qualms about folding the social into the biological: For them, animals and man bowed just as humbly before nature and her laws. But as political socialism took a bite at the Malthusian core of survival of the fittest, as suffrage, labor unrest, and the "Woman Question" ushered in a new age of extremes, a currency was needed to remind civilization of its beastly beginnings. Were the teeming congestion and competitive strife not confirmation enough of Malthus's prediction? Huxley called industrial competition with Germany and the United States a form of international "warfare," and *Nature* and the *Times* applauded. But if mercantilism had morphed into an all-out image of battle, if Darwin's Malthusian struggle had been writ large on the world as a whole, there were those who were prepared to fight it. It was against such men and women that "social Darwinism" would now be wielded (Hofstadter, 1955; Hawkins, 1997; Dickens, 2000; Crook, 2007).

Leading the way was Herbert Spencer, Huxley's X-Club companion, a "bumptious" man with a "breathless vision" of evolution galloping ahead to perfection. No one had swallowed Darwin so wholly, even if some (including Darwin himself) thought it had gone down the wrong pipe. For the "Prince of Progress," the physical, biological, social, and ethical all danced to the tune of evolution (Spencer, 1857). Historical destiny was like the womb and the jungle, the growth of civilization "all of a piece with the development of the embryo or the unfolding of a flower" (Desmond, 1997, 184; Kennedy, 1978; Turner, 1985; Taylor, 1992; Elwick, 2003; Francis, 2007). An eminent Victorian who had dabbled in phrenology, he had coined the "survival of the fittest." (Spencer, 1864). Friend to Mill, follower of Comte, and a lover of George Eliot, Spencer honed to perfection the belief in human perfectibility. But it was the strong, not the meek for him, who carried the future in their bones, their struggles and triumphs the true holy of holies, their might – the right and just. To let it be, government would need to step aside, even when its actions seemed "progressive." Intervention, after all, was really a curse disguised as a blessing, the conquest by maudlin sensibility of the necessity of natural law. Unfettered competition alone would lead to the advance of civilization in the long run – endowments and free education be damned and myopia forlorn.

From the Left, other voices came buzzing. Henry George's *Progress and Poverty,* a popular appeal for land nationalization, was rapidly gaining readers (George, 1885). Touting Rousseau's noble savage, George led a frontal attack on property and competition. Even the codiscoverer of natural selection, Alfred Russel Wallace, from his retirement nest in Dorset, took a jab at "Darwinism" – a term no one had done more than he to establish (Wallace, 1975). Women, he now claimed, when liberated economically by socialism, would freely choose the righteous among men. As such, they would be humankind's great redeemers, breeders of goodness into future generations (Wallace, 1890; Fichman, 2004; Slotten, 2004). This was a different woman from Darwin's in his *Descent of Man*, to say the least. But even if Wallace's utopia seemed farfetched and would need to be nudged along by higher forces (a spiritualist, he had removed man from the arena of natural selection), it hardly mattered anymore. Beaten over the head by natural rights, ancient communes, and the promise of equality, the Darwinian establishment was reeling. Perhaps competition was not the natural law they said it was. Perhaps their "religion of Science" was an illusion, nothing but a false "religion of despair" (Desmond, 1997, 576).

Huxley was taking the fire. After all, he had fashioned himself the very embodiment of "science as panacea." Spencer was a "long-winded pedant," he thought, a "hippopotamus," as misguided in his sacrifice of the masses on the altar of Darwinism as he was in his belief in the inheritance of acquired characteristics. And yet nature really *was* brutal, like "a surface of ten thousand wedges" each representing a species being "driven inward by incessant blows" (Darwin and Wallace, 1858). Success always came at the expense of another's failure. How then to escape the trap into which the patrician Spencer had willfully fallen? How to wrest morality for the masses from the bloody talons of nature?

These were his mind's torments as the train pulled into London Road Station, Manchester. At Town Hall, before his crowd, the darkness in his soul poured itself onto the natural world. Glassy-eyed and imagining his daughter, Huxley unmasked the vision of nature's butchery: "You see a meadow rich in flower & foliage and your memory rests upon it as an image of peaceful beauty. It is a delusion… Not a bird that twitters but is either slayer or [slain and] … not a moment passes in that a holocaust, in every hedge & every copse battle murder & sudden death are the order of the day" (Desmond, 1997, 558).

As "melancholy as a pelican in the wilderness," as he wrote to a friend, Huxley was sinking into depression (Huxley, 1900, 198). The Manchester Address was printed in February's *Nineteenth Century* and soon became a disputed *cause célèbre*. In "The Struggle for Existence in Human Society: A Programme," Huxley asked readers to imagine the chase of a deer by a wolf. Had a man intervened to aid the deer, we would call him "brave and compassionate," as we would judge an abetter of the wolf "base and cruel." But this was a hoax, the spoiled fruit of man's translation of his own world into nature. Under the "dry light of science," none could be more admirable than the other, "the goodness of the right hand which helps the deer, and the wickedness of the left hand which eggs on the wolf" neutralizing each other. Nature was "neither moral nor immoral, but non-moral," the ghost of the deer no more likely to reach a heaven of "perennial existence in clover" than the ghost of the wolf a boneless kennel in hell. "From the point of view of the moralist the animal world is on about the same level as a gladiator's show," Huxley wrote, "the strongest, the swiftest, and the cunningest… living to fight another day." There was no need for the spectator to turn his thumbs down, "as no quarter is given," but "he must shut his eyes if he would not see that more or less enduring suffering is the meed of both vanquished and victor" (Huxley, 1883–1884, 197–200).

Darwin and Spencer believed that the struggle for existence "tends to final good," the suffering of the ancestor paid for by the increased perfection of its future offspring. But this was nonsense unless, "in Chinese fashion, the present generation could pay its debts to its ancestors." Otherwise, it was unclear to Huxley "what compensation the *Eohippus* gets for his sorrows in the fact that, some millions of years afterwards, one of his descendants wins the Derby." Besides, life was constantly adapting to its environment. If a "universal winter" came upon the world, as the "physical philosophers" watching the cooling sun and earth now warned, arctic diatoms and protococci of the red snow would be all that was left on the planet. Christians, perhaps, imagined God's fingerprint on nature, but it was Ishtar, the Babylonian goddess, whose meddling seemed to Huxley more true. A blend of Aphrodite and Ares, Ishtar knew neither good nor evil, nor, like the Beneficent Deity, did she promise any rewards. She demanded only that which came to her: the sacrifice of the weak. Nature-Ishtar was the heartless executioner of necessity (Huxley, 1883–1884, 198–200).

But what, then, of man: Was he, too, to bow in deference to the indifferent god of inevitability? As for all other creatures "beyond the limited and temporary relations of the family," for man too, the "Hobbesian war of each against all" had been the normal state of existence. Like them, he had "plashed and floundered amid the general stream of evolution," keeping his head above water and "thinking neither of whence nor whither." Then came the first men who for whatever reason "substituted the state of mutual peace for that of mutual war," and civilization was born. Self-restraint became the negation of the struggle for existence, man's glorious rebellion against the tyranny of need. But as historic as his achievement, ethical man could not abolish "the deep-seated organic impulses which impel the natural man to follow his non-moral course." Chief of these was procreation, the greatest cause of the struggle for existence (Huxley, 1883–1884, 204; 205).

Of all the commandments, "Be fruitful and multiply" was the oldest and the only one generally heeded. Despite his best intentions, then, ethical man was locked once more in the nonmoral "survival of the fittest." Population was driving him to war. For the dark moment Huxley could see no tonic, though, contra the socialists, he was certain that no "fiddle-faddling with the distribution of wealth" could deliver society from its tendency toward self-destruction. Industrial warfare having replaced natural combat, the corporatist Huxley made a plea for state-sponsored technical education. But this was as much medicine, he knew, as an eye doctor's recommending an operation for cataract on a man who is going blind, "without being supposed to undertake that it will cure him of gout" (Huxley, 1883–1884, 212; 235).

For Darwin, morality had come from the evolution of the social instincts, but for Huxley, they were a vestige of amoral beginnings. Instincts were *antisocial*; their primeval lure – the bane of man's precarious existence. Desperately seeking the cure for social ills, Huxley nevertheless would not search for it in nature. Nor, weeping over the loss of Mady on the train ride back from Manchester, could he find any solace there.

Malthus was already dead when *Russian Nights* became a bestseller in the 1840s. The novel's author, Prince Vladimir Odoesky, had created an economist antihero, driven to suicide by his gloomy prophecies of reproduction run amok.

The suicide was cheered on by the Russian reading masses: after all, in a land as vast and underpopulated as theirs, Malthusianism was a joke. England was a cramped furnace on the verge of explosion; Russia – an expanse of bounty almost entirely unfilled. But it was more than that. "The country that wallowed in the moral bookkeeping of the past century," Odoesky explained, "was destined to create a man who focused in himself the crimes, all the fallacies of his epoch, and squeezed strict and mathematical formulated laws of society out of them." Malthus was no hero in Russia (Todes, 1987, 1989; Gould, 1991; Glick, 1988, 227–268).

And so when the *Origin of Species* was translated in 1864, Russian evolutionists found themselves in something of a quandary. Darwin was the champion of science, the father of a great theory, but also an adherent to Malthus, that "malicious mediocrity," according to Tolstoy (Todes, 1987, 542). How to divorce the kind and portly naturalist Whig from Downe from the cleft-palated, fire-breathing, reactionary reverend from Surrey? (James, 1979; Hollander, 1997; Peterson, 1999; Dupâquier, 2001). Both ends of the political spectrum had good grounds for annulment. Radicals like Herzen reviled Malthus for his morals: Unlike bourgeois political economy, the cherished peasant commune allowed "everyone without exception to take his place at the table." Monarchists and conservatives, on the other hand, like the Slavophile biologist Nikolai Danilevsky, contrasted czarist Russia's nobility to Britain's "nation of shopkeepers," pettily counting their coins. Danilevsky saw Darwin's dependence on Malthus as proof of the inseparability of science from cultural values. "The English national type," he wrote, "accepts [struggle] with all its consequences, demands it as his right, tolerates no limits upon it… He boxes one on one, not in a group as we Russians like to spar." Darwinism for Danilevsky was "a purely English doctrine," its pedigree still unfolding: "On usefulness and utilitarianism is founded Benthamite ethics, and essentially Spencer's also; on the war of all against all, now termed the struggle for existence – Hobbes's theory of politics; on competition – the economic theory of Adam Smith… Malthus applied the very same principle to the problem of population….Darwin extended both Malthus's partial theory and the general theory of the political economists to the organic world." Russian values were of a different timber (Todes, 1987, 542; 540; 541–2).

But so was Russian nature. Darwin and Wallace had eavesdropped on life in the shrieking hullabaloo of the tropics. But the winds of the arctic tundra whistled an altogether different melody. And so, wanting to stay loyal to Darwin, Russian evolutionists now turned to their sage, training a torch on those expressions Huxley and the Malthusians had swept aside. "I use this term in a large and metaphorical sense," Darwin wrote of the struggle for existence in *Origin*. "Two canine animals, in a time of dearth, may be truly said to struggle with each other which shall get food and live. *But a plant on the edge of a desert is said to struggle for life against the drought*, though more properly it should be said to be dependent on the moisture" [italics added] (Darwin, 1996, 53). Here was the merciful getaway from *bellum omnium contra omnes*, even if Darwin had not underscored it. For if the struggle could mean both competition with other members of the same species *and* a battle against the elements, it was a matter of evidence which of the two was more important in nature. And if harsh surroundings were the enemy rather than rivals from one's own species, animals might seek other ways than conflict to manage such struggle. Here, in Russia, the fight against the elements could actually lead to cooperation.

London did not keep Kropotkin for long. The Jura Federation that had turned him anarchist during the blizzard in Sonvilliers beckoned once again, and within a few months, he was in Switzerland knee-deep in revolutionary activity. On March 18, 1877, he organized a demonstration in Bern to commemorate the Paris Commune. Other leaders of the Jura feared police reaction, but Kropotkin was certain that, in this instance, violence would serve the cause. He was right. Police brutality galvanized the workers, and membership in the federation doubled after the demonstration. The peacefulness of the Sonvilliers watchmakers notwithstanding, Peter was developing a political program: collectivism, negation of state, and "propaganda of the deed" – violence – as the means to the former through the latter.

It was the young people who would bring about change. "All of you who possess knowledge, talent, capacity, industry," Kropotkin wrote in 1880 in his paper *Le Révolté*, "if you have a spark of sympathy in your nature, come, you and your companions, come and place your services at the disposal of those who most need them. And remember, if you do come, that you come not as masters, but as comrades in the struggle; that you come not to govern but to gain strength for yourselves in a new life which sweeps upward to the conquest of the future; that you come less to teach than to grasp the aspirations of the many; to divine them, to give them shape, and then to work, without rest and without haste, with all the fire of youth and all the judgment of age, to realize them in actual life" (Kropotkin, 1880).

On March 1 (Old Style), 1881, Alexander II was assassinated in Russia. Once his trusted liege, Kropotkin welcomed the news of his death as a harbinger of the coming revolution. But he would have to watch his back now. The successor, Alexander III, had formed the Holy Brotherhood, a secret counteroffensive that soon issued a death warrant against Kropotkin. Luckily, Peter had been expelled from Switzerland for his support for the assassination, and now, back in London, he was given warning of Alexander's plot. Undeterred, he exposed it in the London *Times* and Manchester *Chronicle*, and a deeply embarrassed Czar was made to recall his agents. Still, if Kropotkin had escaped with his life, he was less lucky with his freedom. Despairing of the worker movement in England, he traveled to France, where his reputation as an anarchist preceded him. Within a few months, he was apprehended and sentenced, and spent the next 3 years in prison. It was soon after his release following international pressure that the news arrived: his brother Alexander, exiled for political offenses, had committed suicide in Siberia (Kropotkin, 1978, 261–338).

It was a terrible blow. Alexander had been his lifelong friend, perhaps his only true one. But his suicide also made Peter all the more determined to find confidence in his revolutionary activities. Increasingly, he turned to science: the science of anarchy and the science of nature. They had evolved apart from each other, but the two sciences were now converging, even becoming uncannily interchangeable. When Darwin died in the spring of 1882, Kropotkin penned an obituary in *Le Révolté*. Celebrating, in true Russian fashion, the sage of evolution entirely divorced from Malthus, the prince judged Darwin's ideas "an excellent argument that animal societies are best organized in the community-anarchist manner" (Kropotkin, 1882). In "The Scientific basis of Anarchy," some years later, he made clear that the river ran in both directions. "The anarchist thinker," Kropotkin wrote, "does not resort to metaphysical conceptions (like the 'natural rights', the 'duties of the state' and so on) for establishing what are, in his opinion, the best conditions for realising the greatest happiness for humanity. He follows, on the contrary, the course traced by the modern philosophy of evolution" (Kropotkin, 1887, 238). Finding the answers to society's woes "was no longer a matter of faith; it [is] a matter for scientific discussion" (Kropotkin, 1887, 239).

Meanwhile, navigating anxiously between Spencer's ultraselfish ethics and George and Wallace's socialist nature, Huxley had found an uneasy path to allay his heart's torments. If instincts were bloody, morality would be bought by casting away their yoke. This was the task of civilization – its very *raison d'etre* – to combat, with full force, man's evolutionary heritage. It might seem "an audacious proposal" to create thus "an artificial world within the cosmos," but of course, this was man's "nature within nature," sanctioned by his evolution, a "strange microcosm spinning counter-clockwise." Huxley was hopeful, but this was optimism born of necessity: For a believing Darwinist, any other course would mean utter bleakness and despair (Desmond, 1997, 599; 598).

Like Darwin, Huxley saw ants and bees partake in social behavior and altruism. But this was simply "the perfection of an automatic mechanism, hammered out by the blows of the struggle for existence." Here was no principle to help explain the natural origins of mankind's morals; after all, a drone was born a drone, and could never "aspire" to be a queen or even a worker. Man, on the other hand, had an "innate desire" to enjoy the pleasures and escape the pains of life – his *aviditas vitae* – an essential condition of success in the war of nature outside, "and yet the sure agent of the destruction of society if allowed free play within." Far from trying to emulate nature, man would need to combat it. If he was to show any kindness at all outside the family (to Huxley the only stable haven of "goodness"), it would be through an "artificial personality," a conscience, what Adam Smith called "the man within," the precarious exception to Nature-Ishtar. Were it not for his regard for the opinion of others, his shame before disapproval and condemnation, man would be as ruthless as the animals. No, there could be no "sanction for morality in the ways of the cosmos" for Huxley. Nature's injustice had "burned itself deeply" into his soul (Huxley, 1893, 25; 27; 30; Smith, 1759).

Years in the Afar, in prisons, and in revolutionary politics had coalesced Kropotkin's thoughts, too, into a single, unwavering philosophy. Quite the opposite of Huxley's tortured plea to wrest civilized man away from his savage beginnings, it was rather the *return* to animal origins that promised to save morality for mankind. And so, when in a dank library in Harrow, perusing the latest issue of the *Nineteenth Century*, Kropotkin's eyes fell on Huxley's "The Struggle for Existence," anger swelled within him. He would need to rescue Darwin from the "infidels," men like Huxley who had "raised the 'pitiless' struggle for personal advantage to the height of a biological principle" (Kropotkin, 1955, 4). Moved to action, the "shepherd from the Delectable Mountains" wrote to James Knowles, the *Nineteenth*'s editor, asking that he extend his hospitality for "an elaborate reply." Knowles complied willingly, writing to Huxley that the result was "one of the most refreshing & reviving aspects of Nature that ever I came across" (Kropotkin, 1955; Desmond, 1997, 564).

"Mutual Aid Among Animals" was the first of a series of five articles, written between 1890 and 1896, that would become famously known in 1902 as the book *Mutual Aid*. Here Kropotkin finally sank his talons into "nature red in tooth and claw." For if the bees and ants and termites had "renounced the Hobbesbian war" and were "the better for it," so had shoaling fish, burying beetles, herding deer, lizards, birds, and squirrels. Remembering his years in the great expanses of the Afar, Kropotkin now wrote: "…wherever I saw animal life in abundance, I saw Mutual Aid and Mutual Support" (Kropotkin, 1955, 14; ix).

This was a general principle, not a Siberian exception, as countless examples made clear. There was the common crab, as Darwin's own grandfather Erasmus had noticed, stationing sentinels when its friends are molting. There were the pelicans forming a wide half-circle and paddling toward the shore to entrap fish. There was the house sparrow who "shares any food" and the white-tailed eagles spreading apart high in the sky to get a full view before crying to one another when a meal is spotted. There were the little tee-tees, whose childish faces had so struck Alexander von Humboldt, embracing and protecting one another when it rains, "rolling their tails over the necks of their shivering comrades." And, of course, there were the great hordes of mammals: deer, antelope, elephants, wild donkeys, camels, sheep, jackals, wolves, wild boar – for all of whom "mutual aid [is] the rule." Despite the prevalent picture of "lions and hyenas plunging their bleeding teeth into the flesh of their victims," the hordes were of astonishingly greater numbers than the carnivores. If the altruism of the hymenoptera (ants, bees, and wasps) was imposed by their physiological structure, in these "higher" animals, it was cultivated for the benefits of mutual aid. There was no greater weapon in the struggle of existence. Life *was* a struggle, and in that struggle, the fittest *did* survive. But the answer to the questions, "By which arms is this struggle chiefly carried on?" and "Who are the fittest in the struggle?" made abundantly clear that "natural selection continually seeks out the ways precisely for avoiding competition." Putting limits on physical struggle, sociability left room "for the development of better moral feelings." Intelligence, compassion, and "higher moral sentiments" were where progressive evolution was heading, not bloody competition between the fiercest and the strong (Kropotkin, 1955, 51; 40; 60–1).

But where, then, had mutual aid come from? Some thought from "love" that had grown within the family, but Kropotkin was at once more hardened and more expansive (Büchner, 1879; Drummond, 1894; Sutherland, 1898). To reduce animal sociability to familial love and sympathy meant to reduce its generality and importance. Communities in the wild were not predicated on family ties, nor was mutualism a result of mere "friendship." Despite Huxley's belief in the family as the only refuge from nature's battles, for Kropotkin, the savage tribe, the barbarian village, the primitive community, the guilds, the medieval city, all taught the very same lesson: For mankind, too, mutualism beyond the family had been the natural state of existence "It is not love to my neighbor – whom I often do not know at all -," Kropotkin wrote, "which induces me to seize a pail of water and to rush towards his house when I see it on fire; it is a far wider, even though more vague feeling or instinct of human solidarity and sociability which moves me. So it is also with animals" (Kropotkin, 1955, xiii).

The message was clear: "Don't compete! Competition is always injurious to the species, and you have plenty of resources to avoid it." Kropotkin had a powerful ally on his side. "That is the watchword," he wrote, "which comes to us from the bush, the forest, the river, the ocean." Nature herself would be man's guide. "Therefore combine – practice mutual aid! That is the surest means of giving to each other and to all the greatest safety, the best guarantee of existence and progress, bodily, intellectual, and moral" (Kropotkin, 1955, 75).

If Capitalism had allowed the industrial "war" to corrupt man's natural beginnings; if overpopulation and starvation were the necessary evils of progress – Kropotkin was having none of it. Darwin's Malthusian "bulldog" had gotten it precisely the wrong way around. Far from having to combat his natural instincts in order to gain a modicum of morality, all man needed to find goodness was to train his gaze within.

War or Peace, Nature or Culture: Where had true "goodness" come from? Should mankind seek solace in the ethics of evolution or perhaps in the evolution of ethics? Should he turn to the individual, the family, the community, the tribe? The terms of the debate had been set by its two great gladiators, and theirs would be the everlasting questions.

Huxley died at 3:30 in the afternoon, on April 29, 1895. He was buried, as was his wish, in the quiet family plot in Finchley rather than beside Darwin in the nave of Westminster Abbey. No government representative came to the funeral; there was no "pageantry" or eulogy either. But there were many friends – the greatest of England's scientists, doctors, and engineers; museum directors, presidents, and councils of the learned societies; and the countless "faceless" men from the institutes who had taken the train down from the Midlands and the North – all bowing their heads in silence. His had been a life of pain and duty: from Ealing to the Royal Society, from rugged individualism to corporatism, unitarianism to agnosticism, and finally back again to the merciful extraction of human morality from the pyre of Nature-Ishtar. He was placed in the ground in a grave that, the *Telegraph* noted, had been "deeply excavated" (Desmond, 1997, 612). In line with his view of the exclusive role of family in nature, it was above his firstborn son Noel, who had died aged four in 1860, that Huxley would come to rest.

When the revolution in Russia finally broke out in February 1917, Kropotkin was already old and famous. On May 30, thousands flocked to the Petrograd train station to welcome him home after 41 years in exile (Miller, 1976, 232–237). Czarless and reborn, Russia had revived his optimism in the future. But then came October and the Bolsheviks, and like years ago in the Afar, the spirit of promise soon wasted into disappointment. “We oppose bureaucrats everywhere all the time,” Vladimir Ilyich Lenin said to Kropotkin when he received him in the Kremlin soon after. “We oppose bureaucrats and bureaucracy, and we must tear out those remnants by the roots if they are still nestled in our own new system.” Then he smiled. “But after all, Peter Alekseevich, you understand perfectly well that it is very difficult to make people over, that, as Marx said, the most terrible and most impregnable fortress is the human skull!” (Kropotkin, 1970, 327).

Kropotkin moved from Moscow to the small village of Dimitrov, where a cooperative was being constructed. Increasingly frail, and working against the clock on his magnum opus, *Ethics*, he still found time to help the workers. “I consider it a duty to testify,” he wrote to Lenin on March 4, 1920, “that the situation of these employees is truly desperate. The majority are literally starving… At present, it is the party committees, not the soviets, who rule in Russia… If the present situation continues, the very word ‘socialism’ will turn into a curse” (Kropotkin, 1970, 336).

Lenin never replied. But he did give his personal consent when Peter Kropotkin died on February 8, 1921, that the anarchists arrange his funeral. It would be the last mass gathering of anarchists in Russia.

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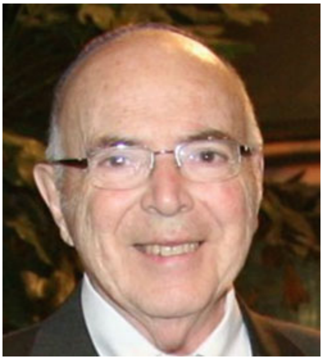
Biodata of **Malcolm E. Schrader**, author of "***Free Will in God's Dice Game***."

**Dr. Malcolm E. Schrader** was born in New York City in 1925. After serving in the US Army during World War II, with award of the Purple Heart and Combat Infantry Badge, he received his Ph.D. in physical chemistry from Brooklyn Polytechnic Institute. He subsequently performed fundamental and applied research for the US Navy, largely in the field of surface chemistry and nanosurface science. He pioneered in the application of radioisotopes to the study of the interface between fiber and matrix in composite materials and was the first to use ultrahigh vacuum techniques in the study of wettability. Some highlights of the achievements of his experimental research are the solving of the famous controversy on the wettability of gold by water, obtaining of a previously elusive result for water-wettability of graphite, and determining of the nanolocus of hydrolytically induced failure of the glass-resin bond in glass-reinforced plastics.

Dr. Schrader served for 4 years as meeting secretary (program manager) of the Division of Colloid and Surface Chemistry of the American Chemical Society and as long-range coordinator of symposia on fluid-solid surface interaction of that division. He served on the Board of Directors of the Society for Plastic Industries and was involved with surface chemistry applications as a member of the American Vacuum Society and the American Society for Testing Materials.

On retiring as senior scientist from the US Navy, he was appointed professor on the research staff of the Hebrew University of Jerusalem. In the theoretical area, he subsequently revised the thermodynamic approach to wettability and showed that, contrary to previously accepted concepts, the adsorption of a nanolayer of its own vapor does not necessarily impede spreading of a given liquid on a solid surface. As a guest scientist with the department of Inorganic and Analytical Chemistry, he is presently pursuing an interest in chemical evolution. His proposal that the traditional "soup" approach be replaced by more rapid land-based prebiotic synthesis has included a natural mechanism for the presence of 5-carbon sugar in RNA/DNA.

E-mail: **schrader@vms.huji.ac.il**



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# FREE WILL IN GOD'S DICE GAME

**MALCOLM E. SCHRADER**
*Department of Inorganic and Analytical Chemistry,*
*Institute of Chemistry, The Hebrew University of Jerusalem,*
*91904 Jerusalem, Israel*

## 1. The Classical Scientific View

In an interview given in Israel in 2006, the physicist Stephen Hawking stated a conflict, as he saw it, between belief in a God-run world and acceptance of the principles of modern science. If the world follows the laws of science without exception, there is no room for God's input, since all events are unequivocally dictated by these laws.

It is clear that the only function for a God in this scheme, then, would be as a one-time creator. Having created the world and set it on its evolutionary path governed by the laws of science, the God then effectively retires, doing nothing more than observe the results as they unfold with time.

## 2. The Problem

This view creates problems for Judaic and Christian theology as well. This chapter will focus on Judaic theology, but it is believed that the results are relevant to Christian approaches as well.

One of the important problems concerns the existence of "free will" in individuals of the human species. Clearly, if all physical phenomena, including human actions, are accurate results of cause and effect, then there can be no free will. What appears as free will is but the necessary consequence of physical activity in the brain which occurs as a necessary consequence of previous physical events, both within and outside that brain itself, all occurring from the evolution of the physical world subject to the laws of nature dating back to original "creation" (presently regarded as the occurrence of the big bang).

## 3. Role of Free Will in Judaism

Sages of Rabbinic Judaism, during the middle ages, have proposed a number of formulations of the required articles of faith for its adherents. The most famous of these is the 13 articles proposed by Maimonides (Maimonides, 2000).

The eleventh article is “belief in divine reward and punishment.” This belief is found, explicitly or implicitly, in all Rabbinical Judaic articles of faith. In order for reward, punishment, or both to be considered as a proper consequence of righteous or evil deeds, the subject, of course, must have the freedom to decide between alternative courses of action. Thus, free will must exist and be operative to some extent at least some of the time.

## 4. The Internal Theological Conflict

It thus seems that there is a conflict between the age of deterministic science and the requirement of theology for the existence of free will. This is only part of the problem, however. The fact is that there is a long-standing contradiction within religious philosophy itself between its need for the existence of free will and its concept of the omniscience of God. The latter concept predates modern science (e.g., Newton in Westfall, 1980) and modern philosophy of science (e.g., Descartes, 1596) as well. It can be stated in the following manner: God is all knowing, including the future as well as past and present. Therefore, if a person is presented with a choice between two alternative courses of action, God knows which course he is going to take. In that case, it is clear that the decision and action must be considered predetermined. This problem has been considered by great philosophers such as Maimonides, for example, approximately 800 years ago. Maimonides claimed, more or less a priori, that it is possible for God to know of a decision and action before they occur without them being predetermined. This solution is, at worst, unconvincing, and at best, requires a weakening of the meaning of “predetermined” that would be unacceptable to many. As the person is about to make his decision, God knows in advance what it is going to be. So, can he be regarded as free to decide otherwise? Is the result not already determined?

Interestingly, then, the problem of free will in religion being in conflict with scientific determinism has been preceded by the problem of free will in religion being in conflict with the concept of an omniscient God. Thus, the conflict is internal within religion itself.

It will be shown below, however, that an examination of free will from the scientific point of view can lead to a solution to the conflict with and within religion.

## 5. The Rise of Probabilistic Physics

Some important fundamental precepts on which the assumed determinism of classical physics is based are now examined:

1. That all physical laws will, at least in principle, lead, by cause and effect, to well-defined unique physical results
2. That well-defined physical events are, at least in principle, observable with complete accuracy

Item no. 1 speaks of what have been called "well-defined unique ….results." Experimental results on many particle systems, where the fundamental particle was an atom, offered no clear-cut contradiction to the concept that a given state of matter, on a local microscopic or universal macroscopic scale, is in principle completely deterministic. This means that if an observer has complete knowledge of a theory of everything, plus all the needed information on a given state at a given time, its future is completely predictable. The possibility that it is impossible to ever have such an observer is not important. The fact remains that the future, even if not known to an observer, is still completely predetermined.

## 5.1. OLD QUANTUM THEORY

In the late nineteenth century, however, classical physics found itself running into considerable difficulties in attempting to correlate divergent phenomena. The accepted solutions are connected to the quantum concept (Planck, 1949). The quantum concept is considered to have its origin in the year 1900 as a result of experiments linking temperature with radiation from black bodies. Planck came up with an empirical formula which described accurately the temperature frequency data at all measurable frequencies. What was needed however was a physical postulate which would lead to this formula. Shortly thereafter, Planck concluded that what was required was the supposition that the energies involved existed in "chunks" or, in modern terminology, discreet quanta. Another area of physics where the experimental results seemed intractable based on classical continuum physics was that of specific heat, where Einstein (1911) introduced the concept of chunkiness to give semiquantitative agreement with experiment. Subsequently, the idea was adopted as a concept by Bohr (Faye, 1991) who applied it to empirical descriptions of atomic light absorption and emission such as the Balmer (Jackson, 1998) series. This was accomplished by the somewhat arbitrary selection of specific quanta to govern energy transitions between stable states and then selection of quanta for the states themselves.

The practice of arbitrary application of quantum rules to various physical situations had its successes, but as time went on, it became clear that important contradictions emerged and the need for a generalized quantum approach became evident.

## 5.2. QUANTUM AND WAVE MECHANICS

The discipline of quantum mechanics, as developed mathematically in 1927 by Werner Heisenberg (1975) in parallel with the wave mechanics of Erwin Schrödinger (1926), both of which consisted of a general approach which solved beautifully remaining loose ends and quandaries of the old quantum theory, can be regarded as having put an end to the absolute determinism of classical physics.

Their results predicted probabilities rather than unique physical values for given events. This concept was considered a basic phenomenon, not merely a limitation associated with incompleteness of current theory. A famous result of the complete Heisenberg approach was in fact the uncertainty principle, which stated that momentum and position (or, equivalently, energy and time), for a particle, could not both be accurately determined simultaneously. The more accurate one quantity is, the less accurate the other. The product of the uncertainty of the two was stated as equal approximately to Planck's constant. Therefore, on a fundamental quantum level, cause and effect does not lead to a unique predetermined result, since the values of the quantities of the small particle on which the cause operates (and of course the resulting quantities) cannot be certain. For Schrödinger's wave mechanics, the physical picture of the uncertainty is that the greater the length of the wave packet representing a particle, the more accurate the velocity, while the shorter the length, the more accurate the position. Quantum mechanics theorists chose to interpret the physical significance of his results by pointing out that the square of his wave equation gave the probability of a particle, say, an electron, occupying a given state or undergoing a given transition. The manner or extent to which these treatments of small particles translate into macroscopic reality is not known. However, as a result, it cannot be said that in principle a given state of matter leads inexorably to a series of uniquely determined succeeding states.

## 6. The Mathematical Approach to Deterministic Science

A parallel result can be obtained through an applied mathematical approach. Here, the question posed is whether, in going from one physical state, macroscopic or otherwise, to another, given complete possible knowledge of the original state, and complete knowledge of the laws governing the change, a resulting final state can be obtained that is known with complete accuracy. The determining factor under consideration involves matching the precision of measurement of the initial and final states.

A. B. Pippard (1990), in a discussion on chaos, quoting M. J. Feigenbaum and R. J. May, sets up a mathematical formula for a sequence of numbers which can give the result of a measurement on out through an indefinite number of significant figures. The result is determined in part by a constant in the formula. For low values of the constant, the arithmetical results, as described by increasing significant figures become either constant or obviously related. For higher values, however, the results, i.e., succeeding numbers, appear unpredictable and chaotic. The author remarks, "to predict the sequence in this particular case out to n terms, one must know the value of $x_0$ to better than $n/8$ places of decimals." The author later concludes "To a considerable degree physicists have been persuaded, in their innocence, that predictability is a characteristic of a well established theoretical structure; given the equations defining a system, it is only a matter of computation to determine how it will behave. However, once it becomes clear how many systems are sufficiently nonlinear to be considered for chaos, it has to be recognized that predictions may be limited to short stretches set by the horizon of predictability."

Now, it may seem that this particular approach does not really describe the situation in principle, but merely the human capabilities in observing the changes. This point is not regarded as relevant. The reason it has previously been supposed that cause and effect must follow accurately, in principle, is because we have devised laws of science which seem to predict that they occur in that manner. The above approach, however, may be regarded as putting a limit to the precision with which many of these laws can be taken as valid. It then becomes a matter of principle that as a whole they cannot lead to complete predictability. This is then another fundamental approach which admits uncertainties that may lead to major differences.

It is concluded here that physical states in general cannot be described with complete precision. For a change from an initial to a final state, therefore, precise predictability for a single change is impossible. Also impossible then is precise predictability for a cascade of changes influencing the macroscopic world.

## 7. Probability and Free Choice

We have now shown that objection to the existence of free will based on scientific determinism as applied to the physical chemistry of brain function is subject to considerable doubt. However, returning to the wave-quantum approach to scientific theory, how does the concept of probability fit in with the idea of a brain having a free choice, albeit to a limited extent, and in limited situations?

It can probably be considered a psychological certainty that completely unlimited free will does not exist. Extreme examples such as that of an alcoholic presented with a container of whiskey, plus compelling situations of varying degrees of subtlety, are ubiquitous, many unknown even to the individual. Every informed citizen of a democracy decides for himself how to vote in a given election. Yet, given information as to his geographical location, age, and education, his choice can be predicted with reasonable probability. The fact that polls work with high accuracy is itself witness to that fact that these decisions are determined largely by forces outside of, and acting on, the individual. Yet, there is "wiggle room" for his final action, and for an individual case, his decision cannot be predicted with certainty.

If the laws of probability show that 55% of a populace will decide "a" while 45% will decide "b," is there free will in every case? Does each individual of the entire population have the free will to declare "b," thus resulting in 100% "b"? It seems not. Yet each individual does have the power to declare either way. So, his power is present but limited. Now, how can it be foreordained that there will be 55 "a" and 45 "b" and yet each individual has the power to declare either way? The answer is that there are many factors influencing each person's decision, largely divorced from free will. These factors determine the approximate 55–45 split. The free will component is superimposed on the others and will either leave the percentage intact or change it within the expected error of the mathematical expectation.

Now, suppose all the individuals have decided and only one remains. Does the law of averages force his hand? The answer of course is no. The mathematical expectation is not precise. He can still go either way. This is the situation as expounded by modern probabilistic science.

## 8. Free Will as Religious Requirement

Now, with respect to the religious problem, since each person, including the last one of a group of deciders, while subject to probability, has enough wiggle room to decide one way or the other, there is no religious free will problem. However, the characteristic of God's omniscience now has to be defined differently, since if God knows in advance the choice in the individual case, it is not possible to assign freedom to the individual for that choice in that instant. The altered omniscience definition then is that God now "chooses" to know in advance approximately how many individuals will place themselves in a and in b, but does not "choose" to know which individuals will make either choice. With respect to the last individual whom we have described above in the scientific analysis, God is granting him free will, or in terms of omniscience, God chooses not to know what his choice will be. In all these cases, however, God knows what the consequences of these different choices will be, leading to a sure knowledge of all the possibilities, without determining them. This leads to a seemingly limited, but nevertheless extremely powerful, omniscience.

In the event that there exists a multi-universe world, in which all possibilities may ultimately take place, this then leads to very interesting eschatological speculations, which are not, of course, the subject of this chapter.

## 9. Summary

1. In classical physics, all events were considered predictable.
2. Accordingly, free will was not possible.
3. In classical religious philosophy, God was considered omniscient (all knowing with respect to future as well as past and present events).
4. Accordingly, free will was not possible.
5. According to modern physics and mathematical analysis, everything is not really predictable, thereby allowing free will to exist in the language of modern science.
6. Free will in religion can also exist when God allows an individual freedom of choice in a given case. God's omniscience is then interpreted as knowledge of all the consequences of all possible choices, including derivative choices and their consequences, past, present, and future. God does not "choose" to know in advance the individual's choice when it is free. He does know, however, all world lines which may follow the choice.

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Biodata of **Chris Chetland**, author of "***Does Biology Need a New Theory of Explanation? A Biological Perspective on a Kant's Critique of Teleological Judgment***."

**Chris Chetland** is currently a Doctoral Candidate of the Department of Evolutionary Biology, School of the Environment, Griffith University, Queensland, Australia.

Chris' academic interests are in the areas of evolutionary theory, theoretical biology, continental philosophy, and consciousness.

E-mail: **chris.chetland@griffithuni.edu.au**

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# DOES BIOLOGY NEED A NEW THEORY OF EXPLANATION? A BIOLOGICAL PERSPECTIVE ON KANT'S CRITIQUE OF TELEOLOGICAL JUDGMENT

**CHRIS CHETLAND**
*Department of Evolutionary Biology, School of the Environment,*
*Griffith University, Brisbane, QLD 4111, Australia*

## 1. Introduction: The Nature of the Problem

In 1790, Immanuel Kant completed and published the final installment of his three *Critiques*. With these, he addressed and changed our world perspective on some of the most fundamental problems with which human knowledge had been wrestling. The nature of these *Critiques* is, amazingly, from a twenty-first-century biologist perspective, still important and relevant in our rapidly evolving discipline to this day, a consequence of the depth and clarity of thought that appeared on the pages Kant presented to the reader. It also provides us with a wealth of bases to reassess problems that we had perhaps in our hubris thought solved in the relentless wave of scientific discovery, or at least had withered away from old age to inconsequential dust. But, as we so often find, dust may merely cover something from view, but in no way affect the structure of the object itself. And with this understanding, it is perhaps time to dust off Kant's third *Critique* and use it to investigate the "sleeping giant" problem of teleology and design-like nature of organisms and assess how this work may inform our understandings of organisms and the process of life in the current day environment.

Look through virtually any biological journal published over the last 10, 20, 30 years and you will run into a large amount of discussions that treat and relate organisms as if they were complex machines, have been designed, or discuss them in relation to a design-like function. So, pervasive and universal is this language that can often be totally immersive, and hence we become blind to its influence and limitations on our way of seeing. Every now and then, we may notice a ripple on the surface and be reminded that, as scientists, we are "not supposed to think of organisms as designed or use teleology," yet here it is still, gracing the pages of our most prestigious journals.

We are often informed (primarily via secondary or tertiary literature as well as in general tearoom conversation) that the problem of teleology was solved or fixed by uses of words like teleonomy or teleomatic some time ago, and we have moved on to more relevant or current problems. But upon investigation of teleonomy and telomatics, we find that they are merely subsets of teleology and still prone to the same fundamental problem (Hull, 1982). The use of design-based language and its teleological perspectives keeps appearing in front of us, plain as day, yet surprisingly invisible nestling in the success of the mechanistic framework that has provided such prescient insights into the nature of the world, whether from physics, chemistry, biology, or the many other approaches to which it lends its hand to.

And so we come to the crux of the problem. Organisms can in many cases be described, thought of, or explained quite successfully as complex machines or the sum of their parts, but for many who devote time to considering this, explanatory outlooks such as mechanism seems to miss an essential aspect of their nature that we intuit, and this is backed up by an increasing amount of experimental evidence of phenomena occurring in organisms that do not fit so well into the mechanistic system. The way that seems to be generally followed to bypass this problem is to explain them in the sense of design-like characteristics, which unfortunately leads to less than ideal consequences of often incorporating some kind of natural theology and teleological argument from design into the picture. And this is something that very few biologists are willing to accept when called to task on it. But regardless, there seems to be a deeply ingrained problem with our explanations of organisms that needs to be addressed, and this is hopefully where we can bring in Kant to exercise his specialization, refereeing two opposing perspectives.

## 2. Introduction to Kantian Philosophy

In his three *Critiques*, Kant investigated the three faculties of knowledge, understanding for the *Critique of Pure Reason* (COPR), reason for the *Critique of Practical Reason* (CPR), and judgment in the *Critique of Judgment* (CJ), with the aim to determine whether they have *a priori* principles. They are an investigation into the very limits of human knowledge and also philosophically inform the natural sciences at a fundamental level. After reading Hume's devastating attack of metaphysics and cause and effect in *Enquiry Concerning Human Understanding*, Kant worked to develop a system whereby we could still have a science of metaphysics and understanding of the world, albeit one with a totally new form. This was the formulation of his "Copernican revolution," to get around the problems brought to light by Hume. Kant did such a good job of his system that it is still influential at a fundamental level to this day, and thanks to more English translations being published of his works, especially over the last 50 years, its audience is expanding.

Kant's *Critiques* can be seen as an attempt at a synthesis between the dominant views of the enlightenment, empiricism versus rationalism, a mechanical conception of the world versus an organic dynamic view, and mechanism versus teleology. One of the main concerns for Kant was the systematicity and bringing to unity of laws of nature. We had no reason, he claimed, for assuming that nature would be systematic and purposive for our understanding of it. Therefore, we had to take this as an *a priori* principle.[1] Without this principle, we could never come to a system of empirical laws, to explain nature (which would place Newton's laws of physics in jeopardy). It was Kant's belief or reliance on the applicability of Newtonian mechanics to nature, coupled with his awareness that the Newtonian, Humean, and Aristotelian models did not allow us to understand or explain important aspects of material nature, in particular organisms, that led to his attempt in the *Critique of Teleological Judgment* at a synthesis between the two major competing explanatory theories of the time with respect to nature, teleology, and mechanism.

The basis of Kant's system for our understanding is composed of *the categories* and developed in the *Critique of Pure Reason*. They are important to understand at least basically for coming to terms with the general ideas and aims of the third *Critique*. The categories are often thought of as analogous to "tinted spectacles" through which we perceive reality. Examples of the categories of understanding, (with which judgments such as teleology and mechanism interact) are space, time, and cause and effect. Everything we perceive is effectively filtered through the categories which thereby color our perspective and make the world outside their scope effectively "invisible" and unknown to us. We innately apply the categories to sensations (such as sight, smell, touch), and without them we cannot have any experience of the phenomena. All human systematic understanding of nature for Kant's system will consequently conform to these categories.

Kant wanted to "explain" nature, or at least determine what were the limits of explanation to which we could attain. On the whole, in the *Critique of*

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[1] As a background, Kant, like earlier philosophers, distinguished between two types of propositions, synthetic and analytic. These can be further divided into two other types, *a priori* and empirical (*a posteriori*).

*A priori* propositions: have fundamental validity, they are not based on perception, for example, "7 + 5 = 12" or "all bachelors are unmarried men." They are available without appeal to experience.

Empirical (*a posteriori*) propositions: depend upon sense perception, for example, "the cat is black" or "the earth moves around the sun." Humans, Kant contends, can only judge by what they see and experience, that is, by what is empirical.

Analytic propositions: the predicate is implicate in the subject, for example, "the black cat is black" or "bachelors are unmarried men." For analytic propositions, the truth is discovered by analysis of the concept itself.

Synthetic propositions: those propositions that cannot be arrived at by pure analysis, for example, "the cat is on the mat." In these propositions, the predicate is not included in the subject; you need to go and investigate its truth.

Synthetic *a priori* propositions: have an *a priori* base but are also synthetic (whereas other *a priori* propositions are analytic). For example, between any two points is one straight line. You cannot get insight into this truth by merely investigating your concept of straight lines or points. The nature of space also has to be considered, which has to be investigated empirically. Synthetic *a priori* propositions show us the limits of our view on reality when we investigate them.

*Judgment*, he investigates, compares, and contrasts the mechanistic explanatory view with that of the teleological explanatory view; he then attempts to determine the possibility of a synthesis between them. This approach is similar to that in the *Critique of Pure Reason*, where the aim was a synthesis between rationalism and empiricism in respect to reason, which he used to develop and extend the theoretical background of the sciences by the addition and formulation of the synthetic *a priori*. By investigating the nature of our judgments in relations to the phenomenon of organisms, the nature of purposiveness in organisms, and how that differs from the purposiveness found in geometric shapes and works of art, Kant provides a basis for developing his system. He also discusses the apparent contradictions that arise from concurrent use of the two main types of explanation we use to make judgments regarding organisms, mechanism, and teleology. Kant discusses this problem in relation to his system and comes to the conclusion that the kind of causality with which to truly explain and understand organisms is still unknown to us and ultimately he believes, unknowable.

But then, we must ask ourselves, are Kant's limits still valid or are they a product of the environment and knowledge limits that they were developed in? Humanity has made many discoveries and developed new ways of seeing the world in the 200 years since Kant's *Critiques* were produced that those in the past would scarcely dream of, and if there is one thing that we can rely on in this world then it is change. Newton's once rock solid system has been expanded and subsumed, and non-Euclidean geometries were developed as just a few examples of important bases that Kant's system used as its cornerstones for relation to the world and science. And just as both of those systems still have validity and use for many day to day investigations, but benefit from the new advances to provide new insights hitherto unrealized, we may be able to expand upon or refine Kant's system as a move toward the next major movements or discoveries in biology. So it is worth examining if these previous constraints placed on our understanding by Kant, strong as they seem to be, can now be surpassed or adjusted to provide new insights in light of current knowledge and potential new fields of study.

But first, let us first clarify Kant's terms and concepts further.

## 3. Types of Judgment: Reflecting and Determining

Kant, in his investigations of the nature of judgment, differentiates two types of judgments, reflecting judgments and determining judgments. Reflecting judgments fall into two categories, aesthetic, which are nonconceptual, and cognitive, which are conceptual. For our investigation of organisms, we will be primarily considering the later. It is Kant's hope in the *Critique of Judgment* to give a basis by which we can see the logically possible move from the reflecting judgments on the nature of organisms to one that is determining, or objective (that is based upon *a priori* principles).

The use of a reflecting-judgment-based system in the study of organisms raised serious concerns for Kant and indeed many other philosophers of his time. It is, however, his novel approach to the problem that allowed him to reformulate the problems of the antinomy (contradiction) of reflecting judgment that arises from combined use of mechanism and teleology and give the possibility of basing it on an objective or determining framework.

This is an important step for the following reasons. Reflecting judgments have particular limits in that they only give laws to themselves and thus are not universal laws, that is, they proceed from an individual instance to the universal, in effect fitting nature into our laws and perspectives. Reflecting judgments work to formulate empirical laws for particular phenomena we encounter in experience and to bring these empirical laws into systematic unity. They proceed from intuition to concept and thus give a law to themselves, not nature, thus they are heuristics. Consequently, true, objective explanation is impossible for a reflecting judgment; however, their value is in that they show what regularities are present. This is of course an essential aspect of science and has been fundamental to supporting many of the most important advances and reliable theories. The primary examples of reflecting judgment used by us that are important for our studies of organisms are the maxims (subjective principles) of teleology and mechanism.

In contrast, determining judgments provide a law that an individual instance partakes of, that is, they proceed from the universal to the individual, concept to intuition, can provide a true explanation. A determining judgment does not devise a law of its own. Unlike the empirical reflecting judgments, determining judgments are experiential and true *a priori*. They are concerned with universal transcendental laws furnished by the understanding and subsume phenomena under them. Ultimately, Kant places a determining judgment of organisms in the realm of the supersensible, which is beyond our human discursive[2] knowledge.

If we are to attempt to make sense of Kant's ideas on the development of a reflecting-based system for the study of organisms to that of a determining framework, then it is useful to give an example of his ideas on the meanings of his notions of particular types of judgment. In a reflecting judgment, one proceeds from the particular, or individual, to the universal (i.e., from our perception of an individual thing and then attempts to categorize this under a concept that is suitable for categorizing the thing). This is the opposite move to a determining judgment (where the move is from a concept (universal) to an intuition (particular or individual)).

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[2] Discursive understanding is knowledge yielded through the understanding through concepts, and thus is ultimately filtered through and limited in scope by the categories. It picks out features that things have in common with other things and applies concepts to them. It is interchangeable with "judgment" and "thought."

For example, in the case of a field study, in making a *reflecting judgment* when we see the individual in question and say "what is that?" we apply various concepts to it in an attempt to unify the sensations under a universal type or concept. So if we then say "that is a peppered moth" in relation to the individual, we have made a reflecting judgment. In contrast, determining judgments proceed from the universal to the individual, that is, from concept to intuition. They subsume an individual or event under a schematized category (McFarland, 1970).

If we are looking for a peppered moth in our field studies, we make a *determining judgment* when we say, "Look, I have found a peppered moth" upon locating the desired individual hiding under a leaf. In doing so, we add further empirical content to the concept of a peppered moth through its affiliation with the individual moth (the intuited thing) (Wicks, 1994).

Reflecting judgments are essential for us to use in our attempts at coming to some form of understanding of the universe. Because of these proposed limits of our minds to understand the universe (CJ §77: 409–410), Kant believes that we cannot conceive of a totally ordered universe without also conceiving it as designed; hence, we must incorporate and in fact are committed to the concept of teleology. This concept of teleology is linked with mechanism, and is, for us, Kant contends ultimately inseparable (CJ §77: 409). Teleology is to be used as a "heuristic principle for investigating the particular laws of nature" (CJ §78: 411), while mechanism is essential for us to incorporate, for without it we cannot judge a product to be a product of nature at all.

## 4. The Problem of Combining Mechanistic and Teleological Explanations of Organisms: The Antinomy of Reflecting Judgment and the Supersensible

Teleological judgments according to Kant do not explain objectively, that is, for the possibility of this kind of things themselves, but do explain "for us," that is, they hold only subjectively. To view or judge a thing to be a product of nature, Kant claims we must use both teleology and mechanism (CJ §78: 414). However, due to the nature of our consciousness and its limitations, not only do we have to work with two seemingly contradictory systems but we must also subordinate one of these principles (mechanism) to the other (teleology). *This subordination is, Kant claims, an essential character of our reason.* When it comes to our understanding of organisms in relation to mechanistic and teleological thought, Kant stresses that the only objective explanation that we are capable of is in terms of mechanical laws (CJ VI 218'). Teleology is to be used merely as a description of nature (CJ §79: 417); it gives us no insight into how organisms are produced. This leads to Kant's claim that the common ancestor argument, by virtue of its teleological base, "only puts off the basis for explanation" (CJ §80: 420). Consequently, we should attempt to explain products and events of nature in terms of mechanism as far as we possibly can, always keeping in mind though that the essential character of reason will lead to us ultimately subordinating the "product we are investigating (of our investigation) regardless of the mechanical causes, to a causality in terms of purposes" (i.e., teleology).

Mechanistic and teleological explanations are the two maxims of reflecting judgment that we use for scientific inquiry and have both been found to have use in attempts to understand the nature of organisms. However, the use of both together in methods of explanation gives rise to a contradiction and antinomy that Kant devoted a great deal of the *Critique of Judgment* attempting to resolve. The basis of the approach was to attempt to reconcile this antinomy and show that what seemed like an antinomy was only an antinomy for us due to our discursive intelligence. By postulating a causality that encompassed the mechanistic and teleological systems where no conflict actually took place, Kant claimed that the antinomy that we experience was only relative. That is, this antinomy only applies to reflecting judgment; it is not an objective one (as this overriding new causality was postulated to be). Any distinction that we believe to be present between mechanism and teleology is, he claimed, only due *to our* incomplete knowledge (i.e., the supersensible mechanistic, efficient cause independent from our understanding would be determinative and see the "purposiveness" of organisms as noncontingent). This attempt to provide a basis for the merging of two types of causality (mechanistic and teleological) into one overriding causality is one of Kant's principle aims in the *Critique of Judgment*. This causality is, he claims, only understandable in the mind of a supersensible intelligence that is not restricted to the limits of understanding and judgment that we as humans face.

It is this positing of the supersensible, something beyond normal, "sensible" intelligence, that is associated with a new type of causality that sits above and encompasses both mechanism and teleology and by which both are understandable in terms of the system as generalizations (just as Newton's and Kepler's physics are subordinate to, explained by, and encompassed by general relativity) that is perhaps one of Kant's most interesting points in the *Critique of Judgment*. Indeed, it would seem that by positing, or invoking this notion of the supersensible, Kant is not restricting the universe ultimately to being completely codable in terms of efficient cause or mechanism (although in many cases, he seems to believe that this may be the case); he seems to leave open the option or possibility of a system that is beyond the notions of and limitations of Aristotelian and Humean cause.

## 5. Why Kant Chose the Argument from Design

Kant rejected the two standard arguments used to justify the use of teleology, namely, the ontological and the cosmological arguments (Kant outlines the problems inherent in these in CPR: A607-8/B635-6). Instead, he based his ideas on the principle based on the argument from design (CPR: A616-17/B644-5). Like his influential predecessor Hume, Kant rejected the Paleyesque watch and its maker analogy, due to its reliance of an external creator (God). However, the argument from design does not necessarily have to include the notion of an external creator and can, as Kant realized, operate as to a certain level as a heuristic. If the "designer" is taken as the organism itself (i.e., as a natural purpose that has purely intrinsic purposiveness), then Kant believes the argument from design still holds some use in our explanations. The argument from design can then be used to act as a foundation and as a heuristic to guide our investigations and explanations of natural phenomena, although we must be aware to keep our descriptions away from art or artifact-based talk. "We say far too little," Kant writes, "if we call [organisms] an analogue of art, for in that case we think of an artist apart from nature… The organization [of living things], infinitely surpasses our ability to exhibit anything similar through art" (Kant, in Grene and Depew, 2004, p. 99).

For Kant, there is something going on in organisms that is more than blind chance. Organisms seem to express a purposiveness, a "fit" to environment that he believes mere chance occurrences cannot explain. So it then makes sense to use an argument that works directly with this purposiveness and then adjust or modify it in relation to the system of knowledge developed and limits of our way of seeing organisms.

As outlined, Kant and Hume wished to steer away from the ontological and cosmological arguments in preference to the argument from design. The reasons for this may be summarized into two main points. Firstly, by the fact that God's existence could not be proved (i.e., we have no way of reaching a theoretical knowledge of God), Kant and Hume were not prepared to use the direct involvement of God in nature, (e.g., CJ §68: 381). Secondly, Kant believed that we had to refrain from explaining the order of nature as coming from the will of a supreme being such as was incorporated into the ontological and cosmological arguments, as this would then cease to be natural philosophy (science). By incorporating a supreme being into our system, we would be "confessing that we had come to the end of it."

As Hume points out in his *Dialogues*, and Kant seems to agree, if we have no way of proving God as the universal organizing process, then we cannot deny that nature may be possible of ordering itself in such a "purposive" manner. The advantage of keeping this process within nature (as opposed to God) is that it avoids problems associated with the ontological argument, which Kant brought to light, such as "existence is not a predicate," that is, the claim "God is" is not equivalent to "God exists." The cosmological argument suffers an infinite regress problem regarding the first cause and also applies the category "cause" to something postulated to be outside the realm of causality and sensation. It also presupposes the ontological argument, which makes it even less appealing philosophically.

Kant's recommendation of using the term "natural purpose" instead of the term design also helps clarify his argument in relation to the Argument from Design. For by use of natural purpose, we keep the purpose as seen to be *within* the organism, rather than have that purpose anything external to it that created it, that is, it is cause and effect of itself. The fact that this is an understanding, as a nature of the structure from within our own minds, is an extra point to be noted, but secondary to the first case in point.

The type of argument that Kant was using is also more sophisticated than the standard Argument from Design, as it does not make the logical leap that Paley's "Watchmaker" argument is so famous for. As clarification, just because we know that every house has an architect does not mean that we can transfer that experience onto the universe and organisms and infer a designer of the universe, let alone one with a similar mind to humans. There are far more things that resemble organisms in the world than resemble machines, things of intention, and designed artifacts, so the designer outlook is loaded with a prejudicial view of the enhanced importance of a relatively minor subset of things out of the world set. Organisms appear purposive by the nature of the structure and categorization of our mind rather than actually being so. They are a completely different mode of being than machines or designed objects, that is, they are self-organizing, and their purposiveness is internal. This is why Kant proposes a new type of causal explanation for them. They are, however, similar enough in machine-like characteristics for our categorization to create, for the most part, a workable day to day system for study of them that can also produce adequate, regular, and reliably useful results in many cases, a benefit of reflecting judgments. This also backs up Hume's claim that the cause of order in the universe probably bears some remote analogy to human intelligence (Hume, *Dialogues,* p. 227), but unfortunately, this in no way infers that we will ever be able to understand it and make use of that understanding.

So, with this, Kant's utilization of a form of the argument from design has laid out his basis for the use as a heuristic for teleology as well as describing in a sense in terms of purpose for our descriptions of organisms. It then remains for him to see how this teleological system can be related to the notion of a causal (in the sense of efficient cause) world that these organisms exist in. This is of course a major point to investigate. Organisms seem (to our understanding and way of seeing) to exhibit design-like characteristics (such as the relationship and properties of internal organs), yet there is no external designer.

## 6. The Apparent Design-Like Nature of Organisms

For Kant's system, organisms seem to exhibit design like characteristics to our way of understanding. If it is living, then we automatically utilize our teleological faculty of judgment. And this is a fact that if we are to develop any coherent theories of biology, we seriously need to address the implications of.

The biological sciences generally claim that living things are to be understood mechanistically, yet we keep falling back into design-based thinking, constantly switching between two contradictory views. Organisms for even the most begrudging perspective when put to the test appear to exhibit a "designedness," a "fit" to their environment that not only models humanities greatest utensils, but generally totally outclasses them. The problem for Kant then becomes where does this designedness come from as evidence? His answer is well developed in the course of his work and fundamentally simple, determining that "[We] slip the concept of a purpose into the nature of things rather than take it from objects and our empirical cognition" (CJ §61: 360). That is, that the structure of our consciousness through our most fundamental concepts of understanding, "the categories" results in us not being able to see organisms as *things-in-themselve*s, but merely as abstracted representations of their true form and being.

So, throughout Kant's writings, we find the idea continually surfacing that there is some form of inner "purpose," or prefiguring of the forms of systematically organized beings. Chance, or mechanical laws he believes, to our understanding are not capable of producing this interrelationship, whether it be in the formation of structures of the animal or its developmental changes over its life, and so organisms must be considered an exception to the general mechanistic treatment of nature (which had been so successful for physics, especially since Newton). Kant's problem seems to rest upon the assumption that may be summarized as follows.

In nature, there are things (systematically organized beings) that seem to exhibit a purposive nature; however, mechanistic processes are blind (CJ §66: 377, §67: 381), or solely due to chance and so cannot produce this purposiveness. Therefore, the only other option that Kant believes is left to us is that of teleology. It is from this standpoint that he develops his investigation into the nature of organisms and the limits of scientific knowledge. However, it must be noted that Kant states that while we may conduct our investigations under the principle of purposiveness to obtain *possible* teleological connections, once we have found such connections, we must go on to look for the mechanical laws that produce them (CJ §78: 411).

## 7. Bridging a Divide

One of the defining features for Kant of organisms is that they are organized and self-organizing beings [systems] (CJ §65: 374); this defines them in his system as natural purposes. We should remember that as such they have formative force, "a force that mechanism cannot explain" (CJ §65: 374) and strictly speaking *"has nothing analogous to any form of causality known to us"* (CJ §65: 375). Organisms as such "give objective reality to the concept of a purpose of nature rather than a practical one and which hence gives natural science the basis for a teleology… [we otherwise] simply would not be justified in introducing into natural science" (CJ §65: 376).

While in the *Critique of Judgment* Kant investigates what he believes to be the limits of our scientific knowledge, he, on the whole (and in fact by virtue of the line of thought he is addressing), leaves alone what is probably one of the most important parts of what would have been important for him to investigate further, the similarities between organisms and nonorganic naturally occurring forms (or at least the lack of a definite separation).

In attempting to form a distinction between the organic realm and the inorganic realm, Kant falls into the problem that is then used as the basis for his argument. That is, if no meaningful distinction can be shown to exist, or that it is questionable on the basis of empirical evidence, then a theory based on the assumption that such a distinction is present may fall into some major problems.

It is Kant's attempts at distinguishing "living things" from "nonliving things" in relation to the self-organization and determining of their parts (such as his example of an organism regenerating a lost body part) that does though create a confusion. Crystals also exhibit this property, for example, ammonium oleate liquid crystals after breaking regenerate into the same pattern, as does an alum crystal (Lima-de-Faria, 1988, pp. 121–22; 1995, pp. 281–295). Human societies also seem to operate under the same principles (Waldrop, 1991) as do ant colonies (Gordon, 2002). This in many ways seems to undermine his belief that biology is autonomous to the rest of science (especially physics). Self-regulating systems occur throughout nature whether organic or inorganic, matter or waves (or something in between). One wonders what line Kant's investigation would have taken if he had been aware of the shapes defined by Fractal geometry in organisms. The fractal tree model of the Mandelbrot has many features in common with the pulmonary airway system (Weibel, 1991), and plants also express fractal shapes in their form as the popular examples of the Romanesco broccoli or fern fronds show. The plant forms that can be modeled in these ways are beautiful and many, as displayed in the graphical representations of L-System Fractals (Prusinkiewicz and Lindenmayer, 1996).

As Kant alludes, it may be more a factor of our conditioning that prevents us from seeing organisms and nonorganic beings as part of the same system (including separating out and prioritizing teleology and the mechanistic/efficient cause and leaving other aspects of causality, for example, Bohm's notion of formative cause out of the description/investigation (Bohm, 1980)). A great many (if not all) of the forms of organisms (which for Kant then imply purposiveness and function) can be found in "mere aggregates." The convergences of form between the "living" and "nonliving" realms appear everywhere before us. Works by Thompson (1942) and Lima-de-Faria (1988) have shown that there are cases that trained professionals cannot distinguish between the organism and the aggregate, not only that, but these aggregates self-regulate and self-organize. This does not though necessarily threaten the idea that organisms are more than mere aggregates, but it does lead us then to question whether what have been previously thought of or classed as "mere aggregates" (and in fact the way we also class organisms) are in fact a whole different mode of interconnected being that biologists are gradually in the process of updating our understanding of. That is, that we may be starting to discover the methods and ways of seeing to bring what Kant thought could only be known by a supersensible intelligence into our perception and understanding of nature and science.

While Kant may believe that this is a limit that we must adhere to, there are other possibilities that may also be possible, not just by achieving supersensible intuition (which by definition is beyond us). It is therefore important for us to investigate postulated types of "bidirectional causality," or the potential of types of "causality" and systems such as extremal principles that may supersede the limits of Aristotelian and Humean causes and hopefully allow us to utilize a system for our investigations of organisms and nature.

The antinomy of mechanism and teleology does create problems for our investigations, and as Kant believes we have to leave it at that and leave the answer to the mind of a supersensible intelligence. But perhaps we could take an alternate approach in relation to life and nonlife. The resolution of a paradox or apparent contradiction of something that we can see sitting in front of our eyes is often simple – we are asking the wrong question.

Kant states that organisms must be treated differently from the inorganic realm due to what appears to be purposive design. But what reasons does he give to distinguish the nature of this designedness? What is it that distinguishes their apparent designedness from that of something such as crystal formation? In the *Critique of Teleological Judgment*, Kant gives mention to the similarity between organisms and crystals (CJ VI: 218'). If it can be shown that it seems likely that this apparent "purposiveness" between organisms and crystals, and nonorganic forms is not just apparent but is in fact important, and as such that organisms cannot be meaningfully distinguished from the nonorganic, then where does this leave Kant, and where can it lead us? It would appear to give us a number of options. It would help to justify Kant's claim that ultimately nature is understandable under the same noncontradictory principle (i.e., in his concept of the supersensible intuition). It would also cause us to question the validity of his claims of (for us) a distinction of organic and nonorganic (i.e., what Kant believes are merely aggregates) forms and related to this; it may lead us to investigate and consider the possibility of self-organization to a deeper level.

As our first example into the investigation of this, let us start with the organism, and let us look for instances of crystal type formations in it. If we investigate what seems to be one of the most obvious starting points, the vertebrate skeleton then we will not be disappointed. The bones of vertebrates are composed of a lattice of calcium crystals, enmeshed in this are bone cells. Diatoms such as the radiolarians have the majority of their mass being a silica crystalline lattice; "these owe their multitudinous variety to symmetrical repetitions of one simple crystalline form – a beautiful illustration of Plato's *One among the Many*" (Thompson, 1942, p. 695) and also a reminder to us of Goethe's notion of the Urpflanze. Indeed, true crystals of celestine have been reported to occur in the central capsules of radiolaria, such as the genus *Collosphaera* (Muller in Thompson, 1942, pp. 697–698).

Next, if we turn our observation to the plant kingdom, we discover the occurrence of the druse and raphides, compound crystals composed of calcium oxalate that can be found in epidermal cells. At an even deeper level, both DNA and cell membranes are considered liquid crystal, (Calendar and Abedon, 2006; Collings, 2002). Not only is there this evidence of actual crystals being integral components of the organism, but also the shapes and forms of organisms are in many cases homologous to mineral formations, and going beyond this also exhibit similarity in shape to processes such as fluid dynamics. The formation of the Rhizopod *Diflugia* in this manner is documented by Thompson (1942, pp. 73–74).

Many groups of animals exhibit an extremely similar form/structure to a certain type of crystal structure. The class Echinodermata displays fivefold symmetry just as does the class of quasicrystals, and many plants, animals, and crystals exhibit threefold symmetry (Lima-de-Faria, 1988). The structures of plants can be seen to have homologs throughout the mineral kingdom, while the sponges (Class Porifera) are built around a crystalline lattice of spicules (Thompson, 1942).

This of course then raises interesting consequences for the mechanistic framework. If, as it would appear, there is no clear distinction between the organic and inorganic bodies and that these "design-like natures" do not distinguish between them, this offers us at least two possibilities with regard to the antinomy of mechanism and teleology. Firstly, the view that would probably be proposed by the majority of scientists that this evidence shows that organisms and "reality" are ultimately describable purely using efficient cause and teleology at best merely holds place until we understand the mechanism. But alternately, we are also given hope for the basis of a nonmechanistic explanatory system, that is, the link may operate both ways. Consequently, this may provide us with a deeper explanatory and ultimately more consistent palette to work with and also help us break out of the standard ways of seeing that we are enframed within (such as the reductionist or atomist perspective). If inorganic and organic forms exhibit similarities at this relatively basic level, then it may start to provide ways of incorporating these two commonly distinguished/separated things in relation to the nonmechanistic claims of various schools of investigation such as quantum physics and emergence. We already have evidence of members of the class of solitons (which are described as "wave-atoms" and exhibit the properties of fermions (Petoukhov, 2002)) occurring in many aspects of organisms including as activation waves in morphogenesis (Goodwin, personal communication).

This in many ways lends us a number of reasons to encompass organisms and nonorganisms under the same system. With the nature of organisms being in so many ways a catalyst for nonmechanistic thinking (or even cited as evidence for it), it may allow us a way to subsume mechanism ultimately to another form of causality, not the teleology based on purposes as Kant proposed (CJ §80), but another, "above," or encompassing mechanism and teleology, but "below", or within Kant's idea of the supersensible causal explanation (which of course is by definition beyond us). Kant famously claimed that it is "absurd for human beings even to attempt to explain how organisms are possible in terms of natural laws unordered by any intention" (CJ §75: 400). Development of greater understanding of these forms, while of course not a complete explanation, may be looking to provide us with one important aspect of the total view, not certain types of activity functions, for example, reproductive drive, but in relation to the production of a theory of form in evolution, it may be a solid starter for the job.

Mechanistic thinking may be, like the notion of design in many ways, merely an artifact of us concentrating too heavily upon simple systems, or abstracted systems that may easily "fall into" the notions of mechanism and that we then try and draw everything else into. If we attempt to get a sense of these allegedly nonmechanistic systems, we may be able to reassess these mechanistically described occurrences in either a nonmechanistic way or reside mechanism to a simplified version of the nature of reality, useful in particular aspects, but fundamentally misleading when we attempt to apply it to the universe as some kind of blanket theory. Equally, it is important to be aware that even if we develop a new form of covering explanation for teleology and mechanism, we should not believe that we have determined the nature of the universe nor that we are even close to any sort of "ultimate" explanation.

## 8. Conclusions

If Kant is correct, it seems that we are currently stuck with having to use teleology to a certain extent. But it also seems that science may be, slowly but surely, collecting information and developing pathways worth traveling to allow us to minimize the use of teleology and also perhaps start to "wean ourselves off." It is likely that this mechanism-teleology debate will not die soon nor be solved in a hurry, for it is rooted at too deep a level, not just due to our training from the first time we walk into a science class, but also due to the very structure of our ability to make judgments about the world.

Kant's reworking of the Argument from Design and critique of the ontological and cosmological arguments does leave us on firmer ground. Removing "God" from the equation keeps natural science intact, and the notion of internal purposiveness successfully reduces some of the other problems that the Argument from Design runs into. It does of course still have problems, which Kant left open by describing the limits of our ability to make judgments of organisms and resolving that explanations that we make using teleology and mechanism are nothing more than heuristics.

With the apparent logical problem of our mechanistic and design-based teleological explanations of organisms, coupled with substantial literary evidence that the problem has such a strong hold throughout biology perhaps we should be asking ourselves, "*Do we need to start looking at developing a new theory of explanation specifically to account for the nature of organisms*?" Could this ever be possible in light of Kant's limit of placing the causality by which to truly explain organisms in the realm of the supersensible? Using more than one type of causal explanation would also tend toward overdetermination with regard to Kant's primary role of mechanism, and Kant would be reticent to do this. We have, however, made many new movements and developed new ways of seeing in many other fields that have allowed us to explain things and phenomena that until then we never knew existed, but had perhaps intuited, so why not also aim for a similar thing for understanding of organisms. If the sciences pride themselves on one thing it is in the achievement of that which was said to be impossible. Our worldview and ability to apply new knowledge to different situations continually evolves, and biology more than any discipline should be open to that.

Kant limits teleology in its ability to provide explanation due to the nature of design in organisms creating many problems that he dismisses early on in his investigations (such as the links forward and backward in time). He does not, however, address more than fleetingly the possibility of a connection in terms of organization. That is in terms of the link being forward and backward in terms of organization. Bidirectional causality does not necessarily imply purpose; just because you invert the normal cause-effect series does not mean that you have the right to infer purpose and use teleology in organic nature. Kant may reply that this is just a limit of our understanding that forces us to do this. However, it still leaves us another potential avenue to investigate to get out of the current problem.

We should also perhaps be considering the crossover between the organic and nonorganic world of "mere aggregates" more closely with respect to self-organization and emergence. This may allow us to reduce the set size of our teleological statements as well as uncover some long held distinctions that may no longer be entirely appropriate.

Can we also perhaps find ways in which to experimentally manipulate the fundamental aspects of our concepts and understanding, and so in effect adjust our relationship with the categories and how we make judgments? From a Kantian perspective, this would not arguably not be viable; however, Schopenhauer's development of Kant's system in works such as *The World as Will and Representation* may allow us to pursue this potential opportunity, at least philosophically for the meantime and thus allow a deeper and less contradictory experience of living things. We have evolved with the nature of our understanding as it is regarding our view of the world and understanding of organisms, but this does not necessarily preclude that there are not other states that could be sitting nearby in evolutionary space and "jumped to" in the future as evolution progresses, perhaps as an emergent type phenomena. Biology is making progress all the time, and we should not discount a future possibility of experimental "category" or "judgment" manipulation in this field that makes this possible and perhaps offer us the potential of another kind of "Copernican Revolution." Kant does leave the door open for the possibility of sensibly conditioned understandings with different pure intuitions and/or logical categories than our own

(CPR B145–6), for example, an alien intelligence. Of course translating any of these understandings back into our discursive knowledge system would be expected to be highly problematic, as it would be extremely hard if not impossible "to render in any way conceivable to ourselves; and assuming that we could do so, they still would not belong to experience – the only kind of knowledge in which objects are given to us" (CPR A230). Regardless of Kant's opinion, it does provide a theoretical avenue for investigation, and at least for the moment, thought experiments.

In summary, in biology, we currently have a problem that we generally have not been publicly aware of that affects the amount we can ultimately know in relation to the limits of our knowledge as a consequence of the innate structure of our minds, ability to make judgments, and form concepts. But there may be ways to lessen the current level of the problem if we start looking (unless of course Kant is completely correct). True, our mechanistic and teleological explanations despite the problem that they are contradictory when used together, and appear incomplete when used alone, do a relatively effective job at allowing us create experiments to manipulate organisms reliably and repeatably, and this will allow years of productive research. But still when it comes down to it we know are not seeing things *as they actually are*. Until we can learn to bypass this problem, we will continue to have problems with the most fundamental areas of biology such as defining life, and developing a total theory of evolution that does not just explain differential survival but also allows us to understand the true nature of forms of organisms, their "design-like" fit to the environment, and fascinating phenomena such as convergent evolution.

As a last thought, one of the particular benefits of philosophy is that it lets us cognize the landscape of the future without the limits of the now and look toward the possibility of a system to explain organisms that is neither mechanistic nor teleological. With philosophy, we can pre-empt by the power of our thought, reason, and understanding of the world of now potentially available paths to discoveries of the future, as well as the scope and limits of what could be valuable avenues of investigation. By actively applying and creating a synthesis of relevant philosophical processes and methodologies to our scientific knowledge, we can potentially catalyze development of these new pathways as well as alert to the potential dead ends before they appear on the horizon. This is the strength of a philosophically informed natural science.

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Biodata of **Tibor Solymosi**, author of "***Pragmatism, Inquiry, and Design: A Dynamic Approach***."

**Tibor Solymosi** is currently an Instructor of Philosophy in the Department of Philosophy and Religious Studies at Allegheny College in Meadville, PA. After graduating *magna cum laude* from Allegheny in 2003, he earned his PhD at Southern Illinois University, Carbondale, where he studied at the Center for John Dewey Studies. His research focuses on the consequences of the life and mind sciences for our self-conception as conscious, free, and morally-responsible selves. He has spoken throughout the United States and in Europe. His writing appears in peer-reviewed journals, such as *Phenomenology and the Cognitive Sciences* and *Contemporary Pragmatism*. He has also contributed to other interdisciplinary volumes, such as *The Handbook of Neurosociology*. He runs an interdisciplinary website focusing on neurophilosophical pragmatism, or *neuropragmatism*, at www.neuropragmatism.com. He may be reached at tibor@neuropragmatism.com.

E-mail: **tibor@neuropragmatism.com**

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# PRAGMATISM, INQUIRY, AND DESIGN: A DYNAMIC APPROACH

**TIBOR SOLYMOSI**
*Department of Philosophy, Southern Illinois University,*
*Mailcode 4505, Faner Hall 3065, Carbondale, IL 62901, USA*

## 1. Introduction

Darwin's theory of evolution by means of natural selection has been rightfully thought to undermine the argument from design. Many Darwinists have drawn the conclusion that if there is no designer, then there is no design in the natural, that is, nonhuman, world. Nevertheless, to speak of living bodies as though they are designed entities comes so very naturally to us. Humans, one might say, are equipped with design-detection systems. The more we inquire into ourselves, our inner workings, and our larger connections to the external world of nature, we find a Janus-faced truth: on the one hand, we and the components of which we are made are purposeful entities – things or processes that accomplish aims that are productive – yet on the other hand, these apparently designed entities are not optimal: things fall apart; flaws in design abound. Since Darwin provided a new account of the adaptive fit between an organism and its environment that undermined the argument from design, many have struggled with how to account for the appearance of design in nature. Some have simply used euphemisms like *Mother Nature* as a useful metaphor for describing the workings of natural selection, but they ultimately contend there is no design, no purpose in nature. Others, however, have argued that there really is design in nature and that Darwin's theory provides the algorithm for producing design in nature without a designer. This position is largely counterintuitive. Here I present the argument for design without a designer as put forth by Daniel C. Dennett. I do so by orienting his argument within the larger philosophical context of pragmatism and the larger scientific context of dynamic systems theory. Both of which share an affinity with Dennett's position. The subsequent synthesis I believe yields a reconstruction of the nature of inquiry and design that deserves further considerations beyond those with which I conclude.

Charles Sanders Peirce and John Dewey, both founders, along with William James, of American pragmatism, sought to develop a theory of inquiry – what Dewey tellingly referred to as *logic* – that was rooted in biology but refined through the self-conscious and self-corrective practice of experimental science. The biological basis of inquiry, I argue, is found in the dynamic between allostasis and homeostasis (i.e., regulatory processes in the body). This dynamic is at work when an organism's interaction with its environment becomes problematic.

Through repeated though diverse interactions within organisms themselves and with their environments, evolution proceeds such that greater adaptability or flexibility to problematic situations emerges. This evolutionary process that leads to full-fledged inquiry and subsequently to the recognition of and the ability to design is Darwinian. This evolution through the algorithmic process of natural selection, however, occurs within pragmatic constraints of self-organization as described by complexity and chaos theorists such as Stuart Kauffman (1991, 1993) and Brian Goodwin (1994). The advances made in applying dynamic systems theory to biology and to the sciences of the mind have been well appreciated by the philosopher Daniel Dennett (1995, 2003, 2009). He argues that this dynamic process of evolution is the basis for biological and cultural design. Through Darwin's theory of evolution, we effectively get design without a designer.

This view is underappreciated by many if not all contemporary pragmatists. However, it is integral to the advance of pragmatism, especially if we are to take seriously Dewey's principle of continuity. This principle states that not only does all life have common ancestry through modified descent but that all experience – reconstructed as the transaction between organism and environment – is a continuous process (Dewey, 1938/LW12; Johnson, 2009, 2010). If Darwin's theory undermines the argument from design, and if we are to continue living purposeful lives, there must be an alternative account of meaning, purpose, and design that is not only coherent with but productively utilizes Darwin's theory of evolution. I argue that such an account is possible and that many of the parts of such an account can be found in a pragmatic account of inquiry as seen through a broadly Darwinian lens. Fortunately, much of this work has been done by philosophers Daniel Dennett and Larry Hickman.

In order to present a pragmatic account of inquiry and design in nature, I first provide a review of traditional philosophical reflections on design. I then proceed to articulate a pragmatic theory of inquiry – what Hickman has called pragmatic technology or pragmatechnics (Hickman, 1990, 2001, 2007) – and base it in the biological processes of allostasis and homeostasis. In doing so, I utilize central concepts from dynamic systems theory. I then turn to Dennett's arguments that biology not only is engineering but that the dynamic process of natural selection is a natural source of design.

## 2. Design Considerations

When people talk about design, what is it that they are thinking about? How do they use the word? If any sense is to be made of the origins of design in nature, it would behoove us to begin with considerations on design. Most people see some sort of connection between design and purpose. Whatever a design is or does, a purpose of some sort is involved. There is a reason behind or for the design. This is Aristotle's Final Cause. But Aristotle's Formal Cause is also at play when it comes to design: more precisely, a design is often seen as a blueprint or a plan – an articulation of structure – for bringing about or guiding a building process. When, for example, a person designs a house, one does so through initial sketches and measurements, review of proposals, up through detailed, and nowadays computer-generated schematics that indicate not only the number of rooms and their orientation to one another but also every nut, bolt, and screw for each plank, beam, and sheet – indeed, we now see, Aristotle's Material Cause is at play too. And with the design in mind or at hand, the actual entity that was just designed is not necessarily at work. That is, till it actually is, the entity is only potentially real. In the example of the house, one often finds that the design is complete but construction of the house has yet to begin – behold Aristotle's Efficient Cause.

Design, then, is a loaded word with many connotations that we must be careful to distinguish when discussing the consequences of Darwin's theory of evolution. Likewise, the phrase "pragmatic considerations," which is ubiquitous in much philosophical literature, deserves attention here as I make considerably use of it as it pertains to inquiry and design. Moreover, there is an intricate and inextricable connection between inquiry and design that recent work on explicating the phrase "pragmatic considerations" simply does not address. Here I consider this relationship in such a manner that it constitutes a minor thesis of this essay that underlies its major one. (N.B. I believe this minor thesis is only necessary because of the lack of appreciation of the pragmatic account of inquiry among analytic philosophy of science.) I then return to the relationship between inquiry and design by means of transition to an introduction to the pragmatist account of inquiry.

Mark Tschaepe has brought attention to the inadequacy of discussion of pragmatic considerations within the philosophical debate over the nature of scientific explanation (2009). His focus is exclusively on the debate between realism and antirealism, and he says nothing about the nature of design. However, his approach, like mine, draws heavily on pragmatism and the nature of inquiry. For this reason, I address his position to distinguish it from mine. Here is Tschaepe's definition of a pragmatic consideration:

> Generally, pragmatic considerations are *those specific factors within an explanatory situation that determine what causes and effects are problematic and desirable, while being constrained by the exigence (or potential exigence) and its corresponding phenomenon. Pragmatic considerations entail the recognition that such considerations will lead to explanations that function as part of a solution or prevention.* (Tschaepe 2009, 37)

Note that, for Tschaepe, pragmatic considerations are only involved in *explanatory* situations, which appear to be a variety of problematic situation. While explanations may serve as functions or parts of solutions or evasions of problems, not all problems are solved or evaded by scientific explanations. A design is a tool for production that may utilize explanations (which are more general), for the specific purpose of effecting activity in a specific context, with very specific resources at hand, which may include scientific explanations or theories. In short, the difference is whether or not there is an inquirer in this situation. In order for there to be a scientific explanation, there must be a scientist.

In order for there to be a design, there need not be a designer, yet pragmatic considerations, as I understand them, are nevertheless at play in a designer-less design process. I return to this relationship between design and explanation with regard to pragmatic considerations throughout the chapter. For now, however, I hope the following remarks will further illustrate my use of pragmatic considerations.

To continue with the house example, the designer of the house begins inquiring upon recognizing the particular situation. Here details matter: is this designer a professional architect? If so, many design tools are readily at hand. If not, then the designer needs either to educate oneself or to hire an architect. If the designer is an architect, there are different questions to be addressed than if the designer lacks a background in architecture. For instance, a hired architect must satisfy the demands of the client, whereas the amateur designer needs to satisfy only oneself (which may nevertheless require professional help). Other concerns about the particular situation involve the location of the house, which includes everything from the sort of ground it is to be built on to government ordinances dictating what structures are and are not permissible as well as what materials must be used. Further concerns include the budget as well as the material resources available, from the raw materials from which the house is built to the labor – that is, humans and their tools – to do the building. All these factors help form the detailed understanding of the particular situation. As they are each addressed, the inquiry pushes forth, raising and answering various particular questions, until the designer has a ready design at hand. This detailed plan of action allows those involved in the production of the house to begin construction as instructed by the design. The various struggles and irritations that come and go throughout the process of building a house are numerous and contingent on the particularities of the situation (a medieval king, for example, would have different problems to face than an upper-middle class American in the early twenty-first century).

What this example illustrates is that our typical, everyday understanding of design is that it is a product of our inquiries. Design – used in the ambiguous yet convenient sense that encompasses all four of Aristotle's causes – requires a lot of work done by some sort of intelligence (whether it be a single person or a committee matters little for my present point). What matters is that there is foresight, an anticipation of likely consequences of certain courses of activity and the means to evaluate them prior to enacting on one or several. In short, design seems to require an engineer, a designer, to produce the design as well as to put the design to work to produce the designed entity. What is not necessarily required – though surely useful in many instances – is an explanation of the design. Provided the design produces what it promises, no further reflections that would yield explanations are required, for there is no further need of them to effect the designed entity. This difference will become clearer in the next section on inquiry.

The pre-Darwinian view of design in the West held that the model of a human designer and his artifacts was a microcosm of the cosmos and that all artifacts ultimately derive from the grand designer, God. As William Paley forcefully argued, just as we infer from the existence of a complex entity such as a watch, that there must be a watchmaker, himself more complex than his artifact, there must be some intelligence, greater than human intelligence, that is responsible for such an intricate design as the human being. It is this easily made inference from human intelligences to Ultimate Intelligence that Darwin's theory of evolution undermines. Daniel Dennett has questioned both the inference, in light of Darwin, as well as the more nihilistic conclusions of other Darwinians that all design and thus all purpose and all meaning disappear as well. I argue, following Dennett, that the algorithm of natural selection is a process from which we get design – and all that comes with it, viz., meaning, purpose, foresight, etc. – without a designer, an Ultimate Artificer from which such meaning and purpose are derived. Rather such valuable aspects of our condition are the ongoing products of our inquiries.

## 3. Inquiry: Natural Rhythms, Homeostasis, and Allostasis

A central theme to John Dewey's pragmatic theory of inquiry is a pattern or rhythm found throughout nature, such as inhaling/exhaling or anticipation/consummation. These phases within the experience of organism-environment transaction naturally occur as part of the metabolic process. That is, in order to maintain viability, organisms must transact with their environments to exchange resources. This give-and-take is well illustrated by the dynamic relationship between allostasis and homeostasis. While I will argue momentarily that this relationship is the biological basis of inquiry, my purposes are better served by first defining inquiry as Peirce and Dewey articulated it.

Inquiry, as Charles Sanders Peirce (1877) described it, is the process of resolving doubt by fixing a belief about a problematic situation such that the irritation which makes the situation problematic is resolved. That is, doubt is overcome by fixing belief through the process of inquiry. Doubt as pragmatists understand it is the nagging, irritating feeling that prevents us from taking action, from effectively achieving our goals, whatever they may be. Peirce sees a continuum of doubt that ranges from that moment's hesitation of whether to use, following Peirce's example, a quarter or two dimes and a nickel to the years of study and devotion required for scientific experimentation. Doubt comes about because there is some degree of incoherence between our beliefs and goings-on in the world. Beliefs, as guides to action, are good or true insofar as they are productive in action. If I have an inadequate or false belief about the world, I cannot effectively produce actions or outcomes that fit with the rest of my beliefs, desires, and anticipations about the world and its goings-on. When such disruptions happen, doubt arises. The strength of the doubt corresponds to the degree of paralysis in my activities. The greater the doubt, the less likely I am to continue living my life, with ease of action, without disruption. The feeling of doubt continues on until I am able to resolve it by first recognizing the situation as problematic and then proceeding to manipulate the situation till the source of doubt is established, at which point appropriate actions may be taken to eradicate the doubt. This process of eliminating doubt is a process of fixing belief. To fix belief consists of changing old beliefs in light of new evidence or in adding new beliefs that allow for old beliefs to better cohere when it comes to acting. This overall process is the process of inquiry.

Peirce discussed four general methods of fixing belief but settled only on the method of science as having any promise for fixing beliefs that are true. In other words, as pragmatists since Peirce have argued, beliefs fixed by the method of science are true insofar as they serve as useful or productive guides – habits of action – to handling, navigating, or manipulating one's situation in the world. Given the Darwinian background to this view of inquisitive organisms interacting with their environing situations, we should not find it surprising that nonhuman animals, including our evolutionary ancestors, performed some sort of inquiry. While they certainly did not perform what we now call science, there is continuity between science today and the first organic inquirers.

Jay Schulkin has done valuable work in examining the relationship between homeostasis and allostasis that is worthwhile in its own right. He ties it to the pattern of anticipation and consummation that Dewey often described (Schulkin, 2003, 38). For my purposes, however, I pass over the scientific details of Schulkin's work so that I can focus primarily on the general pattern of inquiry that emerges from the dynamic relationship between homeostasis and allostasis. (For readers interested in the scientific details, see Schulkin, 2003.) Homeostasis is the process of maintaining equilibrium within an organism as it routinely interacts with its environment. It is important to note that this interaction is not necessarily static or passive, rather it is a state of dynamic equilibrium. When this activity is disrupted through changes in the environment or in atypical changes within the organism's structure – in short, through stress – disorder, disease, pathology come about. Allostasis is the bodily response to such stresses. More specifically, homeostasis is (re)established through the anticipatory and coordinating activity of allostasis, predominantly through the activity of the nervous system. This activity is noncognitive, that is, it is not something that the organism is consciously aware of doing (at least until humans become self-conscious about their inquiries, which is a very rarefied event in evolution). The activity, however, is the product of electricochemical reactions and energy transfers at the molecular level, of excitation and inhibition at the neuronal level, and of attractor patterns at the level of neuron populations (what Walter J. Freeman calls the mesoscopic; see Freeman, 2000, for further details).

Organisms whose environmental transactions include successful allostatic activities are more likely to survive and thrive. This ontogenic viability carefully becomes recapitulated phylogenetically through a long process of natural selection that operates on self-organizing principles of the organism-environment transaction. This development can be understood in terms of dynamical systems. Consider the fitness landscape in which a group of organisms are in a state of homeostasis, which would be represented in the landscape as a peak or hill. As the landscape changes (e.g., there is an influx of sodium or calcium), disorder sets in from the stress of the changed landscape. The state space permits only a few likely routes toward reclaiming equilibrium. Since each of the organisms in this population have various idiosyncratic quirks, some will take routes that lead to more or less immediate satisfaction. Some will perish. Still others will take trajectories toward entirely new peaks formed from the changing landscape. The attractor basins that appear in this landscape are not accessible by all of these organisms. The group breaks apart. Those with adequate allostatic systems will be more likely to survive than those allostatically lacking. Eventually, the productive allostatic traits will permeate throughout the new landscape until new stressors arrive bringing about further demands for adjustment.

This process of adaptive adjustment has been usefully explicated by Power and Schulkin (2009) and Hickman (2001, 2007). Power and Schulkin distinguish between adaptations that are evolutionary and those that are physiological. The former refer to changes made at the species level that affect fitness traits across a population. The latter refer to changes made by individual organisms in order to respond to problems or challenges. This sense of adaptation fits with one of the two aspects of adjustment that Hickman discusses. For Hickman, adjustment comes by two means, adaptation or alteration. Adaptation here is the physiological adaptation distinguished by Power and Schulkin. Alteration differs from adaptation in that the organism does not modify itself but its environment in order to overcome a challenge brought about by a disruption in homeostasis.

What should be clear by now is that the pattern of inquiry articulated by pragmatists like Peirce and Dewey has its basis in the dynamic relationship between homeostasis and allostasis. Generally speaking, homeostasis is akin to a state of belief in which the process of living goes about with ease: no difficulties arise. But when a difficulty does arrive, when homeostasis breaks down, when doubt sets in, there are physiological changes that are not anticipated, that are not part of the normal pattern of activity. This chaos, if left unaddressed, can lead to pathology. Disease conceived as *dis-ease* is pertinent here. Only through a process of productive change can equilibrium be reached. This process is allostasis at the strictly biological level. When extended to the cultural, allostasis is the biological basis of the process of inquiry. When belief is fixed, when doubt is resolved, allostasis is complete, for homeostasis is attained. Organic activity proceeds without difficulty. How this resolution comes about is a matter of the particulars of the situation. That is, whether it is through physiological adaptation or environmental alteration depends on the contextual details and on the pragmatic considerations of the inquiry. For humans, scientific explanation is becoming ever more the best and most powerful means of resolving a problematic situation, but it is not nor will it ever be the exclusive means. Just as life has solved its problems through design modifications prior to the rise of science, so will it continue to do so, for humans and nonhumans alike, without explanations. Before moving on to discussing full-blown human or cultural inquiry (in which explanations are only to be found), I turn to the process that is at the basis of all productive inquiry and design, natural selection.

## 4. The Darwinian Algorithm of Natural Selection: Strict Darwinism and Darwinism by Analogy

In order to appreciate Dennett's position that there is design without a designer, we need to understand the general workings of Darwin's theory. But we also need to understand the scope of the theory. Dennett talks of Darwin's theory as a "universal acid" that modifies everything it touches – and it seems to touch everything or at least promises to (Dennett, 1995). But in seeing the scope of Darwin's theory as universal, Dennett is not arguing that everything about humans or everything about the biological world can be explained through the fitness of genes. Rather there is a difference between a strict Darwinism and a Darwinism by analogy (see Flanagan, 2009 for an excellent discussion on this point). The former does seek to explain through gene fitness, whereas the latter does not seek to explain through gene fitness. Instead, Darwinism by analogy seeks to explain a wide variety of phenomena through recursive feedback loops, through iterations of trial and error, which share an analogous structure to the natural selection that works on genes, the traits for which they are responsible, and reproductive fitness. What this distinction permits is the generalization of natural selection into an algorithm that suits both strict Darwinism and Darwinism by analogy – provided adequate modifications are made in light of the pragmatic considerations of the particular situation.

Dennett has emphasized the algorithmic nature of Darwin's theory of natural selection, drawing out the conditional inferences Darwin makes in a step-by-step fashion. Here is my reconstruction of Dennett's Darwinian Algorithm of Natural Selection (this follows Dennett, 1995, 48, which follows Darwin, 1859, 127):

1. If there is variation among organisms' organizational structure;
2. If there is a struggle for life, that is, if resources are limited at some point in time;
3. Then some of those variations are useful and thereby advantageous toward acquiring those resources than the other variations – viz., there is better fit among some.
4. If there are such useful variations, then those organisms with such variations "have the best chance of being preserved in the struggle for life," for survival.
5. From the principle of inheritance, we may conclude that the offspring of such fortunate organisms will tend to have similar useful traits, thereby preserving adaptations across generations.

It is not difficult to imagine how to apply this algorithm to traits we know to be genetic, such as the beak of a finch. What may not be so easily imagined is the algorithm's application to nongenetic traits, such as a hammer or a house. Consider this further alteration of the algorithm:

1. If there is variation among the organizational structure of entities or processes;
2. If there is a struggle for persistence, that is, if resources necessary for continuation are limited at some point in time;

3. Then some of those variations are useful and thereby advantageous toward acquiring those resources than the other variations – viz., there is better fit among some.
4. If there are such useful variations, then those entities or processes with such variations "have the best chance of being preserved in the struggle for" persistence, for continuation.
5. From the principle of inheritance, we may conclude that the replication of such fortunate entities or processes will tend to have similar useful aspects, thereby preserving adaptations across generations.

Hammers and houses do not have any genetic basis. However, as anthropologists and historians can easily tell us, hammers and houses have evolved: over time, aspects of each have changed to better suit the circumstances. Of course, much of the evolution of artifacts like houses and hammers is directed by human intelligences. But we should not see this direction as opposed to natural selection. First of all, many of the changes that occur over the years are due to material restrictions: designs are not optimal but necessarily adjust to pragmatic considerations. Secondly, as Darwin pointed out, artificial selection is a species of natural selection. We may select for a certain trait (e.g., a benevolent temperament in dogs) but also effect other undesired or unanticipated traits (floppy ears in dogs).

What I hope is beginning to become clear here is that the entirely dumb algorithmic process of natural selection is applicable to situations beyond genetics and well into intelligent human affairs. This continuity permits our taking a specific stance or attitude to biology, especially when it comes to understanding adaptations of organism(s) to environment(s). This is Dennett's intentional stance adapted to biology as an engineering stance (Dennett, 1988, 1995). It is what Larry Hickman has described as Dewey's technological pragmatism, or *pragmatechnics* (1990, 2001, 2007). Regardless of what we call it, it is the recognition that in order to understand the natural world, a normative appraisal is necessary, much like it is in other inquiries such as farming or engineering.

## 5. Pragmatechnics: Biology as Engineering?

According to philosophical tradition going back to Plato and Aristotle, skill or *techne* was believed to be inferior to knowledge or *episteme*. This hierarchy of knowing-that over knowing-how is undermined by Darwin's theory. Dennett's adoption of an early criticism of Darwin's theory is apt here: Darwin's thinking is a strange inversion of reasoning (1995, 2009). This hierarchy has led to the still all-too-common presumption that science is pure because it is objective, viz., value free, whereas technology or engineering is applied science and thus less objective because values must be employed. This hierarchy persists in dualisms throughout our culture, notably the opposition between what CP Snow described as the two cultures of the humanities and the sciences (Snow, 1959). This conception of science, argues Dennett, is dissolved by the universal acid of Darwin's theory of natural selection.

Hickman argues even more forcefully than Dennett that this conception of science and technology is not only inappropriate in light of an evolutionary standpoint but simply chronologically and ontologically backward (2001).

The ever-growing set of methods that are considered scientific share some general characteristics, Hickman argues. The most notable is the experimental nature of these methods. What allows these experiments to occur in the first place, however, are the tools, techniques, and observational data that have accumulated through myriad means over substantial amounts of time. These tools, techniques, and data range from specific measurements taken with tools like a meter stick to abstract concepts such as a sine curve. In order for experimentation to occur in the first place, certain techniques need to be in place. The cognitive familiarity – what we traditionally call *habit* – of mathematics or a specialized language like that of chemistry is a condition necessary for doing advanced, specialized science. This much is hardly in dispute. But just as necessary for scientific inquiry are the notepads and beakers with which such cognitive activity is performed. In other words, from numbers to calculators, from the idea of a chemical formula to a beaker full of a molecular solution, what has traditionally been called "pure science" is utterly dependent upon its so-called applications.

What marks scientific inquiry from the tools and techniques on which it is dependent is its self-recognition as experimental. In other words, as Hickman argues, scientific inquiry is technological: an inquiry (*logos*) into and by means of the skills, tools, and techniques of the situation (*techne*). For this reason, Hickman suggests the term *technoscience* (2001). For similar reasons, Dennett argues that biology *is* engineering.

Engineers solve problems of design. Pragmatechnics is a theory of inquiry based on the biology of homeostasis and allostasis that is culturally developed into the social, systematic institutional activity of technoscience. Hickman's definition of pragmatic technology is worth quoting here specifically: "Technology in its most robust sense… involves the *invention, development, and cognitive deployment of tools and other artifacts, brought to bear on raw materials and intermediate stock parts, with a view to the resolution of perceived problems*" (Hickman, 2001, 12). Hickman articulates pragmatechnics as "a thoroughgoing program of problem-solving that involves analysis, testing, and production: production of new tools, new habits, new values, new ends-in-view…" (Hickman, 2007, 99–100). As I argued earlier that inquiry more generally is based in the dynamic relationship of allostasis and homeostasis, pragmatechnics clearly goes beyond that relationship yet remains continuous with it. Dennett's contention that biology is engineering serves Hickman's position well and is served well by Hickman's conception of technoscience.

The salience of these mutual contributions will become clearer as my argument proceeds. For now, it is worth noting the following points. First, Hickman's pragmatechnics is full-blown inquiry. Only a specific subset of humans participate in it. Among the products of pragmatechnics are designs that are understood, recognized, and articulated. But in order for there to be recognition of design in nature, there needs to be an account of the so-called raw materials that technoscience inquires into and puts to use. The bootstrapping process of evolution needs to be tied to this pragmatechnic account of inquiry. Fortunately, this conception of technoscience combined with the Darwinism by analogy provides us with the means to ask how these tools and techniques, the conditions for technoscience, came about. In other words, if among the products of technoscience are designs for various entities, from organisms to hammers to houses, there must be a story to be told about how the component parts and processes of these entities came about. From the perspective of pragmatechnics, these entities are solutions to problems, predominantly of survival (in the broad sense). The difference between pragmatic considerations in explanation and pragmatic considerations in design is important here. There are designs that lack explanations but are nevertheless explainable, thanks to what Dennett calls "free-floating rationales" (2009). As the evolutionary story shows, to paraphrase Hilary Putnam, we (or nature) *create* strategies, explanations, or designs, but we (or nature) *discover* which ones work better than others by testing them in the world (Putnam, 2002, 97); the ones that work last longer than those that do not. Only the part of nature, however, that is human inquiry can tell *why* one strategy or design works better than another – and that is what we call an explanation. The story I tell here draws from Dennett's heuristic for understanding the evolution of intelligence, what he calls the Tower of Generate-and-Test, and dynamic systems theory. Through it, this distinction between design and explanation, and creation and discovery, will be further elucidated.

## 6. Dennett's Tower of Generate-and-Test

Dennett has developed an instructive heuristic called the Tower of Generate-and-Test to illustrate in an idealized and simplistic fashion how intelligence can develop out of mindless matter (1995, 373ff). Here I simply introduce the levels of the Tower before setting it into the larger context of pragmatechnics and dynamic systems theory. The process of natural selection serves as the basic builder of the Tower of Generate-and-Test. Its construction begins as soon as self-replicating molecules begin replicating. The purpose of this sketch is to provide "synoptic insight" (ibid., 373). Dennett argues that "as each new floor of the Tower gets constructed, it empowers the organisms at that level to find better and better moves, and find them more efficiently" (ibid., 373). In short, moves are generated in action or in thought and are tested in environmental interaction – in experience, as Dewey would say.

The ground floor of the Tower of Generate-and-Test is occupied by the simplest self-replicating entities imaginable. Dennett playfully labels these replicators as *Darwinian creatures*. Some of these organisms are just "lucky" enough to have been hardwired in the right way to replicate into the next generation. Only some lineages become fortunate enough to replicate on and on for millions of generations till a few fell upon an organizational state that allows for some flexibility in their interaction with the environment. The development of *phenotypic plasticity*, of the ability to learn via environmental conditioning marks the construction of a new level on the Tower. Its occupants are *Skinnerian creatures*.

The skill of operant conditioning is superior to the do-or-die approach of Darwinian creatures. But a better approach still would be the ability to imagine possibilities before actually trying them out. This skill of preselection marks the arrival of *Popperian creatures*, so named after Sir Karl Popper who quipped that such a skill "permits our hypotheses to die in our stead." Dennett writes that "Unlike the merely Skinnerian creatures, many of whom survive only because they make lucky first moves, Popperian creatures survive because they're smart enough to make better-than-chance first moves. Of course, they're just lucky to be smart, but that's better than just being lucky" (ibid., 375).

The major development here that distinguishes the Popperian creatures from the Skinnerian is the emergence of some sort of foresight. In order to imagine plausible scenarios, a Popperian creature needs to have some physical means of imagination in which information *about* the environment in which it engages is considered. This "inner environment" is not simply a miniature replica of the actual or possible external environment. As Dennett notes, in such a scenario, "the little hot stove in your head would be hot enough actually to burn the little finger in your head that you placed on it!" (ibid., 376) Nevertheless, there must be some sort of awareness *of* the external environment. The development of complex nervous systems, what many simply call *brains* for short, functions as these anticipators of what could happen. In order to anticipate what is going to happen in the external environment, a brain needs to be *about* that environment. With the rise of Popperian creatures, we see the arrival of *intentional consciousness*.

In a certain respect, intentionality is an internalization of the environment that results from interaction with that environment. At each level of the Tower, greater chances for learning emerge due to ever-more sophisticated and imaginative interaction with the environment – none of which results from actual foresight as there simply are random variations that from generation to generation are of the slightest change and that over millions of generations these subtle differences accumulate into some significant differences that nevertheless remain continuous with their ancestors out of which they are constructed. At the level of Popperian creatures, the creatures are able to generate ideas or plans of action and to test them out prior to actually carrying them out in the external environment where they had traditionally been tested. Prior to this, there is nothing like intentional consciousness (though there are the precursors to intentionality that reach back to the sort of lock-and-key aboutness found in something like a molecules' fit with its environment, especially when that molecular key is a neurotransmitter and its lock a synapse – viz., the precursors reside in the first allostatic systems).

The Popperian level of the Tower continues to grow in size and height as more and more diverse organisms evolve with these capacities for foresight. Once there is this internalization of the environment, where else is there to go for the evolution of intelligence? Dennett's answer is to go back into the environment. *Gregorian creatures* are the next level on Dennett's Tower. They are named after the psychologist Richard Gregory in honor of his work on the role of information in tools and artifacts. In the externalization of information *about* the environment back into the environment in the forms of tools and artifacts, Gregorian creatures mark the arrival of a new medium for evolution: *culture*. Where the previous levels of the Tower evolved through genetic selection, the externalization of intentionality into the environment enables a newer, faster medium of evolution. This externalization is found, for example, in social animals that imitate one another, whether it is by repeating vocalizations or making faces or in sharing tools or in the use of words.

So powerful is the effect of *language* on an organism that Dennett sees words as "mind-tools" that radically alter an organism's inner environment through the cultural interaction within its exterior environment that is now full of "words, words, words" (ibid., 417). In other words, as intentional consciousness first emerges with the development of nervous systems, full-blown language, above and beyond mere communication, evolves among the interactions of the nervous systems of social organisms. The intelligence that such mind-tools bestow on a cultural organism through what we could call *enculturation* but already do call *education* is so empowering that the information a mind can process *about* the environment becomes staggering in comparison with nonlinguistic Popperian creatures. For this very reason, Dewey refers to language as "the tool of tools" (Dewey, 1925/LW1: 134).

Within the Gregorian level of the Tower of Generate-and-Test, there is one last achievement made that is a real game changer: "it is the one that gives our minds their greatest power," writes Dennett, "once we have language – a bountiful kit of mind-tools – we can use these tools in the structure of deliberate, foresightful generate-and-test known as science. All the other varieties of generate-and-test are willy-nilly" (Dennett, 1995, 380).

What makes science a particularly potent form of generate-and-test is not simply that it makes mistakes, which all other forms do as well, but that it makes them *publicly* in such a way that allows science to be self-corrective in ways that all other forms of fixing belief are not. Prior to science, all the generating-and-testing of ideas and actions were done as a matter of survival necessity. Where there was foresight, it was short term and quickly tested. Its results were never quite clear on what went wrong or why. Science, however, has gone above and beyond by setting up a sensitive social structure that is open to and indeed thrives upon self-critique through the comparison of ideas, methods, activities, etc. – all of which is made possible by language.

Now if language is a tool and is what, on Dennett's account, makes science possible, then it is appropriate, in light of the arguments covered in previous sections, to reconstruct Dennett's evolutionary story of the evolution of intelligence that culminates with science as a dynamic story that culminates in technoscience. In other words, I can now finish bridging the previous section's connections between Hickman's pragmatechnics with Dennett's contention that biology is engineering. I do so first by reiterating the story in the language of dynamic systems theory and then by returning to the pragmatic theory of inquiry that sees design as a product of natural processes.

Each level of the Tower of Generate-and-Test can be seen as a basin of attraction within state space – or, more precisely, what Dennett himself refers to as Design Space, the set of all possible designs (1995). Initially among organisms, the only basin that can be reached is the Darwinian level. But as that level becomes more sophisticated and diverse – as the landscape changes with various peaks and hills – the phylogenetic trajectory that emerges pushes forth to the Skinnerian level. Here another basin of attraction emerges within state or Design Space. This iterative process continues till further changes to the landscape brings about sufficient chaos that effectively produces further possibilities of adaptive fitness, namely the Popperian and Gregorian levels of the Tower. At each stage, the activity of the Darwinian creatures continues. In some cases, the creatures are on their own. But, in others, the creatures are part of larger conglomerates and symbionts. In other words, the hills or peaks of the lower levels of the Tower are the necessary platforms for the higher levels. There would be no Popperian creatures if all Skinnerian creatures were suddenly eliminated. But, there could still be Darwinian creatures that remain upon the demise of the Skinnerian. The path up the mountain can be retraced on the way down, even as the mountain begins to crumble.

## 7. Pragmatic Considerations on Design

Even though the Tower of Generate-and-Test is a highly idealized heuristic schema, it nevertheless permits discussion of pragmatic considerations, particularly in the language of dynamic systems. What occurs and when it occurs on each level – in each attractor basin – determines the likely path the trajectory will take. There is no ultimate end that pulls the path forward no matter what. That sort of teleology is what supported the old argument from design and the Aristotelian worldview that living things served fixed and final ends. Nevertheless, it is not a total free for all either. Once certain activities are performed or paths taken, other activities can no longer be performed, other paths become closed. Research from complexity and chaos theorists has shown that such dynamics yield specific self-organizing properties to molecular and organic compounds. By its very organization, the stuff of life closes off a plethora of possibilities while focusing in on only a few. This insight of theorists like Stuart Kauffman and Brian Goodwin has been well appreciated by Dennett (see Kauffman, 1991, 1993; Goodwin, 1994; Dennett, 1995). Strikingly, the import of self-organization for evolution by means of natural selection was appreciated early on by John Dewey (see Dewey, 1925/LW1, 195ff).

Let us return to the original motivation for this essay: the origin of design in nature through processes of natural selection and inquiry. The general pattern of inquiry rooted in the ontogenetic biological processes of homeostasis and allostasis and described in earlier sections of this chapter is recapitulated in the evolution of intelligence itself, as illustrated through Dennett's Tower of Generate-and-Test. Pragmatechnic inquiry or technoscience is the culmination of the algorithmic design process of natural selection. After all, the lower levels are the tools – what Hickman calls platforms, what Dennett calls cranes – that make the activities of the Gregorian level possible. Yet pragmatic inquiry is not identical to natural selection, but they are continuous. There are considerable pragmatic considerations on the differences in design between Mother Nature, so to speak, and human engineers. Fortunately, Dennett has carefully addressed these differences (see Dennett, 1995, 213–217).

To appreciate the differences, we must remember that Dennett argues that with each move up the Tower of Generate-and-Test, problems of survival and viability are solved. There is no solver to these problems, when we understand "solver" to mean an active intelligence, like a designer. Rather, following the Darwinian Algorithm of Natural Selection, some patterns of activity are going to do a better job than others at solving problems of survival. Through a significant number of iterations (viz., over a vast number of generations and time), these patterns of activity are modified and specialized for more subtle tasks of adaptation.

Among the specialized and highly modified patterns of activity is the scientific (as discussed on the Gregorian level of the Tower). Among its products are theories and explanations. Prior to language, there are only solutions to problems without explanations in nature. These solutions are designs and are determined by pragmatic considerations of the problematic but not explanatory situation. Only when human scientists retroactively inquire into the history of these problematic situations and their solutions can we claim to have explanations, which have their own pragmatic considerations for the problematic *and* explanatory situation of the human inquirers. The design patterns that they utilize for their explanations are creations of natural selection that the scientists discover. These discovered creations, as I noted earlier, are what Dennett calls "free-floating rationales" (2009). Natural selection serves as the design or creation process but does so mindlessly. Human engineers and scientists can produce explanations of both the process of natural selection *and* their own means of creation and discovery. While continuous with one another, these two processes are not identical.

For Dennett, the differences between the engineering design process of natural selection and that of humans come to two. When inquiring into how to solve a problem, humans not only have an idea of what the problem is but also consider possible models for the solution. Part of inquiring is to modify these model solutions to encourage better predictability as to what is most likely to work in solving the problem. Evolution, unlike humans, has a lot of time to solve problems. But these problems are never felt or perceived by the algorithmic process of natural selection. Rather, evolution can simply produce as many plausible solutions as resources allow and see what is selected. It makes no predictions because it has no need to. One way to appreciate the difference is that humans condense the amount of time needed to solve a design problem by concentrating greater energy into less time. This concentration of resources has thus far culminated in technoscience. That is, humans make use of foresight whereas evolution has none. This is the second major difference in design processes that Dennett notes. There is an interesting benefit, though, to evolution's chronologically drawn-out process: multiple functionality. One reason why humans have struggled more with understanding biological organisms than they have with simpler physical mechanisms is that some systems in biology perform multiple tasks where we have become accustom to giving one system one task to perform. While human engineers are improving on both understanding multiple functionality and in developing their own applications of it, the evolutionary process is distinct from the standard human engineer when it comes to the ingenuity of its solutions. But this, again, is the benefit of having a far more significant amount of time to try a multitude of solutions – a luxury humans do not enjoy.

In light of the distinction I am making between pragmatic considerations in design and those in explanation, there appears to be a third difference between Mother Nature (i.e., the myopic design process of natural selection) and human designers. Mother Nature produces designs but no explanations on her own. To produce explanations, she first had to design human technoscientists to account for and thus help improve upon the design capacities of nature and culture.

Another way of understanding these key differences is that humans in inquiring have among their raw materials and tools at hand the models and designs of previous inquiries – and more recently previous scientific explanations. Going back far enough in the history of inquiry, we would find ancestors who are going through the motions of allostasis. There are reasons for what they do, but they do not know what they do or why they do it. Thanks to the advances of the descendants of those early ancestors, we now have a grasp of why organisms and their components fit so well together within their environments. Dennett refers to these reasons as "free-floating rationales" (2009). For most life on earth, there are good reasons for the specific functions and productivities of life. It just so happens that most of that life never knows what those reasons are. But for a small group of one species of life, methods have developed that go beyond the survival skills of ancestral life. This development has become self-conscious as well as self-regulating. Designs can be understood and produced through technoscientific inquiries that take into account the pragmatic considerations of the particular organism-environment transactions of both the subject matter and the inquiring organisms.

## 8. Conclusion

The entirely algorithmic and myopic process of natural selection operates on the particular self-organizations of organic life. This process eventually yields dynamic processes of homeostasis and allostasis that serve as the biological basis for inquiry. The language of dynamic systems theory helps us to understand the crucial role pragmatic considerations play in the production of life, especially human life. Design is not something that precedes life and living. It is, however, an outcome of the sort of world in which life abounds. Among such outcomes are the specific designs of human artificers. Still other designs are those now beginning to be understood by humans, who inquire into the natural world. The normative assessments of such inquirers produce designs that enable humans to not only understand how their components are productive but enable humans themselves to become more productive in light of their knowledge of their own design.

The pragmatic theory of inquiry developed initially by American philosophers like Charles Sanders Peirce and John Dewey and more recently elaborated upon by Larry Hickman provides a useful perspective for appreciating Dennett's biology-as-engineering position through which design can be produced in nature without a designer. Likewise, Dennett's evolutionary account of intelligence provides a useful tool to American pragmatists who are interested in the biological basis of inquiry. The language of dynamic systems theory is a useful bridge between Dennett's Darwinism and Hickman's pragmatechnics. Future considerations on the nature of inquiry and design would benefit greatly from pursuing the affinity between Dennett and Hickman in greater detail than I have here.

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Biodata of **John R. Shook**, author of "***The Design of Morality***."

**John R. Shook**, **Ph.D**. is a scholar and professor living in Washington, DC. He is Director of Education and Senior Research Fellow of the Center for Inquiry. He also is a visiting assistant professor of science education at the University at Buffalo and associate fellow at the Center for Neurotechnology Studies in the Potomac Institute for Policy Studies in Arlington, Virginia. From 2000 to 2006, he was a professor of philosophy at Oklahoma State University. Among his books are *A Companion to Pragmatism* (2005), *Ectogenesis* (2006), *The Future of Naturalism* (2009), and *The God Debates* (2010).

E-mail: **jshook@pragmatism.org**

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# THE DESIGN OF MORALITY

**JOHN R. SHOOK**[1,2]
[1] *University at Buffalo, Buffalo, NY 14260, USA*
[2] *George Mason University, Fairfax, VA, USA*

## 1. Morality in Nature

Scientific research into our primate cousins and our own human capacities are providing insights into the long history behind the design of morality and our facility with conducting and modifying morality (see, e.g., de Waal, 2009). An account of the origins of human morality must recognize three main phases: a long period of protomorality evolving among the primates; another long period of protomorality growing into morality in the several Homo species as brain size increased; and a relatively brief period down to present times when *Homo sapiens* has been self-consciously modifying morality. Both natural evolution and cultural evolution have been involved in intertwined ways to design morality, and both will continue to shape morality. A naturalistic account of human morality must be both backward-looking and forward-looking. This account looks far back in time when evolution was forming the building blocks of morality and then morality itself without any conscious designing, and then it shows why humans would look forward to take some measure of deliberate control of their inherited morality utilizing only the cognitive resources naturally available to them.

An internally consistent and gradual evolutionary account of these three main phases is needed. Any abrupt break, some strange leap or dramatic shift, presents a severe problem for a naturalistic understanding of the development of morality. For example, if earlier hominid species are thought to have had nothing like morality, only competing in a fierce "selfish" struggle where most kindnesses and cooperations are punished in the long run by natural selection, it becomes hard to explain how *Homo sapiens* would be practicing a far more social morality instead. Some extraneous factor must be abruptly introduced to account for that leap, and speculative theories abound. Perhaps there was a suddenly evolved capacity for universal empathy or for a separate rationality untainted by emotion or ego. Even less naturalistic are proposals about how humans must utilize a spiritual free will uncaused by anything physical or must consult divine revelations descended from above. No great leap is needed, however, if primate behavior displays the building blocks of morality and if the differences between hominid protomorality and human morality are mediated by gradual stages. Nor would there be a forced choice between crediting nature or nurture for morality. The long-standing debate over whether human morality is mostly the product of natural evolution or cultural evolution presumes a dividing line during our hominid ancestry where morality could be placed primarily on one side or the other. Morality's design is likely more complex than that nature-cultural debate admits.

An objective investigation of morality is needed in the course of pursuing an evolutionary account of human morality. For the sciences to be able to study human morality, it must have some place in the natural world, available for observation and experimentation. Not surprisingly, the most obvious place to investigate human morality is to examine the conduct of natural humans. By regarding humans as entirely natural entities with biological properties and cultural capacities, the sciences have plenty of morality within view for study. Let "moral naturalism" stand for the view that there is a natural phenomenon properly called morality that exists in human societies and that everything about morality's operations or evaluations is open to scientific scrutiny. Moral naturalism holds that human morality can be objectively studied by the several social and natural sciences and that nothing about human morality must elude scientific understanding. This is not the same enterprise as using science to answer our questions about what the morally right thing is to do. As a descriptive effort only, moral naturalism is actually a quite modest and limited enterprise. "What is morality?" is not the same question as "What is morally right?" There is a distinction between studying a practice and having expertise in that practice. For example, we can observe how agriculture works without acquiring farming expertise, and we can observe how people build all kinds of bridges without ourselves having to answer questions about the best way to build a bridge.

Although often taken synonymously, it is useful to distinguish moral naturalism from ethical naturalism. Morality refers to related kinds of actual human conduct, while ethics refers to philosophical questions that arise about morality. Ethics is the philosophical domain that deals with metalevel issues about ways for determining the applicability of moral norms and terms, questions about the appropriate methods for judging and answering moral problems, and concerns over whether one correct morality can be determined. Adding the naturalistic outlook to morality and then to ethics yields two quite distinct fields of study. Moral naturalism takes humans to be doing morality naturally, without any nonnatural features (such as a spiritual soul, free will, or pure reason) involved in the process. Ethical naturalism goes much further than moral naturalism, by regarding all metalevel issues about morality as issues to be resolved naturalistically, and typically includes views that moral rightness and personal goodness are reducible to nonmoral features of nature, that things like moral values and moral facts refer only to natural entities known by science, and that there are true propositions of morality that are made objectively true by nature alone regardless of any human cognition or consensus. Moral naturalism, as the term is used here, is entirely unaffected by the validity or invalidity of ethical naturalism or moral realism. Moral naturalism and ethical naturalism share a respect for science and agree that science should take the lead when investigating morality. Indeed, determining the degree of ethical naturalism's validity largely rests on first carrying out the program of moral naturalism as far as it can go. No moral naturalist needs to first decide whether any part of ethical naturalism is valid. Indeed, moral naturalism remains useful even if ethical naturalism is invalid. There are good prospects for ethical naturalism all the same. Moral naturalism has made great strides, and there are sound varieties of naturalism capable of grappling with philosophical ethics (see, e.g., Darwall et al., 1997; Foot, 2001; Wong, 2006; Flanagan et al., 2008).

Regardless of ethical naturalism's prospects, we are here only concerned with moral naturalism. Ethical naturalism's interest in discerning moral goodness, value, and truth naturalistically is not shared by moral naturalism. For example, only confusion arises if it is first supposed that there are moral truths, or something like one "true" morality, and that moral naturalism should determine or ground true morality. The project of moral naturalism may not lead to a victory for ethical naturalism. Moral naturalism is compatible in theory with moral relativism, for example – the many varieties of moral societies and their deep disagreements indicate that there may be no way to determine a uniquely correct morality. Still, moral naturalism need not imply any simplistic relativism, since there may yet be better and worse moralities even if there is no perfect morality (see Harris, 2010). Moral naturalism may even reveal that even our "best" human moralities are hardly as good as we think they are because much seemingly moral conduct is actually motivated by selfish concerns, either consciously or unconsciously. All the same, the very fact that humans spend so much time deliberating about good and better moralities, discerning whether each other's conduct is genuinely moral or not, and encouraging each other to be more moral proves that morality is no illusion even if it cannot be so prevalent. Humans put a great deal of effort into morality and, by extension, into ethical inquiry. Moral naturalism's ability to explain how humans now regard morality as variable and modifiable does show why ethical theorizing bothers to seek moral reform and agreement about moral correctness. We envision possible better moralities because we already understand what it is like to redesign inherited moralities.

Because societies do think about what the best morality may be, and whether there ought to be one morality for all, and because societies frequently try to impose one morality on everyone, moral naturalism also gets confused with moral universalism. Despite widely shared hopes, moral naturalism is not a method for determining one uniquely correct morality. Conversely, moral universalism is a bad starting point for undertaking moral naturalism. Those in thrall of one universal morality tend to denigrate as either immoral or nonmoral any mode of human conduct that strays too far from the one correct morality, whatever that may be. Universal moralizers are not alone in this inability to recognize different moral systems. Since we all have been encultured into at least one moral system, any of us can feel susceptible to this inability when we read accounts of the moralities of societies which endorse such things as paternalism or slavery. "That's not any kind of morality," we feel compelled to say, and we may not be assuaged by reminders that those practices are considered moral by those other societies. Relativism is not intuitive for morally trained people; those other "immoral" societies equally judge our morals be immoral. But scientific objectivity is needed here. Moral naturalism takes its subject matter to be those modes of conduct which peoples themselves have regarded as fulfilling morality, regardless of whether those morals are presently regarded as moral conduct by us. Morals have and will forever vary widely across humanity, and moral naturalism attempts to naturalistically account for all of them.

Moral naturalism limits its interest to the actual moral conduct of humans, but this is a wide field, since all human societies use morality. Unlike many ethical naturalisms and some other ethical theories, moral naturalism does not limit the meaning of "morality" to only some allegedly correct propositions of morality, as if societies unaware of "the" correct morality therefore fail to have any morality at all. Moral naturalism treats morality rather like food production or child rearing: these are things which all human societies do, even if some societies may do them somewhat differently or even better than others. While setting aside the question of one "correct" morality, moral naturalism is primarily concerned with morality as practiced by humans and hominid ancestors, and it uses a definition of morality as humanity now practices it (this definition is coming in the next section). While moral naturalism cannot begin from any single moral system, it must start from a unitary notion of what "morality" is, in order to specify the subject matter for inquiry. Similarly, any study of agriculture starts from a preliminary definition of what "agriculture" consists of, without also premising criteria for some "best" kind of agriculture. It will not serve to leave open what "morality" might be, supposing that empirical inquiry will settle the matter down the road. After all, moral naturalism primarily aims at accounting for what humans currently are capable of doing and not accounting for something we do not do. Although there are researchers inquiring into other species from dolphins to wolves who claim that those species have "moralities" of their own (de Waal, 1996, 2006; Bekoff and Pierce, 2009), their conclusions about nonhuman moralities are just that conclusions about nonhuman moralities. Moral naturalism inquires into the homologous features among human and hominid moralities, regarding them as sharing a common ancestry and remaining grounded in anthropology. It can only recognize near morality or components of human morality in other species. While it may ultimately be a good idea to extend moral relativism to other social mammals and cetaceans, moral naturalism aims at explaining morality as humans have come to practice it.

## 2. Human Morality

A rough definition of human morality would start from the way that morality is practiced. Morality is naturally embodied in the ways that human individuals voluntarily and habitually conduct themselves in accord with understood norms regulating social interactions and related deeds of social concern, by not only regulating their own behavior but also by participating in the needed enforcements of moral norms and by teaching these norms and the modes of enforcement to those who need moral education. Morality is primarily designed to regulate social relationships. Moral rules about what a person does in private have their ultimate basis in what society deems as unfit for relationships: disgusting, vulgar, disabling, sacrilegious, or dishonorable deeds that offend society and render a person unfit for some social relationship. Enforcement and education are essential to morality because morality is embodied in the voluntary habits of understood normative conduct. The noticeable way that people frequently avoid or violate norms of conduct reinforces this crucial point about morality: while morality must be to some degree habitual, it must also be voluntary, and hence violable and irregular. By "habitual" we do not mean instinctive, reflexive, or robotic – there is nothing necessary or fixed about learned human habits. Indeed, precisely because acquired habits inculcated by cultural training have only a modest way of guiding our conduct, so much enforcement and education is needed throughout life. On the other side, "habitual" should not be taken to always mean rule following – people can acquire habits by guided imitation and not memorization of express rules, and people usually practice habits without reflecting on any rules governing their habits. Some cultures may get around to expressing and teaching expected moral habits and social roles with explicit rules, and many need not. Self-conscious rule following is not essential to morality but only comprehension of what normally ought to be done in a particular situation.

A morality, like any normative practice, is largely internalized. When people are conducting themselves morally, they are following moral norms not because they feel a sudden urge to be kind, or they are forced or coerced to do so, or because they strategically regard obedience as simply a means to obtain what they really want, but rather because habitual respect for moral norms and other people are among their own important motivating values. Neither sympathy to needs, obedience to commands, nor compliance with expectations is sufficient to constitute morality (although those three factors can enhance moral conduct). A person is not being moral by feeling motivated to help because a sudden discomfort of sympathy or pity has been aroused. A person is not being moral simply by obeying a command because it is backed by threats of punishment that she wants to avoid. A person is not being moral by complying with a rule of conduct because compliance is the best way to get what he wants anyways. A person is behaving morally when they willingly conform to a moral norm because this person's respect for that norm is a sufficient and effective motivation to habitually want to conform.

Moralists frequently demand that genuine morality must spring from a purely altruistic desire to help another regardless of any estimation of duty. Perhaps the idea that morality should be like the characteristic altruism of close kinship has perpetuated this intense moralism. Finding so little angelic purity across humanity, disappointed moralists are heard to complain that people have little or no morality, but such cynicism arises from looking in the wrong place for morality. Philosophical ethicists frequently demand that genuine morality occurs when that person's respect for moral obligations provides an overriding and compelling reason for complying regardless of that person's emotions, desires, or values. But we are not undertaking philosophical ethics here, either. Moral naturalism need not postulate anything like a detached rationality capable of dictating conduct quite apart from emotions, desires, or values. This is fortunate, since there may be no such detached thing in human psychology (see, e.g., Gazzaniga, 2005; Greene, 2008). Nor is moral naturalism premised on moral realism or on any claims that truth or rightness attaches to the moral judgments people make. Moral naturalism is unaffected by the alleged prevalence of vast moral error (as claimed by many such as Joyce, 2001; Lillehammer, 2003), and morality has not been "debunked," so moral naturalism still has a subject matter. Whether morality is actually what people suppose it to be is a concern for philosophical ethics, not moral naturalism. Despite the fond dreams of some moralists or ethicists, neither pious altruism, pure reason, nor perfect judgment has been powering human morality, even if we may presently want to modify morality to become more altruistic or rational.

Moral conduct, when it occurs, is primarily motivated by a perceived duty. There may be other motivations to conform as well: nonconformity may bring unwanted punishment; conformity may be a means to get what one really wants; or conformity may assuage one's uncomfortable emotions. However, when a person sufficiently respects a norm, that person conforms even where nonconformity may bring no punishment or personal benefits, and even if no compassionate emotions are dominant. There are degrees of respect for moral norms, and enforcement and education are common means to increase respect. Enforcement and education rely on the deeper morality-building motivations of caring for others, avoiding harms from others, or getting benefits from others, but encultured morality results in motivating habits not reducible to any combination of these more basic and evolutionarily older motivators. Because human societies can promulgate a wide variety of moral habits, we may say that in a sense, morality is socially conventional, but only in one sense. While morality persists in human culture largely because humans do the training, that does not mean that humans must regard their moralities as conventional. Indeed, many societies teach that their own morality is the only morality, and some additionally teach that their morality is grounded on nonhuman matters like nature's ways or a god's wishes. A well-trained moral individual is not likely to regard moral duty as based merely on what society wants – the moral individual is more likely to regard what is morally right as enjoying a foundation independent from humanity. Similarly, although the practices of mathematics persist because human societies promulgate them, mathematics practitioners are unlikely to regard the truths of mathematics as dependent on what society happens to promulgate. Socially designed morality is functioning well for people when they do not regard it merely as locally and conventionally designed. We must not make too much of this looming paradox when we are pursuing moral naturalism. It is a peculiar problem for ethics, and not moral naturalism, to help reconcile the seeming independence of general moral duty with its actual dependence on local moral education.

Morality is designed to function somewhat differently from other socially normative practices. In human societies, morality can be distinguished from two similar social practices concerning relationships that extend beyond the range of the family: the norms of political laws on the one side and the norms of etiquette on the other. Political laws backed by government force can secure widespread and uniform obedience from the people, but entirely voluntary respect for those laws may be weak or far from universal. Laws backed by effective threats do their proper work of preventing harms and violence by appealing to an individual's basic desires to avoid public shame and harsh punishment. Civil etiquette is commonly quite voluntary, but it can vary so widely among individuals in the same society, and so irregularly enforced by sanctions, that specific norms accepted by all cannot be clearly identified. Nevertheless, norms of etiquette do their proper work of promoting aid and altruism by appealing to an individual's basic capacities for feeling sympathy and compassion toward others. Research on primates indicates that a protomoral sense of compassionate altruism and respectful fairness can occasionally be observed in their social behavior, approximating what is labeled here as "etiquette" (not in the sense of refined manners, of course, but just the simple gestures of nice and fair treatment).

Morality is in the middle ground between law and etiquette and overlaps them on each side – it concerns specifiable norms about social relationships and interactions for the entire society to willingly conform and mutually enforce. In every human society, such norms are evident and powerful, although their specific scope and content varies widely across cultures. A type of social interaction dictated by morality in one culture may be left up to etiquette in another; what is assigned to law to enforce in one culture may be left up to morality in another; and some societies may not regulate some kinds of conduct which other societies heavily regulate using morality and law. However, morality has a distinctive role in every society: it concerns those norms in a society where that society regards them as both universally applicable and universally worthy of sufficient respect. Society demonstrates its regard for morality by expecting voluntary conformity to its norms, expecting people to help enforce conformity where needed, and expecting people to help instruct the young to acquire moral norms. Where society encounters individuals unable or unwilling to conform morally, even if they conform obediently or self-servingly, that society expends efforts to reform that person's attitudes and habits, or failing in that effort, reclassifies them into some subnormal status (e.g., with unreformed criminals, the mentally ill, or the cognitively disabled).

Just as morality, while having universal applicability within a society, can vary in scope and content from society to society, morality can vary in effectiveness. If it were somehow impossible for morality to vary in its effective impact on the lives of society's members, they would not even think to try to modify it. Since morality obviously can and does have varying noticeable impacts on different individuals, so where there is sufficient intelligence, morality can therefore become an object of interest and an object of manipulation.

The opportunities for deliberate modification of morality are everywhere, since individuals can acquire some intelligent control over their conduct, even much of their habitual conduct, if they can consider their conduct as something controllable and modifiable over time. The story of the evolution of culture is essentially the story of the increased capacity for humans to regard some of their habitual conduct as modifiable with attention and practice and as teachable through instruction. The story of the evolution of morality, as a mode of enculturation, is essentially the story of the increased capacity for hominids to regard and enforce some social norms as worthy of everyone's willing conformity. As objects of intelligent attention in their own right, humans then gradually came to regard such moral norms as deliberately modifiable and proceeded to experimentally redesign the many moralities now embodied in diverse human cultures. By analogy, early hominids developed habitual tool use over two million years ago, but few modifications to choppers, flakes, and blades occurred until brain size had dramatically increased; the immense proliferation and complexity of tools associated with *Homo sapiens* indicate how hominids and humans gradually took deliberate control over experimental tool construction.

## 3. The Function of Morality

Humans would not experimentally redesign morality unless it came to be viewed as something not just modifiable but as modifiable for serving some end. An experimental modification to something, as opposed to an accidental, sporting, or aesthetic modification, treats it as a means for achieving envisioned consequences. What is it like to regard morality as a means functioning to serve ends? What would be the function of morality? We have located morality among the modes of human conduct, where individuals willingly regulate their social interactions out of respect for its norms and they expect everyone to do likewise. This descriptive view of morality omits its functionality: why would humans have morality? Couldn't human societies do well with just familial altruism and social etiquette, or some combination of familial love, etiquette, and law?

Morality supplies something that neither familial love, etiquette, nor law can provide. Morality permits standardized modes of interactions which each individual can reliably expect from all others under conditions when kinship is absent, etiquette is doubtful, and punishment is uncertain, unwise, or too costly. Etiquette is not standardized and not evenly enforced; indeed, norms of etiquette are precisely those optional norms which lack overriding respect and little punishment if any is attached to their enforcement. (That is why reciprocal altruism cannot be the essence of morality but only a display of optional etiquette – see Tullberg 2004 on differences between altruism and reciprocity.) The most important norms of etiquette overlap with the minor norms of morality, and in modern human societies that range of normative conduct makes up what we call civility. On the other side, where a society uses law, the most important codes of morality overlap with much of law, and that range of normative conduct presently makes up what can be called good citizenship. Law promises standardized modes of interactions and high probabilities of punishment, but enforcing law has many costs because it is very intrusive on individuals and requires large resources for adjudication and punishment; that is why societies which use laws are regulating only the most important kinds of social interactions. Morality serves to regulate conduct across a broad array of human interactions where norms must be both universally respected and efficiently enforced.

What sorts of social interactions would benefit from something like morality? The obvious kinds of interactions are cooperations. Moral norms, because they regulate everyone's conduct in an efficiently uniform manner, are highly useful for promoting cooperation among all members of society. Where the more basic components of morality are already in place, especially the norms of etiquette encouraging mutual assistance and fair treatment, stable patterns of mutually beneficial cooperation can emerge and grow. If individuals can be confident that mutual assistance will reliably yield sufficient benefits, without worry that unfair treatment might occur, they will naturally undertake cooperative projects with some frequency. In short, the original effects of occasional friendly etiquette can magnify into the repetitive trusting cooperation that can deliver even higher benefits for individuals in intensely social societies. Indeed, a highly social society is precisely that society in which both simple etiquette and complex cooperation are regularly occurring to the high benefit of all members across lifetimes and over generations.

The mutual helpfulness and fair cooperation permitted by basic etiquette can yet remain unstable and less frequent compared to other strategic modes of social interaction going on within a society. To become the dominant mode of social interaction, robust cooperation across societies requires more than just etiquette. The additional assistance comes from morality's universal and stricter obligations. The deliberate invention and design of law was a further extension of this same process in highly complex human societies, increasing the benefits of cooperative social environments by applying more costly regulation to the most important behaviors threatening the proper functioning of a civil society. The continuities between stages of moral development, proposed at the outset of our expectations for moral naturalism, can be observed in theory and fact. If etiquette had utility for small groups, morality would evolve that utility to larger groups, and law extends that normative development to fully complex societies, making higher civilization possible. A society concurrently utilizing all three modes of etiquette, morality, and law would then maximize efficient continuity: making everything a matter of law would be too costly, as would folding all of etiquette into morality. It may be theorized that an optimal society, therefore, would attempt to match its expenditures for normative implementation to the social significance of the behavior regulated. We do observe many modern human societies displaying such effort to efficiently utilize etiquette, morality, and law concurrently, although societies design their own distinctive modes of assigning expected conduct to each category.

## 4. Morality and Cooperation

Intuitively, cooperation and morality are a good functional match. However, we must not hastily assume that morality only exists where intense cooperation is ongoing, and we must not assume that cooperation requires morality. Species can evolve intense forms of social cooperation without any morality or even social intelligence (take ants for example) because such cooperation can be sustained by close kinship alone. For its part, morality could theoretically serve other functions besides cooperation. There are competitive "zero-sum" games of winners and losers, what can be called "win-lose" games, that can be better sustained if some moral norms are added to the rules of the game. However, the impressive value of morality is revealed when it is added to cooperative "win-win" or "non-zero-sum" games of mutual benefit. Indeed, it is hard to imagine how any sustained forms of intense cooperation across large societies would last without support from moral norms. All the same, the question stands: could non-zero-sum cooperation be worth it, relatively speaking? Numerous studies of forms of reciprocity generally suggest that this is the case (see, e.g., Trivers, 1971, 1985; Hirshleifer and Martinez Coll, 1988; Sober and Wilson, 1998; Henrich et al., 2001; Sachs et al., 2004; Taylor and Nowak, 2007).

It is widely agreed that, in theory, non-zero-sum cooperation tends to delivers greater overall benefits to most individuals over time in a complex society than any combination of competitive zero-sum games, provided that individuals have cognitive skills sufficient for conducting such social cooperation. A resulting overall advantage of cooperation over competition would practically explain why larger groups of increasingly intelligent hominids and humans evolved to have greater reliance on non-zero-sum cooperation than all other zero-sum interactions combined. Cooperation for common and mutually beneficial ends is a pervasive and important feature of any human society; indeed, across several hominid species, social cooperation largely determines the welfare of any of its members. For modern humans especially, avoiding social cooperation is the path to death; even a "self-sufficient" hermit or a combative aggressor was taught survival and fighting skills by others.

Where does the role of morality enter? The modest amount of social cooperation that gradually arose in early hominid species would have benefitted greatly from simple moral norms, over and above the contributions to cooperation made by the sentiments of sympathy, compassion, and altruism. Those crucial sentiments secure the bonds of commonality among closely related kin and a few caring friends, but they do not function well for impartial extension to everyone. The value of morality only increased as *Homo sapiens* gradually lived in larger tribal units and invented more complex forms of social cooperation occurring across the boundaries of close family and friends. Where the emotions guiding family commonality are absent, a different kind of cooperative relationship with acquaintances can develop instead, one based on reciprocity. Given the above sketch of what morality is and how it basically functions, we can understand why morality is well-suited to facilitating widespread cooperation for high mutual benefit. The universality and overriding respect for moral norms is a good functional match with the widespread and repetitive modes of cooperation going on within social groups. Reliance on etiquette does not vanish as reciprocal cooperation increases, but its unsteady and varying force would enjoy a dramatic supplementation with morality. In fact, etiquette and morality would reenforce each other among the most cooperative members of a society; that is why distinguishing merely compassionate acts from genuinely moral conduct is no simple matter. (Similarly, when modern humans invented political law, it hardly replaced etiquette and morality, but supplemented them in an integrated fashion, so that refraining from murder is simultaneously legal, moral, and nice.)

Where any two members of a group can both have some assurance that significant mutual benefit is possible and no unfair harm is forthcoming, they have a greater rational incentive to engage in reciprocity cooperation. Core moral norms helpful for such cooperation would naturally include prescriptions against coercion or harms by physical domination, deception, cheating, stealing, and unfair treatment. Respect for morality provides needed assurances for all parties, and the value of that assurance increases with the size of the social group. In very small groups where everyone is closely related and quite familiar to each other, instinctive emotions of sympathy and compassion could be strong enough to ensure care and cooperation, so familial love and kind etiquette is usually sufficiently and no morality is needed. But in larger groups, where individuals will encounter distant relations (or nonfamily as well), morality adds its distinctive service to increasing cooperation over and above the bonds of family and vagaries of etiquette. In such societies, where individuals could benefit from cooperation with others known primarily by reputation, moral norms increase the chances of successful cooperation. In effect, morality would be displayed in situations where two or more individuals know each other primarily by reputation, they have repeated opportunities to mutually benefit from cooperation, and they conform to moral norms about cooperating fairly and not harming each other in the process.

This view of morality's functioning presupposes that individuals have enough cognitive resources to absorb and understand prevailing moral norms in their society, to know how to strategically comply or ignore those moral norms, and to judge the other members' reputations for complying with those norms as well. There is no well-established theory about when early hominids developed all of these cognitive resources and began doing what we know as morality. Perhaps our primate cousins are capable of occasionally performing very simple versions of morality. But it may prove difficult to determine whether their conformity to norms is due to sympathetic feelings, strategic aims, or actual respect for the norms themselves (just as judging motives of fellow humans is not easy). In any case, as hominids gradually came to rely on social strategies demanding intense daily cooperation, it is reasonable to suppose that the basic primate toolkit for protomorality underwent development too. That development led to us: we can observe how the intelligence of *Homo sapiens* is highly developed for tracking the conduct and reputations of many individuals and for enforcing and teaching morality right along with the other aspects of complex culture.

When morality is supplemented into the manner in which individuals cooperate, this moral cooperation is dramatically enhanced in two ways: they will cooperate more frequently, and their cooperation will be much more efficient. Where cooperation is conducted morally, the participants will generally display a high level of cooperativeness with most if not all other members of the society. Specifically, each member will tend to be willing to cooperate when there is an opportunity, and each member will take an opportunity to cooperate with most or all other members of the society as situations warrant. In simplistic terms, where morality is robust, we would expect to observe lots of niceness and very little choosiness. On an emotional level, robust morality is experienced as trust: a felt confidence that reciprocity interactions with another will be reliably safe, beneficial, and fair.

We should not overrationalize the gradual emergence of a rational morality within social groups. It is unnecessary to depict hominids as cold calculators thoughtfully rationalizing cooperation. The cognitive capacities needed for morality's emergence would not need to be more sophisticated than the "fast and frugal heuristics" of severely bounded rationality (see Gigerenzer and Selten, 2001). Like so many other evolved features of hominid brains, the evolving emotions do most of the work of social intelligence anyways, and humans have inherited and use them (see Haidt, 2003; Nichols, 2004). Individuals growing up in a relatively cooperative society will be guided by the feelings of enjoying mutual trust. Nor is necessary to depict early hominids or *Homo sapiens* as utilitarians who regard morality as a means to enhancing social welfare. Actually, individuals committed to morality will instead generally regard morality as binding regardless of calculations of social welfare. On a personal level, a moral person will try to be virtuous on a daily basis, and a group of moral people will regard each other as dutiful agents. Perhaps only when a society's morality is under widespread dispute or under discussion as a problem in itself would people think to inspect morality in regard to its service to society. Whether virtue theory, deontology, or utilitarianism has greater merits is an issue for philosophical ethics, not moral naturalism. For its part, moral naturalism can at least account for the distinctive ways that morally trained people would regard how morality works. Moral psychology has the unenviable task of sorting out the actual motivators for moral judgment from the stated justifications that people will supply when asked (see, e.g., Doris et al., 2010; Brinkmann, 2011).

So far, a naturalistic explanation involving both natural and cultural evolution for morality's enhancement to routine and widespread cooperation seems possible.

However, as already noted, there are many other strategies for conducting social interactions besides morality. Even if we might see how morality can enhance cooperation, individuals can still benefit from competitive, neglectful, unfair, or harmful conduct toward others too. Why would morality come to have any large role to play in hominid societies? Perhaps morality has long been just one optional mode of social conduct among many others, and individuals could vary widely in the extent to which they rely on morality over other strategies. Perhaps a society that does use much morality could be successfully "infiltrated" by individuals using more selfish strategies. Is there good reason to conclude that individuals in societies using lots of moral cooperation enjoy enough benefits to survive or to conclude that societies using moral cooperation might just as well drift away from morality as time goes by?

There is no point to accounting for the widespread reliance on morality among contemporary humans with an evolutionary story of hominid development unless moral cooperation can work well, at least better than zero-sum interactions. It is unnecessary to think that the proliferation and supremacy of nonzero cooperation was in some sense evolutionarily inevitable (as suggested in Wright, 2000), but there are good reasons to think that plenty of non-zero-sum cooperations would be stumbled upon and repeated by sufficiently intelligent species, such as our primate and hominid ancestors, giving rise to culture (a survey of reasons is given by Boyd and Richerson, 2005; Nowak, 2011). Are there good reasons to think that moral cooperation delivers generally high benefits to the members of a society and delivers results more beneficial to all individuals within that society than any other strategy? Further study is needed to analyze the benefits of moral cooperation in a society.

A commonly used tool for analyzing the supposed benefits of reciprocity cooperation is the prisoner's dilemma game. Computer modeling of groups utilizing various strategies shows that a small number of simple strategies, such as "Tit For Tat," tend to garner the most benefits (though there is no provably optimal strategy for indefinitely extended iterations). However, the prisoner's dilemma game models a very specific kind of basic social interaction, which is too simplistic to bring morality into full view. What is needed is a revised type of prisoner's dilemma game that models the more complex kind of social interaction where emerging morality would be occurring.

## 5. The "Indirect Reciprocity" Prisoner's Dilemma Game

The prisoner's dilemma is a way to model simple interactions between individual agents where there is the possibility of reciprocity, cooperation, and betrayal. This section describes a computer program which models a tournament of players taking part in what I have termed the "indirect reciprocity" version of the prisoner's dilemma game, or the IRPD game. I first presented the IRPD game at the Seventh Annual Conference on Computers and Philosophy at the University of Central

Florida in August 1992, and a more sophisticated version was presented at Oklahoma State University in 2003. The basic inspiration for this project comes from Robert Axelrod's (1984) ground-breaking exploration of the prisoner's dilemma. The study of the prisoner's dilemma has been widely perceived as an opportunity to gain insights into the nature and origins of morality. A full explanation of the prisoner's dilemma and its importance is found in Axelrod's book and subsequent books on its analysis (see, e.g., Colman, 1995; Barash, 2003).

The essential point is that while the prisoner's dilemma (PD) is a single interaction, the prisoner's dilemma game is a long series of such dilemma interactions, where neither player knows when the series will end. A strategy is a method of playing this PD game. The PD by itself has one optimal strategy regardless of the opponent's strategy: defect. The PD game by contrast need not have one optimal strategy, for reasons involving the uncertainty regarding when the last interaction will occur and, if groups of players are interacting, the variability of the strategies involved. The study of the PD game primarily involves the examination of the performance of the possible strategies available to the players, relative to the size and characteristics of the rest of the group.

Axelrod studied how various strategies, embodied in computer programs, performed as they competed in round-robin tournaments. His use of the PD game involves players in a round-robin tournament who use strategies to try to obtain the most points from PD games with the other players. The crucial aspect to Axelrod's methodology is that the strategies permitted by Axelrod can only exhibit direct reciprocity. This direct reciprocity is characterized by the information upon which a player has to base the decision whether to cooperate or defect in a dilemma: the only information available to a player is the history of interactions he has had with the other player. This explains the results of Axelrod's tournament; the winning player's strategy, Tit For Tat, is not nearly as sophisticated as most of the forms which moral behavior can take. Is it possible that Tit For Tat is a morality? As far as familiar codes of morality go, it does resemble the ancient "eye for an eye" rule of retribution: what you have done to me, I will do to you. The important question is whether the methodology of using the PD game can be altered so as to permit more complicated forms of behavior. The answer lies in understanding reciprocity.

There are two kinds of reciprocity: direct and indirect. Direct reciprocity is of the form: A helps B, B helps A. Indirect reciprocity is of the form: A helps B, B helps C, C helps A; or A helps B, C who is observing, later helps A, A helps C. Alexander (1987) and Boyd and Richerson (1989) have emphasized how the more complex behaviors associated with morality are mostly dependent upon the ability to use strategies that exhibit indirect reciprocity instead. Indirect reciprocity requires an additional piece of information: the history of the opponent's interactions with the rest of the players in the tournament. After a discussion of direct and indirect reciprocity, the basic scheme of the "indirect reciprocity" prisoner's dilemma game computer program is laid out, and preliminary results from this program are described. The IRPD game shows how genuine moral cooperation can be highly beneficial and evolutionarily stable. The following brief account of the IRPD computer program describes its capacity to formulate strategies, group various strategies together, and have them interact in tournaments in a way similar to Axelrod's. The key departure from Axelrod's work lies in the difference between direct and indirect reciprocity.

In the PD game, help comes in the form of cooperation. Direct reciprocity only requires a player to have access to information on an individual level: a record of how the other player has treated one in past dilemmas. The modeling of indirect reciprocity requires additional information: knowledge of the other player's interactions with the rest of the group. Additionally, the modeling must permit a player to make a choice as to whether she will engage another player in a prisoner's dilemma interaction. No such choice is allowed in the direct reciprocity model.

For our purposes designing a basic IRPD game, we shall assume that every player has complete and reliable information; other models of the IRPD game need not do so. We shall also assume that no player will err in making decisions based upon the information; other models may include the possibility of judgment error. On this foundation, we can proceed to construct a prisoner's dilemma model of indirect reciprocity. What follows is but one way to model indirect reciprocity, using discrete, agent-based modeling that tracks the performance of identifiable agents as they interact or avoid each other over time. Aggregative modeling of populations undergoing interactions involving indirect reciprocity has already been attempted (see, e.g., Nowak and Sigmund, 1998; Panchanathan and Boyd, 2004). However, aggregative population dynamics assumes that every individual has an equally likely chance of interacting with every other individual. Because indirect reciprocity permits an individual to abstain from an interaction, as well as to engage in an interaction, full indirect reciprocity is imperfectly modeled by aggregative modeling (see Hauert et al., 2008 for discussion of this point). Indirect reciprocity also works best for finite populations in which members possess some information about everyone's reputation for cooperating or not. Without an estimate of reputation, indirect reciprocity gains little for cooperators, while much knowledge of reputations can produce stable cooperative societies (Milinski et al., 2002; Nowak and Sigmund, 2005).

The IRPD game described here is probably one of the simplest models for agent-based modeling of strategies for undertaking indirect reciprocity with all other social members in a finite population that include the basic features of reputation, avoidance, cooperativeness, niceness, and choosiness. We shall first look at the structure of a strategy which can enable a player to engage in indirect reciprocity. A look at the structure of the round-robin tournament follows.

As we know, indirect reciprocity requires that each player should have the option of whether to have a PD interaction with another player. The judgment that entering into a dilemma with a particular opponent is not in a player's best interests will result in a "shun"; the player will opt out of a PD interaction with the other. (In the basic kind of IRPD game described here, a "shun" is the only mode of "punishment" exacted by a strategy.) In the IRPD game, this judgment will be made upon the information of how often the other player cooperates in all the games he has played. When a player has decided to enter into a PD interaction, the strategy must direct the move to be made. Accordingly, a strategy will require access to three kinds of information: (a) how often the player should cooperate, (b) how often the opponent has cooperated in all of its interactions with all other players in the past, and (c) what standard the player should use to evaluate other strategies.

The first kind of information is placed in the form of a number ranging from 0 to 1, representing what the frequency of the player's choice to cooperate in an interaction will be. 1 = always cooperates, 0 = always defects, .5 = there is a 50% chance of cooperation, etc. The name for this number is niceness. For the purpose of modeling agents with limited cognitive and deliberative resources, we may regard a player's niceness more as a habit rather than a thoughtful choice upon each interaction.

The second kind of information shall be just the opponent's niceness. This represents each tournament as taking place in the course of the life of a society, after each player has established a reputation among the group. Again, for the purpose of modeling agents with limited cognitive and deliberative resources, we may regard a player's understanding of an opponent's niceness not as the recollection of all the outcomes of the opponent's past interactions, or the recollection of what others have gossiped (no presumption of advanced language use is made here), but rather just as an understanding of the opponent's reputation as far as a player can tell from some observation.

The third kind of information shall again be placed in the form of a number ranging from 0 to 1, representing the standard used to evaluate the other player's niceness in order to make the decision upon whether to interact in a dilemma with the other player (1 = will only choose to play will those having niceness of 1, 0 = will play with anybody, .5 = will play with only those having a niceness of .5 or higher, etc.). The name for this number is choosiness, and again this represents only a habitual inclination of the player and not a series of reflective deliberations.

Since a player's niceness and the choosiness do not change for a strategy during a tournament, we can simply refer to these two qualities as a strategy. In this way, we can say that the entire possible range of strategies can be represented by the points on a one unit by one unit graph.

To get an IRPD tournament started, the decision as to which strategies shall play in a tournament must first be made. The program I wrote permitted the user to form the group either by setting each strategy's niceness and choosiness, or to choose a preset group by selecting a size equal to a perfect square (4, 9, 16, 25, etc.) The preset groups have an even distribution of qualities: with four members, the strategies are 1,1 1,0 0,1 0,0. With nine members, the preset group looks like: 1,1 1,.5 1,0 .5,1 .5,.5 .5,0 0,1 0,.5, 0,0. With groups of 400 and more, the tournament can be very inclusive. Each of the preset groups will have an average niceness and choosiness of .500. Other kinds of preset groups are possible as well, with differing distributions, but await a future version of my program.

A round-robin tournament for the group is scheduled as follows. In one "round," a designated strategy will meet (have the opportunity to interact) each of the other strategies consecutively. In the span of one "season," a number of rounds take place, equal to the number of the strategies in the group, so that each of the strategies will take the role of the designated strategy in one season. Each strategy will thus meet every other strategy twice in one season. As the computer program proceeds through the schedule, for each scheduled meeting allows the two strategies to first decide if the PD interaction should take place. If either player declines because the opponent's niceness is not great enough (does not equal or exceed the player's choosiness), no PD interaction takes place and the programs proceed to the next scheduled meeting. If both do choose to interact, then each strategy decides whether to cooperate or defect in the PD interaction. This decision will be based on the strategy's niceness, by finding whether a cooperation would bring its overall record (ratio of cooperations to total games played) closer to its niceness or not. After each has chosen, the program determines the outcome of the game by assigning points accordingly (e.g., in the standard assignment, 3 points go to each if they both cooperated, 1 point goes to each if they both defected, or 5 points goes to the defector and none to the cooperator; the points awarded can be preset by the user). The computer program saves a database of each player's cumulative points, for reporting at any selected stage of a tournament.

To summarize the program:

1. The number of players and their assigned strategies are chosen by the user.
2. The tournament length (the number of seasons to play) is chosen by the user.
3. The ordering of the group is scrambled.
4. In each season, the necessary number of rounds occurs.
    A. Inw each round, the meetings are assigned.
    B. For each scheduled meeting:
        a. The program determines if the two decide to interact.
        b. If they will interact, it finds each strategy's chosen move.
        c. The outcome of the game is found and points are awarded.
    C. At the end of the season, the ordering of the group is rescrambled.
5. Each strategy's cumulative points are recorded for later reporting.

There are some ways to complicate the IRPD game so that the player's environment and playing conditions more closely approximate the "real world." In the real world, organisms have to "pay" the costs of living from day to day, they will someday die from natural causes, they must reproduce to continue their genetic line, their offspring can have mutated genetic codes, and so forth. In the game, a preset amount of points can be subtracted from the player's total at each scheduled meeting (this is called the "meeting cost"), so that death could occur (total points dropping to zero or below). When a meeting cost is exacted, all strategies begin with an allowance of points equal to 50 times the meeting cost. This amount is not figured into the final results and succeeds in preventing a strategy's chance bad luck in meeting assignments in the early stages from prematurely killing it. In effect, this tries to compensate for the mere pseudorandomness of the computer and simulates the natural fact that typically organisms are not born (nor enter adulthood) on the very edge of death; they have some (however small) stored resources.

The players who are able to accumulate points at a faster rate will tend to survive, and then the effects on a player of competing in an evolving group can be studied. The players can be given a preset lifespan, in terms of a maximum number of scheduled meetings, after which “death” occurs. In the program, the timing of death is not the same for all: the probability of death for a strategy begins some meetings before the preset lifespan and steadily increases each meeting afterward, so that the actual death can occur in a range around the lifespan.

In more sophisticated versions of the computer program, players can use points to have offspring and use up points just to keep living. To “give birth,” a player can be permitted to create a clone of itself after it has accumulated a preset amount of points. The new player has the identical strategy as its “parent” and is entered into the tournament, and some amount of points are subtracted from the parent’s total. However, giving birth will not unduly harm a strategy. It is only set back to its original amount of points and keeps its margin of safety from lack of randomness if there is a meeting cost in a tournament. The result is that a more successful player will have a higher birthrate. Also, at the cloning, a mutation can be permitted, to change a new player’s strategy so that it differs from the parent’s. In addition, the meeting cost can be variabilized according to a change in the size of the group, so that meeting cost rises proportionately to the group size if the group size should rise through births. This models a realistic aspect of a group living in an environment with limited resources, where a rise in population makes it harder for all to survive.

When these complications are put together, natural evolution is modeled. The first generation of strategies can compete, give “birth,” and die, giving rise to the second generation, which in turn repeats the cycle. In this way, the evolutionary success of a strategy can be measured. Also, the composition of a group of strategies can be evaluated over many generations for survival (does the group grow, or does it die off) and for total overall success (the cumulative amounts of points of all living strategies).

## 6. The IRPD Game Results

Some basic results have been confirmed through many hundreds of tournament experiments, and they are consistent and very striking. When there is no meeting cost exacted, the winner always has a very high niceness and a very low choosiness. In fact, the ranking of the strategies by points earned consistently follows the degree to which a strategy’s niceness approaches 1 and choosiness approaches 0. The worst finishers are quite nasty and very choosy. For example, the strategy (1, 0)

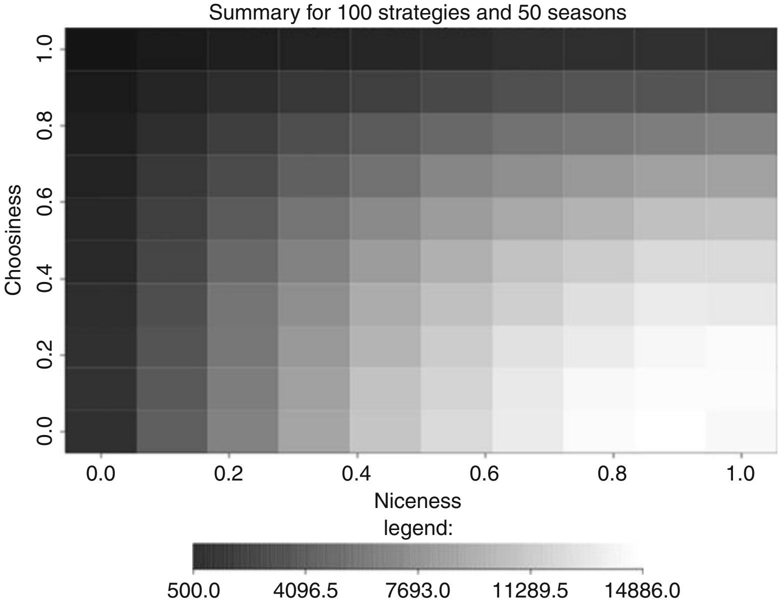

**Figure 1.** One hundred strategies after 50 seasons. The worst strategies accumulate less than 4,000 points.

nearly always finishes in the top 5%, regardless of the size of the preset group, and the strategy (0, 1) finishes in the bottom 5%. I have been able to confirm this for groups containing up to several thousand strategies. Figures 1 and 2 show arrays of the points accumulated by strategies in groups of 100 and 224 who have played typical tournaments lasting 50 seasons.

If there is a meeting cost exacted from all strategies, four major phenomena occur. First, some strategies will die at some point in the tournament because they fail to accumulate points fast enough to cover the subtracted meeting costs. Without exception, the nastier and choosier strategies die first, so the meeting cost results in a gradual rise in the average Niceness and a drop in the average choosiness until no more strategies die. This should be expected, given knowledge of the results of tournaments lacking a meeting cost in which the nastier and choosier strategies garnered fewer points (gained points at a slower rate) than the rest. In tournaments with a meeting cost, these strategies' points would drop closer to zero, and those whose rate of points per meeting remained less that the meeting cost rate eventually die. The second phenomenon is observed when the meeting cost is varied. There is a direct relationship between the size of the meeting cost and the group's average niceness; an inverse relationship holds between the size of the meeting cost and the group's average choosiness. For example, in a tournament in which the meeting cost is set at .5 point per meeting, the average niceness increases to around .60 and the average choosiness drops to

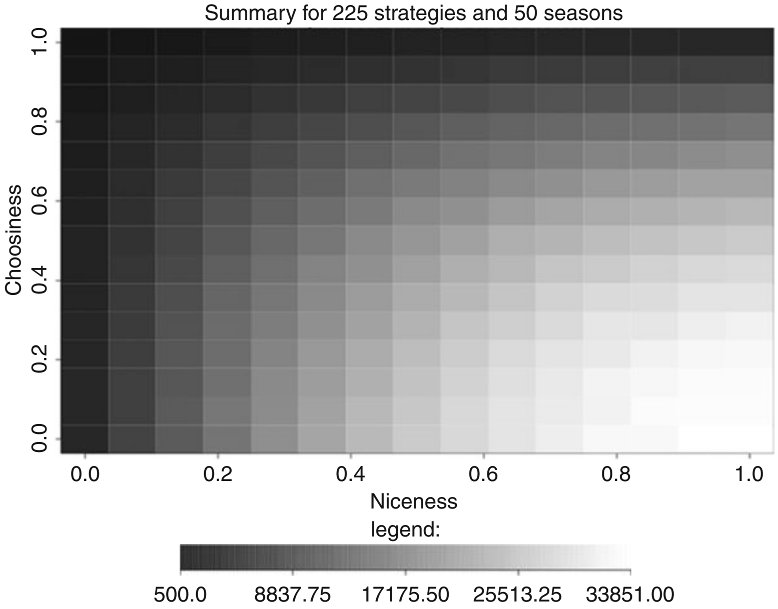

**Figure 2.** Two hundred and twenty-five players and 50 seasons. No matter the number of strategies, the same strategies perform the worst.

around .40. If the meeting cost is 1.0 point per meeting, the average niceness is around .66 and the average choosiness is around .34. Figures 3 and 4 show an array of 100 strategies playing tournaments of 500 and 1,000 seasons with a meeting cost of .5 point.

If the meeting cost is 1.0 point per meeting, the average niceness rises to around .66 and the average choosiness drops further to around .34. Figures 5 and 6 show an array of 100 strategies playing tournaments of 500 and 1,000 seasons with a meeting cost of 1.0 point. Keep in mind that these are summaries of many independent runs of tournaments so they will display inconsistencies among them. For example, Fig. 5 shows how the strategy (.5, .1) had died in its tournament of 500 seasons, while Fig. 6 shows how the same strategy managed to survive to the 1,000 season mark in another tournament.

This variable meeting cost trend toward higher niceness and lower choosiness does not seem to persist indefinitely, however, as very high meeting costs stabilize the niceness and choosiness of the few surviving strategies in the vicinity of .50 and .40. This experimental model result conveniently corresponds to the familiar resurgence of uncooperative selfishness among primates and humans under very stressful conditions.

The third phenomenon is also seen when the meeting cost is varied: the leaders in these tournaments are not as nice nor as indifferent as those from tournaments lacking a meeting cost. As the meeting cost rises and the group becomes

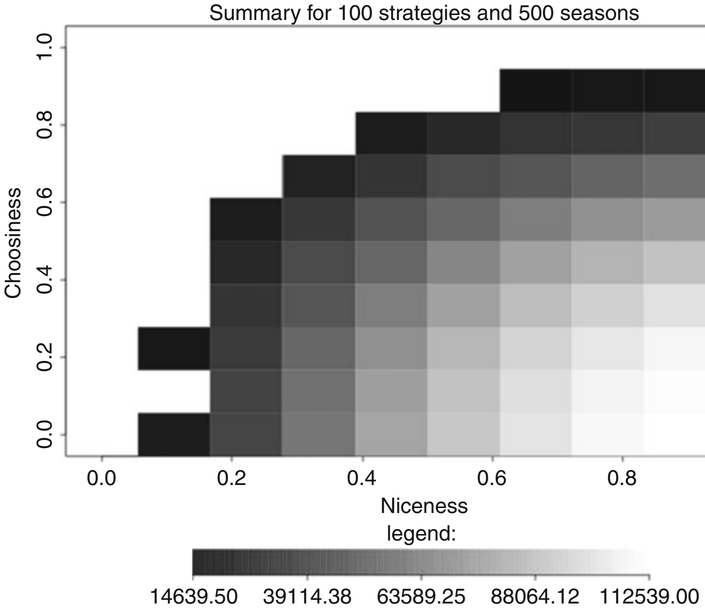

**Figure 3.** One hundred strategies after 500 seasons and .5 meeting cost. The *white spaces* indicate the dead strategies.

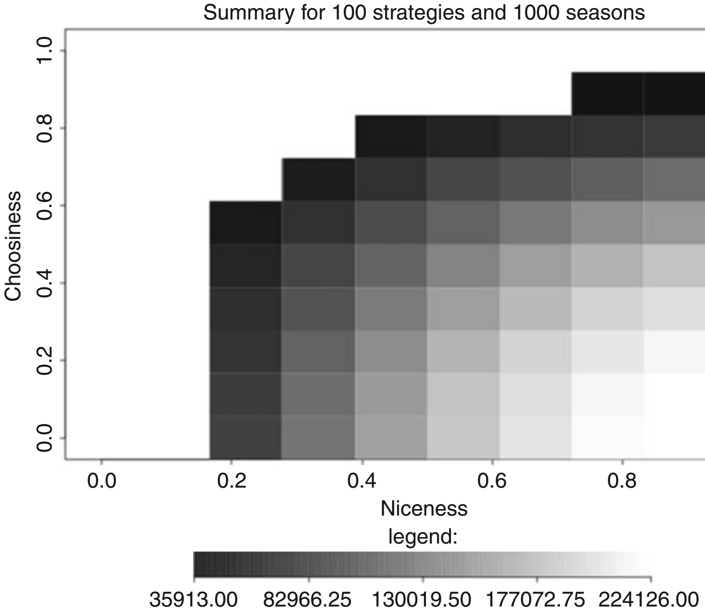

**Figure 4.** One hundred strategies after 1,000 seasons and .5 meeting cost. The nicest strategies continue to perform well.

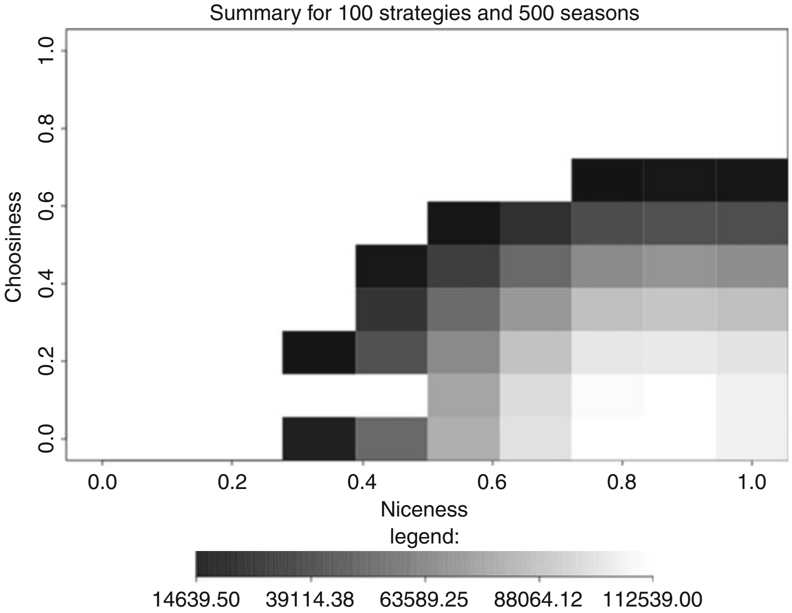

**Figure 5.** One hundred strategies after 500 seasons and 1.0 meeting cost. The nicest strategies are not doing quite as well.

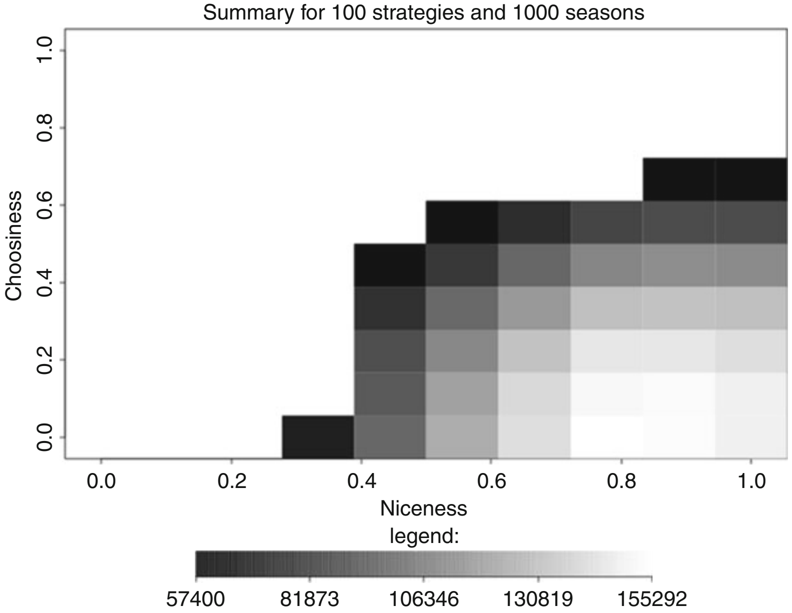

**Figure 6.** One hundred strategies after 1,000 seasons and 1.0 meeting cost. The surviving strategies have stabilized to compose a group that is fairly nice and not choosy.

nicer and more indifferent, the leaders become further removed from the (1, 0) standard. This is evidence for thinking that the nicest and least choosy strategies do very well (relative to the group) only when there are plenty of quite nasty and choosy strategies in the group. Another way of stating this phenomena is to note that as the meeting cost rises, the average niceness and the leaders' niceness both move toward convergence, while the average choosiness and the leaders' choosiness similarly converges. Under conditions of significant environing strain, very high niceness is not rewarded as much. Again, this result seems to also correspond to the way that cooperativeness diminishes somewhat when life is very hard.

The fourth phenomenon is observed in tournaments with both modest meeting costs and permitted births (available space regrettably forbids more graphs). The group gradually evolves toward an overall average higher niceness and an average lower choosiness. The most striking long-term stable trait of the group is how most of the strategies cluster to converge around a fairly high niceness and a fairly low choosiness.

The IRPG game exemplifies one way to show how the members of group who can monitor reputations and engage in voluntary cooperations will display, all other things being equal, an evolutionary convergence upon a relatively high niceness and a relatively low choosiness. This convergence on reciprocal cooperativeness remains quite robust even under conditions of moderate strain, and extreme strain only diminishes cooperativeness to a degree without disappearing. These features are the marks of a society well on its way to conducting itself morally as we have defined morality in previous sections, since moral conduct (more so than just etiquette) expects a habitually high degree of cooperativeness and a habitually high willingness to cooperate with most if not all other members of the group.

These remarkable traits by themselves are not sufficient for judging that these strategies are fully moral in the sense specified in earlier sections. Some features of moral practices are not modeled in this version of the IRPD game, such as imitative and instructive education and more exacting punishments than just shunning. However, these limitations are consistent with the way that this IRPD game can attempt to model hominid conduct. Furthermore, adding education and punishment to the IRPD game should produce similar overall results displaying the advantages of nice reciprocal cooperation, since imitating better strategies and supplementing punishment tend to enhance widespread cooperation (see Boyd and Richerson, 1992; Henrich and Boyd, 2001; Fehr and Fischbacher, 2004; Alexander, 2007; Marlowe, 2009). The role of punishment, from simple shunning and shaming to direct infliction of physical harm, is as crucial to indirect reciprocity as it is to morality and law, as would be evolutionarily expected. Sripada (2005) claims that only punishments and not reciprocity's benefits are behind morality, but this cannot be right, since agents would not long suffer the costs of enforcing something that itself offers few benefits.

Third-party punishment is probably deeply connected to the emergence of in-group morality. Third-party punishment would be a conspicuous display of fidelity to the group's welfare, but it would presumably require group sanction (include group pity for the victim but not the transgressor) to produce net benefits to punishers (Okimoto and Wenzel, 2011). Furthermore, precisely because the retaliation by the punished back against punishers can diminish punishment's effectiveness (and hence effective reduce the situation to a zero-sum game of whom can dominate the other – see Janssen and Bushman, 2008), genuine morality would depend on a high degree of internalization so that just punishment is usually passively accepted. This dependency on internalization may account for the intuitive moral rightness of retribution. In small societies, the desire to avoid shaming and suffering from group sanction would have to powerfully instilled and maintained. In large societies, the development of law to reinforce important moral norms is commensurate with the emergence of police to wield sufficient force to forestall retaliation by those unrestrained by internalized morals.

## 7. Natural Morality

Early in hominid evolution, shunning and shaming would have been the primary means of punishing enforcement, along with intermittent physical violence. Our preliminary analysis of a basic IRPD game indicates that shunning would be very effective by itself, and other indirect reciprocity studies show that physical punishment with group sanction would only heighten enforcement and obedience. It is therefore reasonable to find both protomorality and the emergence of universal moral habits in those groups able to engage in non-zero-sum patterns of cooperation and to track each others' performance with just a small amount of information about reputation. The IRPD game successfully models something of what early hominid groups were likely capable of doing. The dominance and stability of such habitual social niceness does make a good practical fit with the sort of forms of intense and widespread cooperation our hominid ancestors were developing.

Despite intriguing modeling of the development of moral cooperation, we cannot forget how these capacities for reciprocal cooperation and protomorality would still be "in-group" features emerging among members of a social group. Even as cruelty or betrayal are subsiding within hominid tribes over hundreds of thousands of years as social intelligence increases to decrease reputation errors, those nasty deeds can robustly survive between tribes. Familiarity and closeness remain essential to our evolved sense of morality, as they have remained essential to charity. Efforts to expand the range of morality would hence require further reductions to errors of social judgment, expansions of who shall count as part of the "in-group," and enhancements of the sense of closeness to others through such things as new technologies of communication. And the field of ethics has indeed typically focused of these factors; cognitive psychology has also recommended increasing the availability of reliable information about other people, their reputations, and their social interactions (Pollock and Dugatkin, 1992; Paolucci and Conte, 2009).

Furthermore, once humans were able to cognitively appreciate how the norms of moral cooperation were modifiable, they could take some control over their habits and try to deliberate enhance morality's effectiveness at making cooperation even more reliably beneficial for all. Such experimental efforts must have been halting and unsteady, yet not without practical value, since humans did not abandon the effort and social morality eventually came to dominate human life. Without having to suddenly invent compassion, niceness, fairness, cooperativeness, civility, and trust, humans did intensify efforts to deliberately instill strong respect for morality's norms through operant conditionings and educational training, so that everyone would be more likely to habitually and voluntarily comply in all situations even if motivational feelings, strategic benefits, or punishments are not there.

Moral cooperation appears to be so consistently of higher benefit to all members of a social group in the long run that no one would be smarter for reverting to nothing but ruthless zero-sum games or outright harmful treachery. Of course, morality is hardly the only kind of practice that would enjoy long-term survival; we are just the sort of species in which multiple "strategies" would be distributed across a population. The habits of morality, installed by instinct and instilled by instruction, will always be statistically distributed: people will occasionally be mean, short-sighted, and selfish. Morality is designed to prevent, so far as possible, lapses by individuals into hurtful conduct and unintelligent noncooperation and to foster firm reforms of nonconforming members. In any society, of course, actual conduct will only approximately track that society's moral expectations, but those noticeable deviances are the exceptions that prove the normative rule.

Morality appears to be just the kind of low-information and largely habitual practice that could stably emerge among agents capable of recognizing many individuals, observing others' interactions, and tracking their reputations. Social intelligence leads to moral intelligence, and in return, morality improves society. In essence, during moral cooperation's long unconscious evolution in social groups, it represented long-term wisdom for most members even if individuals could not yet cognitively appreciate that fact. Furthermore, if indirect reciprocity morality can be propelled by group selection over long stretches of time (as suggested by Boyd and Richerson, 1990; Soltis et al., 1995; Nowak, 2011), in-group moral cooperation can also serve as a smart survival strategy for competing groups of hominids. The fact that no human society in recorded history has entirely abandoned morality of its own accord further indicates morality's durable value. Morality among hominids displayed a functional design by natural evolution, and our human moralities now display the imprint of our own redesigns as well.

Moral naturalism appears to have the resources needed to account for the origin and gradual development of the human practice of morality, so that no great leaps in emotional, cognitive, or spiritual abilities need to be postulated. Moral naturalism also appears to be able to account for why humans living in large societies put so much deliberative effort in ethical redesigns of moralities and their enforcement with law. During the past 10,000 years, dramatically larger societies have been suffering from the inherited limitations of morality and getting obsessed with ethics and law, precisely because morality is naturally so emotional, limited to familiar in-groups, controlled by perceived reputation, and yet so essential to the needed expansion of nonviolent encounters and reciprocal cooperations among strangers.

## 8. Acknowledgments

Jeffrey Miecznikowski's helpful expertise in biostatistics at the Roswell Park Cancer Institute is responsible for the current coding for implementing the IRPD game and the graphs displaying its results. This chapter is also deeply indebted to Richard Carrier for his insightful criticisms and suggestions which resulted in many improvements and to Liz Stillwaggon Swan who patiently encouraged every stage of this chapter's progress from mere notion to fulfillment.

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# PART III:
# THEOLOGICAL ASPECTS OF DESIGN

**Rozenson**
**Glicksberg**
**Berger**
**Klostermaier**
**Rees-Dessauer**
**Rošker**
**Schroeder**

The portrait of Odin – the chief divinity of the Norse pantheon – god of war, death, poetry and wisdom in Norse mythology. Stained red by Natalie Gordon.

Biodata of **Yisrael Rozenson**, author of "***The Best Mislaid Plans: A Religious Approach to the Question of the Planning of Reality***."

**Professor Yisrael Rozenson** is the President of the Efrata Teachers College in Jerusalem. He received his Ph.D. from the Hebrew University of Jerusalem (Department of Geology) in 1981. For the past 27 years, he has been involved in teaching education and has researched the Bible and its relationship to relevant fields of inquiry, which include geography, ecology, history, and literature. He has published articles on various topics including Midrash and Biblical criticism.

E-mail: **efrata@macam.ac.il**

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# THE BEST MISLAID PLANS: A RELIGIOUS APPROACH TO THE QUESTION OF THE PLANNING OF REALITY

**YISRAEL ROZENSON**
*Efrata College, 17 Ben Yefunae St., Jerusalem 93710, Israel*

## 1. Introduction

In this essay, we shall propose an outlook that we believe is reflected in Jewish sources, enfolded within its texts and emerging from within its exegeses, regarding the level of planning that is part of an individual's experience and which he/she decides to examine. This approach clarifies issues related to planning in the philosophical sense, issues dealt with by people who examine and analyze their place and position relative to their world. It is needless to point out the extent to which the possible "existence" of preordination in reality influences philosophy, thought, and human morality, and yet notwithstanding the basic philosophical aspect of the matter, it may also influence indirectly the manner in which a person directs his/her investigations into the natural sciences as well.

No matter how, and in accordance with whatever creed or belief, one may define Creation, we will claim, as background to our argument, that approaches whose sources are in ancient philosophy consider Creation a transformation from an unordered state into an ordered state. Thus, for example, does Plato present it in his famous dialogue, Timaeus, which touches upon the question of "Creation": "…God desired that all things should be good and nothing bad, so far as this was attainable. Wherefore also finding the whole visible sphere not at rest, but moving in an irregular and chaotic fashion, out of chaos he brought order, considering that this was in every way better than the other" (Jowett, 78); "As I said at first, when all things were in chaos, God created in each thing in relation to itself, and in all things in relation to each other, all the measures and harmonies which they could possibly receive" (Jowett, 106). This should not be the place to discuss the basis for this approach, but it seems that the love of mathematics that determines the rule of logic, and the evaluation of its philosophical importance, interrelate here with a deep understanding that a correct form of life entails order and organization. Below we shall demonstrate that the Biblical world, even when addressing similar thoughts, perhaps uses an entirely different language, and its concern with the concept of planning entails the use of more obscure visual concepts, such as *formlessness and void* (the King James edition Bible translation for what we would refer to as *chaos*) that, even when their perception is as a known and tangible entity – water and desert, for example – they too leave in their wake an inherent dimension of vagueness in their relation to the topic of planning.

After all, how can you speak of planning in a world that is based in chaos? One aspect of this that the writer of these lines believes to be inherent to the Jewish conception will be discussed below.

## 2. Two Methodological Comments

The fundamental question of design discussed here requires a methodological explanation, whose very brevity is dictated by the general framework of discussion. We will establish ourselves in two comments. The first posits that a monotheistic approach is related in one way or another to planning; allegedly, the essential unity inherent in divinity enables a single master plan; thus, a single authority "manufactures" a single intent and intuitively connects with a planning potential. That is not to say that this single authority may not reveal capriciousness nor ostensibly act arbitrarily! Genesis offers quite a few chapters, as does the Book of Job and others, in which a heroic attempt is made to deal in a moral manner with this aspect of God's actions, but compared to the pagan world that presupposes the mutual and simultaneous existence of several authorities whose hierarchical relationships and divisions of territory are never clear and are subject to incessant struggle, the monotheistic world could function otherwise. The pagan approach sees the world at any given moment as a product of struggles that are fuelled by multiple desires and interest not by preplanning that is the fruit of a single desire stamped upon the world. Briefly, one may state that we intuitively associate uniformity of experience, in one sense or another, with a certain sense of planning.

The second comment is related to the manners of expression related to planning or nonplanning. A term such as *planning* is determined upon a certain ratio of *planning*:*nonplanning*, insofar as planning is in essence an expressible term or one that may be measured and not merely the representation of a certain intent. Here, too, we will return to use intuition, which can perceive a system's alteration from *condition a* to *condition b*, the latter being more orderly, a result of planning, whereas the reverse alteration to the lesser ordered condition is considered disintegration. Such planning, although seen through human eyes, may be expressed mathematically and statistically. The quantification of the term *chaos* and its affinity to the chemical-physical property, *entropy*, requires a statistical underpinning. Plato, who understood so well the power of geometry and drew from it his inspiration for formulating many philosophical insights regarding order and perfection, could not precisely relate to the concept of chaos because he lacked the necessary statistical tools. The Bible is even more problematic! Even if in everyday biblical life, biblical Man (we refer here throughout – of course – to humans of both genders) could relate to some form of mathematical knowledge, he could not attain the level of abstraction required in order to speak of "order." That is to say, not only does the Bible lack statistics but also geometry, and if in the Timaeus, Plato can describe an ordered universe using complex geometrical (multifaceted) forms, the Bible needs to address all this in an entirely different fashion.

Clearly, it is more likely that a scientific investigation of *order*:*chaos* evolves from the Platonic approach – needless to reiterate his influence on western thought in general – rather than from the visual form in which the Bible expresses these terms. The Bible is expressly literate! Nevertheless, it does have advantages in presenting the concepts *planning* and *order*; indeed, some interesting insights may be gleaned from its visual and tangible language. This is so, not merely because a representation of reality – even one using mathematics – often requires language to be set in between the formulas; indeed, natural sciences often utilize explanations that employ rather literary language (sometimes even a parable!); it is also so because visual language leaves room for a different sort of description of development, one that has its own intrinsic value. For our purpose, suffice to say that this description will be much less deterministic. To illustrate, the mechanism of the Book of Jubilees, which relies upon the framing of the time dimension by overusing the number seven, results in a much more determinist worldview than that of the Bible. Simply stated, Genesis and the Bible presuppose a planned universe, but not to that extent! We shall return to this point at the end of this essay.

### 3. "Now the Earth Was …" – Genesis 1:2

The second verse in Genesis, "And the earth was without form, and void; and darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters" (1:2) presents a concrete number, or a condition, both which can be seen as the source of the creation, which was so joyfully heralded in the first verse. An element of this joy, a form of accentuated opening – described by Moshe David Cassuto (Cassuto, 5743, p. 10) – seems to have influenced the second verse, which uses flowery language involving irregular expressions. We are indeed dealing with flowery expressions, and yet they are nevertheless open to commentary that employs regular forms of exegesis based on intrabiblical linguistic comparisons and external comparisons with ancient eastern sources. Nevertheless, we should not err: even if we reasonably understand the words and the grammar, the actual combination of words represented by the terms used here to describe *chaos* – "Tohu (*lit: without form*) and va-Vohu (*lit: void*), darkness was upon the face of the deep" – does not provide a reasonable vision of that which "was." This point, which relates directly to the question of order and planning, will be discussed below, but first, a short explanation regarding *source material* is given.

### 4. Formless and Empty: The Desert

*Without form* (*tohu*) and *void* (*vohu*) as separate terms are commonly used in the Bible (especially *void*), and their most *simplistic reference* is toward the desert. I stress *simplistic reference* since Cassuto (Cassuto 5743, pp 11–12) finds it difficult to accept any form of explanation for this term, and one should not exclude the possibility that defining Creation as *creatio ex-nihilo* (and this is certainly not the literal meaning – the *P'shat*) knowingly or unknowingly relies upon this obstacle. And yet, considering the relative widespread use of *without form and void* in relation to the desert, and especially in light of its reflection in the beginning of the story of Creation in Genesis chapter 2 (in Rozenson, *Bereshit Davar – Interpretive Studies in the Book of Genesis*, soon to be published), we may understand *without form and void* as a poetic term meaning *desert*.

This explanation has already been proposed by traditional commentators, such as Ibn Ezra following the translation to Aramaic: "… and the translator was correct in saying Aramaic [Onkelos: 'Tzadi veRekanya' – desolate and empty], and so 'in a barren and howling waste' (Deuteronomy 32:10)…"; additionally, we attach special value to SHADAL's commentary, which will be returned to below: "Tohu vaVohu are terms that deal with desolation, since the related verbs *Taha* (questions) and *Baha* (stares) deal with amazement, as has been said in the Bereshit Raba midrash (2:1) He has it until he questions and stares, that is to say, stands amazed, and also in the language of the Syrian… and just as the desert is referred to as desolation and wilderness, so are *without form and void*, and the meaning is that there were no plants or animals" (Genesis 1:2).

Indeed, the acknowledged affinity of Biblical Hebrew to the Ugarit language, on one hand, and the use of the term in the Bible, on the other, indicate the basic accuracy of this explanation. It is also noteworthy that, besides the excerpt, several other quotes – "In a desert land he found him, in a barren and howling waste" (Deuteronomy 32:10), where *barren* reflects *desert* and other such terms (*waste*) – the equation of *Tohu* to *desert* is specifically raised in other verses, as well, all having flowery tendencies and taken from Biblical poetry: "…it shall lie waste; none shall pass through it forever and ever. But the cormorant and the bittern shall possess it; the owl also and the raven shall dwell in it: and he shall stretch out upon it the line of confusion, and the stones of emptiness" (Isaiah 34:10–12); "For thus saith the LORD that created the heavens; God himself that formed the earth and made it; he hath established it, he created it not in vain…" (Isaiah 45:18); "He poureth contempt upon princes, and causeth them to wander in the wilderness, where there is no way" (Psalms 107:40); "He taketh away the heart of the chief of the people of the earth, and causeth them to wander in a wilderness where there is no way" (Job 12:24); "The paths of their way are turned aside; they go to nothing, and perish" (Job 6:18). This is not the place to comment on these passages, and yet they all – at first glance – seem to transmit a psychological sense of enforced loneliness, a path gone astray, and loss, and for our purpose, they describe the dissolution of a framework that relates to the sense of chaos and an antiplanning effect.

Within this context, special attention should be paid to the words of the prophet: "I beheld the earth, and, lo, it was without form, and void; and the heavens, and they had no light." (Jeremiah 4:23). This verse is a mirror reflection of the second verse of Genesis that describes the return to the source condition – darkness, formlessness, and void.

The desert thus serves as a symbol for chaos; it is a setting that the modern biologist or geologist will of course find difficult to accept since, to their mind, the desert is subject to the same rules of nature as every other corner of the universe, but here we have a reflection of the desert within human consciousness, and due to psychological effects, it is a symbol whose denotation is clear. After all, we are dealing in literature, and based on the premise that it is strong and powerful, the desert is the initial condition for the planning that is part of the subsequent process of creation.

To sum up, the idea that formlessness and void are related to chaos is known and accepted: "A state of desolation and clutter where everything is mixed with everything; a sort of reality, an emptiness within which you cannot discern anything. Chaos and disorder is the opposite of harmonious order that was instilled by God in His world so that we can settle it, as the Prophet said, 'he created it not in vain, he formed it to be inhabited' (Isaiah 45:18)" (Biblical Encyclopedia vol. 8, pp 436–437). Concomitantly, the desert is also perceived of as related to formlessness and void. Here, we have related them all to the conception of *the desert* as a symbol for chaos; the desert, not unlike formlessness and void, symbolizes significant chaos.

## 5. Darkness Was Upon the Face of the Deep: The Bond of the Desert and the Dark

*Tehom* (*lit: the deep*) is also a very visual term, quite prevalent in the Bible (36 occurrences) in situations requiring a poetic description of a large underground body of water. The source of this word is also Ugaritic, related to the water goddess Tiamat (Biblical Encyclopedia, vol. 2, pp 343–346), and thus bears clear and sharp mythological connotations. In the context of our discussion, it may be said that here, too, we are dealing with a primal and chaotic situation, within which one cannot discern between the various components; the disjointed appearance of components within the primal *deep* will be presented in the first chapter of Genesis, where in a process referred to as *Havdala* (lit: separation), the great watery entity separates into its components ("And God said, Let there be a firmament in the midst of the waters, and let it divide the waters from the waters" – Genesis 1:6).

At this point, we should dedicate some attention to the nature of the mixture presented in the second verse: "…without form, and void; and darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters" (1:2). The correlation of *desert* and *darkness* is established in the Bible – "… through a land of deserts and of pits…" (Jeremiah 2:6) – and in other ancient eastern literature (Biblical Encyclopedia, vol. 4, p 674). Clearly, it is based on a subjective impression of life in the desert that raises sensations related to darkness. The inclusion of *the deep* in the verse dealing with *formlessness* and *void* is a linguistic compulsion, as succinctly explained by Cassuto: "… and yet, deep is not mentioned in the *parasha*, which is to say that the term without form and void was included before our forefathers understood the meaning of the deep" (Cassuto, 5743, p 12). What is the significance of this inclusion? According to Cassuto, who for fundamental reasons prefers not to attempt a complete understanding of the term *formlessness and void*, this inclusion does not present any fundamental difficulty, but for us, and the predilection to relate *formlessness and void* with the desert, what is the character of this mixture? Or, more precisely, what possible meaning may be gleaned from the presentation in the written sources of this mixture. We should reiterate that the linking of the components mentioned in the verse with darkness, may in itself be comprehensible in relation to the symbolic affinity marked by the ancients between it and the desert, as is its clear affinity to underground water; the problem remains in the linkage of desert to source water that exists under circumstances in which separation, which is characteristic of discernable reality, has not yet been attained – a separation in the geographical and physical sense between bodies of water in the world and other geographical entities, such as desert, a separation that we experience in our everyday lives. If so, considering the intense symbolic significance inherent in these basic elements, I tend to assume that the second verse in Genesis represents an indiscernible mixture of essential contradictions, which in themselves and individually were familiar in the ancient world: water and desert. Within the shroud of unity that envelopes this mixture, which is linguistically reinforced by the lucid play that links *Tohu* (formlessness) to *Tehom* (the deep) by force of their root "T" and "H," contrasts that represent a sort of plus and minus become clear; they are enforced in a single primal essence, and they suffice to serve as the potential energy for organizing Creation by promoting the level of orderliness that is subordinated to the design of the products as created by God.

## 6. What "Happened" During Creation?

We take care to place the word *happened* in quotes so that it will not denote a realistic occurrence in the strict scientific sense of the word but rather a literary process that has implications upon a worldview and that – finally – may also influence the manner in which we view the world scientifically. The Creation involves the ordering of source materials through a process of refinement, that is, *improvement* of inherent contradictions. The *plus* and the *minus* take on the forms of discernable and existent entities. Land separates into land and sky, light separates from darkness, the waters above from the waters below, continents from seas, and all these – a basis for the separation between the living, the plants, and the inanimate. This process takes place entirely within the material realm, and it is based upon the contrast enveloped within the essence of matter. Unlike other ancient approaches, there is no imminent contrast between male and female essence, or between good and evil; evil is not a participant in this game.

The word *good* accompanies the development of Creation. In Hebrew, the word *tov* is given to two possible definitions: fitting, proper, a description of manner or situation that relates to the proximity of the object described by the word *good* to perfection, that is, a functional description; the second definition pertains to good in the moral sense, the right thing to do based on a set of ethical values. Here, the word serves as a guiding principle; *good* develops accumulatively until that moment when the world is worthy of the appellation: *very good* (the Sabbath). This radiates upon the world's moral perception but, at the same time, upon its orderliness and sophistication, which – from a religious standpoint – we consider a product of preplanning and organization. Theoretically, this resembles Plato's Timaeus; here too a bond is created between the world's instrumental order and its moral underpinnings. This brings us to the one remaining question after Creation has been accomplished: what happened to the formlessness and void, the *Tohu* and the *Vohu*? We know what happened to the water – the deep that became organized. But the visual expression of formlessness and void remains without clear continuance. An interesting Talmudic legend deals with this question. The verse "… comprehended the dust of the earth in a measure (*shlish*)…" (Isaiah 40:12) is part of the description of Creation found in that book. The literal meaning (*p'shat*) of the *shlish* mentioned – the measure – is a measuring instrument, but RASHI offers a *midrashic* (scholarly) interpretation: "measured in a third [=divided into three parts] a third desert, a third settlement, a third seas and rivers." Based on this, the desert included in the formlessness and void remains, as do the seas.

The desert remains hidden, somehow, in the story of Creation but persists beyond it; nowhere in the story is it written that the desert is a product of Creation, but it clearly remains. We do not know for sure why the water was treated with such clarity in Creation, including its destiny, and the desert – that is, the formlessness and void – not. It would seem that the first story of Creation has no interest in maintaining a demonic desert within the description of an experience ruled entirely by God; it is as if the desert is not worthy of special mention. Notably, though, the presence of the desert throughout the rest of the Bible – especially as the birthplace of the Israeli nation in the Book of Numbers – testifies to its significance. Insofar as this essay is concerned, there does remain an element of disorder within a system that ostensibly achieved perfection in Chapter I.

## 7. The Garden and Order

Thus far, the discussion has followed the events of Genesis Chapter 1, concentrating primarily on the question of source materials and their destinies. Chapter 2 contains another version of the Creation that leads directly to Man, with the central environment containing him – a park called the Garden of Eden. There are many interesting and thought-provoking parallels between the first and second stories of Creation; however, we will not deal with them here (Rozenson, *Bereshit Davar* – see above). Instead, we shall limit ourselves to specifying the source conditions in the second: "And every plant of the field before it was in the earth, and every herb of the field before it grew: for the LORD God had not caused it to rain upon the earth, and there was not a man to till the ground" (Genesis 2:4). These conditions are specified in the negative (**Before** it was in the earth… **before** it grew… had **not** caused it … and there was **not** a man), and they describe an unirrigated land – a desert. Now, we shall see how this land becomes one that is more familiar to man: "And the LORD God planted a garden eastward in Eden; and there he put the man whom he had formed" (2:8). We claim that the term *garden* denotes an ordered entity, and so, here too, and without mentioning the term *without form and void*, we see before us a transformation from a sort of desert to the organized entity embodied in the term *garden*.

Why should the term *garden* represent order? As mentioned, the conscious status is that which determines, and because the garden is not only a mere irrigated area (not even one that requires the basic planning of irrigation canals), it relates to construction, and as such was considered part of the regal backdrop, that is, the environment of a palace, one that requires structured planning. Without entering upon details, Man is banished from the Garden of Eden for reasons that we will not dwell upon here; however, by his expulsion from that symbolic garden he is distanced from the orderly and he enters the "real world" – a different sort of entity, rich in uncertainties and doubts, in which order is not a given. From this point of view, the second story of Creation complements the first, in that man is required to create by himself the order and planning that were intrinsic to his childish worldview, as represented in the chapter describing his sojourn in the Garden of Eden. According to this, the process of organizing and planning the world, depicted by planting the garden, is divine, but in the same breath, one may claim that the process of disintegration, which involves leaving the organized and psychologically protected environment, is also divinely steered.

## 8. Creation According to the Book of Jubilees

The above observations afford an interesting insight when compared to the Book of Jubilees, which presents a sort of fusion of the trends mentioned above, trying to harmonize them in a manner that in no way exists in Genesis' founding narratives.

The Book of Jubilees begins the tale on the first day: "…For on the first day He created the heavens which are above and the earth and the waters…" (Jubilees 2:2), and this follows the opening declaration that highlights the Sabbath: "…the Lord God finished all His works and all that He created, and kept Sabbath on the seventh day and hallowed it …" (2:1). As for the Garden of Eden, it is already alluded to in the enumeration of deeds for the third day of Creation: "…And on that day He created … fruit-bearing trees, and trees of the wood, and the garden of Eden, in Eden…" (2:7). Thus, the planting of the garden that justified an additional story in Genesis is transferred into the first and only recounting in the Book of Jubilees; in other words, what was divided in Genesis into two stories of

Creation is welded into one, in this case, joining the garden with the forests, etc., on the basis of their common botanical denominator.

The conclusions derived from this succinct description are clear and astute. The Book of Jubilees is constructed upon a logical basis; arrangement is a product of its manner, of organizing the history of the world in sets of 7-year schemata that repeat themselves and provide a basic measurement of time; it provides a known deterministic character that presupposes radical planning that is embossed upon the world order (this matter was investigated mainly in the context of the concept of time perception: Elior, 5763; Ben Dov, 5755). Organized time is the substrata for events that have been predetermined and situations that cannot be changed; at most, one may have been able to reveal to Moses atop Mount Sinai as he opens the Book what will happen in the future. Within this context, a single account of the Creation is set, constructed in principle in accordance with the skeletal structure of Genesis chapter 1, but it is most detailed and comprehensive, including all the elements of Creation – this, at any rate, seems to be the intention of the writer. In this manner, the writer leaves no room for a second telling. What is important for our discussion of this story is the absence of source materials – there is no formlessness or void! This absence may be explained on the basis of the book's basic premise, which claims that there is no room for disorder; the world is organized and planned *a priori*; the garden is part of the botanical world, and its function is not to tell a parallel tale, primarily because the world is so organized and planned. There simply cannot be a parallel story! And as stated, the plan is reflected in the moral world, thus subordinating man to strict deterministic laws.

## 9. Discussion

In Genesis, one may discuss trends of organization whose simple interpretation means "to be planned"; this planning is part and parcel of the world (and this has bearing upon human constructs, such as history and psychology). Organization includes a shift from formlessness, chaos, and void to a created world and from an absence of plants to a garden. The linkage of *desert* to chaos and disorder is raised in several exegeses; we have attempted to strengthen this effect, concentrating on its ramifications upon the manner in which the world was planned using the following arguments: (1) the interpretive ambiguity – the not entirely cogent terms *formlessness and void* add to the lack of clarity and strengthen the disorderly effect; (2) undefined mixture – the condition of the strange basic mixture that cannot survive in our familiar world strengthens the disorder; and (3) a complex story – a situation where two stories describe the Creation highlights the basic lack of understanding regarding the creation of a world as related to disorder; not everything can be included in one homogenous framework.

All of this manufactures a setting of disorder that is not merely the background for organization but something much more essential. Depicting the desert or the void enables their utilization later on – each one using its own unique literary tools – during the telling of the story of the world. Even if it is not referred to in Genesis chapter 1, the desert as an entity remains.

Finally, we are dealing here with language that is an ensemble of manners of expression, which relate to the manner in which things are described and our attempts to understand them. Superficially, the ancient stories of Genesis present us with innocent tales, but in a vein quite similar to the Greek belief in their myths (Van, 5753), these stories can also be seen as code systems that represent insights into the ways of the world. Within the framework of this discussion, it has been suggested that the Jewish system of codes is open to commentary (and to my taste, this is the very strength of Judaism, even if that is not the matter at hand). One branch of exegesis is that which is proposed in the Book of Jubilees; it too developed as a part of Judaism (Second Temple period), but it construes a totally different comprehension of Creation, one that raises other religious challenges based on a harsh attenuation of free will, which is so crucial to moral conduct in its most basic form.

The Bible not only preserves chaos, it gives it a central role! It serves as a necessary backdrop to free will on the individual plane, and it serves other developments in human behavior. *Desolation*, a synonym for *desert*, relates to *amazement* – as explained above by SHADAL; that means that the desert (desolation) is a prerequisite for amazement, which denotes curiosity, leading after all to investigation and the desire for knowledge. In another context, the desert chaos is a background for national organization, one of the basic tenets of history. We are referring, of course, to the Israeli nation's wandering in the desert, the vision of the camp described at the beginning of the Book of Numbers projecting exemplary order, and the drama of national cohesion developing against the backdrop of a desert landscape, transforming the narrative into a master plan: the blueprint for the nation is drawn up amid its interaction with the desert (Rozenson, 5754).

To conclude, the Book of Genesis perceives creation as a function of planning, but this planning also describes the presence of a *lack* of planning, which is essential for man and the manifestation of his humanity. I doubt if Plato, who considered reality a pale reflection of a superior heavenly ideal, would agree with this approach.

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Biodata of **Shlomo E. Glicksberg**, author of "***Judaism and Evolution in Four Dimensions: Biological, Spiritual, Cultural, and Intellectual***."

**Dr. Shlomo E. Glicksberg** obtained his second degree in Jewish History and his Ph.D. in Jewish law at the Bar-Ilan University in 2006. His doctoral thesis was on the subject of the preventing of environmental hazards in the Jewish law. He is a senior lecturer and manager of the M.A. program at Efrata College and teaches at the Lander institute Jerusalem academic center and Bar-Ilan University. Dr. Glicksberg is the rabbi of a large congregation in Jerusalem and the coeditor of "Siah Sadeh" which is an online journal on Judaism and the environment. His research interests are the historical, legal, and philosophical aspects of Jewish law with a focus on the meeting points of Judaism and the environment.

E-mail: **glicksberg@neto.net.il**

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# JUDAISM AND EVOLUTION IN FOUR DIMENSIONS: BIOLOGICAL, SPIRITUAL, CULTURAL, AND INTELLECTUAL

**SHLOMO E. GLICKSBERG**
*Efrata College, Jerusalem, Israel*

## 1. The Challenge of Evolution

Ever since the advent of evolutionary theories in Europe, researchers and men of learning cast doubt upon them. However, the main opposition came from religious scholars, Jews and non-Jews, who perceived these theories, which contradict the literal understanding of the story of creation in the book of Genesis, as heresy. Consequently, they strived to undermine the foundation of these theories.

Along these lines, Jewish thinkers produced many books and articles that dealt mostly with the conflictual aspect, adopting a *rejectionist stance*, which negated the feasibility of the developmental theory (see, e.g., Goldman, 1988). However, besides these Jewish thinkers, there were others, such as Rabbi Abraham Isaac Kook (Rav Kook), who accepted the basic notion of the theory of development. Along these lines, books and articles were published espousing the *integrative stance*, which perceived the challenge of the new theory and wished to explain various sources in its light and adapt them to the developmental theory.

These writings join many earlier Jewish philosophical and commentary sources, which predate by far the evolutionary theorists, and which show that they considered as possible the feasibility of species' development, for example, Rabbi Josef Albo (Spain 1380–1444), who described the intermediate stages of development between inanimate matter and plants, between plants and animals, and between animals and man:

> Coral is intermediate between inanimate matter and plants. We also find the sea sponge, which only has the sense of touch, and is an intermediate between plant and animal stages. We also find the monkey to be intermediate between animals and man (Albo).

It should be noted, however, that the words of R. Albo can also be explained as a description of a *static* state, existing without any change from the time of creation, as opposed to a dynamic evolutionary process.

An unambiguous evolutionary statement appears in the writings of Rabbi Ovadia Sforno (Italy, 1476–1550), who brings evidence from the sources (Genesis 1:26; 2:7) that the creation of man in God's image is in fact the end of a long process, commencing in the creation of a noncognizant creature, belonging to the animal category. This creature evolved until it acquired a human mind, as well as its physiology of man known to us (Shilat, 2004).

This study follows the integrative approach. Furthermore, it aims to demonstrate that not only is Judaism able to correspond with the notion of evolution through commentary, conscious or otherwise, but that evolution constitutes one of the fundamental deep currents in Jewish philosophy in a variety of areas. This study wishes to demonstrate the compatibility of the evolutionary principle with Jewish thought in a number of dimensions: biological, spiritual, cultural, and intellectual.

## 2. The Biological Dimension

Already in the Middle Ages, several Jewish scholars emphasized that the story of creation as it appears in Genesis should not be read literally. For example, Nachmanides (Spain, 1194–1270) writes:

> The process of creation is a deep mystery not to be understood from the verses, and it cannot truly be known except through the tradition going back to Moses, who received it from the mouth of the Almighty, and those who knew it are obligated to conceal it… as all this cannot be wholly understood from the Scripture…the knowledge remains in the hands of a select few as Oral Law. (Nachmanides, commentary on Genesis 1:1)

Indeed, despite specific descriptions in the Scripture, we find that *Chazal* (the Sages) at times disagreed on the actual occurrence of events, such as whether the world was created in a single day or in 6 (*Torah Shleima*, 1:294, Commentary on Genesis) or which was created first, light or the world (Bereshit Rabbah 3:1).

As a rule, Judaism tended to incorporate scientific information, which constituted a challenge to commentary, through which various subjects were aired and insights on the sayings of the Sages and on the Scriptures survived long after the collapse of the theories from which they derived. An example of this is the acceptance of the Greek theory pertaining to the existence of hylic matter preceding the world's creation (*Chovot Halevavot, shaar Hayichud*, 6; Rabbi Yehuda Halevi, *Kuzari*, fifth essay, 2; Maimonides, *Moreh Nevochim* [Guide to the Perplexed], 2:26; Nachmanides, Commentary on the Torah, 1:8, and more).

Under the premise that one should not read the creation narrative literally, not only does the evolutionary theory at its basis not contradict this narrative, it even provides it with a possible explanation. In this manner, some scholars recognized the potential in the scientific explanation and harnessed it to emphasize the gradual, incremental progress described in the story of creation.

This incremental progress is illustrated in descriptions which are more complex than the literal ones in the Scriptures; in reference to the beginning point of creation, which directly influences the determination of the world's age, and in reference to the point of completion, from which derives the possibility of change being introduced to the structure of creation.

## 2.1. THE WORLD'S AGE

One of the implied premises of evolutionary theory is that the world's age or the date of creation cannot be located within the sequence of events such as described in the biblical creation narrative. Besides head-on opposition to these findings by the supporters of the *rejectionist stance*, as well as some of those supporting the *integrative stance*, others attempted to explain away the contradiction in various ways; some referred to the saying by the Sages that God created a world that came into being at an advanced stage, and therefore it is pointless to try to evaluate the age of the world according to the typical rate of development of each of its components, instead one must assume that the process was shorter by far: "All the creatures formed at the beginning [of the world] were created in their full stature, with their consent, and according to their own character" (Babylonian Talmud, Hullin 60a). Some claimed that the Flood had a crucial impact on the development of the world's components (Malbim, commentary on Genesis 7:23, 8:22). The common denominator to all explanations of this kind is that the world does not evolve but came into being *ex nihilo*.

On the other hand, *Chazal* indicate in several places in their commentary that the date of the world's creation or the calculation of the world's age as arises from the creation narrative and the following sequence also should not be read literally. Therefore, evolutionary theories that suggest that the world requires a lengthy period to develop do not contradict Jewish tradition, and even provide it with a plausible explanation.

Thus, for example, it is brought in several *Midrashim*[1] of *Chazal* that prior to Adam, there were 974 generations which were destroyed because of their sins (Babylonian Talmud, Shabbat 88:2). Some *Midrashim* teach that God created worlds and destroyed them (Bereshit Rabbah, 3:7), which may refer to the destruction of some of earth's external layers, its shell, rather than the entire world. Some kabbalistic sources suggest that the world was preceded by several 7-year cycles (Kasher, 1949; Weinstock, 1967). In this light, Rabbi Yisrael Lifshitz (Germany 1782–1861), the author of the commentary on the Mishna, *Tiferet Yisrael*, viewed the discovery of dinosaur and "mammoth" fossils as reinforcement of the claim that the creation narrative is not literal, that God created worlds and destroyed them, and that the fossils found are remnants from previous worlds:

> From all this, we can see that all that the Kabbalists have told us for hundreds of years – that the world was destroyed and renewed four times already, and that in each renewal the world achieved greater perfection than the last – this has found clear confirmation in our time. (*Tiferet Yisrael*, in the essay "Drush Ohr HaChayim," section 3, printed among the commentaries at the end of Mishnayot Yachin U'Voaz after Sanhedrin Tractate).

*Chazal* emphasized that there is no necessary correspondence between divine and human timeframes, and the scriptural description could very well be representing divine time (e.g., Bereshit Rabbah 8:2; Munk, 1974).

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[1] *Midrashim* – rabbinical commentary on the scriptures and oral law.

## 2.2. CHANGES TO THE STRUCTURE OF CREATION

*Chazal* mention in several places that not only does the creation narrative not indicate the beginning point of creation; neither does it indicate the point of completion. While it should be emphasized that sayings by *Chazal* or the Kabbalists should not be taken at face value, it seems that these sources did perceive creation as an evolving, dynamic reality.

Below are several developmental characteristics, the former found in the biblical verses themselves and the latter brought by latter-day religious decisors (*poskim*).

### *2.2.1. Extinct Animals*

A prominent example is the mention of great *Taninim* in the bible (Genesis 1: 21). *Chazal* describe them as huge animals (Babylonian Talmud, Bava Batra, 74b), and Nachmanides adds to this that some of them were of many *parsas*[2] and that, according to Greek literature, they were of 500 *parsas* in length (Nachmanides on Genesis 1:21). If indeed an animal of this size existed, it is long extinct and may refer to dinosaurs.

*Chazal* also describe unfamiliar human creatures different to us. The Mishna (in Kilayim Tractate 8:5) mentions creatures called "*adnei hasadeh.*" Maimonides (Spain-Egypt, 1138–1204), in his commentary to this mishna verse, explained that this is "an animal resembling a human" and added that it was a creature which was reputed to speak incessantly and whose speech was like that of a human being (Maimonides, Commentary on the Mishnah, ibid.). Rabbi Yisrael Lifshitz even presumed that the description referred to one of the ape types (orangutan or chimpanzee), which resembles the human being (Tiferet Yirael, ibid.; see also Kislev, 2001).

The book of Zohar[3] indicates that strange types of humans existed in other worlds, and they differed from earth-created man (Zohar on Leviticus, p. 10a). Rabbi Kook explains the Zohar's meaning that "different types of human beings existed on earth besides the Man mentioned in the Torah" (Kook, 1962).

*Chazal* also mention animals with more complex characteristics than ones we are familiar with today. Thus, for example, *Chazal* mention a mouse which is half flesh and half earth (Babylonian Talmud, Hullin 126b; Sanhedrin 91a); the Shamir worm, which had the ability to dig through the hardest rocks (Sota 48b; Maimonides, Commentary on the Mishnah, Sota 9:12); or the Salamander, described as an animal created in fire (Rashi on Hullin Tractate 127a). As aforementioned, although these phenomena should not be taken literally (e.g., Kook, 1962), they do reflect a clear perception of creation as an evolving, dynamic reality.

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[2] Distance covered by an average man in a 72-min walk, between 3 and 4 km.

[3] *Zohar* – a central work in the literature of Jewish mystical thought known as Kabbalah.

### *2.2.2. Crossbreeds*

Despite the premise that all living creatures were created within the 6 days of creation, *Chazal* bring Aggadic and Halakhic[4] *midrashim* according to which new types of plants and animals were created by crossbreeding and grafting. The *Tosefta* and the Jerusalem Talmud (on Kilaim Tractate) bring various facts related to the mixed breeding of plant species (even of those with very dissimilar characteristics), creating in this way new strains (Felix, 1967). Pertaining to animals, *Chazal* mentioned the Arvad, which is a crossbreed of a snake and tortoise (Babylonian Talmud, Hullin 127a), and the mule, the crossbreed of a horse and female donkey (Jerusalem Talmud, Berachot Tractate 8:6, 12b).

### *2.2.3. Changes in Characteristics*

In typical allegorical and symbolical form, different Aggadic *midrashim* express a similar principle: At Creation, the creatures were not made in perfect anatomical form, and they continued to develop and change along the way. Several examples for this involve Adam, the first *man* is described as a creature in an intermediate developmental stage: He was created double-faced and only later was separated into two independent entities, male and female (Babylonian Talmud, Berachot Tractate 61a; Eruvin Tractate 18a); he was born as a hermaphrodite (Bereshit Rabbah 8:1); he had joint fingers and only from the period of Noah and onward were humans born with separate fingers (Midrash Avkir on Genesis 5:29); he had a tail or a sting (Babylonian Talmud, ibid.); he fathered strange creatures and only from Seth onward did the human race come into existence (Babylonian Talmud, Eruvin 18b).

The anatomical structure of *animals* also underwent transformation. Thus, *Chazal* describe 7-year cycles of development, and thus, after a 7-year period, a hyena would turn into a bat, a bat after 7 years would turn into a vampire, a vampire into a thistle, and so on (Babylonian Talmud, Bava Kama 16a). *Chazal* explained how various anatomical details in different animals are adapted to their conditions of life, such as the short tail of the camel (to avoid entanglement in bushes) or the long tail of the ox (to enable it to get rid of flies away in the meadow) (Babylonian Talmud, Shabbat 77b). Here too, apparently, we find an adaptation, although not necessarily one that changed over time. This awareness to the adaptive nature of animals, though static, can be conducive to the acceptance of an evolutionary theory.

The *vegetation* is also described as having undergone transformation. The trees were created with special characteristics, such as tasting the same as the fruit they bore (Safra, Midrash Halakha on Leviticus, Parasha 1, ch. 1), and even barren trees bore fruit (Bereshit Rabbah 5:9). Although the development takes a

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[4] *Halakha* – Jewish Law. *Halakhic Midrash* refers to rabbinical discourse on subjects pertaining to Jewish law, *Aggadic Midrash* referes to discourse of subjects pertaining to Jewish philosophy and theology.

downward direction, it seems that these sources nevertheless testify to the possible dynamics of creation. One can add examples from the study of geomorphology, which tell of the *silent* hills and mountains that were created by different climatic processes (Chayut).

In this context, we should mention Rabbi Josef Albo, who described the intermediate stages of development between inanimate matter and plants, between plants and animals, and between animals and man (Albo), and Rabbi Ovadia Sforno, who quotes the sources (Genesis 1:26; 2:7) to prove that initially man was created as a creature belonging to the animal category and evolved until it was given a human mind and human physiology (Shilat, 2004).

#### *2.2.4. Changes in Nature*

Various descriptions in *Chazal*, Halakhic reasonings, and occasionally also the stated logic behind commandments, laws, or decrees were based on scientific data and premises. With the development of science, some of these became incompatible with the updated scientific knowledge. In such situations, *Chazal* and religious decisors often declared that this was not due to errors in these hypotheses, but that nature itself changed over time in different places and according to different conditions (Gutel, 1998b). These changes are not supernatural, but gradual, natural ones, part of the natural system (Gutel, BDD, 1998a). Yet, once more, even though some of the changes take a downward direction, they nevertheless attest to the recognition of the principle of the dynamics of development.

## 3. The Spiritual Dimension: The Kabbalistic Approach According to Rabbi Abraham Isaac Kook

Modern evolutionary theory constitutes a central place in the philosophical thought of Rabbi Abraham Isaac Kook (1865–1935, the first Chief Rabbi of pre-state Israel). He expresses himself boldly on the subject: “The theory of evolution, which is gaining worldwide popularity at present, accords with the secrets of Kabbalah better than any other theory” (Kook, 1985).

The biological evolution he cites in his philosophy is merely the material expression of a process by the entire existence toward divine perfection. Nevertheless, Rabbi Kook does accept some of the precepts of evolutionary theory, not only as a biological model for a metaphysical viewpoint, but as a true description of world phenomena (Ben Shlomo, 1989).

Yet, it is noteworthy that despite his basic acceptance of the biological evolutionary theory, Rabbi Kook completely disagreed with the philosophical and materialistic significance attributed to this theory. He instead incorporated the evolutionary theory into his own developmental doctrine and adapted the spiritual perception of evolution to correspond to Kabbalistic doctrine concepts.

Below is an expansion of this: In various aggadic *midrashim*, *Chazal* give expression to the fact that the realization of Creation is not identical to the original divine plan and that there is, as it were, a disparity between design and outcome. According to midrash, "In the beginning, it came up in Thought to create the world according to the measure of Judgment (*Midat haDin*), but when He saw that the world would not endure under those terms, He started with the measure of Mercy (*Midat haRachamim*) and added it to the measure of Judgment" (Bereshit Raba 12:15). In another *midrashic* source, *Chazal* mention that an example for the gap between plan and execution is the fact that the land did not, after all, produce trees with the same taste as that of the fruit they bore, as was the plan according to Genesis, but only fruit-bearing trees.

Creation endured yet another blow following Adam's sin. As explained by the Kabbalist Ramchal (Rabbi Chaim Luzzatto), Adam prior to his sin was superior to man in his current state, and his level of humanity was an elevated one…. After his sin, his stature greatly deteriorated, as did the human race as a whole, to a level unworthy of the eternally high degree first intended for man, and he became suited only for a much lower level (Ramchal, *The Way of God*, Part 2:2).

We find elsewhere that the Ramchal identifies three types of existence "for man: before the sin, after the sin, and the reality of what could have been had man not sinned, and this is the reality of the future to come" (Ramchal, *Da'at Tevunot*, p. 111).

This principle, which is deeply rooted in *Chazal*, was developed by the Kabbalists. They compared the descent of the world from its proper level to "broken vessels." Yet, they emphasized that the descent is not without ascent, neither are the broken vessels beyond repair. "The worlds were created in a way which would enable their eventual ascent, since the purpose of their descent at the time of the breaking of vessels was to gradually ascend until reaching the level of perfection which existed prior to the breaking of the vessels" (Ramchal, Klach Pitchei Chochma, 12:1), or as Rabbi Kook put it: "…this descent has the foundation for greater ascent stored within" (Kook, *Orot Hateshuva*).

Rabbi Kook's disciple, Rabbi David Cohen (known as "the Nazarite"), also connects between the Kabbalistic theory of the Ramchal and the theory of evolution. He states that the divine method particular to the Ramchal in *Klach Pitchei Chochma* is based on the concept of the worlds' ascension, which has affinity to the new evolutionary theory (Kol Hanevua, 1970).

Rabbi Kook incorporates the evolutionary theory within his doctrine on Kabbalistic development and gives it a fresh moral perspective. In this sense, the clash between the evolutionary theory and religious faith or the Torah's view is not a real clash. A more profound concept of the evolutionary theory can do away with the heretic conclusions derived from it, according to which the world is merely a random struggle arena (Ben Shlomo, ibid.).

Rabbi Kook presents a counter approach in his worldview – an all-encompassing unity. Reality in its entirety constitutes a single unity: all the individuals at strife with one another are in fact parts and nuances of a single, all-encompassing organism. Reality is developing, and this trend has an ethical significance. This single entity, the unified Creation, is the one developing and progressing as a single whole. This development influences every one of its components, which make up the whole. On the other hand, the development of each part on its own influences the others, and thus, with the clear development of a single part, all develops (Filber, 1992; Berger, 2009).

## 4. The Cultural Dimension: Jewish Laws Predicated on Cultural Premises

It seems that the principle of evolution can explain yet another Halakhic and philosophical area: the evolvement of Halakha in light of changing cultural dynamics. Different sources illustrate that different Halakhic principles, some even explicitly mentioned in the Torah, resulted from the aim to contend with a given cultural reality, thereby raising the question of their relevance in a changing reality.

This is illustrated here in two well-known examples: The first refers to the area of ritual – the essence of sacrifices. According to a widespread explanation of the position of one of the greatest religious decisors of the medieval period, Maimonides, the laws related to sacrifices have no intrinsic value; they merely express the aim to sublimate people's need for the practice of *Avoda Zara* (idol worshipping) by channeling this need toward worshipping God (Maimonides, Guide to the Perplexed, part 3, ch. 32).

The revealing of the cultural background for the biblical prohibition and its possible reasoning challenged latter-day scholars to discuss the relevance of sacrifices in a reality in which idol worshipping is nonexistent or at least poses less of a difficulty (Sherlo, 1997). Rabbi Chaim Hirschensohn (United States, 1897–1957) even delineated a practical plan for a rebuilt Temple without sacrifices (Hirschensohn, Malki ba-Kodesh; see also Ben-Eliyahu, 2008).

Although Rabbi Kook sharply disagreed with Hirschensohn regarding his practical plan, he too described a kabbalistic-based futuristic scenario, in which the entire world will develop and ascend spiritually, until the animals will equal man in mind and in general, and in such a situation, animal sacrifices would no longer be practiced (Kook, 1939).

An additional Halakhic and ideological issue illustrating the evolvement of Halakha is women's status in Jewish Law and its implementation in modern reality. Latter-day decisors established that although earlier Halakha prevented women's participation in various areas of Halakhic activity, the cultural changes influence the validity of prohibitions of this kind.

A prominent example is the prohibition on women to study Torah, expressed by Rabbi Eliezer, one of the most prominent scholars of the Mishna period: "Anyone who teaches his daughter Torah is as if he taught her lasciviousness" (Mishna, Sota Tractate 3:4), or more bluntly phrased: "The words of the Torah should be burned rather than entrusted to women" (Jerusalem Talmud, Sota 3:4, 19a). The changes in women's status in the general and Jewish society were reflected in Halakhic decisions, which were favorable and encouraging toward the study of Torah by women (Navon, 2008).

Thus, for example, Rabbi Moshe Malka (Morocco-Israel 1911–1996) states:

> In this day and age, women engage in many of life's activities, enter upon the depths of general knowledge and fill the universities…they are wiser and more developed than the men, surely even Rabbi Eliezer would agree that there is no prohibition to teach women also the oral tradition. (Malka, Mikve HaMayim)

In this spirit, some contemporary decisors referred to other Halakhic decisions that were founded on changeable social premises. For example, the assumption of *Chazal* is that a woman would prefer any husband over remaining alone, an assumption which serves as the basis for a number of Halakhic decisions. When found to be unsuited to the modern woman's way of thinking, it led some scholars to declare this Halakhic decision as no longer binding (see Beeri, 2008; Halivni, 2007).

This description also is in keeping with the Kabbalistic picture according to which, as part of the world's spiritual development, the future status of women will equal that of men, and instead of the curse to Eve, "And he shall be your master" (Genesis 3: 16), the symbolic meaning of the verse in Jeremiah will take its place, "A woman shall compass a man" (Jeremiah 31:21, see also Menusi, 2004).

## 5. The Intellectual Dimension: The Development of Jewish Oral Law

Another area clarified by the internalization of the principles of the evolutionary principle is the Sages' perception of the Oral tradition. The relation between the written Torah, and its five books of the bible, and between its accompanying oral tradition is described by *Chazal* as two doctrines (Torahs) both given at Mount Sinai. However, the oral tradition, it follows, does not consist of a written, detailed doctrine, similar to the written Torah, but of commentative principles whose purpose is to adapt the written Torah to the changing times. According to Rabbi Yosef Albo, at Mount Sinai, Moses was given general rules, in oral form, which are all hinted at in the Torah in short, so that they will enable the Sages of each generation to elaborate on the changing details (Albo, Sefer Ha-Ikkarim, Essay 3, ch. 23). *Chazal* illustrate how the oral tradition does not reveal divine truth but is a development of it, for which the Sages over the generations received authorization to develop the generalities. Various aggadic sources describe how divine truth is irrelevant to the discourse of Torah scholars, and how, on Halakhic disputes, God seemingly turns the power over to the Sages, or how God himself awaits the Sages' verdict on a certain issue (Babylonian Talmud, Bava Metziya Tractate 86a).

Other sources describe the Torah as raw material for human creativity, and the scholars are those who should develop the Torah in the direction they see fit: "When God gave the Torah to Israel, he gave it only as grain to be made into flour and flax to be made into a garment" (Tanna DeVei Eliyahu Zuta, Ish-Shalom edition, Parasha 2). This is a revolutionary and sensational statement: The Torah is given to man as raw material, and man is to use it to create the next strata of oral law.

In a similar vein, *Chazal* are quoted elsewhere to say: "If the Torah were given cut and dried, we would have no leg to stand on. What does this mean? 'The Lord spoke to Moses'. Moses said to God: Master of the Universe, inform me what the Halakha is.' God replied, 'to incline in favor of the majority'. That is, if the majority says to acquit, acquit, and if it says to hold liable, hold liable. All this in order that the Torah be expounded along forty-nine facets toward impurity and forty-nine facets toward purity" (Jerusalem Talmud, Sanhedrin 84b).

Besides engagement in creative commentary, the Sages over generations were also an independent legislative authority. There are three types of legislation: decrees, regulations, and customs. According to Maimonides in the preface to his commentary on the Mishna:

> The fourth part refers to the laws legislated by the prophets and sages of each generation, to create boundaries for the Torah. This is what God generally referred to by 'Therefore you shall keep my requirements' (Leviticus 18:30), which the Sages term 'decrees'… And the fifth part refers to rules reached through investigation and agreement on accepted customs between people, which do not add or detract from the commandments, or in matters on which the words of Torah are beneficial, and these are termed regulations and customs.

This authority provided the Halakhic scholars with the means for solving problems that have not hitherto been discussed in Halakha, or to change existing Halakhic legislations, when reality required it. The great scholars of the past used to decide on various regulations regarding conduct between man and his fellow man, between man and wife, and so forth. These have the ability to determine the appropriate routine to life and to address various issues and problems that arise from a changing reality.

It should be emphasized that customs served an essential factor in the development of Jewish Law. As opposed to the decree or regulation, customs are a clear reflection of the dynamic tradition of the Jewish life routine, which does not come to a halt and is constantly in a process of development. However, the customs give it its Halakhic status (Kook, Eder Hayakar; Ta-Shma, 1992).

This is, therefore, the essence of the evolving oral tradition, a doctrine that is essentially given to development by religious scholars, whether by commentary or by legislating by-laws. Yet, it should be emphasized that by no means is this an evolvement from a primitive type to a sophisticated one, or from the lowly to the superior; much the same as in the biological process described above, we are not necessarily referring to this kind of development but rather to a constant dynamics and development from the primary to the elaborated.

## 6. Conclusion: Can Humanity Be Integrated in the Process of World Development?

The hitherto description discusses the dynamics of the various dimensions of Creation as part of its basis and a self-occurring phenomenon. To conclude, the article discusses the relations between the world's steady, assured progress and human integration within this process. It questions whether man can participate in this process, and generate change, or only respond to change.

According to Rabbi Kook, within the all-encompassing unity, humanity has a unique role. Only man can develop the entire universe, spiritually and physically. Man through his actions influences the world's ascendancy. This insight of course lays great responsibility on man's shoulders. He is required to comprehend and sense his own connection to general reality and act on its behalf: "To fix the world in the kingdom of God." *Chazal* have already given expression to the fact that man's integration can even accelerate the natural evolutionary process. The Talmud explains that the redemption could arrive easily and speedily, by way of a spectacular, divine move, in return for man's good deeds, or in a painful and slow manner, in natural ways since the time for redemption has arrived. The type of redemption will be determined by man's actions (Babylonian Talmud, Sanhedrin 98a). Therefore, man is responsible for the state of the world. Beyond this, man has been privileged with participation in the process, just as he was privileged with the ability to continue the divine creation by his own material development.

On the other hand, *Chazal* warned against attempting to force one's own redemption (Babylonian Talmud, Ketubot 111a) by forcing upon reality processes that do not fit its proper rate of development.

It seems that the tension between the call to understand the world's developmental processes and integration within them, and the apprehension of aggressive integration, on the other hand, is found in the other above-mentioned dimensions.

Regarding Torah study, while the Sages and scholars were invited to be integrated in its development and adaptation to the changing reality, they were nevertheless warned about adding or subtracting from the commandments.

It seems that this tension exists also in the cultural dynamics: The public debate in the Jewish Orthodox society regarding the initiated integration of women in the various areas of action and leadership can attest to this.

Also in biological processes, the Sages discerned the tension between the duty to protect the world from forced changes which are not compatible with its natural rate of development and between their prerogative to develop it. On one hand, the Torah has prohibited the mixed breeding of different species (Nachmanides on Leviticus 19:19), and on the other hand, *Chazal* have determined: "All that was created in 6 days requires completion. Mustard requires sweetening. Turmus requires sweetening. Wheat requires grinding. Even man requires completion" (Bereshit Rabba, Vilna edition, Parasha 11:6; Rakover, 2001). It seems that this tension is contained within the first two assignments given to Adam and general humanity at their outset: "to work it and keep it" (Genesis 2:15).

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Biodata of **Dov Berger**, author of "***Random Natural Laws Versus Direct Trends: A Cabbalistic Interpretation Based on the Teachings of Rabbi Kook***."

**Dov Berger** is currently a lecturer in the Lifshitz College of Jewish Education, Jerusalem, Israel. He also serves as a Rabbi in the Hameiry Yeshiva, Jerusalem. Mr. Berger is a graduate student toward his Ph.D. in Bar Ilan University, Ramat Gan, Israel. His scientific interests are in the areas of theory of evolution, the philosophy of Rabbi Kook, and the relationship between sciences and faith.

E-mail: **berger1@macam.ac.il**

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# RANDOM NATURAL LAWS VERSUS DIRECT TRENDS: A CABBALISTIC INTERPRETATION BASED ON THE TEACHINGS OF RABBI KOOK

**DOV BERGER**
*Lifshits Academic College of Education, 17 Hillel Street,*
*Jerusalem 91022, Israel*

## 1. Introduction

The philosopher and historian of science Thomas Samuel Kuhn (1922–1996) argued that at the root of the scientific theories in any era lies a system of philosophical and scientific premises, and practical research and other guidelines, that comprise a system of thinking which he called a paradigm. Our perception of the world cannot be divorced from the paradigm within which we act and, as such, according to Kuhn, believes that different theories cannot be compared as they not only reflect different theories but also different systems of thinking. Thus, for example, Kuhn claims that one cannot understand the science of Aristotle through the conceptual prism of our contemporaries. This science can only be fathomed through the paradigm through which Aristotle and his contemporaries thought (Kuhn, 1962; Bird, 2000, 2004; Fuller, 2000). This chapter is primarily based on the thoughts of Rabbi Abraham Isaac HaCohen Kook (1865–1935) who served as Chief Rabbi of Israel and who does not approach the laws of science at the scientific research level, rather at the level of cabbalistic philosophy. Naturally, the doctrine that issues from this is different. This contrast serves as the dynamo behind Rabbi Kook's teachings, but also its weak point. This is its source of strength due to the fact that Rabbi Kook examines the theory of evolution through different conceptual spectacles, and this enables him to arrive at nonstandard insights. This is also the source of his doctrine's weakness, as the general public and, in particular, scientists view the laws of nature through the paradigm and accepted interpretation of scientific research. Rabbi Kook's paradigm is alien to them. As Kuhn posited, the members of the science community, the researchers and those who study from a particular paradigm, find it difficult to consider other paradigms as being of value (Kuhn, 1962; Fuller, 2000). It is certainly difficult for scientists to accept a nonconventional interpretation of findings unearthed by science from such a different paradigm such as the cabbala.

This chapter addresses the approach of cabbala to the issue of the contradiction between the laws of nature and its stringent and automatic mechanisms and the religious view of a creator and formative God.

Generations of scientists have led to the discovery of laws of nature and numerous mechanisms which are thought to govern the world. One of the high points of science was in the book of British physicist and mathematician Isaac Newton (1643–1727) Philosophiae Naturalis Principia Mathematica, which was published in 1687. The book, which laid down the foundation for classical mechanics, indicated that the movement of objects across the world and of celestial bodies is governed by a single system of fixed mathematical laws. A compact and precise explanation clarified innumerable natural phenomena. Newton turned the universe into an organized and understandable entity, subject to exact, consistent, and rational mathematical principles. Newton was convinced that his scientific work would enhance the glory of the Creator; however, the absolute laws of nature that emerged had a dismal effect on religious faith in the Christian world. The deterministic laws of nature which lie at the root of Newtonian physics did not leave any room for free will and, even though Newton considered his work as the work of God, the laws of nature he discovered were viewed as wresting control of the universe from God (Ferris, 1988).

A similar problem also subsequently emerged in the field of biology. The religious approach talks about a God who created and formed the world for His own purposes. Do the laws of nature not contradict the rule of God? Does the world not operate according to a fixed and stringent set of laws, or is it governed by the free intervention of the divine will? The two opposing approaches are expressed in correspondence between Charles Robert Darwin (1809–1882) and his good friend, the American botanist, Asa Gray (1810–1888). They had a lively exchange of letters, over a period of close to 2 years, about planning by the Creator compared with the random operation of fixed mechanisms. Darwin viewed the biological process as a mechanistic and incidental process based around natural selection (Hull, 1983; Dawkins, 1986; Ruse, 1996; Jones, 2000; Browne, 2002; Quammen, 2006). Darwin approached reality in a dichotomous manner: either there is an explanation for the phenomena of the laws of nature, or there is a God. If there is no natural explanation, there is a God. On the other hand, if there is a natural explanation, the reality of a God is superfluous, and there is no room for Him. Darwin did not see nature as offering evidence of planning (Burkhardt et al., 1993, Vol. 8, p. 496; Burkhardt et al., 1994, Vol. 9, pp. 267–8; Darwin and Huxley, 1974; Lovtrup, 1987; Bowler, 1989; Browne, 2002). Asa Gray understood the mechanisms to be an expression of the divine will in the design of the world and not as countering the natural theology (Brooke, 1985; Lovtrup, 1987; Bowler, 1989; Ruse, 1996; Miles, 2001; Browne, 2002). The perception of modern biology is sharp and uncompromising: the natural process is viewed as random, mechanistic, and purposeless, and seemingly in opposition to the religious view of a leader and supervisory Creator. These examples depict the question of the contradiction between the automatic and random laws of nature, and the religious belief which sees nature as being created and formed by divine providence.

The concept of randomness is interpreted in the Bible and the Talmudic scriptures in an entirely different way compared with the scientific meaning (Merzbach, 1989, 1996, 2009). According to the religious view, randomness is perceived as a situation in which divine leadership appears in incidental form. Not only does incident not express nonsupervision, but it represents the desirable form of its implementation.

There is no doubt with regard to Rabbi Kook's commitment to HAZAL and the biblical sources. Their view of randomness indicates the basis of Rabbi Kook's approach to the topic. As such, it appears that Rabbi Kook does not believe than any event occurs incidentally (according to the modern meaning of the word). He believes that every event has a planned purpose. Even events that occur based on random processes reveal providence, as we have seen in the Bible and HAZAL. In interpreting the words of the Talmud: "If a person is in a position to ask for mercy for his friend, and does not do so, he is called a sinner" (Babylonian Talmud, Brachot, p. 12 column B), Rabbi Kook explains that there is no coincidence, rather each event has an intentional purpose even, for example, when talking about a private event between two friends, when one of them has a problem, and various events led to the other learning about his friend's problem and he can pray for him. That is no coincidence; instead, there is a guiding hand and a purpose to the event or the chain of events (Ein Aya, Brachot, Vol. A, p. 66). And if that applies to a private individual, when referring to leadership of the whole world, there is certainly no coincidence. God's will is behind phenomena of coincidence.

This perception of Rabbi Kook raises the question of how his teachings explain the issue of the contradiction between the deterministic and random laws of nature, and the religious belief which views nature as being created and managed by the free divine will. In this chapter, I will aim to examine Rabbi Kook's perception in the context of this contradiction. Rabbi Kook extensively addressed the relationship between the fixed and random laws of nature, and the free divine will, and his individual supervision of reality. His perception seeks to reconcile the contradiction between the fixed and random laws of nature, and the free divine will, in the manner in which it clarifies the laws of nature. This chapter will focus on the perception of the laws of nature in the teachings of Rabbi Kook.

## 2. Divine Freedom and the Laws of Nature

The discussion with regard to the concept of randomness and the concept of active theological supervision is based on examination of a more general problem, of the relationship between the fixed and rigid laws of nature (the same law of nature applies to people and a clod of earth, and to a righteous person and an evil person), and the free divine will, and his individual supervision of reality. Jewish philosophy researcher Shalom Rosenberg presents Rabbi Kook's approach to this problem (Rosenberg, 1986, p. 326). According to Rabbi Kook, the world was created by divine free will, but fixed mechanisms and rigid laws of nature were also created in it. The deterministic necessity is evident and open in the existence, God's will is attributed to the infrastructure of the existence – and is concealed. A superficial view indicates that in material reality, there is only mechanistic determinism, while examination of the root of the reality reveals the free will of God (Shmona Kvatzim, 2, 118). The world is not a deterministic machine driven by absolute and all-powerful laws, as the deterministic system is operated by God's free will (Rosenberg, 1986, p. 330).

Jewish philosophy researcher Binyamin Ish Shalom compares this division into levels to the Kantian division into the world itself and the world of phenomena. In the world of phenomena, the mechanistic necessity and laws of nature rule, while the world itself is governed by divine freedom (Ish Shalom, 1990a, pp. 61–62; Ben Shlomo, 1989, p. 263). Jewish philosophy researchers Yossef Ben Shlomo, Tamar Ross, and Shalom Rosenberg firmly believe that, in Rabbi Kook's doctrine, the hidden freedom is not limited to man but is inherent to the entire universe. Freedom or free will is an ontological category, and man's ability to choose freely is only one of its expressions (Ross, 1982b, p. 41; Ben Shlomo, 1989, p. 262; Rosenberg, 1986, p. 330).This freedom – the ability to stray beyond the control of the laws of nature – appears to be rationally absurd as it contradicts the laws of nature that govern the world of phenomena (Ben Shlomo, 1989, p. 262). Nevertheless, freedom is the essence of the world and comprises the main force of the world (Shmona Kvatzim, 1, 788; Shmona Kvatzim, 2, 353; Shmona Kvatzim, 7, 99. See also: Yaron, 1974, p. 62; Ben Shlomo, 1988, p. 264, 1989, pp. 44–45; Gross, 1999, p. 33). Rabbi Kook's doctrine does not seek to forego the world's rational nature rather to guide man to investigate the entity of reality and to look into reality on its deepest level (Ben Shlomo, 1989, pp. 44–45).

The discussion about the relationship between the fixed laws of nature and the free divine will has another deeper, cabbalistic level which I shall address in the next section.

## 3. Divine Freedom and the Laws of Nature: Straight Line and Circles

Rabbi Kook identifies the problem of the laws of nature and the deterministic mechanisms vis-à-vis the free divine will with the cabbalistic issue which is known as "circles and a straight line" (Ben Shlomo, 1992, pp. 452–453, 1989, p. 43; Ross, 1982b, pp. 41–45; Rosenberg, 1986, p. 326; Pechter, 1987, pp. 79–80). Rabbi Kook, in the wake of some of the cabbalists (Pechter, 1987, pp. 79–80) [Rabbi Moshe Haim Luzzato (1707–1747), Rabbi Eliyahu Ben Shlomo Zalman (1720–1797), and Rabbi Yitzhak Isaac Haver (1789–1852)], explains the implementation of "circles" as the fixed and rigid laws of nature, which are identical with regard to man and any other item in the Creation. On the other hand, a "straight line" is the absolute divine freedom (Shmona Kvatzim, 1, 147). According to Rabbi Kook, reality is subject to these two seemingly contradictory forms of application. The application of the circles means the rule of absolute necessity of the laws of nature or, in other words, blind determinism for all value and moral causativeness (Ben Shlomo, 1989, p. 43; Ross, 1982b, pp. 41–45; Rosenberg, 1986, pp. 326–331;

Pechter, 1987, pp. 59–90; Ish Shalom, 1990b, pp. 91–92). On the other hand, the application of a straight line is the utilization of the divine will which operates with straight line and justice in the value and moral sense. Reality is subject to a contradictory rule: on the one hand, of the blind laws of nature and, on the other hand, of the free divine will. In practice, this is not a contradiction. The world appears to us as subject to laws without limitation and which cannot be avoided. However, in truth, behind this concept of reality as a system of circles, there is a straight line or the absolute sovereignty of the divine will:

> A straight line is the main component of existence, the circles are subordinate to it. In other words, freedom of life, absolute freedom, from the sources of existence, freedom in the divinity, whereby the formation of existence derives from the moral aspect, is all. …. Within the actual circles, within the essential laws of existence, within the rigid iron laws which do not change in their operation… in the inner plans of reality there is only a gradually evolving straight line, which leads to the attribute of the straight line and on its behalf. (Shmona Kvatzim, 1, 147)

The straight line, private moral conduct, also illuminates within the laws of nature (the circles). Even within the dark recesses of the most rigid causative necessity, the light of the free divine will shine (Ben Shlomo, 1989, p. 43, 1992, pp. 452–453; Rosenberg, 1986, p. 326; Pechter, 1987, pp. 80–81). Indeed, the laws of nature also indicate that they are a sort of Godly fingerprint, as the laws of nature are also the result of supreme freedom (Rosenberg, 1986, pp. 327, 329; Pechter, 1987, p. 81; Ben Shlomo, 1989, p. 43, 1992, p. 453).

Ben Shlomo and Ross note that, from the standpoint of Rabbi Kook, the application of the straight line, in other words, the freedom from the laws of nature and any limitations, constitutes a breach of the network of laws of nature to whose domination we are so accustomed, but this freedom is, itself, reality (Ben Shlomo, 1988, p. 262). The straight line and freedom are reality and the general framework, and they encompass the circles (the laws of nature) as a private phenomenon. What applies to the world equally applies to human beings. In a world that is subject to empirical experience, the category of causation appears to enjoy absolute dominance, and man does not have recourse to freedom of choice. In truth, man also contains circles and a straight line, and he also has freedom concealed by the total determinism of the laws of nature which, seemingly, controls the world. Moreover, it is man, more than any other creature of Creation, who discovers the freedom in Creation. In acceding to the divine will, and in adapting his personal morals to the divine morals, man can break through the blind laws of nature and divest himself of the yoke of the causative chain (Shmona Kvatzim, 1, 147; Shmona Kvatzim, 2, 5; Ross, 1982b, p. 41; Ben Shlomo, 1988, p. 262; Rosenberg, 1986, pp. 330, 328).

To summarize, the contradiction between the application of circles and the application of a straight line, in Rabbi Kook's view, represents the contradiction between the fixed and restrictive laws of nature and the free divine will. A straight line, or the liberated divine freedom, works clandestinely at the heart of the application of the rigid laws of nature (the circles). In a world that is subject to empirical experience, the causativeness of the laws of nature is seemingly dominant, although it is in fact freedom which is the reality and the general framework in which the application of the laws of nature takes place as a private phenomenon. As such, we have learned about the division of reality into two levels in the teachings of Rabbi Kook. However, Rabbi Kook takes another step in understanding this division, and I will address this in the next section.

## 4. Immanence and Panentheism

According to Rabbi Kook's view of the world, God is immanent to the world. The world and material, the physical processes and the cultural processes – everything that exists – has a soul (Ross, 1982a, b; Ben Shlomo, 1984, 1988; Ish Shalom, 1990a, pp. 55–57, 256; Schwartz, 1996, pp. 83–101). In other words, our world is not a material world which contains spiritual revelations; rather, it is a spiritual world in which the material world was also created. As such, secularity is one particular guise of reality. One can say, therefore, that secularity is spirituality in material form which conceals its spiritual content (Igrot Reaya, Vol. 3, p. 35; Ross, 1982a, b; Ben Shlomo, 1996, pp. 519–521). Referring to this concept, philosopher and researcher Natan Rotenstreich (1914–1993) notes: "… that, in fact, there is no world, only God. Not only is God omnipresent, but everything is present in God (Rotenstreich, 1950, pp. 275–276)." Ben Shlomo cites Rotenstreich and says that this interpretation views Rabbi Kook's doctrine as panentheism (Ben Shlomo, 1984, p. 298). Rabbi Kook rejected the pantheism of Spinoza who believed that everything is divinity and followed the pantheistic approach, "everything is in divinity"; "… all existence is contained in it (Shmona Kvatzim, 2, 93)."

This view of Rabbi Kook also differs from monotheism which looks upon God as a transcendental concept, which is outside the world and, as such, is remote and does not pertain to man and the world. Rabbi Kook related to the relationship between man and God as a perpetual bond (Shmona Kvatzim, 2, 79; Yaron, 1974, pp. 60–61; Ish Shalom, 1990b, pp. 55–54; Ross, 1982a, pp. 115–116). He believed that Jewish faith differs from the faith as expressed in "the accepted desolate and desert-like monotheismus" (Igrot Ra`aya, Vol. 1, pp. 47–48) in which he described God as being apart from the world and is being outside it, and this limits the concept of divinity and "neutralizes" the perception of faith. Rabbi Kook does not place man opposite God, as a separate entity and as impossibly compared with God, as such a comparison dwarfs and invalidates man and the world. He places man and the world within an immanent divinity which vitalizes them, galvanizes them, and gives their lives value by virtue of their connection with the vitalizing divinity (Yaron, 1974, pp. 60–61; Ish Shalom, 1990a, pp. 55–54; Ross, 1982a, pp. 115–116). As Ravizky notes, divine immanence is a living process and not a solely static element (Ravizky, 1999, p. 113). This approach takes man, the world, and the laws of nature and its mechanisms out of detachment from God into the power of the spirit of a bond with God (Shmona Kvatzim, 1, 95–96).

Random laws of nature are also not detached; they also are within and operate inside God.

The prior idea of pantheism is inferred in the Midrash: "It is the place of the world and the world is not its place" (Midra Adaga (Bobber) Exodus 33, 21; Sechel Tov (Bobber) Genesis 30, 13); in other words, God does not exist within the world; rather, the material world exists within God. The physical actuality "exists" within a divinity which brings it to life. This does not mean that the divinity is a place or physical substructure for the material existence rather that the material exists within the divine. The words of the Midrash infer an understanding that the world lives within a divine phase and is driven by the vitality in this phase. This means that the physical causation does not contradict the divine causation; rather, it is driven by its force. As such, in certain situations, the material world will act like a divine world and will demonstrate an ability to exceed the limitations of the material (Pechter, 1987, pp. 82–84). The concept of the divine as immanent to reality explains the fact that Rabbi Kook did not see the need to define holiness as being opposite to nature. He believed that secularity derives from the sacred. On the contrary, he viewed the need to battle nature as a method of sanctity which belongs to the age of the Exile (Orot, pp. 77–78). Those with a sharp perception will discern the divinity through the material guise:

> If you wish, man, look at the light of the shekhinah in the entire Universe, look at the paradise of the celestial life, how they fill every corner and angle of spiritual and material life, that are in front of your physical eyes and your mind's eye. Look in wonder upon the creation, in their divine life …. (Shmona Kvatzim, 1, 181)

The great work actually lies in raising nature up from the secular to the sacred, and in restoring it to its role as a basis for holiness (Olat Ra'ay, Vol. 1, p. 82; Shmona Kvatzim, 3, 66; Ben Shlomo, 1996, pp. 499–500). According to Rabbi Kook, from the outset the Torah channels man's deeds and actions in accordance with the deep and hidden roots of reality which are an expression of the immanent divinity and not based on the revealed layer of reality. These actions – the commandments – impact on the development of reality and build it up (Shmona Kvatzim, 1, 626; Shmona Kvatzim, 1, 233), as well as forming and developing the person who carries them out and enhances him to realize his ability (Hazon Hatzimchonut Vehashalom, p. 30). The commandments are not always understandable, precisely because they derive from the spiritual infrastructure and not from the familiar physical world (Hazon Hatzimchonut Vehashalom, p. 34).

In other words, according to Rabbi Kook's teachings, the entire world hovers within the divinity which grants it life and direction. Incidental mechanisms and blind laws of nature, indeed, function in life; however, they exist within the divine phase which drives and guides them. There is a difference between the general system and the private mechanism which functions within it. A similar division between the system and the particle that functions in it also appears in quantum physics. The uncertainty principle was devised in 1927, by German physicist Werner K. Heisenberg (1901–1976). The principles determine that it is impossible to know precisely the speed (or the momentum) and the location of the particle.

The more precisely we measure the position of the particle, the less exact the measurement of the speed and vice versa. The uncertainty principle is a fundamental attribute of the world and does not result from inaccuracy (the uncertainty principle also applies to other pairs of sizes, such as time and energy). Thus, on the level of the individual particle – the microscopic level – there is uncertainty. Even so, there is certainty on the macroscopic level, and it is possible to know the precise speed and location of a plane or a ball. So we see that, even though the individual particle is subject to uncertainty, on the system level, certainty does exist (Feynman et al., 1965).

If we return to Rabbi Kook's approach, the laws of nature and its mechanisms are blind in the moral sense, but they exist within a guiding divine system. The system provides the meaning and significance. It is because of this, says Ish Shalom, that as long as man ignores the mystic-divine dimension in reality, he will not succeed in explaining the meaning of existence and the meaning of nature. The world of nature and its laws and incidental mechanisms can only be explained through what lies beyond the material and concrete (Ish Shalom, 1988, p. 299).

## 5. Straight Line and Circles: Two Levels of Reality

Rosenberg and Ish Shalom note that one can "position" the division into straight line and circles in the cabbala and according to the teachings of Rabbi Kook. The closer reality is to the higher worlds, the less circles dictate and control while a straight line is more active and more dominating. In other words, leadership of the world lies less in the hands of rigid incidental mechanisms and more with the free divine will. We will not find the circles in the higher cabbalistic spheres, only the straight line (Shmona Kvatzim, 2, 117, Rosenberg, 1986, p. 327 footnote 11; Ish Shalom, 1990a, pp. 91–92). The closer man is to the divine world, the freer he is from the operation of circles, in other words, from the laws of nature and its mechanisms, and is lead more by the straight line, private operation based on its actions (Ein Aya, Brachot, Vol. 1, p. 56). This means that the main factor that leads the individual person or the public to the application of a straight line or of circles is the level of recognition or the level of insights of the person (Shmona Kvatzim, 1, 678). There are two separate levels of recognition. On the first, man engages only on the levels of the circles, in other words the laws of nature and its rigid and incidental mechanisms, and does not see anything beyond them. Rabbi Kook calls this situation "low wisdom." This wisdom should not be denied – all of empirical science is on this level – even though it is low level wisdom. On the second level of recognition, man also perceives the reality of the operation of a straight line. He is aware of the existence of the application of circles, but even more aware of what exists above it – the operation of a straight line. This application sometimes operates clandestinely, within the operation of circles, and sometimes overrides the operation of circles in a situation which we call "a miracle." Ish Shalom notes that a great degree of freedom is required in order to break out of the narrow frameworks of rational thought in order to perceive the whole picture.

The higher dimension of operation of a straight line, alongside the lower level of the operation of circles, comprises the restoration of the human will and human freedom to its source – the divine will and freedom (Ish Shalom, 1990b, p. 255; Rosenberg, 1988, p. 32; Pechter, 1987, p. 84). As such, Rabbi Kook's view of nature is ambivalent. He believes that man has to learn the forces and order from nature but free himself of the absoluteness of the operation of circles and from the moral blindness and wildness of nature:

> We will take from nature its courage, its resoluteness, persistence and perseverance, its moderation and the confident position manifested in its visions of itself. However, we will free ourselves of its blindness, wildness, its factual necessity, the negation of its intent and the lack of idealness. (Shmona Kvatzim, 3, 240)

Rabbi Kook does not reject the laws of nature and its mechanisms, instead calls for man to understand these laws and mechanisms from a viewpoint that annuls the detachment between the world of nature and the metaphysical world within which it exists. This call frees the human perception from the moral blindness of the natural world, as it is perceived through the operation of circles.

On this point, Rabbi Kook addresses the question of contradiction between the incidental and directionless mechanisms, and the will of the formative and creator God. Scientists examine the laws of nature and generally see in them the appearance of everything. Rabbi Kook argues that, while there are incidental laws of nature and incidental mechanisms, they do not dominate! These mechanisms are private phenomena within the framework of the will of the free God – the operation of a straight line. Ultimately, the laws of nature and its mechanisms are an expression of the will of God. The hidden straight line is the true ruler! – a truth that incidental and blind mechanisms and laws govern the world. However, the blind mechanisms are administered by the divine will which gives them a degree of control in the revealed world. The incidental mechanisms are revealed but do not reflect absolute reality. The incidentalness that appears in mechanisms and laws does not infer that the entire system is incidental and directionless. Orderly and oriented systems also contain incidental components. Orderly and precise computer programs (algorithms) also sometimes require the introduction of a random component to the system. There are problems (such as the problem of "the dining philosophers") whereby the software reaches a state of stagnation in the accepted solutions, and the computer is unable to accommodate the solution. In order to overcome such problems, there are algorithms that introduce randomness to the system. The insertion of a random element into the software frees the software from stagnation and allows the computer to reach the solutions. The element of randomness helps the system attain the desired goal – the random mechanism – while the system is goal-oriented. The random factor does not make the system random (Harel, 1992, pp. 309–316). From the standpoint of Rabbi Kook, the divine will which is immanent for the world is the true and absolute reality but is not revealed by superficial consideration (Rosenberg, 1988, p. 327). It is only when we penetrate the interior of reality that we also discover the free divine will.

Thus, we see that there are two separate levels in reality and that the differentiation between them is not absolute. In other words, the wider level comprises a basis and infrastructure for the level that exists within it. The straight line is the basic level, and the circles are the level that exists within straight line. Straight line, as a foundation level, contains the circles. People heading in different directions apparently proceed in different directions. However, when people move inside a plane in flight, the direction of the plane is the absolute direction of the people's movement. Walking moves people but this movement forms part of the main direction of movement, which is the direction of the flight of the plane. This also applies to the operation of circles. The laws of the world of nature and its mechanisms act and impact, but within the main platform of reality – the operation of straight line – which comprises an infrastructure for leading reality.

There is no contradiction between the free divine will and the rigid laws of nature as they do not operate on the same level. The perception of man determines the level of supervision on which he operates – whether on the circle level, which is the level of the determinist laws of nature, or on the level of straight line which reveals that there is no determinism in the material world, or on any intermediary level. The more spiritual his perception and understanding, the more he moves away from the operation of circles and moves closer to the operation of straight line. Science examines reality on the level of the mechanisms and laws of nature and believes that the laws of nature govern everything. Rabbi Kook looks at reality from the level that precedes the laws of nature. He found that the operation of straight line governs and grants a certain space of governance for the determinist laws of nature.

Rabbi Kook's principal innovation on this matter is that there is no contradiction between the mechanist perception of reality and the approach of religious belief. This is not a matter of contradictory approaches, rather different levels of the same reality. Rabbi Kook's view of the random mechanisms derives directly from his perception of panentheism: everything lies within God and there is no existence outside God. Thus, there are mechanisms and laws of nature, but they do not contradict divinity. They do not lie outside God, rather they lie within God. This does not comprise negation of the mechanisms that represent the operation of circles; instead, this refers to their giving within a wider causative framework in which the dominant factor is straight line – the divine free will.

I will attempt to convey Rabbi Kook's explanation. A well-known story about the Haffetz Haim – Rabbi Israel Meir Hacohen Cagan from Radin (1838–1933) – one of the most important rabbis of the pre-Holocaust generation, relates that he arrived at a train station on his way back to his hometown of Radin and discovered he had no money to pay for his train ticket. He sat there in the station and prayed for help. Another inhabitant of Radin also arrived at the station, to return to the city, and he asked the Haffetz Haim why he was not boarding the train. The Haffetz Haim replied that he did not have money to buy a ticket. Why then, he asked, was the Haffetz Haim waiting on the bench next to the train? I believe that God will help me and everything will be alright, came the reply. The man boarded the train after buying a ticket and sat and watched the Haffetz Haim, to see if God was really going to help him. But nothing happened. Just before the train set off, the man had pity on him and bought a ticket for the Haffetz Haim. When he got home, the man told his wife about what had happened to the Haffetz Haim and added that God had not helped him. If I had not bought him a ticket, he would have stayed there forever. The Haffetz Haim also told his wife about what had happened: "At the station I discovered I had no money for a ticket. I prayed that everything would work out and just before the train left the station a man who knows me bought me a ticket."

Each of them gave the event his own, contrasting, interpretation. The donor saw his deed as detached from the divine leadership. The Haffetz Haim perceived that man's deed as part of the complex of divine leadership. On the mechanism level, the donor was right. He loaned the money for the ticket and, thus, he made the trip possible. However, this perspective is only accurate if a person or a mechanism sees themselves as a force within themselves, and not as a component of a larger system. Penetrative understanding is required for a person to perceive himself as a component in an expansive system. A person who has penetrative understanding perceives the system and his own standing within it, and he also sees the position of the mechanisms within the system. As aforesaid, according to Rabbi Kook's view, divine immanence in the world incorporates all the mechanisms and laws of nature. All of nature and its laws exist within the divine will, and the free divine will that leads reality can be found among their actions.

Shmuel Hugo Bergman (not as a commentary on Rabbi Kook) makes it clear that the believer does not intend to say that God's intervention replaces natural causes. The chain of natural causation is only a perspective of actuality, in other words, its affect. This is not to say that the will of God is on the same level as the causes and mechanisms or the material world. The man of science attempts to describe and explain the phenomena. The believer, on the other hand, wants to understand the meaning of the phenomena (Bergman, 1945, pp. 96–97). Bergman demonstrates the position of the believer in citing British astrophysicist Arthur Stanley Eddington (1882–1944) who described a person from another planet. The person visited Earth on the day on which the First World War armistice took place, on November 11, 1918. The noise of the cities abated for 2 min silence in memory of those who died in the war. In physical terms, everything took place in accordance with the laws of nature. The brakes stopped the carts and vehicles, the brake was operated by a foot that was activated by a muscle, etc. However, this description does not express the significance. The visitor from another planet would have missed the important part, even with the physical description – that the silence expressed the collective sadness for the five million people killed in World War I (Bergman, 1945, pp. 63–64).

In summary, Rabbi Kook examines the mechanisms of nature on two levels. On one level, there are blind and directionless mechanisms, but they are only a single organ in reality, and not its exhaustive description. The mechanisms and laws of nature were given power. However, one should not conclude from the automatic mechanisms in nature that nature is entirely automatic (Rosenberg, 1988, pp. 341–345; Ben Shlomo, 1988, p. 264). The second, main, level is the entire system that incorporates all the mechanisms and guides them. The mechanisms appear to be driving reality, but they do not lead, rather they are led. The mechanistic mechanisms operate within the wider metaphysical framework. A wider view of the entire system reveals that the blind mechanism is also not really blind, rather operates in accordance with the purpose of the divine will (Ben Shlomo, 1988, p. 264).

## 6. The Christian Theism

This is the place to examine the fundamental difference between the Jewish perception and the theistic Christian approach. This chapter cannot accommodate extensive discussion of Christian theism. I will only note the approach of American scientific philosopher and historian David Lee Hull to the relationship between God and the physical world. As noted by Hull, the theistic Christian approach (theism) could not accept a picture of the world such as that put forward by Rabbi Kook, as the Christian approach related to God as an active causative factor in the physical world. This was a view held not only by theologians but also by leading Christian scientists such as George Cuvier (1769–1832), Richard Owen (1804–1892), and Swiss-born American biologist Jean Louis Rodolphe Agassiz (1807–1873) (Hull, 1983, p. 74).

This Christian view, which related to God as an active physical force, created a theological problem with the discovery of the laws of nature and, in particular, with the discovery of natural selection. Charles Darwin also perceived the Christian god as a physical causative force which acts on the level of the material world and thus competes with the natural selection explanation. As such, Darwin saw a contradiction between faith in a supervising and guiding God and belief in the fixed laws of nature:

> If we assume that each particular variation was from the beginning of all time preordained, the plasticity of organization, which leads to many injurious deviations of structure, as well as that redundant power of reproduction which inevitably leads to a struggle for existence, and, as a consequence, to the natural selection or survival of the fittest, must appear to us superfluous laws of nature. On the other hand, an omnipotent and omniscient Creator ordains everything and foresees everything. Thus we are brought face to face with a difficulty as insoluble as is that of free will and predestination. (Darwin, 1868, Vol. 2, p. 432)

David Hull notes that the law of evolution ended use of God as a causative factor in scientific explanations (Hull, 1983, p. 63). Hull does not adequately stress the fact that Darwin found it hard to believe in God after discovering natural selection, precisely because he believed in God as a causative factor in the material world in the wake of Christian theism. The perception of God as a causative factor in the physical world created the religious problem, rather than the objective contradiction between natural selection and religious belief per se.

## 7. Conclusion

The rigid laws of nature appear to comprise a contradiction to the free rule of God. In fact, Rabbi Kook does not perceive a contradiction between natural selection and the work of God. He believes that the world was created by the free divine will, but that fixed mechanisms and rigid laws of nature were created within it. It would be a mistake to conclude from the random mechanisms that the whole of reality is random and directionless. The mechanisms are also driven by the force of the divine will.

This approach has another level. Rabbi Kook offers a spiritual image of reality. According to his view, our world is not a material world with spiritual revelations, rather a spiritual world within which the material world was created. This panetheistic school of thought, according to which reality floats within divinity, offers another level to the understanding that both the laws of nature and the mechanisms of nature exist within a guiding divine phase.

Rabbi Kook identifies the problem of rigid laws of nature vis-à-vis the free divine will, with regard to the cabbalistic issue known as a problem of "circles and straight line." The operation of "the circles" represents the fixed and rigid laws of nature, and the implementation of "the straight line" represents the absolute divine freedom. There is no contradiction between these two. Freedom is reality and the general framework within which the operation of the laws of natures takes place as a private phenomenon. The random mechanistic activity takes place within a metaphysical system which guides the mechanisms. This system is not random. Based on a view which only takes in the mechanisms, the behavior appears incidental, while a view of the entire system indicates that the activity is not random. The random laws of nature and the random mechanisms do work, but they are not in control! Ultimately, they too are an expression of the divine will. From Rabbi Kook's point of view, the divine will, which is immanent for the world, is the true and absolute reality. Rabbi Kook is not concerned about the mechanism of nature's mechanisms. As everything exists within God, there is no existence outside God. Thus, there are mechanisms and there are laws of nature, but they too do not exist outside God, rather inside Him. The activity of these laws and mechanisms express the divine will.

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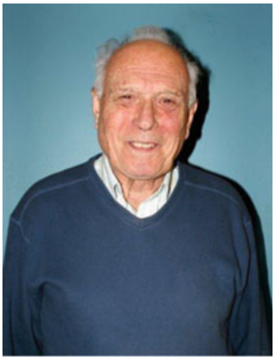
Biodata of **Klaus Konrad Klostermaier**, author of "***The Identity of Designer and Design***."

**Klaus Konrad Klostermaier**, **F.R.S.C**. is university distinguished professor emeritus (1999) at the University of Manitoba. He obtained a Dr. Phil. in Philosophy in 1961 from the Gregorian University/Rome and a Ph.D. in Ancient Indian History and Culture from the University of Bombay (now: Mumbai) in 1969. He joined the Department of Religion at the University of Manitoba (Canada) in 1970 and held the headship from 1986 to 1997. His areas of research and teaching are history of religions, especially Indian religions, and science and religion. He received in 1972 the "Rh Award for Outstanding Contributions to the Humanities," the 1981 Graduate Students Award "For Excellence in Graduate Teaching," and in 1995 a Templeton Course Award for a graduate seminar in science and religion. He was also the founder and director of the University of Manitoba's Centre for Asian Studies (1990–1995). Among his major publications are *Mythologies and Philosophies of Salvation in the Theistic Traditions of India*, Wilfrid Laurier University Press (1984); *A Survey of Hinduism* (1989, 1995, 2007) State University of New York Press; *Buddhism: A Short Introduction*, Oneworld Oxford (1999 and 2001); *Hinduism: A Short History*, Oneworld Oxford (2000); and *The Nature of Nature: Explorations in Science, Philosophy and Religion*, Theosophical Publishing House Adyar/Madras (2004). He contributed "Ecology, Science and Religion" to *Seaweeds and Their Role in Globally Changing Environments*, ed. Alvaro Israel, Rachel Einav, and Joseph Seckbach; Springer (2010).

E-mail: **kklostr@cc.umanitoba.ca**



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# THE IDENTITY OF DESIGNER AND DESIGN

**KLAUS KONRAD KLOSTERMAIER**
*Department of Religion, University of Manitoba,*
*Winnipeg, MB, Canada*

> *The reason, why our sentient, percipient and thinking ego is met nowhere within our scientific world picture can easily be indicated in seven words: because it is itself that world picture.*
>
> – Erwin Schrödinger

## 1. Introduction

One of the major problems when addressing an issue like the *Origin of Design in Nature* concerns the widely different understandings of key words, such as nature, knowledge, origin, etc. Whereas the humanities have often retained the meaning of these terms as defined by classical philosophy, the sciences are using the same terms in a different and frequently reduced sense.

Take the word "nature." Originally *natura*/*physis* comprised all reality that was not "artificial," i.e., human-made. Modern science reduced the meaning to the ensemble of material entities that can be perceived by the senses and/or their extensions, human-made instruments. Thus, the online encyclopedia *Wikipedia* offers the following definition: "Nature in the broadest sense is equivalent to the natural world, physical world, or material world." This definition reflects a widespread but unwarranted reduction in meaning that has no basis in the history of the word "nature." Nature in the traditional sense embraces also human nature: the human body as well as the human mind. Nature thus includes not only objective matter but also subjective consciousness. We humans – and possibly other beings endowed with consciousness – are part of nature.

Similarly, the word "science": beginning with Latin *scientia*, all its derivates in modern languages were originally used to describe knowledge in its widest sense – be it of natural objects, of history, or of metaphysics. Today "science" is almost exclusively understood as "natural science." Its archetype is physics, which attempts to encompass the universe by means of mathematical formulas describing the movement of particles of matter. Other disciplines are vying to come close to this model in order to adopt a "scientific" character. "Objectivity," measuring, testing, and producing statistics – the hallmarks of science – were also applied to the study of humanity in psychology and sociology with the implicit understanding that these yielded the (only reliable) truth about humans. However, the humanities also offer genuine knowledge through other methodologies: the intuitive insights of great thinkers past and present certainly deserve the predicate "knowledge." They express existential truths that are an important complement to the objective truths of the modern sciences. It is widely accepted today that also the great discoveries in the sciences are triggered by intuitions and not by objective measurements.

Wonderment is, according to Aristotle, the beginning of philosophy. At all times people have been looking with wonderment at nature. While it seemed for a while that science had demystified nature and replaced wonderment with scientific explanations, the exploration of nature offers ever more wonderment. The greatest of all wonders is that the universe and everything in it exists. Humans have always wondered: Why are we here? Many are the answers that have been given, but basically there are two sets of responses that one can find throughout history:

(a) A super human mind brought the universe at a particular point in time into existence and fashioned the various creatures.
(b) Impersonal forces immanent in the universe are responsible for the evolution of all of nature, entirely ruled by chance.

Clearly, it is not possible to decide between these two alternatives on the basis of the findings and the methodology of any particular science. Scientists who choose one of the two options do so, on philosophical or religious grounds.

## 2. Chance and Necessity

Jacques Monod, the great French biochemist, prefaced his *Chance and Necessity* (Monod, 1972) – subtitled "An Essay on the Natural Philosophy of Modern Biology" and claimed to offer an "explanation of the universe without causality" – with quotes from two famous philosophers: the first is ascribed to Democritus (460–370 BCE) and the second to Albert Camus (1913–1960). The Democritus quote: "Everything existing in the Universe is the fruit of chance and of necessity," apparently supplied the title to Monod's essay. When searching for the source of this quote – after all, Democritus wrote in Greek and not in French or English – I consulted Herman Diels, the acknowledged authority (Diels, 1960). The text that comes closest to the quote reads:

> ουδεν χρημα ματεν γινεται
> αλλα παντα εκ λογου τε και υπ ανανγκησ

The quote, incidentally, is ascribed by Diels to Leukippus, not to Democritus. It appears on the top of the page where the section on Democritus begins – Monod may have mistakenly assumed it to be a Democritus quote. A literal translation of the sentence would read: "Nothing comes into existence in vain, but all through λογοσ and under ανανκη."

The Greek word λογοσ has many meanings: word, reason, number, proportion, etc. *Chance* is certainly *not* one of these. ανανκη too can be translated variously as fate (it is the name of the Greek goddess of Fate), necessity, lawfulness, force, need, torture, etc. The most one could read out from the Greek sentence is that the author assumes that whatever exists has a reason to exist and that it obeys some (unchanging) laws.

A genuine Democritus fragment that comes close to the above reads:

> παντα γινεται δι αναγκησ θειησ
> "All comes into existence according to a divine lawfulness."

An oft quoted saying ascribed to Democritus is: "In reality we know nothing: for truth dwells in the depths." Democritus would certainly not support Monod's opinion that today's science is "defining a new and unique source of truth" including a "total break with the animist tradition."

It is certainly commendable that scientists connect their own particular insights with larger philosophical ideas, but they should not exempt themselves from the painstaking philological work of correctly translating ancient texts into modern languages and should not twist their meanings to suit their own ideas.

Another, related issue, is the proliferation of specific meanings given to generally used words. Almost every writer on "design" or "chance" introduces his or her new definition of these terms.

There is also a tendency – noticeable among scientists and nonscientists – to consider their own pet theories as commonly accepted truth. To choose but one recent example pertinent to our topic: In *Matter and Consciousness*, philosopher Paul Churchland forcefully asserts: "According to the broad and growing consensus among philosophers and scientists, conscious intelligence is the activity of suitably organized matter, and the sophisticated organization responsible for it is, on this planet at least, the outcome of billions of years of chemical, biological, and neuro-physiological evolution" (Churchland, 1984, p. 147). The study of "matter" is traditionally the field of physics. Hans-Peter Dürr – a highly regarded contemporary physicist – once observed: "What matter is made of, is certainly not matter." We simply do not know what "matter" is – notwithstanding the free use of the word – and we cannot take any arbitrary definition of it as foundation for our notion of reality. Consciousness can no longer be explained by what has been called matter.

Following in the footsteps of Monod, Richard Dawkins – today's most widely known advocate of "chance" (supplemented by "luck") – uses this term to propagate a materialistic theory of everything. However, to explain the evolution of complex entities like living organisms (ourselves included) by "chance" is simply an evasion of the question. "Chance" may be a quite meaningful word to use when flipping coins or playing at a lottery. But it is meaningless in the context of the origin and the evolution of the universe. Before a coin can be flipped, there has to *be* a coin. While it could be called "chance" whether one gets head or tail when flipping a coin, the coin itself did not originate by chance: it is the outcome of purposeful activity of human beings, applied to a piece of already existing metal. Nothing is left to chance in the creation of a coin, requiring the cooperation of several intelligent specialists.

What would entitle us to assume that such a complex and mysterious entity as the universe as a whole and all the beings it contains could be the outcome of "chance?" Does the word chance not lose all meaning when applied in such a context? Whatever we know about evolution – whether it concerns solar systems or living organisms – it operates on something that was already there.

The famous question: "Why is there something rather than nothing?" cannot be satisfactorily answered with a reference to "chance." Chance does not explain anything. It is a cover-up for ignorance. Advocates of "it all happened by chance" remind one of children in a well-to-do home. Whatever they need and want is "there." The question is not "*is* there *something* to eat today?" but only "*what* do we eat today?" From the standpoint of the children, the "*what* do we get to eat" is left to "chance." They take it for granted that there *is* something to eat. Their parents, however, had not left that to "chance" but had to buy the food and plan the meal and get it prepared by someone. Not even a simple lunch can arise by chance – how could an immensely complex universe?

## 3. "Creationism" Old and New

The most vocal opponents to the notion of mere chance are people who trace the existence of the universe back to a superhuman intelligent Creator. There are creation stories in virtually all historic cultures: some are very naïve and simple and some are very elaborate and sophisticated. The Hebrew *Bible* begins with a poem that contains a short creation story with a larger-than-life personal Creator God. The Sanskrit *Vishnu Purana* explains in great detail and with the use of a complex philosophical terminology how the present universe came into being. The Bible story is a fairly simple tale and can easily be proven wrong, if taken literally. Astronomers, archaeologists, and biologists have established a timeframe and a sequence of events quite different from the old creation myths.

"Creationism" comes in many varieties. It can be associated with a naïve fundamentalism: the belief in the literal truth of every word of the Bible or the Quran – even in their English translations! Educated persons, realizing the impossibility of a literal reading, use metaphorical and allegorical interpretation of these scriptures. Attempting to combine scientific findings with a Creator God, scientifically informed believers accept the findings of the sciences with regard to the gradual evolution of the world over long spans of time but insist that this took place under the direction of an all-wise and omnipresent deity. The sophistication of the natural world in every detail and the organization of the cosmos as a whole as well as its dimensions are powerful arguments in favor of creation by God.

## 4. Intelligent Design

When the natural sciences experienced their first flourishing in eighteenth century England, William Paley, the Anglican divine, composed *Natural Theology*, a book that was read by several generations of students, including Charles Darwin. In it he suggested that – as someone, finding a pocket watch lying on a heath would automatically associate the watch with the work of a human watchmaker – we must assume that the existence of something as complex as the human eye, so much more "artistic" in its makeup than a human-made watch, would lead to the conclusion that an intelligent Creator had conceived it.

Evolutionary biology has somewhat weakened the force of that specific argument by documenting the stages of the development from a light-sensitive cell to the complex construct of the (human) eye. There are other instances that seem to suggest supernatural intelligent design. Michael Behe, the best-known contemporary defender of ID, believes to have found the evidence for ID in the "irreducible complexity" of the working of a living cell as well as in the bacterial flagellum. By its opponents, ID has been branded as a variety of creationism and rejected as "unscientific."

The so-called anthropic principle could be considered a form of ID. Its proponents point to the astonishing "fine-tuning" of the universe: some two-dozen basic physical parameters are calibrated to within incredibly small tolerances to make the existence of our universe possible. Out of trillions of possible variants of natural constants, only the ones that are existing in our universe made the emergence of beings like ourselves possible. The "chances" that the proportions between the "building stones" of the universe and the laws that govern them would be suitable to creating out universe are virtually one to infinite.

## 5. "Emergence": A New Science?

The crude materialism of the nineteenth century has been largely given up and with it also the attempt to explain all phenomena by a top-down schema of the sort: living organisms are nothing but an ensemble of specific molecules and chemical reactions, molecules are nothing but assemblies of specific atoms, atoms are nothing but the assembly of protons and electrons, and sooner or later we will also find out that these subatomic particles are nothing but the combination of ultimate particles, oscillating "strings," the basic building blocks of everything.

Parallel to the search for the most elementary particles of matter, a new type of research is flourishing: complexity research. It rests on the insight that knowledge of the properties of atoms does not provide us with information on the properties of the molecules into which they combine. In a wider context, it also means that physics and chemistry are not sufficient to explain life. Complexity research speaks of the "emergence" of new qualities that cannot be derived from the knowledge of its components. The properties of water cannot be deduced from the study of hydrogen and oxygen, and the shape of a flock of starlings cannot be predicted from a study of the bodies of individual birds that make up the flock.

"Emergence" forms also the backdrop to the most recent attempts to reconcile science and religion. An immense literature has already grown around the topic. One of the latest is a volume jointly edited by the theologian Philip Clayton and the physicist Paul Davies: *The Re-Emergence of Emergence: The Emergentist Hypothesis from Science to Religion.* It has sections on physics, biology, consciousness, and religion (Clayton and Davies, 2006) The volume not only gives evidence of the wide application of "emergence" but also for the many different ways, the term is understood today by various authors.

In a very broad sense, the traditional (religious) notion of "creation" could be seen as "emergence," and the "emergence" of new, unforeseen properties arising from the merging of individual entities into a unity could be interpreted as "creativity." However, the classical Christian [biblical] concept of a *creatio ex nihilo* could not be maintained in that way. Thomas Aquinas, in Summa Theologica 1, 4, 5, offers the classical definition in these terms: *Creatio quae est emanatio totius esse est ex non-ente, quod est nihil.* ["Creation, meaning the emanation of the entire existence, is out of non-being, which is nothing."] Today's science would not accept a "nothing" as the source of the cosmos and its evolution. It speculatively accepts an endless succession of universes.

## 6. A Critical Look at Chance, Creationism, Intelligent Design, and Emergence

(a) In the light of the latest findings of contemporary physics concerning the nature of matter, crude materialisms of any kind cannot be taken seriously as explanatory devices of the universe as we know it. "Chance" does not explain anything either. It is at best a descriptive term that is applicable to certain processes, but it is misapplied in the context of the origin of either the universe or of design in nature. Mathematicians have calculated that the entire history of the universe is not long enough to create a single bacterium by pure chance, not to speak of more complex organisms like ours. To refer to "chance" as the cause of anything is simply avoiding the question, not a solution. Paul Churchland's thesis that we have to accept, and live with, the ultimate insight that everything – including our personal consciousness – is the result of matter organizing itself "by chance" is both unscientific and unwarranted. It oversteps the boundaries of what science does or can find.

(b) In matters that can be objectively examined, such as the material composition and structure of organisms, the records of paleontology, the number and distribution of galaxies, etc., we must give the last word to the sciences and we have to abandon earlier poetical or theological views. A fundamentalist creationism that rests on the authority of a naïve literal reading of an ancient text – regardless in which language it is written – cannot expect to be taken seriously today. However, there are also more sophisticated versions of it. Darwin, while believing that all life "evolved" from one original entity, still held that it was the Creator "who breathed life into the first living being."

(c) Intelligent design appears to be a slightly modified creationism, moving the hand of the Creator to specific points in the history of evolution. It also is strongly anthropomorphic: it suggests the image of an engineer in a construction bureau who draws a blueprint for a construction that is then transferred onto materials, such as the design of a chassis of a motorcar that then goes into mass production. Apart from the intrinsic flaw that such an explanation suffers from, there is one feature of "real nature" that does not fit into the picture of ID: the fact (!) that each organism – from the tiniest bacterium to the most massive animal – is unique and not an identical copy of an "original design."

(d) "Emergence theory" cannot explain the origins. Nothing could "emerge" if there was not something to begin with. The properties of water could not emerge without the preexisting hydrogen and oxygen. Life could not "emerge" without a great deal of already existent materials. While "emergence" as such cannot be denied, it does not explain anything either: It is descriptive, not explanatory. We are not told why something emerges, only informed that something emerged that could not have been predicted.

## 7. The Identity of Design and Designer

Emergence has been defined as "self-organization of discrete elements." If the *self* in the *self-organization* is not a meaningless cipher, it must have some identifiable sense. Obviously, we do not assume a "ghost in the machine," i.e., a new and strange additional entity that takes hold of the physical elements concerned. In everyday language, the word "self" is used to identify a subject over against objects. Referring to my "self" I mean to say that I consider myself an individual different from other individuals. Humans living in societies share many features, but over and above all these, each human is also a noninterchangeable self. When a number of chemical elements *"self*-organize," a subjective element is introduced into the objective world: the resulting entity is more than the sum total of the properties of all the constitutive elements put together by some outsider agent. It does suggest an overarching "subjective process" – a "self" that organizes the universe in every part and as a whole.

(a) While traditional, prominently biblical notions of a Creator God have been eliminated from scientific discourse, other more impersonal "creation" ideas have been brought into the discussion. Ervin Laszlo operates with the ancient Indian notion of *akasha*/'ether' and identifies it with a plenum of information (Laszlo, 2007). Erwin Schrödinger used the language of the Upanishads as interpreted by the medieval Indian sage Shankara: he assumed an omnipresence of consciousness and a radical distinction between objects, created by *maya,* and the subject: *atman/Brahman*. Nature has a dual identity: it is both a subject and an object. And nature is One: it is designer and design. Designer and design are one and the same – it is only our (wrong) perspective, the assumption of an identity of individualized perception and reality, that makes us differentiate between them.

(b) There are numerous Indian texts that presuppose and proclaim the identity of designer and design, from the popular *Bhagavadgita* to the *Upanishads* and the writings of the great *acaryas.* The *Chandogya Upanishad* (VI, xii, 1f) explains it with the help of an experiment, through which the philosopher Aruni attempts to teach his son Svetaketu the true nature of the *atman*: Aruni asks Svetaketu to pluck one of the small fruits of the huge Nyagrodha – the Indian fig tree – and asks him to divide it:

> "What do you see there?"
> "These rather fine seeds."
> "Divide one of these! What do you see?"
> "Nothing at all."
> "Verily, my dear: that finest essence, which you do not perceive from that this great Nyagrodha tree arises. That which is the finest essence – the whole world has that as its self. That is the Real. That is the Self: That *you* are!"
>
> – Radhakrishnan-Moore (1957)

In another passage, Aruni says: "The Self is below. The Self is above.The Self is to the west. The Self is to the east. The Self is to the south. The Self is to the North. The Self indeed is the whole world. I indeed am below. I am above. I am to the West, I am to the East, I am to the South, I am to the North: I, indeed, am the whole world" (ibid., p. 72).

In a more drastic form, the teaching is conveyed in the 11th chapter of the *Bhagavadgita*, where Arjuna is made to see the *vishvarupa* of Krsna – a vision of the universe compressed in time and space (ibid., p. 138 ff).

The most systematic elaboration of this view has been made by Ramanuja (1017–1137) in his commentary on the *Bhagavadgita*: "This entire universe, composed of spiritual and non-spiritual entities, is pervaded by God who is its inner ruler. God pervades the spiritual and non-spiritual entities of this universe by being their inner ruler, and He does so in order to reign and maintain them, although they themselves are unable to see him. In this way all beings depend on God because they constitute his body. But God does not depend on them form they serve no purpose in maintaining His being; nor does God contain these beings like a jug contains water. How then, does God pervade them? By virtue of His will! It is His will, which originates, sustains and rules the beings. … Not only the maintenance and activity but also the origination and annihilation of all beings depend on the will of God. At the end of Brahma's life all beings will in obedience to God's will dissolve in the *prakrti,* which constitutes God's body and in which no individual distinctness by name-and-form can possibly exist; and at the beginning of a new *kalpa* God creates these beings anew" (Van Buitenen, 1963).

A similar view seems to have been held by some American Indians. As the environmental philosopher J. Baird Callicott reports: "For Lame Deer [a Sioux Indian] all creatures, indeed all things are a part of the Great Spirit. The Great Spirit has split itself up into stones, trees, insects, and other animals, including people, and all flow back to their spiritual source" (Rosenstand, 2003, p. 104).

(c) "Oneness" was always seen as a mark of an in-depth understanding of reality from the Pythagorean/Platonic *One* to attempts to unify all reality under one God. In physics too, the move toward unification of the laws of nature was a major driving factor: the very conception of universally valid "laws of nature" is a reflection of the ultimate "One." Each law of nature unifies a great many disparate phenomena at a higher level of understanding. The unification of all the laws themselves – ending with a "theory of everything" (TOE) – is the great dream of today's physicists.

The more we learn about nature, the more we are amazed by the complexity of even the most "simple" entities. And also by the "puzzle of coherence," i.e., the interconnection of everything with everything else.

(d) The assumption of identity of designer and design might explain the uniqueness of each organism, nay of each protein molecule. An ordinary designer making a design would make an undetermined number of exact copies of the design – he would not vary each. He could not possibly foresee that nonidentical copies would be able to function in compounds that are essential for an organism. The fact that each organism is different from every other organism – also within the same species – gives subjectivity to each. Every "natural object" is in and for itself a subject, i.e., a unique "self." To a bureaucratic agency, millions of people may fall under one "objective" rubric – a particular race, an income bracket, age, etc. – to the people themselves, each member of any such group is an individual.

It would also provide an explanation for the simultaneity of events and explain the fact that there exists an instant communication between all components of the universe that makes the validity of universal physical laws possible.

It would further explain the "oneness of mind" that Schrödinger assumed, and extend the notion of consciousness beyond the Cartesian (human) subject: "The universe too, has consciousness" according to physicist Hans-Peter Duerr. The uncanny behavior of split electrons would suggest a "cosmic consciousness" (Kafatos and Nadeau, 1990).

The theory of the identity of design and designer would connect ethics with physics and biology and form the foundation of a "physics/biology of ethics" as well as an "ethics of physics and biology." It would personalize research and lead to a recognition of the reality of realms other than cosmic material particles.

Would it lead to new insights in physics or biology, as these sciences are understood today? Perhaps it would help to discover not only "emergence" in the area of molecules, etc., but also emergence in the totality of the world.

It would make "responsibility" a physically/biologically relevant matter. "Ethics" is intrinsic to nature – as "emergent feature" in its own right. As Kauffman shows, "emergence" has also to do with the formation of societies and economies: ethical thinking as emerging from a sufficiently large number of (self-) conscious individuals (Kauffman, 2008).

It would reverse research from looking into the smallest "building blocks" and counting the number of particles in the universe to recognizing the dynamics of complex entities: After all, much of "emergence" comes from "complexity" studies. Nature is not exhausted by the sum total of particles in the universe, but it also comprises a great number of evolved beings and their interaction. A molecule is qualitatively different from a single atom – a living cell is qualitatively different from the molecules it is made from – and the (human) mind, a part of nature (!), is qualitatively different from the aggregates of cells that make up the brain.

It would also delink ethics from "revealed books" and "sacred traditions" and reconnect it with nature itself: that would allow us to establish certain boundaries to "freedom" that are not arbitrary or suggested by religious bodies but are "givens." Above all, it would bring the "two cultures" together: give more validity to the sciences in the area of culture and more "spirit" to the sciences.

(e) "Emergence" may be a widely accepted term nowadays and certainly attests to the recognition of a new (immaterial?) element that comes into the picture, but it does not explain where it came from and what it leads to. Laszlo's *akashic* field does give a plausible answer to this. It is equally far from the materialistic "everything happened by chance" as from a naïve creationist "everything was created by God in six days". It gives an answer to the question of "why is there something" as well to the question "why is the world as it is." It is not materialistic and not idealistic and makes room for (genuine) information form "beyond."

(f) Ervin Laszlo's description of the One in *Science and the Akashic Field* is suggestive: "A lightless, formless, soundless plenum. It is filled both with the primeval consciousness that is the womb of all mind and spirit in the cosmos and with the fluctuating energies out of which all things come to exist in space and time. Everything that can and will ever happen is here, in formless, soundless, lightless, quiescent turbulence" (Laszlo, 2007, p. 130).

(g) Stephen Hawking had ended his popular *A Short History of Time* with a sentence that looked like a reference to the biblical Creator. His most recent work does away with such a notion: the initial universe, according to him, contained everything that was needed to make the earth and us and everything else. For a "creationist" that will be a bombshell – for someone who assumes the "identity of designer and design" – it is a confirmation: the universe contained everything from its beginning that and from which everything has sprung is none other than the *atman-brahman* of the Upanishads: *tat tvam asi* – You are that.

(h) The "top-down" analysis of mind shows the brain, the nervous system, the ganglia, cells, molecules, and atoms interconnected with the process of thinking, but the analysis of atoms does not yield the properties of molecules that form cells, and the analysis of cells does not lead to a knowledge of brain structure, and the knowledge of the brain structure does not result in a knowledge of the thoughts that a person thinks. Why do aggregates of subatomic particles result in so many different kinds of atoms? Why do the same elements produce such a variety of molecules? Why do molecules produce so many different kinds of "stuff?" All that would not need an answer, if the end result were not a curious individual human being, who is vexed by the question "where did I come from?" and "whether am I going?"

(i) Artists are identified by their work: Mozart's works are uniquely his. In a way, he is identical with his works. Without Mozart, *Eine kleine Nachtmusik* would not exist, and if we want to know, who Mozart was, we have to listen to this and his other works. This may not exhaust the reality of the human being called Wolfgang Amadeus Mozart, but it is an essential part of his. If each human individual is biologically unique, so are each individual's acts. We are what we do and what we do shows who we are.

(j) The most convincing argument for the identity of designer and design is the unity of the universe, addressed by Laszlo under the term "puzzles of coherence." He details "puzzles of coherence" in quantum physics, in cosmology, biology, and consciousness. "The inseparable whole" is a physical fact! Laszlo uses the expression "quantum vacuum or plenum" and addresses the "information in the quantum vacuum." He speaks of the "holographic nature of the universe." In my view, all this reinforces the notion of identity of designer and design as well as the individuality and subject nature of everything.

(k) "The Unity of Nature" – the title of a book by physicist-philosopher C. F. von Weizsäcker – is a topic that has intrigued thinking people from as far back as we know. Even the least sophisticated people speak of a universe in which we live, and the most sophisticated marvel at the universal validity of laws of nature explored on our tiny earth. Recent physics has discovered the surprising continuing unity of electrons after they had been split from an atom. The very fact that physical laws are universally valid leads to the conclusion that everything in the universe is connected with everything else. All attempts to find the "world formula" are predicated on such a conviction. Ervin Lazlo's "Akashic Field" not only promises to be such an "integral theory of everything," but it goes beyond the standard TOE by introducing a nonmaterial dimension, integrating consciousness into our world picture. By the choice of the Sanskrit word *akasha*, Laszlo connects with age-old Indian traditions but supports them with the most recent findings of the contemporary sciences.

(l) "Top-down analysis" has given us stupendous insights into the structures of the world of objects and will probably give us more in times to come: it has helped us to understand much of "how the world is put together," but it also has definite limits. One of these limits is the limit of observability: the Planck quantum: Indeterminacy and lawlessness have become accepted as real features of the universe. Another one is the impossibility of predicting the properties of compositions of elements: the emergence life in a combinations of lifeless molecules. "The whole is more than the sum of its parts" has implications that fundamentally impinge on the validity of "top-down" analyses.

The Unity of Nature has its parallel in the "Unity of Mind" assumed by Vedanta and supported by Erwin Schrödinger: there is only one mind, individualized in many minds, who are under the illusion that their consciousness is identical with their body.

(m) The identity of designer and design makes not only room for evolution in nature but also for its unpredictability. Instead of leading to Monod's nihilistic conclusion ("Man knows at last that he is alone in the universe's unfeeling immensity, out of which he only emerged by chance"), it brings back purpose into the universe and endows human life with meaning. Life cannot fully be explained by physics and chemistry. Consciousness cannot be explained by materialism: but it is an undeniably real ingredient of the universe. Future events cannot be predicted from (known) natural laws. All our sciences are inventions to the same degree as they are discoveries: they transform perceptions into ideas and adapt these to our (present) human understanding of nature. Religions too are invented. So-called revelations are "receiver conditioned," i.e., they are intuitions subject to the vocabulary and the intellectual state of the person who claims to have received them. All human ideas are "invented," including our image of the world that is projected by our senses into our brains.

(n) While rejecting a "chance-and-necessity" explanation for life for obvious reasons, one must also reject intelligent design as too mechanical and extraneous an understanding of the workings of nature. I am proposing the identity of designer and design in nature. Nature = reality is one. Nature = reality is not only object but also subject. Many dimensions of nature/reality are not being dealt with by the present-day "objective" natural sciences. If evolution is the "crane" that brought complex organisms forth, it must also include the consciousness of higher organisms and their creations. It is a commonly agreed insight that evolution works in ways that are not foreseeable. "Emergence" is the word that is widely used to describe the unpredictability of the course of evolution. We cannot derive the properties of water from a study of hydrogen and oxygen and we cannot infer the manifestations of life from the properties of carbon. "Natural selection" does not explain the emergence of self-consciousness and what we call mind. But they exist and must be accounted for in a full description of nature/reality.

(o) Since the beginning of modern science it was held that mathematics was the language of nature and that the supreme aim of science was to establish equations. To speak of mathematics as the language of nature (or even the language of God) is clearly anthropomorphic. Humans, however, speak many languages that cannot easily be reduced to each other. Why not recognize the language of philosophy and poetry, of music and art as equally valid attempts to probe the reality of nature.

(p) The vagueness of the meaning of key terms in the present discussion of issues like "design" or "creation" is one of the reasons why it is yielding so little genuine insight. "Chance," supplemented by "luck," is all that Richard Dawkins, the author of *The God Delusion* offers in lieu of a Creator to explain the immense richness of the world of nature, including our own existence. He does not say what he means by chance or by luck, assuming that people go by the common understanding of these terms. Competent scientists have calculated that for chance – as understood in the probability calculus– the entire history of the universe has not been long enough to produce a single bacterium. The improbability then is reaching astronomical heights, when calculating the chances of the emergence of the abundance of other life forms. It is simply "beyond chance."

(q) One of the hallmarks of (modern) science was its ability to predict future events. The investigation of the movement of the planets and the laws that were formulated permitted the exact prediction of lunar and solar eclipses. Newton's laws inspired people like Laplace with the confidence that a knowledge of the position and movements of all particles in the universe, all future events could be predicted. Today we know that this is not so. The world is more complex. We have learned that we cannot even predict the properties of entities that arise out of well-known components. A knowledge of the properties of oxygen and hydrogen does not provide us with a knowledge of the properties of water, formed of a composition of these elements and so on. "Emergence" has become a major area of research in various disciplines that scientists (re)discover "the sacred" outside the territory that had been claimed by traditional religions for it. Suzuki has discovered "the sacred balance" in nature, and Kauffman draws his evidence for the "reinvention of the sacred" from the latest of scientific discoveries about the fine-tuning of the universal constants, etc. None refer to the "sacred objects" or "sacred persons" of traditional organized religions. For them, water is not holy because someone spoke some words over it or because it comes from a particular place but because of its intricate molecular composition and its fundamental necessity for life.

## 8. Conclusion

A theory is valued according to its explanatory power and its capacity to throw light on old puzzles. The theory of "identity of designer and design" would explain some features of nature that have remained open questions so far, such as:

- The uniqueness of each physical object in the universe: it is established for all organic molecules but probably extends also to other molecules and beyond.

- The simultaneity of events: the instantaneous communication between all components of the universe, the basis for the universal.
- The presence of consciousness in the universe at large and in its individual components.
- The creativity of the universe.
- The interconnection of all components of the earth and the universe as a whole.
- The multidimensionality of reality.

Erwin Schrödinger found that the state of existence of the electron depends on the existence of an observer. Perhaps the very state of existence of the universe too depends on the existence of an observer: “The all-pervading Reality, though One, is regarded as many. It is the Self of all beings. It is the innermost self of all that exists. It is seated in the hearts of all. It is the Ruler of all. All beings become One in It” (*Taittiriyaranyaka III, 2* in Swami Yatiswarananda, 1963, p. 247).

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Biodata of **Elisabeth Rees-Dessauer**, author of "***In the Beginning There Was Lightning: Fulguro-Genesis and Eduard Loewenthal's Religion of Religions***."

**Elisabeth Rees-Dessauer** studied political science, modern history, and philosophy in Munich and Tel Aviv. In 2007, she earned her M.A. from the Ludwig-Maximilians-Universität in Munich with a thesis entitled "Politik und Weltanschauung bei Eduard Loewenthal." Currently a doctoral student at the University of Munich's Department of Jewish History and Culture, she is working on a thesis on "Jews in Germany and Their Concept of *Heimat* since 1945."

E-mail: **edessauer@gmx.de**

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# IN THE BEGINNING THERE WAS LIGHTNING: FULGURO-GENESIS AND EDUARD LOEWENTHAL'S RELIGION OF RELIGIONS

**ELISABETH REES-DESSAUER**
*Historisches Seminar, Abteilung für Jüdische Geschichte*
*und Kultur, Ludwig-Maximilians-Universität München,*
*Geschwister-Scholl-Platz 1, 80539 Munich, Germany*

## 1. Introduction

In the beginning, massive bolts of lightning rent the darkness. As they subsided, there was motion on earth. The first plants unrolled their leaves, the first fish darted off in search of a meal, the first wolves raised their voices in a howl, and the first humans got up and began to go about their business. No millions of years of evolution were required. The world was ready, the plant and animal kingdoms fully populated from great to small. History could begin apace.

This, in a nutshell, is the theory of creation which Eduard Loewenthal developed at the end of the nineteenth and the beginning of the twentieth century. Compared with Charles Darwin's assertion that humans had descended accidentally from lower forms of life, a lightning-based origin of species, or, in Loewenthal's phrase, "Fulguro-Genesis," displayed obvious advantages. First, there was the issue of intuitive plausibility. Irrespective of religious dogma, the idea that the complexity of nature resulted from a chain of "accidents" over mind-boggling expanses of time is hard to grasp. Loewenthal was hardly alone in thinking that the simultaneous creation of the various species was a far more reasonable proposition. Secondly, lightning creation also seemed to offer concrete benefits for human life today. While Darwinism relegates humans to the animal realm, the theory of Fulguro-Genesis accords them a unique moral capacity from the start. In this respect, Fulguro-Genesis resembles the biblical creation story. Indeed, Loewenthal designed his theory as the creation story of a new religion he called Cogitantism.

Today, few people are aware of Eduard Loewenthal and his theory of Fulguro-Genesis. From the practical standpoint of modern science, this may not be a tragedy. For the historian of the nineteenth and early twentieth centuries, however, the man, his theory, and his religion represent a fascinating chapter in the fields of science, philosophy, and social thought.

In order to elucidate this unknown chapter, I will examine the theory of Fulguro-Genesis and its concomitant religion, Cogitantism, in the context of Loewenthal's life and work. Who was Eduard Loewenthal? How exactly does his theory of creation work? In addition to these questions, I will consider Loewenthal's philosophical background and his efforts on behalf of political and social reform in Germany and Europe. Then I will consider the development of his new religion from its initial concern with rationalism and marriage rights to a full-blown alternative both to Darwinism and traditional religions. Finally, I will reflect on Loewenthal's place in the field of German-Jewish history.

## 2. Eduard Loewenthal and His Theory of Fulguro-Genesis

On March 12, 1836, Eduard Loewenthal, the fourth of six children, was born in the German town of Ernsbach in Württemberg. His mother, Lilly, came from Bavaria. His father, Isaak Ephraim, cantor and teacher in the Ernsbach Jewish community, was of French origin (Jüdisches Personenstandsregister). At the age of 19, Loewenthal began his studies in law and philosophy at the University of Tübingen, receiving his doctorate in philosophy in 1859 (Beilagen). He then began his career as a writer, journalist, and editor of various newspapers. Four years later, he moved to Berlin, which, with the exception of a brief stay in Dresden and a total of 15 years spent in exile, he was to call home until his death in 1917.

In 1859, the same year Loewenthal received his degree, Darwin's *Origin of Species* appeared in England. Only a few months later, a German translation appeared. Subsequently, the theory of evolution, especially as it was propagated by German Darwinists such as Matthias Jacob Schleiden and Ernst Haeckel, was to become a lifelong red flag to Loewenthal. In a diatribe published in 1864, he attempted to dismiss the stir generated by Darwin and his disciples as mere "humbug" (Loewenthal, 1864). The "humbug," however, did not abate, and soon Loewenthal saw no choice but to confront it head on. In the coming years, he devoted considerable energy to developing and propagating his own thinking as a serious alternative to evolutionary theory. This project culminated with Loewenthal's vision of the origin of species, which we encounter in 1896 for the first time as a coherent theory. In 1902, Loewenthal christened it "Fulguro-Genesis."

In considering the theory of Fulguro-Genesis, we should bear in mind that its author came from a world entirely different from that of the natural scientists. While Darwin and others made voyages of discovery and laboratory observations, Loewenthal worked as a philosopher for whom, in a tradition going back to antiquity, both the physical and the metaphysical world constitute proper objects of contemplation and categorization. Darwin's theory of evolution relies on the concept of adaptive development. Loewenthal, however, insisted on measuring the former's theory by the Neo-Platonic concept of derivation, according to which any given thing can only produce things of a lower degree of perfection. According to this view, the evolution of complex organisms from less complex forms of life is a logical impossibility.

With this caveat in mind, we can now consider the theory of Fulguro-Genesis itself. How exactly does creation by lightning work?

First, we must understand that the cosmic lightning storm at the beginning of life is the end of the process of creation. Loewenthal's theory states that the primordial bolts of lightning merely animated those lifeless shells that, having emerged from the cosmic soup, were destined to become living things. An entire inventory of species, with a preset hierarchy from plants and animals to humans, received the spark of life in one great flash. Loewenthal makes no effort to explain the secret of life itself. Apparently he did not consider it necessary. Rather, he was more interested in the fact that all species originated simultaneously. He does, however, devote considerable attention to describing what happened *before* the beginning or how the forms of the individual species were created.

The concept of "before the beginning" has always posed difficulties for scientists and philosophers alike. For Loewenthal the matter is clear. There can be no "nothing"; therefore, there must have been something before the beginning. The theory of aether, widely accepted in the nineteenth century, offered a solution, and Loewenthal made aether the cornerstone of his cosmology. As the basic substance of the universe, he points out, aether can neither be created nor destroyed. Strictly speaking, there was never any beginning at all. Consisting of infinitely small, identical atoms, aether pervades everything at all times, including "empty" spaces. In its purest form, it is free, neutral, and evenly dispersed; however, its dispersion is fixed at a specific density. Like a solid, aether moves elastically; like a liquid, it flows in waves; like a gas, it expands and contracts. All objects, Loewenthal explained, are made up of densities of aether: electrons, chemical elements, interstellar clouds, stars, and planets, as well as water, stones, plants, animals, and humans. At some early stage of our solar system, the aether began to condense, thus forming the sun and planets. On earth, the aether continued to harden into new forms and patterns, thus producing the lifeless shells of the species. In the meantime, the friction of the planet earth moving through the lighter aether surrounding it in space generated a tremendous static charge. When that charge was finally released, it triggered a wave of electric events on the surface of the planet, in the course of which the waiting forms of all organisms were imbued with life. At this point, we are back to the beginning of life on earth.

Important for Loewenthal's theory is his assumption that the formation of the species is not a result of chance. Rather, he posited that the physical properties of aether dictate the several forms of species into which it may condense. Everything was created according to the design, as it were, of the aether. Even the human capacity for moral behavior is a result of the laws of nature. Humans could not have been created any other way. At the same time, he assumed that there is nothing special about the planet Earth. Given the universally consistent laws of aether, Loewenthal found it only reasonable to assume that the same species we know on earth have also formed on countless other planets throughout the universe. Nor is there anything unique about *this* particular universe. Rather, Loewenthal assumed that aether moves in cycles, ceaselessly creating and recreating the visible cosmos over the course of the eons.

To Loewenthal's nonscientific contemporaries, the theory of Fulguro-Genesis probably seemed less strange than it does today. For the most part, it operates with scientific notions that were well known at the time. In 1771, Luigi Galvani had used electric shocks to make dismembered frog legs twitch of their own accord. For Loewenthal, the notion of electricity as an animating force, made famous in the twentieth century by films of Frankenstein's monster coming to life, would not have seemed absurd. As for Loewenthal's billowing formations of interstellar clouds of aether, astronomers had been discovering large numbers of nebulae since the eighteenth century. The existence of the aether itself was widely accepted, and Loewenthal was moving on conventional terrain. Albert Einstein, for example, also assumed the existence of aether until he developed his theory of relativity in 1905 (Ziegelmann, 2005).

Despite the layers of scientific terms and concepts, the theory of Fulguro-Genesis is, to be sure, highly speculative. As far as we know, Loewenthal never carried out any experiments or observations of his own to corroborate his ideas, nor did he propose any concrete experiments that others might perform to prove – or disprove – his notions. Measured by Karl Popper's criterion of falsifiability, the theory of Fulguro-Genesis would have to be filed under the heading of pseudoscience rather than that of science. Or perhaps the theory should be categorized as science fiction; indeed, Loewenthal's expatiations on cosmology at times recall the work of one of his contemporaries, Jules Verne. Yet it must be stressed that Loewenthal never claimed that his ideas were based on the scientific method. He made no bones about the fact that he was writing primarily as a philosopher. It is only as an aside that he remarked, in 1904, that experimental proof of his ideas someday might well be possible (Loewenthal, 1904, 8). In the meantime, however, it is clear that he considered their proof far less important than their social and religious value.

Although Loewenthal's theory of Fulguro-Genesis employs popular (pseudo)scientific terms and concepts, there can be no mistaking certain elements of the biblical version of creation. First, there is the fact that the theory of Fulguro-Genesis allows no room for an evolution of species. Loewenthal was certain that humans were created in a ready-made world and ridiculed the proposition that the world is millions of years old (Loewenthal, 1902, 11ff). Moreover, after expounding upon the motion of the aether and the life-giving bolts of lightning, Loewenthal went on to provide humans, unlike animals, with something very much like a soul and a unique moral capacity. Yet he took pains to explain both the immortality of the soul and the imperative of moral behavior in the rational terms of natural science. Not surprisingly, perhaps, the aether again plays a crucial role. First, we must recall that all the physical forms of the universe are really condensations of the aether congealed, as it were, in solidity. Among the solid forms, some remained in their solid state longer than others. Within the human organism, thoughts and actions produce electrical currents in the region of the brain and spinal cord. When a person furthers the cause of truth, justice, humanity, and the individual dignity of man, his organism produces, according to the natural laws of aether, a special kind of electric current. Little by little, this current – and only this current – "welds" the aether comprising the cerebral and spinal regions into a more permanent unit: the "aetheric ego" (*ätherisches Ich*) (Loewenthal, 1910, 10ff). If an individual conducts himself in a sufficiently moral fashion during his lifetime, his aetheric ego will become so permanent that it will linger on in its configuration after his death. The aetheric ego of a morally deficient individual, however, will gradually redistribute itself into new formations of the aether.

Thus, Loewenthal's theory of Fulguro-Genesis supplants biblical creationism with an alternative in the scientific mode. Yet with its positions on evolution, the age of the world, the soul, the moral imperative, and the afterlife, it retains many salient features of the religious mode. In essence, Loewenthal availed himself of the brick of science in order to smash the shop window of religion – only to redecorate with a similar display. What did he hope to gain from such a maneuver?

## 3. Moral Matter: Between Materialism and Ethics

Understanding Loewenthal's motivations for formulating his theory of Fulguro-Genesis requires that we consider it in the context of his larger vision of social, political, and religious reform in Germany and beyond. Loewenthal was a fervent social reformer. Impressed by his acquaintance with liberals of the 1848 revolutions, he turned as a young man to the fight for social justice and helped found the European pacifist movement. Loewenthal's connection to France, through his father, may help explain why he was less receptive to German nationalism than many of his peers and an outspoken opponent of the Franco-Prussian War in 1870–1871. In 1869, 1 year before the outbreak of hostilities, he founded his first interest group, the pacifist "European Union Society," to promote cooperation among the states of Europe (Loewenthal, 1907, 14). Over the years, he revived the group several times under various names in order to promote peace through the establishment of strong international organizations.

Loewenthal's dissertation, a comparison of Gottfried Wilhelm Leibniz and Baruch Spinoza, seems to have contributed important impulses to his philosophical outlook. We know that Spinoza's pantheism impressed him, and indeed, it is not hard to recognize the pantheistic element in the all-pervading aether in the theory of Fulguro-Genesis. Likewise, Loewenthal probably also had Leibniz's concept of monads as the smallest, indivisible units of existence in mind when he described the properties of aether. In social questions, however, Loewenthal viewed Leibniz as a negative foil. In particular, he found the latter's theodicy – claiming that the real world is the best of all possible worlds and that evil is merely a misunderstood element in God's general perfection – inadequate and unacceptable. Such a view, he felt, meant acquiescing to evils, such as war and social injustice, that could and should be eradicated.

Thus, early on, Loewenthal found speculative philosophy insufficient. He looked for succor in nontranscendentalist, materialistic philosophy. While still a student in Tübingen, he fell under the spell of Ludwig Büchner's philosophy of force and matter (*Kraft und Stoff*), which sought to discredit both religion and superstition by positing the observable material world as the only realm of existence. For a time, Loewenthal also considered himself a follower of Ludwig Feuerbach, the Left Hegelian precursor of Karl Marx and Friedrich Engels. The fact that the German authorities persecuted both Büchner and Feuerbach for their philosophy earned them credibility in Loewenthal's eyes. It bothered him that university professors were well-pensioned civil servants bound by oath to uphold religion and state.

Initially, Loewenthal understood materialism as synonymous with rationalism, regarding it as a powerful tool for creating a more liberal society. Already in his first major publication after his dissertation, he boldly cast himself as a champion of reason doing battle against the retarding effect of established religion. On the title page, he included as his motto a programmatic verse: "The time is fast approaching when force of Knowledge/Shall topple gods and tear down altars; / Then Nature alone will shine a holy icon, / And Reason herself, righteous revelation. / – And church: blown to bits by raging ideas!" (Loewenthal, 1861). The lines stem from a piece he had written as a student some 6 years earlier about Arnold von Brescia, the twelfth-century figure whom many of Loewenthal's contemporaries lionized as a proto-social reformer and opponent of the church.[1]

In the hands of German Darwinists such as Haeckel and Loewenthal's former hero, Büchner, however, materialism soon appeared to Loewenthal as a purely destructive weapon. By reducing the mind to chemical functions of the brain and humans to an accident of evolution, materialist teachings seemed to preclude any possibility of an innate moral mission in humans. Without moral purpose, there could be no compelling reason to improve social reality. Even worse, the principle of survival of the fittest seemed destined to replace ethics. In the specter of social Darwinism, Loewenthal saw resignation to and even celebration of the warfare and injustice he had set out to abolish. In short, the materialists had thrown the baby out with the bathwater.[2]

At odds now with both materialism and religion, Loewenthal set about salvaging their better elements. While he did not regret any weakening of Christianity's role in society, he clearly saw the need to offer a substitute. In order to avoid the pitfalls of the past, any substitute would have to be based not on metaphysics but on a rational approach to the observable world. Accordingly, he invented a religion of reason: Cogitantism.

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[1] Loewenthal wrote the play *Arnold von Brescia* in 1855 and first published it 2 years later (Loewenthal, 1857, 95–123).

[2] To distinguish his own thinking from the direction taken by the German Darwinists, Loewenthal later changed the appellation on his calling card, designating himself a "rational naturalist," while Büchner and other Darwinists became in his parlance "materialist naturalists" (Loewenthal, 1875).

## 4. From Religion of Reason to Religion of Religions: A Short History of Cogitantism

In 1865, the Prussian authorities officially recognized Cogitantism as an approved religious community (Loewenthal, 1890, 5). In the initial version of the religion's statutes, spirituality appears as synonymous with intellectual pleasures. The rationalist bent of the religion's motto – "Our knowledge is our faith" – is reflected in the "worship" service. Every Sunday morning, the Cogitants were to gather to hear a lecture on intellectual, moral, or social topics, preceded and followed only by singing to the accompaniment of an organ. On three special occasions – the New Year's holiday, May holiday, and September holiday – there was to be, in addition to the worship service, a folk festival in the afternoon, with parades organized by the various professional guilds (Loewenthal, 1865, 6f).

The second line of the motto – "Our dignity is our morality" – seems to be a swipe at the theory of evolution. Loewenthal's first diatribe against German Darwinism had appeared only a year before he founded his religion. In an appendix to the statutes of Cogitantism, in which he explained its "physiological, ethical, and social" premises, he made a point of denigrating Darwin's views on the undignified origins of man (Loewenthal, 1865, 32). The remaining lines of the motto, with its suggestive dashes, present more of a puzzle: "Our cult is – the State, / Our religion is – our secret." At what secret is Loewenthal hinting?

In addition to rational and moral concerns, Loewenthal may well have intended Cogitantism as a subterfuge to enable nonreligious marriages despite then-current legal restrictions. At a time when, in most of the German lands, marriage was only permitted within the jurisdiction of recognized religions, civil marriage was technically impossible.[3] Until a conversion had taken place, a Jew could not marry a Christian, a Protestant could not marry a Catholic, and a professing atheist or an unaffiliated individual could not, in fact, marry anybody. As an officially recognized religion, Cogitantism offered a solution. Anybody could declare himself a Cogitant and be married under the aegis of the new religion. For someone who did not believe in metaphysics, Loewenthal's dogma-free religion of reason required no breach of principles. One merely needed to confess that one was a thinking person – a "Cogitant" – in order to belong to the new religion. Moreover, a Cogitant did not have to sever connections to his previous religion. Loewenthal himself officially left Judaism only in 1904, almost 40 years after he had founded Cogitantism (Austrittskartei).

Thus, with regard to marriage rights, Cogitantism represented a giant leap forward. From a modern point of view, it is easy to understand why Loewenthal expected there would soon be millions of new adherents to his religion (Loewenthal, 1865, 4f). In his opinion, his contemporaries did not really believe

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[3] Civil marriage was made legal in the German Reich in February, 1875. In a few places it had existed earlier, for example, in the Free Hanseatic City of Bremen since 1855 (Overath, 1987, 167–182).

the dogmas of their religions but remained in the fold primarily for practical reasons – such as marriage. As a recognized religion, Cogitantism even threatened the monopoly of the established religions on cemeteries and funerals. Now, Loewenthal thought, nothing would be left to prevent the masses from openly professing their lack of religious faith and becoming Cogitants. Loewenthal's expectations were, however, mistaken. As far as we can tell, the ranks of the Cogitants never grew beyond a small group of the "faithful."

One more factor must be considered in connection with Cogitantism and civil marriage: Loewenthal's first customer may well have been himself. We do not know for sure when he married Emmy Nerling, his first wife, nor whether she was Jewish. If so, it would be in keeping with Loewenthal's objections to established religions if he had refused a traditional wedding on grounds of principle. If Emmy was not Jewish, we may assume that he refused the pro forma conversion demanded by what he saw as an oppressive law.

It is not clear how many members Loewenthal won for his new religion. By March of 1866, however, he seems to have had one or more followers. From that date, we have a panegyric which the "Berlin Cogitant Community" dedicated to "Herrn Dr. Eduard Loewenthal" on the occasion of his thirtieth birthday. In no uncertain terms, the poet, a certain Hermann Kuntze, praised him as a modern messiah: "Your wisdom opened the gates for us … / Your knowledge became our Ariadne's thread … / As the last clouds of blind faith/To thy teaching's light doth yield, / Posterity weaveth thy crown of laurels" (Loewenthal, 1890, 17ff).

Two years after establishing his new religion, Loewenthal founded a "Cogitant Academy."[4] While his new religion was designed to take established religion out of marrying and burying, his new academy attempted the same for higher education. The German universities were closely intertwined with church and state. Without converting to Christianity, a Jew such as Loewenthal had little chance of attaining an academic position in Germany. In his academy, individuals were to be free to study and teach without regard to religious or political affiliation. As with the issue of civil marriage, Loewenthal probably also had his own situation in mind. If the academy had taken off, its founder would surely have been one of its first professors.

Loewenthal's plans for both religion and academy suffered a setback in 1870, shortly after the outbreak of the Franco-Prussian War, when he was convicted on charges of blasphemy stemming from an article he had published in Dresden. Rather than serve a 6-week prison sentence, he spent the next 6 months in Switzerland. Four years later, Loewenthal's journalistic activities again aroused the ire of the Prussian censorship. Again he went into exile, this time for 13 years. Plans for the academy were abandoned. Apart from a French version of the statutes of Cogitantism that he published in Paris during this time, his new religion

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[4] The Cogitant Academy was officially inaugurated in Dresden on October 27, 1867, with a public lecture by Loewenthal. Regular classes were to start on November 12, 1867 (Loewenthal, 1867).

seems to have been dormant (Loewenthal, 1886). Only after a general amnesty enabled him to return to Berlin in 1888 was Loewenthal able to resume propaganda activities for the faith. Two years later, he published a booklet in celebration of the 25th anniversary of the founding of Cogitantism.

This commemorative booklet, or *Gedenkschrift*, heralds a dramatic new development in the history of Cogitantism by unabashedly introducing God into the picture. Not only does it contain a heavily revised version of the statutes of 1865 but also, among other things, "The Five Commandments of Cogitantism" and the "Cogitant's Prayer." The title of the *Gedenkschrift* heralds the new development in Loewenthal's thinking. Whereas the first version of the statutes had appeared under the title, "A Religion without a Creed," the Gedenkschrift bears the title, "The Religion of Religions." No longer does Cogitantism equate faith solely with reason and intellectual stimulation. Instead, it now allows for a personal relationship with a genderless Maker. The "Cogitant's Prayer," for example, begins thus, "Holy Deity, which I revere in its deeds, hear my supplication…," and concludes with a traditional "Amen" (Loewenthal, 1890, 16). Along the way, it beseeches the deity to grant peace for deceased relatives, the strength to achieve material well-being and perform good deeds, peace and happiness on earth, and the grace to praise the glory of the godhead and thereby atone for one's sins. The "Five Commandments" begin even more directly, with the exhortation to "Honor God as the spiritual creator of everything and strive to act in accordance with the reason and goodness of his deeds" (Loewenthal, 1890, 15).

The remaining four of the "Five Commandments" run the gamut from the Old Testament to the Golden Rule, socialism, and stoicism: (2) Honor father and mother; (3) Do unto others as you would have others do unto you; (4) Strive to promote, according to your means, the interest of humanity as a whole; (5) Eschew in your actions immoderate influence of anger, hate, envy, joy, and pain. Their humanistic eclecticism in no way detracts from the new religious tenor of the religion after its prophet's return from exile. Indeed, in his essay on the "Mission of Cogitantism," which he includes in the *Gedenkschrift*, Loewenthal credits the "emancipating power of Cogitantism" with freeing true religion from the decaying remnants of the older religions (Loewenthal, 1890, 7f).

Never one for half measures, Loewenthal made the second version of his faith as unabashedly religious as he had shunned the trappings of religion in the first. The historian yearns for the articles, letters, and diaries that would grant insights into this intellectual shift. Why did Loewenthal move from a religion beyond metaphysics to a religion that reforms and reinstates the deity? Perhaps he had learned a lesson from the failure of the earlier, more cerebral version of Cogitantism and was now trying to match the product better to its market. Perhaps he himself had simply discovered a need for spiritual comfort. After all, he was now over 50 years old and already once a widower.

Despite the marked differences between the earlier and later versions of Cogitantism, Loewenthal's moral-ethical concerns and rejection of Darwinism remain dominant. When he writes in the *Gedenkschrift* that the mission of

Cogitantism involves preserving humanity from the dangers of "Verthierung," or "degenerating into bestiality," the German word carries multiple nuances (Loewenthal, 1890, 7). The following pages make it clear that Loewenthal was, among other things, referring to the notion that humans are merely the descendents of animals. In the revised statutes, he categorically denied the logical possibility of evolution. He then proceeded to place man at the nexus between the physical and the spiritual world. Following this new interest in metaphysics, Loewenthal soon found it necessary to reinstate some basic concepts of traditional religion: creation, the soul, and the afterlife.

The theory of Fulguro-Genesis was the ultimate result of Loewenthal's metaphysical turn. In 1896, 6 years after the revised statutes of Cogitantism had appeared, Loewenthal published the first version of his theory of creation of species through aether and lightning. He concluded the pamphlet with the remark that its contents may be regarded as "the *newest* Gospel" of Cogitantism, the religion of the future (Loewenthal, 1896, 20). In 1902, he republished his theory, in more developed form, under the name of Fulguro-Genesis.

With his theory of creation, Loewenthal again repositioned himself. Unlike the revised statutes of Cogitantism from 1890, his writings on Fulguro-Genesis contain no reference to a deity. The new tone is entirely philosophical, the vocabulary (pseudo)scientific. Also with regard to the immortality of the soul, Loewenthal backtracks considerably. Now the soul, instead of being immortal by virtue of man's place in the scheme of things, appears as a formation of aether that may or may not attain to an afterlife. With the earlier version of Cogitantism, the pendulum had swung toward stark materialism; with the later version, it swung back toward spiritual enthusiasm. With his notion of Fulguro-Genesis, Loewenthal tried to catch it in the middle. The result is a hybrid form: a scientific myth of creation as the cornerstone of a rationalist religion of all religions.

## 5. Subversive Print: Eduard Loewenthal and German-Jewish History

For the modern reader, Fulguro-Genesis seems to unite incompatible categories: materialism and metaphysics, rationalism and myth, science and creationism. Loewenthal, however, came to see the danger of the modern world precisely in the drifting apart of such binary categories. A sensitive critic of his times, he felt that the rational-scientific view of the world alone threatened religious and ethical feeling. With his "scientific" myth of creation, in which he combined rational insight with spiritual mystery, he sought a balanced diet for what he felt was a soul-sick era.

Loewenthal pursued his commitment to both sides of the spiritual/rational equation with an intensity that would have been unthinkable for someone with a reputation to lose, either as a serious scientist or as a man of the cloth. Rather than discounting subsequent scientific discovery, he found room for scientific progress within his system of Fulguro-Genesis. In 1904, for example, he published a pamphlet on the recently discovered element radium in which he reconciled "the invisible radiation" to his own theory of aether (Loewenthal, 1904). On the other hand, he did not shrink from writing to the Prussian Academy of the Sciences with the news that he was prepared to prove the existence of an aetheric afterlife by means of communications from his recently deceased second wife (Krajewski, 2001).

Precisely Loewenthal's position at the periphery of the German academic, religious, and political establishment is crucial to understanding his thinking in its proper context. As a journalist and freelance writer, he developed his thinking in the newest, most anarchist arena of social life in the nineteenth century: cheap print. Printing had been around for hundreds of years, but common literacy and mass readership were still developing during Loewenthal's life. As an independent writer, Loewenthal sought to strike the nerve of his time with his reception of Darwinism and other scientific and cultural developments. He had nothing to gain from a cautious, tentative tone. By being bold and controversial on fashionable topics, he could hope to achieve a certain status or, more importantly, financial security.

Indeed, Loewenthal, like many independent writers, sometimes lived from pen to mouth. During his years of exile, when he lived far removed from the publishing scene in Germany, he was forced to rely on the charity of relatives. Cogitantism, had it been a success, would have offered him a secure existence; in the 1865 version of the statutes, he had made provisions for the well-paid position of "cult magister" in every larger community of Cogitants (Loewenthal, 1865, 6). The commercial aspect of Loewenthal's writing does not detract from his fascinating ideas, but it must be taken into account.

A final implication of Loewenthal's modern creation myth deserves attention here. Fulguro-Genesis belongs not only to the history of ideas, as well as to that of social and religious reform at the end of the nineteenth and beginning of the twentieth century. It also has a special place in the history of German Jewry. During the nineteenth century, Jews in Germany went through a long process of political emancipation and social integration. While in France Jews received full civil rights in the course of the French Revolution, in Germany the authorities demanded that Jews "improve" themselves before becoming citizens. Essentially, they expected German (and Austrian) Jews to give up their Jewish particularity and assimilate culturally in exchange for political rights. In Germany, Jews only received citizenship in 1871, 6 years after Loewenthal first published the statutes of Cogitantism. Heinrich Heine converted to Christianity in 1825 in order to gain an "entrée billet" to society. Many other Jews followed his example. Others assimilated culturally while remaining Jewish. Careers in universities, the military, and the civil service were blocked to Jews, to some extent even after 1871. For this reason, Jews tended to gravitate to the "free" professions: law, medicine, and journalism.

Some Jews felt uneasy about the bargain offered by the German model of emancipation. The biography of Loewenthal's journalist colleague in Vienna, Theodor Herzl, illustrates two attempts to resolve the tension: As a young man, Herzl designed a plan to convert in a mass ceremony all the Viennese Jews to Christianity, thereby solving the problem of a particular Jewish identity once and for all. Most famously, he later took the opposite tack when he called for Jews to abandon Europe and create for themselves a nonhyphenated Jewish identity in a Jewish land. It is a curious confluence of dates – perhaps not entirely coincidental – that Herzl's Zionist manifesto, *The Jewish State*, appeared in the same year, 1896, in which Loewenthal first published his theory of Fulguro-Genesis. Whereas Herzl was convinced that European society would never really accept Jews as equals, Loewenthal took a more optimistic – and subversive – approach. In the context of German-Jewish history, Fulguro-Genesis appears on the one hand as a deep commitment to European society and, on the other, as a blatant attempt to renegotiate Europe's Christian foundations. Loewenthal essentially acknowledged the biblical creation story as a vital myth of European civilization and thus preserved most of its features in his alternative myth of "lightning creation." The difference is that he completely removes the confessional element. This maneuver resembles, in its intent, if not in its success, the accomplishment of Irving Berlin, another Jew in another field on another continent. When Berlin wrote the all-time hit "White Christmas" without reference to Jesus, Mary, redemption from sin, or the like, he effectively took Christianity out of Christmas, converting it into a neutral folk holiday (Whitfield, 1999, 99). Likewise, the theory of Fulguro-Genesis is not about theology, in whose name Jews had long been excluded. Rather, it is about science, about which all rational people can, theoretically, agree. On this common ground of reason, Loewenthal proffered an unburdened ethical foundation for a new, inclusive society.

## 6. Conclusion: Modern Myths

Loewenthal achieved a degree of fame during his lifetime. We find him and his work discussed at length in an encyclopedia of famous Jews throughout history from 1901 (Kohut, 1901, 218f). In 1912, the editor of a standard German encyclopedia of philosophers devoted to him a full-column article, in which both the theory of Fulguro-Genesis and Cogitantism are mentioned (Eisler, 1912). In the decades following Loewenthal's death in 1917, the man and his theories continued to be mentioned in Jewish and philosophical reference works. Today, however, if he is remembered at all, it is for his pacifist activities, for which he received, between 1901 and 1913, six nominations for the Nobel Peace Prize. Indeed, the present-day reality of international organizations such as the European Union and the United Nations have lent credence to Loewenthal's pioneering efforts to promote such organizations a century earlier.

The theory of Fulguro-Genesis also finds certain modern-day parallels. With his firm belief in the unique design of man, Loewenthal certainly would have considered the big bang theory just as much materialistic humbug as the evolution of species. Yet the farther modern science penetrates into the secrets of the universe, the more frequently we may glimpse regions where reason meets a gap it cannot fill. In this sense, the big bang theory has something besides the bang in common with Loewenthal's notion of lightning creation. Both theories push the origins of the universe back to a mysterious point beyond the limit of scrutiny. Where did the aether come from? How does lightning give life? Or, today, what was there before the big bang?

The inscrutable origin of things is characteristic of the mythical mode. True or false, the theory of a big bang constitutes one of the main myths of contemporary society. Loewenthal understood that, from a moral-ethical point of view, some myths are better than others. He recognized that myths are man-made and believed that humans have the power – indeed, the moral obligation – to choose for themselves the best myth for their time. But how are we to choose? The classic alternative between the rational-scientific and the religious-ethical approach remains largely intact today. The former dictates its own path by virtue of its internal logic; the resulting myths may or may not be "good." The latter starts out with a vision of the "good"; in order to protect this mythical starting place, it sets limits to the play of reason. In his theory of Fulguro-Genesis, Loewenthal attempted to stake out a third option, a vision in which science and ethics could find common ground, becoming the foundation of a peaceful, open, and inclusive society.

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Biodata of **Jana S. Rošker,** author of "***Structure and Creativeness: A Reinterpretation of the Neo-Confucian Binary Category Li* 理 *and Qi* 氣.**"

**Professor Jana S. Rošker** (1960) is an expert in Chinese philosophy and is currently head of the Department of Asian and African Studies at the Faculty of Arts in the University of Ljubljana, Slovenia, and the chief editor of the academic journal *Asian and African Studies*. In 1988, she obtained her Ph.D. from the Department of Sinology at Vienna University in Austria and continued her studies and research at the Center for Chinese Studies in Taipei, Beijing University, Nankai University in Tianjin, and National Hsinchu University of Education. Her research interests and publication areas are mainly in the fields of methodology of intercultural research, traditional Chinese theory of perception, Chinese epistemology, and comparative philosophy.

E-mail: **jana.rosker@guest.arnes.si**

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# STRUCTURE AND CREATIVENESS: A REINTERPRETATION OF THE NEO-CONFUCIAN BINARY CATEGORY LI 理 AND QI 氣

**JANA S. ROŠKER**
*Department of Asian and African Studies, Faculty of Arts,*
*University of Ljubljana, Aškerčeva 2,*
*1000 Ljubljana, Slovenia*

## 1. Introduction: Structuralist Approaches to Reality and the Chinese Model

At the dawn of the third millennium, the concept of structure is perceived as something self-evident and omnipresent by most scholars and theorists. Structure has become a basic, although often vague, notion, which enables us to think in a coherent way about the external world, the stability and nature of patterns of existence, but also about observation, comprehension, as well as relations among individual entities. As a result, we see the creation, formation, and changing of objects as something that occurs within certain structural patterns. Recently, structural realism has been revived as a compromise candidate to resolve the long-standing question of scientific realism. However, critics contend that structural realism incorporates an untenable distinction between structure and nature and is therefore unworkable (McArthur, 2006: 209).

Although they produced many valuable theoretical insights, Western discourses have still not produced any general, integral, and coherent structural model of ontology and/or epistemology. The present article intends to show that such a model can be found in Chinese neo-Confucian onto-epistemology (960–1644), which was based upon the central binary category of structure and creativity creativeness (li 理 and qi 氣).

In order to introduce the interaction and the implications of this dual binary category that represented in the neo-Confucian discourse the basic foundation of ontological and epistemological as well as ethical system, we first have to draw attention to the importance of understanding essential and culturally determined specifics of categories and concepts. Exploring Chinese tradition without an analytical comprehension of such methodological foundations could easily result in false interpretations. In current research, however, the debate on the onto-epistemological dimensions of classical and premodern Chinese texts and their role in the context of traditional Chinese thought has been developed increasingly successfully under the aegis of rediscovering and applying specific traditional Chinese methodological approaches and traditional categories.

## 2. Binary Categories and the Principle of Complementarity as Specific Features of Traditional Chinese Thought

Traditional Chinese philosophic discourses differ in many basic ways from those in the West. In this context, we have first of all to mention the principle of immanence, which is essentially dissimilar to basic approaches of transcendental metaphysics. Immanent notions, which define most of traditional Chinese theories, are, of course, necessary products of the holistic world view. If there is no division between two worlds (material and ideal or subjective and objective), it is hard to define which of them ought to be more important or more absolute. This is the very reason for the fact that the majority of prevailing ideal discourses of traditional China do not contain any notion of transcendence in the sense of exceeding one and crossing into another (usually "higher") sphere.

Another specific characteristic of Chinese philosophy is a structural–holistic world view, based upon relations of binary antagonistic notions, called binary categories. The process of mutual interaction of both antipoles that form these binary pairs manifests itself in the principle of complementarity; it belongs to the basic paradigms of such reasoning leading to typical patterns of Chinese analogies. In the context of our present inquiry, however, the major point is that all the abovementioned features are also visible in the elementary paradigms of the medieval and premodern Chinese cosmology, expressed through interactions between structure (li 理) and creativeness (qi 氣).

As is well known, the traditional Chinese world view was a holistic one. Traditional Chinese thinkers did not strictly or categorically distinguish between the spheres of matter and idea, nor between any other dualistic connotations resulting from this basic dichotomy. Far less known or recognized is the fact that this holism was by no means indiscriminate; the traditional Chinese holistic world was not a sort of homogenous unity in which everything was connected to everything else, without demarcations or distinctions. On the contrary, the traditional Chinese world view was logically ordered based on relatively strict binary oppositional patterns. On a mental–reflective level, these patterns formed a series of specific Chinese analogies which provided the bases for the prevailing method of logical thought (Cui, 2005: 14–24).

Binary concepts can thus be seen as one of the fundamental characteristics of traditional Chinese philosophy. They represent a kind of duality that seeks to attain the most real (possible) state of actuality through relativity, expressed in the relation between two oppositional notions.

> Distinctions are seen in binary terms, and primarily between pairs of opposites (with even figure and color reduced to square/round and white/black); having drawn them, and recognized some recurring or persisting pattern (for example large, round, hard, heavy, and white) we detach a stone from other things as we cut out a piece of cloth or chop off a piece of meat. Things are not seen as isolated each with its own essential and accidental properties; on the contrary, distinguishing characteristics are seen as mostly relative. (Graham, 1989: 286)

Of course, binary patterns as such are by no means a specific feature of Chinese philosophy since in their divisional effect they form a basic condition of human thought as such. What distinguishes the Chinese binary categories from traditional Western dualisms is the principle of complementarity which represents the basic method of their functioning.

What we have here is a structural pattern of binary oppositions which, however, is fundamentally different from the model of Cartesian dualism. This latter involves a dialectic posited upon the relation between the mutually exclusive and polar opposites of thesis and antithesis, which have been determined by an opposition which is also a contradiction. This contradiction creates a tension, in which the reciprocal negation of thesis and antithesis creates a synthesis. The complementary model, which was prevalent in the Chinese tradition of thought, is instead based upon a noncontradictory opposition between two poles which do not exclude but complement each other and which are interdependent (Rošker, 1995:196ff). Such binary patterns do not produce any separate syntheses that can preserve "positive" elements of the previous state while simultaneously eliminating the "negative" ones. The ancient Chinese Daoist philosopher Zhuangzi (ca 380–300 B.C.) described the relation between the two binary poles of a complementary model as follows:

> 故曰, 蓋師是而无非, 師治而无亂乎?是未明天地之理, 萬物之情者也。是猶師天而无地, 師陰而无陽, 其不可行明矣。(Zhuangzi, 2000: XVII)
>
> Therefore I'm saying: why don't we preserve truth and abolish falseness? Why don't we preserve order and abolish chaos? If we think in this way, we do not understand the structure of nature, nor the state of being in which everything exists. This would mean preserving earth and abolishing heaven, preserving yin and abolishing yang. It's quite clear that this wouldn't work.

Such valuations of binary relations differ a great deal from those logocentric dualisms developed in the Hellenistic and Judeo–Christian traditions that were grounded upon mutual contradiction of both antipoles, tending to preserve one of the poles while eliminating the other. The most important specific features of complementary relations which demarcate them as well from the binary Cartesian type of dualisms are therefore the noncontradictionality of both antipoles, their interdependence, their axiological equality, as well as their mutual supplementation. The latter characteristic is also the reason for the fact that neither of either antipole has a primary position: their existence is conditioned by their mutual interaction which surpasses the limitations of special and chronological conceptualizations. Zhu Xi 朱熹 (1130–1200), the central representative of the neo-Confucian renovation, described it in the following way:

> 在陰陽言, 則用在陽而體在陰, 然動靜無端, 陰陽無始, 不可分先後。今只就起處言之, 畢竟動前又是靜, 用前又是體, 感前又是寂, 陽前又是陰, 而寂前又是感, 靜前又是動, 將何者為先後?不可只道今日動便為始, 而昨日靜更不說也。如鼻息, 言呼吸則辭順, 不可道吸呼。畢竟呼前又是吸, 吸前又是呼。(Zhu Xi, 1996: 11)

> When we speak about yin and yang, saying that function is yin, while substance is yang, we (have to know) that movement and stillness are without end, and yin and yang are without a beginning. Here, we cannot differentiate between before and afterward. If we speak about it from the point of origination, then there is always stillness before movement, there is always substance before function, silence before perception, and yin before yang. But before every silence, there is also perception, and before stillness there is movement. What should be taken as prior and what as posterior? We cannot simply say that today's movement is taken to be the beginning and neglect to mention the stillness that was there yesterday. This is like breathing: if we express it by exhale–inhale, it sounds right. We cannot describe it as inhale–exhale. But in fact, there is an inhalation before every exhalation and before every inhalation there is exhalation.

## 3. Traditional Western Interpretations of the Neo-Confucian Binary Category Li 理 and Qi 氣

Neo-Confucianism (960–1644) as the late (and final) renaissance of Chinese philosophic tradition exhaled the autumn fragrance of "authentic" Chinese philosophy. In his extensive writings, Zhu Xi 朱 熹 (1130–1200), the founder of the new, neo-Confucian state doctrine, provides a masterly epitome of ancient Confucianism while, at the same time, incorporating into it a number of cosmological, primarily (more or less concealed) Buddhist and Daoist, elements. From the time of this renewal onward, Confucianism repeatedly played the leading role in establishing the prevailing forms of traditional thought. In its ontology (as well as epistemology), this philosophical current has been founded upon the dual complementary relation between the abovementioned concepts li 理 and qi 氣. This binary category represented a new insight into the composition of cosmos, based upon structure and creativity. Although such an insight could represent a valuable contribution to investigating the ontological roots of existence, the Western philosophers of the time were not given an opportunity to genuinely comprehend the neo-Confucian theory and the problems of cultural incommensurability which condition the transfer of concepts from one culture to another.

When the first sinologists (who were Christian missionaries) initially encountered neo-Confucian philosophy in the seventeenth century, it was perfectly natural for them to interpret its bipolar conception of the world, consisting of something called qi 氣 and organized in accordance with something else called li 理, in terms of, respectively, matter and idea. However, in our view, the concept li cannot be understood as idea or principle in the "Western" sense but rather as structure or a structural pattern, which can, of course, also pertain to the sphere of abstractions or ideas (Rošker, 2010: 79–80). Similarly, and based on a more profound understanding of neo-Confucian philosophy, it is evident that the concept qi can hardly be understood as matter in the "Western" sense. In fact, the neo-Confucian philosophers defined it as something which is not necessarily substantial, for air or even a vacuum (the Great void 太虛) is composed of it. Thus, it represents a concept which could be more appropriately defined as creativity creativeness or a potential that functions in a creative way:

> 氣之聚散於太虛由冰釋於水.
>
> In the Great void, qi condenses and dissolves again. This can be compared to ice dissolving in water. (Zhang Zai, 1989: 389)

As noted, the majority of traditional European and American sinologists have translated this concept as matter. To illustrate this point, we can cite the translation of this passage by the renowned French sinologist from the beginning of the nineteenth century, Le Gall, in which the notion qi is clearly understood as atom(s):

> Le condensation et les dispersions des atomes dans la T'ai-hiu peuvent se comparer a la fonte de la glace dans l'eau. (Le Gall, quoted from Graham, 1992: 60)

This translation of the concept qi is problematic for it derives from a profoundly intrinsic sense of the criteria based upon the model of Cartesian dualism. Although Zhang Zai's comparison with water explicitly states that qi is a continuous state, and not an aggregate of atoms, the analogy with matter was so deeply rooted in Le Gall's perception that he automatically saw the notion qi as an entity which contains or is composed of atoms. Hence, for centuries, Le Gall and other sinologists who followed his reading have misled scholars regarding the question whether traditional Chinese philosophy applied the concept of atomicity (Graham, 1992: 61).

The second term, or the concept li, indicates the notion of structure, a structural pattern and the structural order of things. Taken as a whole, li represents a cosmic pattern, defining lines of movement or the dynamicity of men and nature. These structural lines are seen as relations which define both the sphere of ideas and that of phenomena. At the same time, they make possible the mutual adjustment of binary oppositions with complementary functions as well as their orderly fusion within the cosmic unity.

> The concept li is not obeyed or violated like a law; instead, one either goes with or against the grain of it, as in chopping wood. Le Gall translated it as *forme*, thus remolding the whole neo-Confucian cosmology after the analogy of Aristotelian form and matter (atoms). J. Percy Bruce instead translated this term as "law", thereby incorporating into neo-Confucian terminology itself the wrong answer to the question "Are there laws of nature in China?" (ibid.)

Li and qi are thus complementary concepts, which can be explained as a structure (or structural pattern) and a creative formative potential (creativity creativeness). Both are of immanent nature and can therefore be realized in the spheres of both ideas and phenomena. Euro-American philosophy offers no precise equivalents for these two terms. If we want to comprehend the modes of their existence and their functions, we must first free ourselves from reasoning in terms of Cartesian dualisms and try thinking based on the model of analogy, which arose from and was prevalent in the immanent metaphysic of traditional Chinese thought.

Graham (1992: 61, 62) cautions that discourses of Chinese complementary binarity may seem to be merely the result of concrete thinking to someone who views Chinese cosmology in terms of dualistic binarity. According to this bias, the Chinese mode of thinking seems to be based on the analogies of "real" physical coagulation and dissolution or of real patterns in jade instead of viewing these elements as abstractions. If the cosmos is composed of matter which functions according to concrete natural laws, then traditional Chinese philosophers are clearly mistaken, locked as they were into immutable conceptual schemes that have since been superseded. Such misinterpretations result from a lack of insight into the nature of abstraction, which follows different paradigmatic methods. For someone raised within a specific cultural-linguistic context, the corresponding modes of thought are so ingrained and automatic that they need not constantly reflect on the underlying metaphorical roots of their thoughts. Such reflection becomes necessary, however, whenever we are confronted with theories arising from differently structured discourses.

> Chinese concepts appear concrete to us only because the inquiring outsider, unlike the insider who habitually thinks with them, needs to fix his attention on their metaphorical roots. He is much less conscious of the metaphors underlying his own "matter" and "law", which, however, he must rediscover if he wants to explore the differences in a radical or fundamental way. (ibid.)

In the neo-Confucian tradition, li as a structural principle is thus a potential which cannot exist without its opposite pole, the potential of creative formation (qi). But this binary opposition includes concepts which are not comparable to the concepts of idea and matter, given that they can appear in both spheres and forms. Perhaps even more importantly, this binary concept differs from the dualistic model of idea and matter not only in terms of its inherent relational pattern but also in terms of its function.

Given that li and qi form a binary concept for which the question of the priority of idea or matter is not an issue, the translation of the term li as (natural) law is clearly incorrect.

As opposed to li's immanent nature, the notion of law in the Euro-American tradition represents an external axiom which influences and determines things from outside. Similar problems arise with the translation of li as "principle," a concept usually understood in terms of its effects and not its causes and function.

> While interpreting the term li 理 to mean "structure" may seem highly unusual, there are several good reasons for doing so. This meaning is already apparent in the original etymology of the character li 理, which is composed of the phonetic element 里 and the radical 玉, which designates jade. Originally, it denoted the lines or colored stripes in jade. In this context, Wolfgang Bauer points out the fact, that in classical Chinese, this character in a figurative sense also denoted structure, for example in the meaning of a crystal net that represents the immaterial principle of ordered matter,

> and was already used with this sense in the Confucian commentary on the *Book of Changes* 易經. (Bauer, 2000: 256–257)

A.C. Graham, a modern pioneer in the study of ancient Chinese logic, is one of the very few sinologists who consider the concept li as the expression of both a structural pattern and a structure (Graham, 1989: 191–2).

This term underwent numerous semantic variations. Originally, it expressed cosmic then social structure; subsequently, its semantic connotations also included the structure of language and meaning and, finally, the structure of the mind and consciousness. All these specific kinds of structural patterns were unified in the Chinese tradition, especially from the Song 宋 (960–1279) Dynasty onward, in a single, general, and basic rational structure, which was distinguished by its fundamental compatibility with innumerable kinds of different structural patterns. A basic criterion or *ultima ratio* of this compatibility can be found either in the ethically determined “justice” and “righteousness” of Confucian discourses or in the “naturalness” of Daoist texts.

The notion qi has also caused many troubles to sinologists over the centuries; in Western languages, it is extremely hard to find an equivalent locution. Legge, for instance, translated it as *passion-nature*; Couvreur writes in this context about *sensibility*; Faber about *instincts*; and Wilhelm describes it as vital energy, similar to Julien, who denotes it as *spiritus vitalis* (Forke, 1934a: 200). Most Chinese interpreters define it as a concept, denoting matter or substantiality; while in Western sinology in recent years the most common translation of qi is vital energy. For people who have practiced Tai Ji or Qi Gong for a while, qi seems to be more of universal term for life energy or even energy. In such experiences, it is almost equated with heat and infrared as a healing force. There are scientific studies and studies of brain function which support the concept of qi not as an abstract term but as a real force which can influence brain states.

But since qi doubtlessly belongs to immanent concepts that can be found in ideal as well as in material spheres, both of the abovementioned translations are problematic. The concepts of matter or substantiality cannot coherently refer to the ideal sphere, while energy is always exclusively immaterial.

In any case, qi was a central notion that appeared repeatedly in different theories throughout the entire history of Chinese thought. The concept qi, similar in its respective semantic scope of structure and structural pattern, has also been subject to several semantic developments and alternations. It thus occurred in the work of different philosophers in divergent semantic concatenations.

## 4. Structure and Creativeness as Basic Features of Cosmic Formation

As the binary opposition of the concept of structure and structural pattern, respectively, the term qi has not been carried into effect before the rise of the neo-Confucian discourses of the Song (969–1279) and Ming Dynasties (1368–1644).

In this respect, Zhu Xi and his contemporaries have in the main adhered to philosophical notions that have been assigned to the term qi by Zhang Zai 張載 (1020–1077), one of the most distinguished pioneers of the neo-Confucian restoration. Their essential content has become relatively evident from the earlier cited quotation in which qi is described as a substance defined by its characteristics of condensation and dispersion. The span of its consistency has not been limited to either matter or idea. In its condensed condition, it can appear as the first, and in a highly dispersed state, as the latter. In both cases, however, it represents something, which is void in essence.

> 太虛無形, 氣之本體。 (Zhang Zai, 1989/2: 389)
>
> The Great void is formless, and yet it constitutes the essence of creativeness.

Although Zhang has defined this creative potential quite precisely as the ontological basis of the universe, it nevertheless has been conditioned and defined by the structure of this maxim. According to Zhang Zai, the concept li still represents the concretization of the basic ideal structural order that makes any existence possible (Bauer, 2000: 253).

Without this structural order, the potential of creativeness could not transfer itself from the "Great void" into the world of material forms, condensing into concrete objects. The neo-Confucians, however, have also seen the concept qi as a primary notion which amalgamates the complementary oppositions of the binary category yin 陰 and yang 陽. In this sense, it was already applied by Zhou Dunyi (1017–1073).

> 二氣交感, 化生萬物， 萬物生生， 而變化無窮. (Zhou Dunyi, 2000: 48)
>
> Mutual interaction between both (basic principles) of creativeness produces all that exists. The changes of all that exists are innumerable (infinite).

Zhang Zais' followers, the Cheng 程 brothers, also saw Qi as the creative potential which concretizes itself in numerous elements of sensual–perceptible phenomena that can be categorized in dual oppositions of yin and yang, although they also often define it as a dual opposition of the highest principle dao.

> 程子曰： 有形總是氣， 無形只是 . (Cheng Hao and Cheng Yi, 1981/IV Sui Yan: 2168)
>
> The Masters Cheng said: What has a form is creativeness and what doesn't have a form is the Way (dao).

Thus, dao and qi were understood as oppositional concepts, expressing different forms of existence. At this conceptually abstract level, they are not perceivable. Dao, however, can be realized as li, manifesting itself in the effects of the structure of nature. In contrast, qi is primarily present within the phenomenal world as the very potential which inspires life into this structure.

The Cheng brothers pointed out that both concepts, li and qi, were real. But qi as manifestation of all concrete objects is inevitably linked to structural patterns, expressed by the concept li. Their mutual relation is complementary; but while the structural principle li cannot be directly perceived, the principle qi can be seized in the innumerable materialized forms of the phenomenal world.

> 有理，則有氣. 有氣, 則有數. (ibid.: 1225)
>
> If there is structure, there is also creativeness. And if there is creativeness, there is also the multitude (of things).

Thus, the Cheng brothers saw the concept of creativeness as divided into two basic moments that were named yin and yang by Cheng Yi. They were understood as the bipolar foundation of the phenomenal world. It is clear that yin and yang as expressions of the basic structure of material world are thus similar to qi, inevitably linked to the basic ideal principle dao:

> 離陰陽則無道，陰陽氣也, 形而下也，道太虛也, 形而上也. (ibid.)
>
> Without yin and yang there is no dao. But yin and yang together form the potential of creativeness that realizes itself in external forms (of phenomena), while dao is the great void that is situated above the forms (of phenomena).

This raises the question of how the Cheng brothers understood the notion dao that in their system denoted a manifestation of the world of ideas. The effects of dao that can also be perceived and seized in the phenomenal world are always conditioned by the basic paradigms of nature. Most of the relevant Song philosophers have equated these paradigms with the structure of nature (heaven) (天理):

> 道心天理. (ibid., I., Yi shu: 312)
>
> Dao's mind (consciousness) is the structure of nature (heaven).

Grounded upon this basic supposition, their follower Zhu Xi interpreted the complementary relation between structure and creativeness similarly:

> 天地之間有理有氣. 理也者，形而上之道也，生物之本也，氣也者，形而下之器也，生物之具也. 是以人物之生, 必稟此理，然後有性，必稟此氣，然後有形. (Zhu Xi, 1996: 5680)
>
> Between earth and heaven there are structure (li) and creativeness (qi). The structure is dao which is abstract and represents the basis of all beings and things. The creativeness is concrete and represents the tool for creating living beings and things. Thus, structure is necessarily required for the creation of human nature and the nature of things, and creativeness for the production of their (concrete) appearances.

## 5. The Relative Priority of Structure

Despite the fact that both mentioned elements form a complementary pair representing an undividable basis of everything that exists, and Zhu Xi basically claimed that in complementary pairs we could not differentiate between primary and secondary poles in respect to time or space, he still stressed the central relevance of structure. His opinion on the creative potential consequently was obviously not that respectable:

> 問，先有理抑先有氣，曰，理未嘗離乎氣，然理形而上者，氣形而下者, 自形而上下言，豈無先後，理無形，氣便粗有渣滓. (Zhu Xi, 2000: 137)
>
> (The disciple) asked: What was previous – structure or creativeness? (Zhu Xi) replied: Structure can not cannot exist without creativeness. But structure is abstract (above the forms or phenomena), while creativeness is concrete (bellow the forms or phenomena). Speaking from this viewpoint, we obviously can not cannot do without progression (lit.: without before and after or ahead an behind). The structure has no external form, while creativeness is full of excrements.

In this way, we can also begin to understand his following statements, from which we can infer his inclination to push back toward the prior role of the structure:

> 先有個天理了，卻有氣，氣積為質，而性具焉. (ibid.: 136)
>
> The cosmic structure is primary; only after it there can be creativeness. When creativeness accumulates, it becomes matter. In such way, nature fulfills itself.
>
> 有是理，便有是氣，但理是. (ibid.)
>
> If there is structure, there is also creativeness. But structure is fundamental.
>
> 是有理，後生是氣. (ibid.: 137)
>
> First, there is structure. Then creativeness is born.

Qi is a potential, basically similar to air or evaporation (Forke, 1934b: 173). It mainly represents the capability of realization or for experiencing of all that is established within the structural patterns of existence. Physical matter arises when there is enough accumulated qi. For Zhu Xi, the dividing line between matter and idea is still miniscule, irrelevant, and blurred. The categorization, according to which the term li would correspond to idea and qi to matter, is – in spite of everything – mainly a product of Westernized thinking and therefore completely out of place. According to Zhu Xi, creativeness (in the sense of substance) can and should remain equated to spirit or mind:

> 心者，氣之精爽. (ibid.: 223)
>
> Mind is the finest essence of creativeness.

Thus, the relation between both concepts is still a complementary one. Nevertheless, in modern interpretations, the neo-Confucian concept li has often still been identified with the ancient Greek notion of logos, mainly because it simultaneously represents both natural laws and the highest and ultimate ethical criterion. On the other hand, the concept of suchlike organic–structural linking of natural and (inter)human factors of existence appears as the central principle of holistic cosmo-ontology that constitutes the basis of specific classical Chinese discourses. Whereas dao in Daoist discourses is a foundation of all spiritual and physical cosmic elements, in neo-Confucian discourse it merely appears at the metaphysical level, inherently uniting natural as well as ethical principles. In this system, the concept of creativeness is realized through bipolar structured processes of the correlative interaction of yin and yang. It fulfills the function of conducting the concrete proceedings that create, form, and preserve the dynamic coherence of the physical world.

## 6. Zhu Xi's Elaboration of Traditional Cosmology: Linking Ontology, Epistemology, and Ethics

This elementary, all-embracing interaction between structure and creativeness did not remain limited to ontological frameworks. In Chinese tradition, it has also been projected into the sphere of epistemology and had certain ethical implications.

Thus, traditional Chinese theories of knowledge can be called structural or relational epistemologies because the subject they refer to are relations, forming a relative fixed structure. In China, the structural approach to comprehension had already been elaborated in ancient times (Rošker, 2010). It has been developed as an epistemological model that arises out of the compatibility between the structures of the external world and those of the human mind. Such structural compatibility has been seen as the basic precondition of human perception.

The material condition of life forms a framework that cannot be converted by human beings, just like they cannot change the basic physical forms of their own bodies. Within this framework, however, we have the right and the duty to live in maximum concordance with the paradigms of the integral order of cosmic structure. These paradigms permeate nature and society and are expressions of the spontaneous reality of dao. Actually, according to most modern readers, ethics is the field in which the neo-Confucian Zhu Xi did not create anything genuinely new. We must not forget, however, that all his debates were composed in the context of developing the original Confucian ethics; it is thus advisable to read them in this context. It seems reasonable to claim he elaborated this field by new interpretations of the classical works of Confucian morality by integrating them into his own philosophic system. By establishing the binary category of structure and creativeness, this crucial neo-Confucian philosopher elaborated not only the existing methodological aspects of traditional Chinese philosophy but also the classical Confucian ethics which had until then been rooted in necessary, mechanistic adjustments of individuals to the ancient patterns of prevailing morality.

The complementary nature of traditional Chinese dialectics, however, also prevented him from establishing a radical execution of classical idealism. His obvious inclination to the sphere of ideas cannot cross the threshold toward a complete negation of the material sphere, i.e., to the antithesis in the sense of the Western comprehension of a dialectic contradiction. For him, structure and its innumerable patterns are of primary importance, not only in the sense of the original principle of being but also in the sense of positing an ultimate ethical criterion for everything that exists. Nevertheless, Zhu Xi's notion of structure still forms a concept that is inevitably closely connected to the concept of creativeness. He explicitly states that without concrete forms, the existence of structure would remain unfounded and thus superfluous.

> 理氣本無先後之可言，然必欲推其所從來，則須說先有是理，然理又非別為一物，即存乎是氣之中，無是氣，則是理亦無掛搭處 . (Zhu Xi, 2000: 137)

> In respect to structure and creativeness, we actually cannot speak about any succession (lit.: before and after or before and behind). But if we still want to follow them till their origin, we have to say that structure is the first one. Structure, however, is by no means a separate thing, since it is situated in creativeness. Without creativeness, the structure would not have anything to hook onto.

In the spirit of traditional Chinese explanations, the neo-Confucian understanding of structure and its creative potential can be exhibited by various allegories referring to human beings, their lives, thoughts, and sensations. Thus, human veins and arteries can be seen as structure, while the blood, flowing through them, as creativeness. The skeleton is structure, while the organs, muscles, and skin form the creativeness which imparts life to it. Inborn particularities of every human being belong to the structural patterns of nature, while his or her concrete life in society is seen as its creative potential. The human mind is a rational structure, and what humans set up by their rational activities is creativeness. The external world is also a structure, while (individual and social) human life is creativeness, having effects that are good or evil.

In any case, both concepts have the nature of ontological duality which is a characteristic feature of immanent philosophy. Besides, the two expressions that literary denoted both spheres above and below phenomena (xing'er shang 形而上 and xing'er xia 形而下) cannot be understood in the sense of ideas and matter or metaphysical and physical sphere, respectively. In neo-Confucian philosophy, the concept of phenomena is much wider, as in discourses dividing physics from metaphysics. It often also refers to the sphere of realities existing merely in the world of ideas or illusions. Although creativeness is the very potential which realizes every structure, it necessarily always belongs to phenomenological categories, even when they only exist in our everyday mind or awareness of the tradition in which we live. But then, what exactly is the nonphenomenal world that has been seen as the basic characteristic of structure by neo-Confucian philosophers? It is an endless, open, and dynamic order which cannot be seized or even less comprehended by our limited perceptional organs. Actually, we cannot even imagine it. Thus, it cannot as such belong to our phenomenal world. However, this does not mean we are not – as part of its innumerable phenomenal patterns – part of this structure.

Thus, in its complementary relation with the creative potential, the concept of structure did not remain limited to ontology or epistemology but also gained a new ethical dimension; the mutual interaction between both antipoles of existence imparted a dynamics of awareness into the former static framework of completely fixed values and virtues. Without a doubt, this awareness is also structured – otherwise, it could not be possible. The property of creativeness, however, is the very potential which can also actuate the limited and transitory system of human mental processes.

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# PART IV:
# DARWINISM AS THE BACKBONE OF THE LIFE SCIENCES

**Adriaens**
**Bishop**
**Galway**
**Garbary**
**Gadoth**
**Mass**
**Seckbach**
**Kamenir**
**Fleury**
**Gordon**
**Yisraeli**
**Barbieri**
**Farge**

Banded argiope spider, *Argiope trifascianta*, enshrouding a grasshopper, with male spider in attendance, photographed by Richard Gordon on the tall grass prairie at Silver Bog, Manitoba, Canada, August 17, 2003. Cf. poem “Design” by Robert Frost.

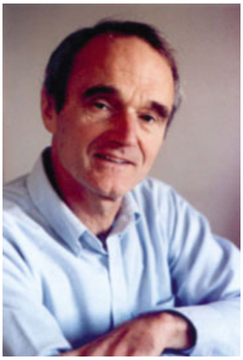
Biodata of **Gerald L. Schroeder**, author of "***Evolution: The Biblical Account of Life's Development***."

**Dr. Gerald L. Schroeder** currently teaches at the College of Jewish Studies in Jerusalem and does research in environmental radioactivity. He earned his Ph.D. (in 1964) at the Massachusetts Institute of Technology in two fields (Earth and Planetary Sciences and Applied Physics). He served 7 years on the staff of the M.I.T. Physics Department prior to moving to Israel where he joined the Weizmann Institute of Science, and then the Volcani Research Institute, and the Hebrew University of Jerusalem Isotope Separation Mass Spectrometer Facility. In work with nuclear disarmament, he witnessed the detonation of six nuclear bombs.

His formal theological training includes 20 years of study under Rabbis Herman Pollack, Chaim Brovender, and Noah Weinberg.

Dr. Schroeder has approximately 60 publications in peer-reviewed scientific journals. He is the author of *Genesis and the Big Bang* (Bantam Doubleday), *The Science of God* (Simon & Schuster), *The Hidden Face of God* (Free Press), and *God According to God* (HarperOne). His books appear in ten languages.

E-mail: **schoerde@013net.net**



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# EVOLUTION: THE BIBLICAL ACCOUNT OF LIFE'S DEVELOPMENT

**GERALD L. SCHROEDER**
*College of Jewish Studies, One Western Wall Plaza*
*91141 Jerusalem, Israel*

## 1. Life: Origin and Evolution

"It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh! What a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc., present, that a proteine compound was chemically formed ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which would not have been the case before living creatures were formed" (Darwin, 1887).

The warm fecund pond scenario was so appealing (and tenacious) that Stanley Miller, a century later, made his reputation by putting the pond to the test. (That was 1953, the same year that Crick, Watson, and Wilkins announced their discovery of the shape of life's genetic library, the double helix of DNA.) And Miller's attempt worked – well almost but not quite. Miller constructed a system of vessels which he loaded with what he and his supervisor, Harold Urey, considered to be representative of the prebiotic earth's waters and atmosphere, some four billion years in the past. These consisted largely of ammonia, methane, hydrogen gas, and water. A cold trap concentrated whatever formed as he passed an electric current through the mix. Within a week, the murky liquid was found to contain three amino acids! The news spread like wild fire. Amino acids are the building blocks of proteins, and proteins are the building blocks of life. Stanley Miller had solved the puzzle of life's origins.

If in a few days within a small flask, a few amino acids would form via totally random reactions, then in millions of years and a biosphere which had as its base a billion trillion liters of water (the approximate volume of today's oceans), surely some form of life would crawl or swim into being. Unfortunately the hoopla which lasted a decade and more was premature and unwarranted. Even with refinements, only a few amino acids ever formed and consistently failed to join into anything resembling a protein. Further, as knowledge of the prebiotic earth advanced, evidence implied that the prebiotic atmosphere contained significant amounts of carbon dioxide which, when present, block the formation of "Miller's" amino acids.

Today, the “Miller” approach is deemed irrelevant to origin of life studies (c.f., Edwards and Rosen, 2004, for a totally secular review of this subject). Unfortunately, most other theories probing the origin of life are equally deficient. One suggestion is an RNA world that mutated into a DNA world. While superficially appealing (what Miller refers to as paper chemistry), such a sequence is unlikely due to the extreme instability of RNA and its precursor components.

That science has failed to find a convincing origin of life scenario is no embarrassment of the scientific method. Science often deals with highly recalcitrant problems. Explanations that initially seem appealing, such as Miller’s, are not always correct upon scrutiny. The planetary model of an atom, with electrons spinning around a nucleus, similar to a miniature solar system of sun and planets, was proposed by the Japanese physicist, Nagaoka Hantaro, in 1904. It still persists in elementary text books although it is quite inaccurate. As with science, to understand life’s origin and development from the biblical perspective, we also require digging below the surface, in this case, mining the subtleties of the literal text. Fortunately for that, we have ancient biblical commentaries. No modern commentaries will be used here since they can bend the Bible’s words to match the modern understanding of the science. Relying only on ancient commentary obviates that possibility. These include, beside the biblical text, the Talmud (ca. 400), Rashi (1090, considered the penultimate in gleaning the meanings of the text), the philosopher Maimonides (1190), and the Kabbalist Nahmanides (1250, the major kabbalist commentator on the Bible).

Now what is the Bible’s take on life’s origin and development?

The opening sentence of the Bible tells us that “God created the heavens and the earth.” The very next sentence tells us that the earth was *tohu* and *bohu*. The Hebrew *tohu* implies all was in a state of chaos, unformed. And *bohu* is a compound word, *bo* – there is and *hu* – in it. There is in it; there is potential. This potential was played out over the succeeding 6 days and/or 14 billions of years depending upon one’s perspective of time. (See the two relevant chapters in The Science of God for an account of this dual view of time, six 24-h days that contain 14 billion years of history, the approach for which has the stamp of approval of the journal *Nature*.)

The Bible differentiates between creation, an act that brings something directly into the universe from the Divine source, and making or forming, which uses already existing material to produce that which is being made. In the “creation chapter” of the Bible, Genesis chapter 1, there are only three sets of creation. The opening sentence records the creation of the universe, the beginning of space time matter as we understand them, and the laws of nature. Initially, matter was in the form of energy which, as per Einstein’s brilliant insight into the laws of nature, could condense and take on the form of solid matter. According to all ancient commentary, this was the only physical creation, the only creation of material. Science refers to this as the big bang.

The next creation does not occur until verse 21. There are only 31 verses in the creation chapter, so we are two-thirds of the way through, and till now, all has ridden of that first creation. This second creation brings to animal life the soul of animal life, the *nefesh*, and instills in animals, all animals including humans, the drives for survival, progeny, and comfort. The final of the three creations is the creation of the soul of humans, the *neshama* (Genesis 1: 27). The *neshama* knows the Oneness within which the entire created universe resides. This is reflected in the statement, "Hear Israel, the Lord our God the Lord is One" (Deut. 6:4; Mark 12:29). The *neshama* argues with the selfish goals of the *nefesh* to acknowledge that Oneness and to act in accord with a unity that embraces and respects all society, even all existence.

The opening chapter of Genesis acts as a zoom lens. First, the entire universe is mentioned, the heavens and the earth. By day 3 of the 6 days of creation, we are only discussing the earth, and by half way through day 6, humanity is the topic. The Bible does not forget that there may be huge "heavens" out there, but its interest focuses on humankind.

Day 3 is the biblical time for life to make its appearance. In Genesis and The Big Bang (1990) and later in The Science of God (1997), I discuss in general terms and then in detail how the 6 days of creation, Genesis chapter 1, remain 24 h each even as they contain the billions of years of our cosmic development, "And God said let the earth bring forth …" (Genesis 1:11). Notice that the word creation is not mentioned here. All the material needed for life to form was already present in potential by the first of the creations. The laws of nature and the energy of the big bang creation are so well tuned for complex life, as if the universe knew we were coming. The journal *Scientific American*, probably the world's most widely read science journal, in an issue titled Infinite Earths in Parallel Universes Really Exist (Tegmark, 2003), infers that there must be these vast numbers of universes, each with its own particular set of natural laws. Why? Because if we are the only universe, the tuning of the laws of nature is so perfect for complex life to develop that it implies that our universe was designed for life. That is an amazing admission for a totally secular scientific journal.

Was this origin of life the result of random reactions guided by the laws of nature, or was it with some Divine tweaking or preprogramming of the system including the laws of nature? The Bible is silent on that. The only name used for God in the creation chapter is, in Hebrew, *Elokiim,* the name that relates to God as acting in nature. All we are told is that God commanded the earth to do its job and bring forth life. And it did.

In this scenario, there are two significant commentaries. First, all of the plants listed on day 3 did not appear at that time. In the worlds of Nahmanides in his commentary on this event, it was the beginning of an on-going phenomenon. The Bible is interested in what might be termed green peace. It has laws related to how planting of crops should be done and which types of trees may be cut down. As such, it may not be a surprise that the Land of Israel had vastly more trees at the end of the twentieth century than it had at the beginning of that century. Essentially, all were planted by the national endowment for forestry. But though the Biblical interest in plant life is clear, the main goal of the text is to get to humankind. As such, it groups together and puts aside at this juncture the discussion of the development of plant life.

This technique of the Bible of condensing information not relevant to the on-going text is made clear elsewhere. Near the end of Genesis chapter 11, we learn that Terah at age 70 became the father of Abraham (at the time named Abram). We are then told that Terah lived another 135 years, dying at the age of 205. Thus, ends chapter 11. Then a few sentences later, near the beginning of chapter 12, we are told that God told Abraham, then 75 years old, to travel to a different land. At this time, Terah was 145, but there was no mention of Terah. In chapter 17, a full five chapters later, Abraham, now 99 years of age, was told that he and Sarah, his wife, would become parents of Isaac the following year: still no mention of Terah who, now age 170, had another 35 years of life. Terah may have bounced baby Isaac on his knee, but no mention is made. After chapter 11, when Terah's life span was summarized, there was no further mention of his name. Terah was important. After all he was father of Abraham. But Terah is no longer relevant to the on-going accounts, and so his history of summarized and 'put aside.' Similarly with the account of the development of plant life listed in day 3. The text was moving onto events not related to vegetation. And so its eventual development is summarized in these few sentences.

The second significant variant found in day 3 events would seem incredulous and was not for the confirmation, in principle if not in exact fact, by investigations into the quantum nature of the material world. In Genesis 1:11, we are told that God called for the earth to bring forth the variety of plant life, including fruit trees that bring forth fruit. The following verse tells that the earth did it, almost. It produced trees that bring forth fruit. Were it not that Rashi, the top of the ancient Biblical commentators, explained the difference it would seem nitpicking. But with the mindset that the Bible is the Divine word, then no word is considered superfluous. God wanted fruit trees that also bring forth fruit. But the earth produced trees that bring forth fruit. God wanted that the tree itself, the bark, for example, to be a fruit, as with the cinnamon tree, as well as the fruit hanging from its branches. According to Rashi in his commentary on Genesis 1:11, the earth went against God's word. The earth, Rashi tell us, has the ability to rebel. The Earth has an aspect of will. And for that reason, Rashi relates that following the expulsion of Adam and Eve from Eden for having eaten the forbidden fruit, when God is chastising Adam for his part of the transgression, the text reads, "And to Adam [the Lord] said 'Because …you ate of the tree about which I commanded you saying You shall not eat of it, cursed is the ground…'" (Gen 3:17). Note the problem? Adam ate and the ground is cursed. Rashi tells us that the ground is cursed here because it went against God's word on day 3.

Can the ground have choice, a will or motivation, an ability to go against a Divine command? That facility sounds very similar to knighted mathematician Sir James Jeans, almost a century ago: "The world begins to look more like a great thought than a great machine" (Jeans, 1931). And also, just a few decades ago, Nobel laureate, Harvard biologist George Wald of blessed memory wrote in the peer-reviewed International Journal of Quantum Chemistry, suggesting that "both questions [the origin of life from nonliving matter and the origin of consciousness in life that originated from nonliving matter] might be brought into some degree of congruence. This is with the assumption that mind, rather emerging as a late outgrowth in the evolution of life, has existed always as the matrix, the source and condition of physical reality…" (Wald, 1984).

But can mind actually be an aspect of the creation? We humans, conscious of our selves, know that we have mind. And those dogs know that they are dogs and not cats. Just take a walk through a park with a dog on a leash and note the dog's totally different reaction to other dogs than the reaction to cats. Fish school and jelly fish, among the most ancient forms of macroscopic life, have enough neurons to observe and maneuver through a maze colored black while shying away from a similar maze colored red. Bacteria extend microscopic tubules, F. pilus, to other bacteria in order to pass genetic material one to another, sharing information that, unfortunately, may hold the key to outsmarting an antibiotic. Medical doctor, Frank Vertosick, Jr., in his book, *The Genius Within*, discovering the intelligence of every living thing (2002), calls it the microbial mind, a sort of communal affair.

Where do all these "smarts" come from? A materialist scientific view would assume that with life existing on earth for over 3.5 billion years and macroscopic animal life just over half a billion years, there is time for randomness to put it together step by step. The Bible sides with Wald and Jeans. There seems to be a mind active in this.

The usual mistranslations of the opening sentence of the Bible are "In the beginning God created the heavens and the earth." Or "In the beginning of God's creating the heavens and the earth." Of course, the word "creating" is nowhere in that Hebrew verse, so the second option is automatically out. The first option, "In the beginning," is also in error since the first word of the Bible is "*Be'rai'sheet*" "In the beginning of," and dropping the "of" in the verse in order to make it grammatically fine is ludicrous. Yet we have all grown up on one of those versions. However, *Be'rai'sheet* has another meaning, "With a first cause" which would render the sentence totally intelligible, "With a first cause God created the heavens and the earth." And what would that first cause be? Again, Rashi and, a 1,000 years later, Nahmanides lead us to the essence. We are told that to understand the opening words of Genesis, read Proverbs 8, verses 12, 22, and 23. "I am wisdom. … The Lord created me [wisdom] as the beginning of His way, the first of His works of old I [wisdom] was established from everlasting from the beginning, before ever there was an earth. …When He established the heavens I [wisdom] was there." The big bang creation was the physical creation of the universe. But prior to that, there was a Divine emanation, wisdom. Every aspect of existence, the entire universe, is an expression of that wisdom. Wisdom (Bible) and thought (Jeans) and mind (Wald) are not two sides of a single coin. They are the same side of that single concept merely spelled in differing ways. The physics of the quantum have come to confirm the opening concept of the Bible. The universe knew (and I use that word in the fullest sense of its meaning) we were coming.

Could the development of the universe, at least in general terms, have been precoded from the very beginning? Attorney Gil Goller in conversation suggested how in theory this could have been accomplished. By a minuscule fraction of a microsecond after the big bang creation, much of the created energy was in the form of intense electromagnetic radiation, another way of writing super powerful light waves. It is electromagnetic radiation that carries the information for cellular telephones, and TV programs replete with exquisite sound and color and precision timing. This information manipulates the mechanics within the instruments designed to receive it. All this is encoded on emitted waves of "light." If we with our clearly limited technology can encode such a density of information, clearly a super intelligence (God) could encode the entire cosmic scenario within the burst of created energy. Neither Goller nor I is suggesting that this is definitely true. Merely that it is worth considering when musing of the finely tuned way that the universe has developed.

Is the genetic code, the single, unique code common to all forms of life, an example of this embedded wisdom? All life has the same DNA/RNA-based system. There is no evidence of any evolution of this basic system over time. Could nature have randomly stumbled onto the only system that seems compatible with life on earth? A parallel example might be language and writing. Crucial for advanced societies, the passage of information via language is essential. Writing appears approximately 5,500 years ago. It spread and in doing so mutated. The Greek alphabet is different from the earlier Hebrew aleph-bet, though we can see the relationship. The opening letters of Hebrew are aleph, beit, and gimmal. The Greek has alpha, beta, and gamma. And both differ from the German and Russian and Chinese. Why do all these variations thrive? Because they are all viable systems for recording and transferring information.

Not so with genetic information. All the information that we can glean from the shapes of primitive microbial fossils and from the genes in all life today points to only one system. The logical conclusion is that DNA/RNA is either the only viable method that can provide the needed variety of information storage and retrieval or that it is so superior to any other system that there is no competition. Either way, based on shapes and dimensions of the oldest microbial fossils, it seems that nature incorporated it from the beginning. Quite an invention for rocks and water and a few simple molecules if there was no guidance involved. But as the Bible and then 3,000 years later, Nobel laureate Wald point out, mind was and is part of the package of the big bang creation.

The first biblical mention of animal life occurs on day 5 when "God said, let the waters swarm with swarms of living creatures, and winged creatures that fly …" (Genesis 1:20). The creation of the animals told in the next verse refers to the spiritual creation of the animal soul, the *nefesh*, not their bodies. And indeed, the first appearance of macroscopic animal life was in the waters, and it was a swarm referred to as the Cambrian explosion of animal life. An error often repeated in English versions of the Bible is the translation of the Hebrew word *oaf* as birds. In modern Hebrew, *oaf* means chickens. In biblical Hebrew, *oaf* means any animals with wings. The first of the winged animals were insects, and they map time-wise right among the types of animals mentioned on day 5.

## 2. Adam: The First Hominid with the Soul of Humanity

Nahmanides in his commentary on the biblical account of Adam and Maimonides in The Guide for the Perplexed, first published in 1190, both tell of beings, animals, existing at the time of Adam and Eve that were totally human in shape and intelligence but lacking the *neshamah*, the soul of humans. Into one of these prehumans, referred today as hominids or Cro-Magnon, God instilled the *neshamah* and that particular being became human. No physical change was involved. The change was spiritual. Hence, in Genesis, we are first told that God made Adam (Genesis 1:26), relating to the physical body and then that God created the Adam (Genesis 1:27), relating to the soul. The Talmud in a section called *Keliim,* mixtures, states that when one of them died, you could not tell them apart from a dead human. The fact of hominids, cave men and women, and predating Adam was never a problem for ancient commentators. The Bible is silent on the origin of these beings. How they came into being is irrelevant since what makes a human human is the soul, not the body, and that is a direct creation from God. This topic is dealt with in depth in my previous writings, primarily in *The Science of God.* It is well to recall that the Bible devotes a mere seven sentences to the entire development of the animal kingdom, from the first mention of animal life (Genesis 1:20) to the appearance of Adam (Genesis 1:26). How the biblical sequence describes this flow is mirrored by the fossil data. Again, what drove that development is not defined.

## 3. The Big Bang Creation: God or the Laws of Nature

In 1973, Edward Tryon published an article in the prestigious peer-reviewed journal, Nature, describing the possibility of how the creation of the universe might be the result of a quantum fluctuation (Tryon, 1973). The physics is complex but is consistent with our understanding of the laws of nature. A quantum fluctuation allows the creation of something from a potential nothing provided that the laws of nature are in existence, not nature, but the laws of nature. Though Tryon's suggestion was largely neglected for several decades, it has become one of the main conjectures for the creation of our universe from absolute nothing. NASA on its web site, in the section dealing with the findings of the Wilkinson Microwave Anisotropy Probe (WMAP), cites quantum fluctuation as the creating cause of the universe. What this means is that there can have been a big bang creation without the help of God, provided the laws of nature (quantum fluctuations being one aspect of the laws of nature) predate the universe.

Our concept of time begins with the creation, so the laws of nature must have existed prior to time, that is, the laws of nature would be outside of time. What we have then is totally nonphysical laws, outside of time, creating a universe. Now that description might sound somewhat familiar. Very much like the biblical concept of God: not physical, outside of time, able to create a universe. The only differentiation would be whether the universe once created functioned in a random fashion or if it seemed to have some hints of a teleological direction. As Moses describes in Deuteronomy 32:7, "Remember the days of old, consider the years generation by generation," those hints might be found either in the physical development of the universe during those 6 days of Genesis (i.e., the days of old) or in the flow of social history, ancient or modern. If either or both of those views seem random, then no need for a Divine direction. If there seem to be events that imply direction or are totally inconsistent with how nature or society normally develops, then there might be a Designer even though the design is not perfect.

Certainly, the Bible makes no claim to perfection. The revamping of the world via the Flood at the time of Noah is but one biblical example of an imperfect world (persons living to 900 years) needing a reworking (following the Flood life spans gradually drop to numbers we know today). Whether the Flood and its related events are literal or metaphor is irrelevant to the biblical lesson that it teaches. A world created by God is not a perfect world, and God "admits" its imperfection.

## 4. Summary

That life developed from the simple to the complex, in my opinion, is an absolute fact. On that, biblical passages and scientific discoveries are in total agreement. All life shares the same genetic coding system and the same system for reading that code. Human arms and hands have the same bones as the forelimb of a beaked whale, and that of an alligator, as well as the hind limb of a salamander. The bones may be of different lengths, but they are all there from shoulder to fingertip. What drove the development of life from the seemingly inert earth to the complexity of today's biosphere is the debate. Was it random mutations or that plus some help by the wisdom embedded within the big bang creation itself? Science classically can only address subjects susceptible to experimentation, that is, subjects of the material world. Quantum physics has brought the nonphysical, the metaphysical, into the physics laboratory.

If the laws of nature, specifically quantum fluctuations as per the NASA statement, were the cause of the big bang and the resulting origins of time space energy/matter, then their existence predates time or, giving a theological spin to the wording, transcends time. We see that even a seemingly scientific account of our origins (NASA) allows for transcendence. Anything transcendent would be supernatural in some sense. Although not necessarily representative of a deity to which one might pray or worship, the idea of transcendent laws of nature conflicts with a thoroughly materialistic account of our origins. Materialism has failed when addressing the question of our ultimate origins.

We have come full circle. How we began in the ultimate sense and why and what caused that beginning are questions that extend beyond the certainty of the material sciences. And so their resolution requires a leap of faith.

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Biodata of **Pieter R. Adriaens**, author of "***Design and Disorder: Gould, Adaptationism and Evolutionary Psychiatry***."

**Pieter R. Adriaens** is a postdoctoral fellow at the University of Leuven's Institute of Philosophy. He obtained his Ph.D. in 2006, with a dissertation about the relationship between philosophy of psychiatry and evolutionary theory. He has held visiting fellowships at the University of Montpellier (*Institut des Sciences de l'Evolution*) and the University of Cambridge (UK; *Department of History and Philosophy of Science* and *Centre for Research in the Arts, Social Sciences and Humanities*) and has engaged in participant observation in various mental hospitals in Belgium. He is spokesman of a Belgium-based research forum (*IdeaLab*) bringing together philosophers, psychiatrists, psychoanalysts and psychopharmacologists. Most of his work is about the history and philosophy of evolutionary psychiatry, but he also published on evolutionary accounts of homosexuality and homophobia. He just started a 3-year research project (as PI) exploring the place and role of culture-bound syndromes in contemporary psychiatry and philosophy of psychiatry and a 4-year project (as co-PI) about the cultural evolution of homophobia. When bored of academia, he plays Fender Rhodes in a post-rock trio called Grim and avidly collects mid-century modern design and decorative arts.

E-mail: **Pieter.adriaens@hiw.kuleuven.be**

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# DESIGN AND DISORDER: GOULD, ADAPTATIONISM AND EVOLUTIONARY PSYCHIATRY

**PIETER R. ADRIAENS**
*Institute of Philosophy, University of Leuven,*
*Kardinaal Mercierplein 2, B-3000 Leuven, Belgium*

> *Evolutionists are essentially unanimous that – where there is "intelligent Design" – it is caused by natural selection (…). Our problem is that, in many adaptive stories, the protagonist does not show dead-obvious signs of Design.*
>
> – H. Allen Orr

## 1. Introduction

Biologists and philosophers agree that the principle of natural selection was Charles Darwin's most important idea, to the extent that it is the sole source of complex design in the biological world. There is considerable debate, however, as to how skilful and efficient it is in its operations. Typically, adaptationists tend to conceptualize natural selection as a smart engineer, leaving in its wake a trail of cunning contrivances. To a certain extent, then, adaptationists endorse the main claim of natural theology – one of Darwin's one-time opponents – in that they view the world as packed with design. In a paper with the population geneticist Richard Lewontin, palaeontologist Stephen J. Gould criticizes this adaptationist philosophy by comparing it to the brimming optimism of Voltaire's Dr. Pangloss, who is widely known for his jolly Leibnizian credo that 'we live in the best of possible worlds'. Contrasting such optimism, he highlights the sometimes sloppy and shoddy work of natural selection, arguing that its design failures are due to the many constraints it has to contend with. If natural selection is an engineer or designer at all, he concludes, it must have two left feet.

In this chapter, I will show, firstly, that adaptationism comes in many guises and that Gould's adversaries are often shifting between varieties – some of which may or may not be harmed by his critique. Conversely, and secondly, Gould has often been ambiguous about the reach of his revolt. Clearly, his work on constraints is intended to debunk the powers of natural selection. But in doing so, is he complementing or contravening the adaptationist stance? In a third and final section, I will illustrate the topicality of the adaptationism debate, which is often referred to as the 'Darwin wars', by focusing on a developing Darwinian discipline: evolutionary psychiatry. Gould's work has already proven relevant for the new science of evolutionary developmental biology (e.g. see Lewens, 2009) as well as for evolutionary medicine (though with some reservations; e.g. see Nesse, 2005). While Gould has rarely written about psychiatry, I will argue that his work can be used to complement (and contravene) adaptationist explanations in evolutionary psychiatry.

## 2. A Clever Engineer

Libraries have been filled with books and papers about the nature of natural selection, while many seem to agree that it is a paragon of sheer simplicity. As Darwin argued, its simplicity consists in its being the conclusion of a simple syllogism of which the three basic premises are demonstrably true. First of all, there is *scarcity*. Theoretically, any biological species could grow exponentially in a handful of generations. The reason why such population explosions rarely occur in the wild is because, sooner or later, growth always meets with some kind of scarcity, for example, shortage of space or scarcity of food. As a result, not all organisms will be able to survive and reproduce. Secondly, there is *variation*. No two specimens of any population are identical, and some of their differences determine which organisms, when confronted with scarcity, will survive and reproduce and which won't. Some variants, it seems, help their carriers to do better than others. Thirdly and lastly, there is *heredity*. In general, children tend to resemble their parents more than they resemble distant relatives or arbitrary strangers. Enabling their carriers to do better than others, useful variants will be transmitted more often than useless or detrimental variants. Darwin concludes that there must be 'an invisible hand' in nature that identifies and maintains useful traits and passes them on to progeny: 'This principle of preservation, or the survival of the fittest, I have called Natural Selection' (Darwin, 1859, 143).

What is being selected and preserved by natural selection are those traits that are somehow useful to the organism in its struggle to survive and reproduce. If such a trait succeeds, throughout a number of generations, in spreading over a population, it is considered to be an adaptation. An adaptation, then, is an inherited trait of an organism that fulfils a certain function in a certain environment and by virtue of which an organism's ancestors have produced more viable offspring than an organism lacking the very same trait. Examples of adaptations are legion and include all sorts of ingenious morphological (e.g. the anteater's snout), physiological (e.g. the antifreeze in Arctic cod), behavioural (e.g. bird migration) and even psychological (e.g. jealousy) characteristics. On Darwin's view, the world's wonderful array of adaptations can only be explained by referring to natural selection.

The view that natural selection and adaptation play a central role in studying the evolution of life is often referred to as *adaptationism*. Recent work in philosophy of biology has shown that adaptationists come in many varieties (Godfrey-Smith, 2001; Lewens, 2009), three of which will be important in the remainder of this chapter. First of all, empirical adaptationists hold that natural selection is the only important mechanism of evolutionary change so that the outcome of evolutionary processes can reliably be predicted and explained by considering the role of natural selection alone. Moreover, empirical adaptationists also hold that natural selection is a very vigorous, creative and unconstrained mechanism, bringing about a sheer endless flood of adaptive design in nature. Explanatory adaptationists, by contrast, freely grant that natural selection may not be as ubiquitous as empirical adaptationists assume and that its working may actually be under heavy constraint by all sorts of evolutionary processes. Nevertheless, they hold that biologists should focus (only) on explaining adaptation and complex design, because these are the key problems in biology. Finally, methodological (or minimal) adaptationists hold that the most promising way to study biological systems is to look for selectionist explanations first, if only to rule them out before considering other options.

As Godfrey-Smith and Lewens show, there are many arguments for and against each of these varieties of adaptationist thinking. It is important, however, to emphasize that any argument for or against one variety of adaptationism need not necessarily affect another variety. Thus, it is possible, in principle, to be an empirical adaptationist without being an explanatory adaptationist. One can argue that the world is truly replete with good design but also that design is not what needs to be explained in biology. Perhaps, diversity should be the focus of the biological sciences, rather than design. Conversely, it is also possible to be an explanatory adaptationist without committing to empirical adaptationism. Some biologists and philosophers of biology would probably argue that complex design is what needs to be explained in biology (because it is much the most interesting aspect of the evolutionary process), even though they would not go as far as to say that it is to be found everywhere in the world. Finally, methodological adaptationism does not imply either empirical or explanatory adaptationism. Adaptive thinking can be an innocent working method in biology that need not be tied to claims about what the world should look like (as in empirical adaptationism) or what biologists should be interested in (as in explanatory adaptationism).

On a superficial reading, many popular biologists and philosophers of biology can be considered as empirical adaptationists. The philosopher Daniel Dennett is a good case in point. In *Darwin's Dangerous Idea*, for example, Dennett openly sympathizes with one of natural theology's basic premises, to wit that the world is full of good design. As such, Dennett would probably concur with any natural theologist's ode to nature. He quotes one such ode himself – Cleanthes' ode in Hume's *Dialogues*:

> Look round the world: Contemplate the whole and every part of it: You will find it to be nothing but one great machine, subdivided into an infinite number of lesser machines, which again admit of subdivisions to a degree beyond what human senses and faculties can trace and explain. All these various machines, and even their most minute parts, are adjusted to each other with an accuracy which ravishes into admiration all men who have ever contemplated them. The curious adapting of means to ends, throughout all nature, resembles, exactly, though it much exceeds, the productions of human contrivance – of human design, thought, wisdom, and intelligence. (quoted in Dennett, 1995, 29)

Cleanthes concludes that if there is design in nature, then there must be a designer. Of course, this is where empirical adaptationists and natural theologians part ways. In the adaptationist view, the overwhelming 'design' in nature need not (some say cannot) be the work of a mysterious deity. Rather, it has to be explained by appealing to a humble mechanism or algorithm called natural selection. The surprising thing is that this simple algorithm has created a world whose beauty and functionality measure up to the world of natural theology. As Dennett says, 'Historical [or selectionist] reasoning about evolution thus depends on accepting Paley's premise: the world is full of good Design, which took work to create' (Dennett, 1995, 144). Unsurprisingly, the word 'design' occupies no less than 52 lines in the index of *Darwin's Dangerous Idea*, closely followed by 'Darwin', 'Dawkins' and of course 'Dennett' (all things interesting begin with a 'D', it seems). Another indication of Dennett's commitment to empirical adaptationism can be found in his abundant use of engineering metaphors. Dennett famously compares natural selection to 'a clever engineer' (not just an ordinary one!) and biology, more generally, to engineering (ibid., 213).[1] Whence this comparison? The world of engineering is built on what Dennett calls 'optimality assumptions' or 'optimality considerations' (ibid., 240). In his view, biologists are like engineers in that they assume every part of an organism or apparatus, or at least the bulk of their parts, to fulfil a particular function. When reconstructing the evolution of a particular trait, biologists simply take it for granted (and rightly so, Dennett believes) that natural selection preferred this trait to every possible alternative because it is the optimal solution to some or other problem that challenged the organism's ancestors. Similarly, when dismantling an enemy device, intelligence engineers expect every part to be there for a reason. As Dennett notes, the optimality assumption is one of the essential features of adaptationism. Obviously, such assumption is, in itself, rather innocent. If anything, it makes Dennett an adherent of methodological adaptationism. However, the engineering metaphor also suggests that natural selection is a very vigorous and skilful mechanism. The etymology of 'engineering' refers to the Latin 'ingenium' which, among many other things, denotes human intelligence, creativity, ingenuity and skilfulness. The engineering metaphor, then, is much more than a visualization of evolutionary biology's working method – it also reveals empirical adaptationism's genuine optimism about the amount of good design in the natural world.[2]

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[1] In this context, it is perhaps instructive to know that, when examined on Dennett's engineering metaphor, students typically go astray by presenting Dennett as a proponent of the Intelligent Design movement, confusing his 'engineer' with ID's 'Designer'. The engineering metaphor is also central to contemporary evolutionary psychology. For example, Tooby and Cosmides (1992, 75) note that 'an evolutionary functional analysis consists of asking a series of engineering questions'.

[2] A similar take on the use of engineering metaphors in evolutionary biology can be found in Lewens (2007, 47–8).

On a slightly less superficial reading, Dennett can also be considered as a proponent of explanatory adaptationism (as Godfrey-Smith, 2001, 339–40 already suggested). It could be argued, for example, that Dennett's obsession with design is simply due to his philosophical background and interests. For the existence of apparent design in nature is a vexingly old philosophical problem which, in Dennett's view, can only be solved in a satisfying manner by invoking Darwin's theory of evolution by natural selection. Understanding and explaining design is *the* challenge for contemporary biology (and philosophy of biology), and the mechanism of natural selection allows us to do just that. Even so, and contrary to his view that the world is full of good design, Dennett also acknowledges that natural selection is in many respects *anything but* a clever engineer. The engineering metaphor is quite central in *Darwin's Dangerous Idea*, and yet in the very same book, Dennett (1995, 213ff) identifies two reasons why natural selection is in fact the absolute antithesis of a clever engineer.

First of all, natural selection is a historical process. Unlike most engineers, it cannot freely create new materials or techniques to solve particular design problems (nor hire a promising assistant to do so). Natural selection can only endlessly recycle available characters, with sometimes intriguing, sometimes annoying and sometimes disastrous consequences. The human appendix is a good case in point (see, e.g. Nesse and Williams, 1994). In some non-human animal species, the appendix is used to digest cellulose from low-nutrient, high-fibre plants, thus optimizing food intake. In humans, it has become useless at best, and harmful at worst, as infected appendices can perforate or rupture, eventually leading to death.[3] So why do we still have an appendix? One answer is that evolution has checkmated itself here. Reducing the size of the appendix will hamper its blood circulation, thus increasing the risk of infection. The appendix, it seems, cannot simply be spirited away, as any sensible engineer or designer would certainly can and do.

Secondly, unlike any engineer, natural selection is a blind process. In Darwin's view, selection does not follow any working plan, as it cannot look ahead, nor look back. Rather, it uses an ad hoc problem-solving technique known as trial and error. Now it is true that some contemporary industrial design and engineering, such as drug development, is also based on trial and error, but the main difference with natural selection is that the latter's error rate is so excessive that if natural selection would be an engineer, it would probably be sued by its own company for wasting massive amounts of time and resources. And rightly so, for how would we think of, say, a designer who needs half a rain forest to build one wooden frame for an armchair? As we cannot possibly imagine how many specimens natural selection has used up to come out with a handful of successful designs, no

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[3] However, a recent theory suggests that the appendix may act as a safe house for beneficial bacteria in the human gut (Bollinger et al., 2007).

matter how beautiful they are, it would be awfully cynical to consider it as a clever engineer, wouldn't it?[4]

Acknowledging these shortcomings classifies Dennett as an explanatory adaptationist, rather than an empirical adaptationist. So what is he? Is he the founder of a new religion devoted to worshipping design in nature? Or is he just drawing the attention of biologists to a pressing problem which, when solved, would substantially lighten the job responsibilities of a philosopher? The only answer to this question is that he is both, even within the limited space of one (impressive) book. Dennett seems to be unaware of his constant switching between two adaptationist positions, yet in my view, the switching can help us explain both the vehement criticism his work has attracted and Dennett's own exasperation at these criticisms (see also Godfrey-Smith, 2001, 340–1). In the next section, I will scrutinize one of these criticisms, originally put forwards by Stephen Gould and Richard Lewontin in 'The spandrels of San Marco and the Panglossian paradigm' (1979). The 'spandrel paper' did not take aim at Dennett yet; it only took issue with a number of so-called sociobiologists, including Edward O. Wilson. Yet as the 'Darwin wars' continued, Dennett soon became one of Gould's new targets.

## 3. Adaptationism and Its Constraints

'The Panglossian paradigm' in Gould and Lewontin's original paper refers to the infamous Dr. Pangloss, the protagonist's guru in Voltaire's *Candide ou l'Optimisme*. Pangloss is widely known for his credo that 'we live in the best of possible worlds'. Brimming with optimism, he considered every disease and disaster to be a blessing in disguise. When infected with syphilis, he reminded Candide of the history of the disease, claiming that it was introduced in Europe by Christopher Columbus (or one of his assistants) on his way from the newly discovered America. No pain, no gain, Pangloss concludes, 'for if Columbus had not in an island of America caught this disease (…) we should have neither chocolate nor cochineal' (Voltaire, 2010 [1759], 14). According to Gould and Lewontin, adaptationism is the revival of Pangloss' philosophy, because it emphasizes 'the near omnipotence of natural selection in forging organic design and fashioning the best among possible worlds' (Gould and Lewontin, 1979, 150–1). Needless to say, Gould and Lewontin's main

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[4] In a similar vein, Jacob (1977, 1163–4) famously compares natural selection to a tinkerer, rather than an engineer: '[I]f one wanted to play with a comparison, one would have to say that natural selection does not work as an engineer works. It works like a tinkerer – a tinkerer who does not know exactly what he is going to produce but uses whatever he finds around him (…) [and] who uses everything at his disposal to produce some kind of workable object. (…) The tinkerer (…) always manages with odds and ends. What he ultimately produces is generally related to no special project, and it results from a series of contingent events, of all the opportunities he had to enrich his stock with leftovers'.

target is empirical adaptationism. In this section, I will first consider their arguments against this position. Then, I will show that they can also be said to argue against some of the claims of explanatory adaptationism.

According to Gould and Lewontin, the panglossians' inveterate optimism is due, firstly, to their overestimating the powers of natural selection. Even though some of them, including Dennett, seem to be aware of the many constraints restricting or limiting the outcome of evolution, and obstructing natural selection, somehow they fail to take these constraints seriously. The authors themselves distinguish between three types of constraints. Firstly, there are *architectural* constraints, which Gould and Lewontin define as necessary by-products of some or other adaptive characteristic of the organism. Famously, they compared these by-products to spandrels in architecture, which can be defined as spherical surfaces created by the crossing of a number of round arches. As Gould and Lewontin relate, the basilica of San Marco in Venice is studded with spandrels, and the fact that they are all covered with gorgeous mosaics suggests that spandrels are part of the original design of the church. Yet nothing is further from the truth. Combining any number of round arches inevitably creates spherical spaces which, conveniently, happen to lend themselves to be covered with mosaics. Initially, however, these spandrels did not fulfil any function at all. A good example of a spandrel in the biological world is a snail's umbilicus, i.e. the cone-shaped hollow space within the whorls of a coiled shell (Gould, 1997, 10754). An umbilicus has no evolutionary function – it automatically arises whenever one creates a shell by coiling a tube around an axis.

Though originating as non-adaptive by-products of other adaptations, some spandrels evolve to be picked up in their turn by natural selection and thus end up being adaptive. In some snail species, for example, the umbilicus is used as a brooding chamber to protect their eggs. In Gould's terminology, these spandrels-turned-adaptations are called *exaptations* (Gould and Vrba, 1982). Importantly, and unlike the spandrels of San Marco, not all characters resulting from architectural constraints are exaptations. Gould and Lewontin seem to imply that at least some spandrels actually remain useless or non-adaptive, while still being 'central to our understanding and analysis of organic form in evolution' (Gould, 1997, 10755).[5] Using Sterelny and Griffiths' vocabulary, spandrels are not adaptations, even though they may sometimes turn out to be adaptive: '[S]ome traits exist as a consequence of natural selection for one or more of their effects. These are adaptations. Some, but not all, of these traits continue to contribute to the fitness of organisms that have them. These traits are adaptive.

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[5] Given their criticism of the adaptationist stance, Gould's (and Lewontin's) heavy focus on exaptations, rather than non-adaptive spandrels, is very curious and has led many commentators astray. Spandrels are often confused with exaptations, even though not all spandrels are exaptations and, conversely, not all exaptations are spandrels, since the set of exaptations also includes characters directly shaped by natural selection and then co-opted for a new use (see, e.g. Gould, 2002, 1233 and 1248).

Other traits are mere side effects of evolution, and these include some that happen now to be adaptive' (Sterelny and Griffiths, 1999, 218). Importantly, as non-adaptive or neutral traits, spandrels can easily escape the 'daily and hourly scrutinizing' of natural selection (as Darwin once put it), because they do not affect the fitness of their bearers.

Architectural constraints can be seen as part of a broader category of developmental constraints, which have been defined as 'limitations on the set of possible developmental states and their morphological expressions' (Arnold, 1992, 95). In Gould's view, Darwin already acknowledged the existence of developmental constraints when discussing 'correlations of growth' or, later on, 'correlated variabilities', even though Darwin downplayed their importance vis-à-vis the output of natural selection.[6] As to Gould (and Lewontin), adaptationists wrongly assume (and particularly so when using the engineering metaphor) that any organism can easily be atomized in its constituent parts, thus allowing natural selection to optimize the design of each of these parts. Organisms, however, are not miscellaneous assortments of traits. Rather, they are integrated wholes, and tinkering with one part will inevitably affect (the development of) other parts. Darwin illustrated his view with a number of examples, including the supposed correlation between some forms of inherited baldness and weakness of dentition and, conversely, the tragic case of Julia Pastrana, the famous 'bearded and hairy lady' exhibited in many circus shows in late nineteenth-century Europe, who also had an irregular double set of teeth (Darwin, 1868, 328). As Lewens notes, 'If organisms are too tightly integrated, so that any slight change to one trait tends to be accompanied by slight changes to all the others, then it becomes very unlikely that natural selection will be able to produce elegant adaptation' (Lewens, 2007, 48). As such, correlation of growth is one more reason *not* to think of natural selection as a clever engineer.

Evolution by natural selection is not just constrained by the organism's developmental trajectory; it is also constrained by its phylogenetic trajectory. As noted earlier, natural selection is a blind and historical process, so it cannot start all over again when constructing a new organism or a new species. Thus, it continuously recycles earlier characters, even though these may not be the best solutions to the new challenges at hand. Gould and Lewontin speak of *phyletic*

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[6] Originally, Gould and Lewontin were very favourable to Darwin, praising his 'pluralism' in thinking about the many causes of evolutionary change (see also Gould, 2000) against the panglossians' monomaniac obsession with natural selection. Throughout the years, however, Gould has slightly changed his mind (even though his reverence remains): 'I have already noted Darwin's own excellent strategy [in dealing with exceptions or constraints to natural selection]: admit the historical inputs [phylogenetic constraints, see below], but attribute their cause to natural selection in the past; then admit the structural inputs [architectural and developmental constraints] as genuine exceptions, but relegate them to a low and insignificant relative frequency. Thus, all "constraints" either record the operation of the canonical mechanism in the past, or stand as genuine exceptions rendered impotent by their rarity' (Gould, 2002, 1058).

constraints – constraints to the powers of natural selection that relate to our being evolved from earlier life forms. Many annoying defects of the human body, for example, are due to the fact that, even though we walk upright, we still have the basic body plan of our four-footed ancestors. Clearly, a clever engineer would never have fitted a bipedal creature with a lower back as vulnerable as it is in humans. Tellingly, one of the labels of a recent exhibition about human evolution reads: 'Every year, more than 200,000 Americans have disabling back problems. To a large degree, they can blame evolution for their pain'. It would have been great if natural selection had provided us with more solid lower spinal discs when pushing us to walk upright – but then again, natural selection is obviously not a clever engineer.

A third category of constraints does not concern natural selection's limited elbow room but rather its source of energy. To do its work properly and deliver good design, natural selection needs cartloads of variation. As noted earlier, natural selection does not materially produce anything – it just makes a selection of what is on offer: 'Variation proposes; natural selection disposes' (Gould, 2002, 1031–2). Without a decent range of variants, natural selection cannot provide optimum solutions to the problems posed by the environment. And this is precisely the problem: not all populations abound with variation – even though adaptationists often take this for granted. Take the bottleneck effect, for example. Sweeping events, such as natural disasters or overhunting, can decimate a population in a more or less haphazard way, i.e. regardless of the differential fitness of its members. Therefore, their survival is a matter of brute luck, rather than the work of natural selection.

In short, Gould and Lewontin kindly remind us of the possibility that not all characters of living organisms were designed for the best. In their view, the world is not full of good design. Many characters are in fact non-adaptive, and there is no need to deny that there is even some positively sloppy design out there. This patchwork suggests that there are a number of constraints to natural selection's creativity – constraints that often result in suboptimal design. It is quite clear, then, that when Gould and Lewontin (1979) themselves describe their work as 'a critique of the adaptationist programme', they are objecting first and foremost to empirical adaptationism, rather than explanatory or methodological adaptationism. Most commentators seem to agree on this (for Lewontin, see Godfrey-Smith, 2001, 341; for Gould, see Sterelny and Griffiths, 1999, 226ff). Therefore, it would be easy to claim that, in later years at least, Gould is mistaken when aiming his arrows at people like Daniel Dennett and Richard Dawkins, who seem to be very aware of the many limitations on natural selection. To add fuel to the fire, let me supplement my rendering of Dennett's discussion of constraints with an illuminating quote from Dawkins' *The Extended Phenotype*. Here the author wonders what would have become of the aviation industry if the designers of the first jet engine had been forced to recycle all parts and technical schemes of the propeller engine: 'A jet engine so assembled would be a weird contraption indeed. It is hard to imagine that an aeroplane designed in that evolutionary way would ever get off the ground'. And he continues, in a remarkably non-adaptationist mood: 'When looked at in this light, far from expecting animals [and other living organisms] to be perfect we may wonder that anything about them works at all' (Dawkins, 1982, 38–9).[7] If anything, Dawkins seems to agree with Gould (and Lewontin) in claiming that natural selection has to deal with severe phyletic constraints.

So is Gould barking at the wrong tree? I believe he is not and for two reasons. First of all, my discussion of Dennett already indicated that his work contains at least some traces of empirical adaptationism. Godfrey-Smith (2001, 340) agrees: 'Although Dawkins and Dennett often exemplify explanatory adaptationism without empirical adaptationism, this is not how they always write. Sometimes they move to a more ambitious position, one that does make a claim about the *amount* of the biological world that has been shaped by selection (…) [and] in which design is seen as ubiquitous even when it is not obvious'. Acknowledging constraints can be part of this position (i.e. empirical adaptationism) when it is assumed that natural selection will eventually be powerful enough to cope with and even overcome its constraints. Against Godfrey-Smith, I believe that explanatory adaptationists will never grant that natural selection is 'massively constrained' or 'positively feeble most of the time' (Godfrey-Smith, 2001, 336) and that, therefore, the distinction between empirical and explanatory adaptationism is not as clear-cut as he would have it.[8] Secondly, and related to that, Gould and Lewontin are not only criticizing Dennett and Dawkins as empirical adaptationists; they are also criticizing them as explanatory adaptationists. In a nutshell, the latter make three claims: (a) there are constraints to natural selection, (b) biologists should focus on explaining design in nature (no matter how many constraints there are and, consequently, how little design there actually is), and (c) natural selection is the sole source of design in nature. As I understand their critique, Gould and Lewontin would certainly dispute neither the first nor the last claim. I think they would freely grant that, whenever natural selection is given free rein, it can and does produce wonderful design. They would even grant that good design can only be explained by referring to the work of natural selection, even though this analysis seems to be potentially problematical (Lewens, 2005). (Given that they do not deny the existence of good design in the world, it may surprise us that Gould and Lewontin have often been characterized in the literature as 'anti-adaptationists' (see, e.g. Nesse, 2005, 69)).

However, Gould and Lewontin do not agree with the second claim, i.e. that design is what needs to be explained in evolutionary biology. Why not?

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[7] Darwin made a very similar remark in warning his readers not to expect evolution to produce perfect design: 'Nor ought we to marvel if all the contrivances in nature be not, as far as we can judge, absolutely perfect. (…) The wonder indeed is, on the theory of natural selection, that more cases of the want of absolute perfection have not been observed' (Darwin, 1859, 472).

[8] Godfrey-Smith (2001, 338) explicitly notes that all three varieties of adaptationism are 'logically independent' of each other, adding that 'no one of these forms of adaptationism implies another'.

Towards the end of their 1979 paper, Gould and Lewontin claim that their criticism highlights ‘much the most *interesting* aspect of evolution’ (1979, 160; italics mine). Understanding and explaining constraints and alternative mechanisms of evolutionary change, they argue, is simply more *interesting* than understanding and explaining design in nature. Conversely, Dawkins thinks non-adaptationist explanations are *boring*: ‘Large quantities of evolutionary change may be non-adaptive, in which case these alternative theories may well be important in parts of evolution, but only in the *boring* parts of evolution’ (Dawkins, 1986, 303; italics mine). This conflict may not seem particularly interesting, as it draws on criteria (‘interesting’ and ‘boring’) that are impossible to operationalize. What does it mean to say that constraints are ‘much the most interesting aspect of evolution’? Does their interest reflect Gould’s quirky character or something more fundamental? Maybe what Gould really wants to say is that biologists should focus on constraints because they are the most salient and most important elements in understanding the evolution of living organisms.

At this point, it is interesting to note that there is a fundamental ambiguity to be found in all of Gould’s work. In his early work (with Lewontin), he explicitly notes that they don’t have any doubts about the importance of natural selection in explaining evolutionary change: ‘Darwin regarded selection as the most important of evolutionary mechanisms (*as do we*)’ (Gould and Lewontin, 1979, 155; italics mine). Gould and Lewontin even admit that the many constraints and alternatives to natural selection may perhaps explain only a fraction of nature’s diversity. In his later work, Gould also emphasizes that, as a mechanism of evolutionary change, natural selection is ‘truly primus inter pares’ (Gould, 2000, 448) and that his work on constraints should be seen as complimentary to the selectionist orthodoxy: ‘The concept of constraint must be sharpened and restricted in meaning to a coherent set of causal factors that can promote evolutionary change from a structuralist perspective different from – in the helpful sense of “in addition to” or “in conjunction with (…)”, rather than “in opposition to” – the functionalist logic of Darwinian natural selection’ (Gould, 2002, 1026). Taken together, these quotes add to the overall view that, if anything, Gould is offering a *complimentary* perspective to the adaptationist programme.

Quite contrary to this view, and again on numerous occasions, Gould has also framed his work on constraints as ‘a major *challenge* to selectionist orthodoxy’ (ibid., 1067; italics mine), underlining that spandrels, for example, have to be considered as ‘central’ in evolutionary theory and ‘ubiquitous’ in nature (ibid., 1258; see also Gould, 2000, 458ff). In the ‘spandrel paper’, Gould (and Lewontin) probably wanted to say something similar, but did not dare to, when claiming that their view ‘does not deny that change, when it occurs, may be mediated by natural selection, but it holds that constraints restrict possible paths and modes of change so strongly that the constraints themselves become much the most interesting aspect of evolution’ (Gould and Lewontin, 1979, 160). Claiming that constraints obstruct natural selection ‘so strongly’ implies that constraints are ‘much the most *important*’ (rather than ‘much the most *interesting*’) elements in studying evolution.

But obviously such claim would have contradicted their earlier statement (in the same paper) that natural selection is ‘the most important of evolutionary mechanisms’ (ibid., 155). Thus, Gould often constructs his view as a fully fledged *alternative* (rather than as an *addition*) to adaptationism. This is indeed how many advocates of adaptationism have interpreted Gould and Lewontin’s criticism, even from the very beginning. Sterelny and Griffiths, for example, consider Gould and Lewontin’s revival of the ‘Bauplan’ (or body plan) as one of the ‘biological explanations that are held up as *alternatives* to adaptationism’ (Sterelny and Griffiths, 1999, 228; italics mine).[9]

The most salient example of Gould’s ambiguous ambitions can be found in a retrospective paper on spandrels, where Gould swears that he has no intention whatsoever ‘to overthrow the centrality of adaptation in evolutionary theory’ (Gould, 1997, 10755), only to headline the next section as ‘the centrality of the principle of spandrels in evolutionary thought’. So what does he really want: an addition or an alternative to the adaptationist programme? The answer depends, I think, on what variety of adaptationism he is envisaging. First of all, he is keen on *challenging* explanatory adaptationism in that he thinks constraints are ‘much the most interesting’ aspect of evolution. In his view, constraints are what needs to be explained in evolutionary biology, rather than design.[10] Secondly, Gould wants to *complement* the empirical adaptationists’ ode to design by drawing our attention to the many non-adaptations and design flaws in nature. Basically, he agrees that there is some good design in the world and that natural selection is the sole systematic source of such design. So there is no dissensus between Gould and (empirical) adaptationism about the origins of design in nature. The disagreement, then, is mainly about the relative importance of natural selection and its constraints in understanding and explaining nature’s diversity and, related to that, about how much design or adaptation there really is in nature.

At first sight, assessing the amount of design in nature may seem to be an empirical question, as many commentators have suggested. Roberta Millstein (2002, 232), for example, notes that ‘the debate is over the degree to which adaptation is found in nature, with both sides generally accepting that some traits are adaptive and some are nonadaptive. (…) But should philosophers of biology be taking sides on this empirical question? It certainly does seem that philosophers can clarify (and have clarified) these kinds of empirical debates, both in terms of the concepts and the arguments involved. However, in the end, the question is an empirical one, and philosophers should not take sides’ (for similar views, see Godfrey-Smith, 2001; Pigliucci and Kaplan, 2000). Yet on the very same page,

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[9] However, my discussion of the persistence of particular basic body plans throughout evolutionary history shows that Gould and Lewontin take it to be an example of a (phyletic) constraint to natural selection, rather than ‘an alternative to explanation by adaptation’ (Sterelny and Griffiths, 1999, 229).

[10] Gould would probably argue against methodological adaptationism on similar grounds. For if spandrels are as ubiquitous as Gould thinks they are, then why should we start any investigation of a biological trait by assuming that it is an adaptation?

Millstein contradicts herself by saying that ‘these kinds of “relative significance” debates may not even be resolvable. After all, if one is to argue that evolution has been significantly adaptive, what does that mean? Ninety percent? Greater than fifty percent? At least ten percent? (…) How would we even answer such questions? Certainly, we cannot examine all living populations and it is unclear what a representative sample would amount to in this situation’ (ibid.). And these are just pragmatic issues. A more fundamental issue is how we are to distinguish between adaptations and exaptations. Some exaptations originate as non-adaptive spandrels, and yet they are adaptive. As such, do they count as evidence for ‘spandrelists’ or for ‘panglossians’? For these reasons, it is highly unlikely that we will ever have a final and authoritative answer to the question how much design there is in nature. Any such claim will ultimately depend on one’s temperament and, most importantly, one’s interests, as Brown already noted in *The Darwin Wars*: ‘The answer to a question such as “How important is adaptation?” is as much a matter of temperament and philosophical interest as it is of fact’ (Brown, 1997, 80–1).

In the third and final section of this chapter, I will argue that there is something genuinely valuable in Gould’s perspective, no matter how hard their adversaries have tried to downplay its importance. The value of this perspective reveals itself whenever we focus on the many examples of sloppy design in nature. Nowhere, it seems, is natural selection’s bungling more obvious than in man’s vulnerability to disease and disorder. For reasons of space, and because of a long-standing interest in psychiatry, in the next section, I will limit myself to discussing evolutionary explanations of *mental* disorders, and their link with Gould’s work.

## 4. Spandrels in Evolutionary Psychiatry, or: Taking Gould Seriously

The topicality of the debate between ‘panglossians’ and ‘spandrelists’ reveals itself in contemporary evolutionary psychiatry – a developing Darwinian discipline devoted to making sense of mental disorders, such as depression, schizophrenia and phobia, from within an evolutionary point of view (Stevens and Price, 1996; McGuire and Troisi, 1998; Brüne, 2008). Intuitively, one would expect spandrelists to be drawn to this endeavour, given their general interest in ‘the useless, the odd, the peculiar, and the incongruous’ (Gould, 1980, 27) and in all sorts of misfits and maladaptations. It is remarkable, then, that Gould barely wrote anything on the topic of (mental) disorders and even more so since, as we will see, his concept of spandrels (or architectural constraints) can help us understand one of the most popular theories in evolutionary psychiatry.

Most evolutionary psychiatrists, however, are tried and tested in the adaptationist tradition. Generally, there are two ways to be an adaptationist about mental disorders. First of all, some evolutionary psychiatrists disagree with mainstream psychiatry in suggesting that mental *disorders* are not disorders or dysfunctions at all, but adaptations. Thus, they have been spread over the population by natural selection because they confer some reproductive advantage to their bearers. The idea that some mental disorders may have some functional significance may seem outrageous, but such adaptationist hypotheses have been and are still being defended in the literature today, particularly in relation to depressive disorders. Hagen (1999), for example, has hypothesized that women affected by postpartum depression may signal that they are suffering an important fitness cost, either because they lack paternal or social support or because their newborn baby is in bad health. In this view, postpartum depression would be a bargaining strategy, enabling women to negotiate greater levels of investment from others. Similar hypotheses suggest that typical depressive symptoms, such as a loss of appetite and excessive ruminating, may have been designed by natural selection to signal yielding in a fierce social competition that cannot be won (Price et al., 2007) and to reconsider unfeasible ambitions and investments (Watson and Andrews, 2002). The gist of these hypotheses is that depression is not a disorder, but a useful psychological mechanism that enables us to cope with the inevitable adversities of life, much like how fever enables us to fight bacterial infections and how coughing and sneezing help us to keep our airways clear (Nesse and Williams, 1994).

Imagine that someday these claims would turn out to be true – wouldn't that be the ultimate victory for any kind of adaptationism? Dr. Pangloss would certainly be very excited by such discovery. 'How extremely stupid not to have thought of that!', he would exclaim – just like Huxley did when hearing about Darwin's theory of natural selection. And there seems to be some logic in these hypotheses. For why would natural selection put up with a fairly common set of behavioural and psychological mechanisms that have been around for at least thousands of years if they do not in any way contribute to our reproductive success? Surely the persistence of depressive disorders across cultures and time must tell us something about their adaptive value? The point is that if we can show that even mental disorders are adaptations, then there are no limits whatsoever to the powers of natural selection. Then, the world truly is a paragon of good design.

Unfortunately, there are many reasons to believe that adaptationist theories of depression are bogus. For one thing, the analogy between depression and bodily defences, such as fever and sneezing, does not hold. Fever may well be adaptive (even though it need not always be, since treating fever with Advil generally doesn't harm patients), because it meets evolutionary biology's basic criteria for an adaptation. For example, fever's form (raising the body's temperature) fits its function (to fight bacteria) since bacteria do not like it hot. Also, most of the times fever is evoked in appropriate circumstances, i.e. when and only when bacteria invade the body. Depression clearly does not meet these criteria (for an extensive account of this argument, see Nettle, 2004). Many people become clinically depressed for no good reason at all. Moreover, the symptoms of depression often obstruct its supposed function, as they make others more hostile and rejecting, and limit important social problem-solving skills. Interestingly, though, many of the proposed functions of depression do fit its normal counterpart, i.e. low mood, suggesting that low mood is an adaptation, rather than depression. In this view, depression would be a dysfunction or an adaptation 'gone wild'.

To my knowledge, Gould has barely written anything about (mental) disorders. On a rare occasion, however, he does discuss the evolution of mental disorders, in a book review of Sigmund Freud's posthumously published *A Phylogenetic Fantasy* (Freud, 1987 [1915]). Freud's text is a rather rumbling attempt to examine 'how much the phylogenetic disposition can contribute to the understanding of the neuroses' (ibid., 13–4), particularly by linking up our ancestor's vicissitudes during and immediately after the last Ice Age with man's present day vulnerability to a series of mental illnesses. In Freud's view, for example, the disposition to phobia derives from our progenitors' useful fears when confronted with the privations of the Ice Age. Freud's just-so story confirms Gould's earlier claim that psychoanalysis is a textbook example of the pervasive influence of recapitulationism and Lamarckism (Gould, 1977). But there is more. In one of the last paragraphs of his review, Gould notes: 'I also deplore the overly adaptationist premise that any evolved feature not making sense in our present life must have arisen long ago for a good reason rooted in past conditions now altered. In our tough, complex, and partly random world, many features just don't make functional sense, period' (Gould, 1987, 478). Remarkably, Gould doesn't even consider the above-discussed possibility that some mental disorders may still be adaptive today – he only criticizes the view that some mental disorders may be adaptations that have lost their functional significance somewhere in the tempestuous transition from the world of our ancestors to our contemporary environment.

Here we have a second way of being an adaptationist about mental disorders. For convenience's sake, I will refer to such explanations as mismatch explanations (for an overview of the many types of explanations in evolutionary psychiatry, see De Block and Adriaens, 2011). Mismatch explanations of mental disorders build on one of the central ideas in evolutionary psychology – another recent evolutionary discipline crucified by Gould for being 'ultra-adaptationist' (Gould, 2000, 452ff). Evolutionary psychologists claim that our ancestral environment, i.e. the environment in which most of the evolution of our species took place, differs substantially from our modern cultural environment. Or, in the words of Tooby and Cosmides, 'our modern skulls house a stone age mind' (Tooby and Cosmides, 1997). As a result, we are much better at solving the problems faced by our hunter-gatherer ancestors than the problems we encounter in modern cities. Evolutionary psychiatrists often consider this mismatch to be the hotbed of many of today's mental disorders. Continuing Freud's example of phobia, they hold that such disorders mostly involve natural threats, such as snakes, spiders and heights. These threats were probably common in our ancestral environment, but they certainly aren't the most dangerous things in our contemporary environment. We do not fear guns the way we fear snakes, for example, even though guns pose a much greater threat to our fitness today than snakes do (Ohman and Mineka, 2001; but see Faucher and Blanchette, 2011).

In Gould's view, however, there is no need to assume that currently maladaptive traits were once adaptive. Mental disorders, he suggests, may not have an evolutionary history at all, let alone a functional one: 'We need not view schizophrenia, paranoia, and depression as postglacial adaptations gone awry: perhaps these illnesses are immediate pathologies, with remediable medical causes, pure and simple' (Gould, 1987, 478). In evolutionary psychiatry, Gould's solution is known as a breakdown explanation or medical explanation – a third category of evolutionary explanations of mental disorders. As Murphy notes, for example, both adaptationist and mismatch explanations seem to assume that 'none of our psychopathology involves something going wrong with our minds', while 'nobody should deny that our evolved nature suffers from a variety of malfunctions and other pathologies' (Murphy, 2005, 746). In short, we need not refer to natural selection to understand mental disorders. It may well be, for example, that low mood has some functional significance, but any trait or capacity can *dys*function, resulting, in the case of low mood, in 'malignant' sadness or depression. Evolutionary psychiatrists using this model mention a number of proximate causes as the factors responsible for the dysfunction. Infections, lesions and deleterious mutations are sometimes at the heart of psychiatric aetiology.

However, in claiming that all mental disorders are immediate (as opposed to ultimate or evolutionary) pathologies, Gould overlooks a fourth and final type of evolutionary explanations of mental disorders, which can actually be conceptualized by means of his own work on architectural constraints or spandrels. Gould himself repeatedly claims that the human brain, because of its dazzling complexity, must be bursting with spandrels.[11] If this is the case, and if mental disorders somehow relate to the brain, then the question is as follows: can mental disorders be considered as spandrels? Earlier on, I indicated that spandrels are automatic and inevitable side effects (or by-products) of particular adaptations. As such, they may be co-opted by natural selection to fulfil a particular function, in which case they are called exaptations. Reading and writing are popular examples of exaptations in the context of the human brain.[12] In Gould's view, however, not all spandrels are exaptations: '[S]pandrels (…) arise nonadaptively as architectural

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[11] Typically, he even claims that 'the implicit spandrels in an organ of such complexity must exceed the overt functional reasons for its origin', conferring more 'evolutionary importance' to spandrels than to 'primary adaptations' (Gould, 1997, 10754–5). It is unclear, however, why any increase in brain complexity must necessarily boost the number of spandrels involved, unless we assume that the human brain is a highly integrated organ, rather than a loose set of separable modules – a claim for which Gould never provides any evidence. Yet for the purpose of this chapter, it is not necessary that the brain is full of spandrels, only that it houses a number of them, some of which may help us to understand and explain mental disorders.

[12] 'Reading and writing are now highly adaptive for humans, but the mental machinery for these crucial capacities must have originated as spandrels that were co-opted later, for the brain reached its current size and conformation tens of thousands of years before any human invented reading and writing' (Gould, 2000, 449).

byproducts but may regulate, and even dominate, the later history of a lineage as a result of their capacity for cooptation to subsequent (and evolutionarily) crucial utility. *Or they may continue as nonadaptive spandrels and still remain important as features central to our understanding and analysis of organic form in evolution*' (Gould, 1997, 10755; italics mine). Given that mental disorders are unlikely to be adaptive themselves, as I have argued above, we can exclude the possibility that mental disorders are exaptations.

So that leaves us with the possibility that mental disorders are non-adaptive spandrels. Gould (2002, 1247) defines 'non-adaptive' as 'effectively or nearly neutral' vis-à-vis the pressures of natural selection. Some by-products of adaptations slip through natural selection's nets because they are 'invisible', neither enhancing nor subverting the fitness of their carriers. Since Gould mostly talks about exaptations when discussing his concept of spandrels, there are few examples in his work of genuinely non-adaptive spandrels. Moreover, the few examples he does mention relate to the human body, rather than to the human brain.[13] Now one can argue that mental disorders cannot be considered as non-adaptive spandrels because most of them simply crush the reproductive success of their carriers. Even though there seem to be some important geographical, ethnic and gender differences in the fitness of contemporary mental health patients (Adriaens, 2007), most disorders have a negative impact on the social and sexual functioning of affected individuals, and most mental health researchers simply assume that this has always been the case (e.g. see Keller and Miller, 2006). In this view, mental disorders are not neutral or non-adaptive, so we should expect them to be weeded out by natural selection sometime soon. Gould seems to follow this line of reasoning when he writes: '*[N]on* adaptive – that is, effectively or nearly neutral – features may persist for several reasons, including the "invisibility" of true neutrality to pressures of selection, and the status of many nonaptations [non-adaptive or neutral traits] as automatic architectural byproducts (…), [but] I do accept the standard view that strongly *in*adaptive features hold little prospect for an evolutionary legacy because natural selection must soon eliminate them' (Gould, 2002, 1247; italics in original). In Gould's view, any spandrel that is harmful to an individual's fitness will be eliminated by natural selection, regardless of the importance of the primary adaptation it is connected with. Spandrels, then, cannot be maladaptive (or inadaptive).

This assumption may come as a surprise for those who are familiar with Gould's work and particularly with his endlessly repeated admonishment (a) not to overestimate the powers of natural selection and (b) not to consider the organism as an assortment of separable traits. Organisms are highly integrated wholes,

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[13] The two examples of non-adaptive spandrels Gould mentions in most works are 'the nonfunctional nipples of males' and 'the clitoral site of female orgasm': 'As a spandrel, the clitoral site would represent the different expression of a male adaptation [i.e. male orgasm], just as male nipples may be the spandrels of a female adaptation [i.e. female breast]' (Gould, 1997, 10754; Gould, 2002, 1263).

and it is naïve to think, Gould says, that ‘correlations [between traits] exist, but can be broken by selection’ (Gould, 1991, 53). As this chapter has demonstrated, one of the main threads of Gould’s work is that natural selection may not be as omnipotent and ubiquitous as adaptationists tend to believe – in fact, Gould seems to think that it may even be positively feeble and massively constrained. Yet apparently, it is still powerful enough, in his view, to get rid of spandrels when they turn out to be maladaptive. Gould seems to be oblivious here to the fact that there are a number of cases in biology where the value of the primary adaptation is such that it offsets the disadvantages of its side effects. Such examples are often conceptualized as package deals or trade-offs and include the classic example of sickle cell anaemia. Sickle cell anaemia is a disease that is commonly observed in people from African and Mediterranean heritage. Geneticists have shown that anaemic patients are (recessively) homozygotic (ss) for the b-haemoglobin locus in their DNA. Dominantly homozygotic (SS) individuals do not develop anaemia, but they are susceptible to malaria, which is very common in some parts of Africa and the Mediterranean. Heterozygotics (Ss), however, do not produce anaemia, and they appear to be resistant to malaria. Thus, the net fitness effects of these allelic variants (ss, SS, Ss) balance each other out. Here then is a case where a primary adaptation, i.e. being resistant to a rampant and life-threatening infectious disease (malaria), is so important that it somehow neutralizes the disadvantages of a trait with which it is correlated (sickle cell anaemia). And it is difficult not to conceptualize sickle cell anaemia as a maladaptive spandrel.

Now, some evolutionary psychiatrists think that such scenario may also apply to the evolution of particular mental disorders, thus constituting the fourth and final type of evolutionary explanations of mental disorders (after adaptationist, mismatch and breakdown explanations): trade-off or spandrel explanations. Schizophrenia is a good case in point. As Stevens and Price (1996, 146) note, ‘In a sense, schizotypic genes are like the genes responsible for sickle-cell anaemia, which enhance the well-being of carriers by protecting them from malaria while impairing those with greater genetic loading by afflicting them with anaemia’. But what possible advantages would schizophrenia be associated with? While some researchers have focused on physiological, and particularly immunological advantages (see, e.g. Huxley et al., 1964), most of them believe that schizophrenia (or bipolar disorder) owes its evolutionary persistence to a (genetic) association with a highly valuable and *typically human* trait, such as sociality (Burns, 2007), language (Crow, 2000) or creativity (Horrobin, 2001; Nettle, 2001). Horrobin (2001), for example, has suggested that minor mutations in the genetic code of the fat metabolism of our early ancestors, and the associated exponential increase of their cerebral capacities, have heralded the beginning of an amazingly creative new species: us. Yet the very same mutations also made us vulnerable for schizophrenia. In other words, schizophrenia arose as a sinister side effect of some or other important human adaptation; it is, on a more dramatic note, the price we pay for our very humanity.

In this view, mental disorders have never been adaptations (against adaptationist and mismatch explanations), yet they do have an evolutionary history (against breakdown explanations), more particularly as sidekicks or spandrels of highly valuable traits. Trade-off explanations of mental disorders are rather popular in contemporary evolutionary psychiatry, and yet they are the object of much criticism, even from within the discipline. According to Keller and Miller, for example, it is highly unlikely that the evolutionary persistence of mental disorders is due to their being part of a trade-off and for various reasons. Paradoxically, their critique partly draws on the work of…yes, Gould.

First of all, they claim that most evolutionary explanations of mental disorders, including trade-off explanations, smell of panglossianism: ‘Evolutionarily oriented mental health researchers, such as Darwinian psychiatrists and evolutionary psychologists, often go to torturous lengths to find hidden adaptive benefits that could explain the evolutionary persistence of profoundly harmful mental disorders such as schizophrenia or anorexia, but these accounts are often frustratingly implausible or hard to test’ (Keller and Miller, 2006, 386). When charging biologists (and, later on, philosophers of biology) with panglossianism, Gould and Lewontin did not only criticize their overly optimistic view of life but also their laziness in testing the predictions that follow from their hypotheses. Anyone can easily come up with stories about the function of, say, male baldness, being homesick or athletic skills, but there is an important difference between just-so stories and real science. Even Dennett agrees with this point: ‘To the extent that adaptationists have been less than energetic in seeking further confirmation (or dreaded disconfirmation) of their stories, this is certainly an excess that deserves criticism’ (Dennett, 1995, 245). Now it may be true that some trade-off or spandrel explanations of mental disorders amount to nothing more than just-so stories, but this certainly isn’t true for all of them. Nettle and Clegg (2005), for example, established that those artists who score high on particular components of a mild form of schizophrenia, i.e. schizotypy, also display enhanced mating success. Thus, they suggest that by fancying male schizotypic artists, women would ensure the evolutionary persistence of a minor variant of schizophrenia. By providing evidence of a link between creativity and psychopathology, Nettle and Clegg have shown that trade-off or spandrel explanations need not necessarily be panglossian.

Secondly, Keller and Miller acknowledge the existence of trade-offs in nature, for example, sickle cell anaemia, but they also argue that such trade-offs are very rare. Moreover, given natural selection’s vigour, and given the sweeping reproductive disadvantages involved in mental disorders, Keller and Miller expect trade-offs to be highly provisional phenomena, awaiting a better solution: ‘[S]election would strongly favour genetic events that overcome the costs of producing homozygotes, such as unequal crossover events that position both S and s [in the above-discussed case of sickle cell anaemia] on the same chromosomal arm, so they can be passed on together without disruption, or mutations that reduce the fitness costs of either homozygote (Keller and Miller, 2006, 395). Basically, the authors would agree with Gould's argument that strongly maladaptive features will soon be eliminated by natural selection. However, this argument is a probability argument which, in a sense, begs the question that pervades this chapter: exactly how omnipotent and ubiquitous is natural selection, especially when it has to deal with highly integrated organisms? Assuming that sickle cell anaemia and schizophrenia are intricately connected to adaptations of primary importance, how likely is it that selection will break the correlations involved and come up with a better alternative?

However, whether or not spandrel explanations will eventually prove to be important in the evolutionary sciences, including evolutionary psychiatry, is not the issue here. Rather, I wanted to point out, firstly, that the adaptationism debate is still being held in contemporary evolutionary psychiatry and, secondly, that Gould's work can be used to complement the predominantly adaptationist stance in explaining and understanding mental disorders.

## 5. Conclusion

Stephen J. Gould and the so-called ultra-Darwinists (Gould's nickname for adaptationists, including Daniel Dennett and Richard Dawkins) famously differ in opinion about the importance of natural selection as a mechanism of evolution. While agreeing that natural selection is the only origin of design in nature, they disagree about how powerful it is vis-à-vis the many constraints it has to struggle with and how ubiquitous it is vis-à-vis alternative mechanisms of evolutionary change. My analysis of the debate shows that, in the end, the basic disagreement between 'panglossians' and 'spandrelists' relates to how much design there is in nature. At first sight, this may seem to be an empirical question, which should be answered by means of rigorous research in the biological sciences. Provided, however, that we live on a fabulously complex and constantly evolving planet, it is highly unlikely that we will ever have a final and authoritative answer to this question. Any claim about the amount of good design in nature will ultimately depend on one's character.

Gould's dogged interest in all sorts of misfits and maladaptations led him to believe that natural selection may not be of primary importance in explaining and understanding nature's diversity. If we consider mental disorders as prototypes of maladaptations, it is rather surprising to note that many evolutionary explanations in psychiatry are in fact adaptationist explanations. Even though Gould hardly ever wrote about mental disorders, I have shown that part of his work can be used to criticize adaptationist explanations in psychiatry while at the same time providing a number of alternative explanations. However impressive its accomplishments, the human brain is not a paragon of good design, so it should not surprise us that, every now and then, it fails on us.

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Biodata of **Cory D. Bishop, Moira E. Galway** and **David J. Garbary**, authors of "***Architecture and Design Among Plants and Animals: Convergent and Divergent Developmental Mechanisms***."

**Dr. Cory D. Bishop** is assistant professor of Biology at St. Francis Xavier University in Antigonish, Nova Scotia, where he studied marine invertebrate reproduction, development, and evolution. Bishop completed an H.BSc in Biology at Carleton University, Ottawa, Canada, in 1996 and then obtained a Ph.D. in Development and Evolution at Simon Fraser University, British Columbia, Canada, in 2003. He held postdoctoral fellowships with Michael Hadfield at the Kewalo Marine Lab, University of Hawaii, and Brian K. Hall, Dalhousie University, Halifax, Canada.

E-mail: **cbishop@stfx.ca**

**Dr. Moira E. Galway** was awarded a B.Sc. honours degree in Biology from Carleton University in Ottawa, Canada, and a Ph.D. in 1993 from the Australian National University in Canberra. Following postdoctoral positions at the University of Saskatchewan in Saskatoon and subsequently at the University of Michigan in Ann Arbor, she joined the Biology Department at St. Francis Xavier University in Antigonish, Nova Scotia, where she pursues research in plant development and genetics.

E-mail: **mgalway@stfx.ca**

**Cory D. Bishop**

**Moira E. Galway**

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**Dr. David J. Garbary** received B.Sc. and M.Sc. degrees at Acadia University and his Ph.D. in 1978 from the University of Liverpool. After 6 years as a research associate and university research fellow at the University of British Columbia, he became a faculty member at St. Francis Xavier University where he has been chair of Biology and coordinator of Interdisciplinary Studies in Aquatic Resources. He has been involved with diverse research programs including many areas of seaweed biology, evolution of land plants, and impacts of sea level rise on coastal plant communities.

E-mail: **dgarbary@gmail.com**

# ARCHITECTURE AND DESIGN AMONG PLANTS AND ANIMALS: CONVERGENT AND DIVERGENT DEVELOPMENTAL MECHANISMS

**CORY D. BISHOP, MOIRA E. GALWAY, AND DAVID J. GARBARY**
*Department of Biology, St. Francis Xavier University, Antigonish, NS B2G 2W5, Canada*

## 1. Introduction

A cursory glance at a typical animal (e.g., a dog or a salmon) or a typical plant (e.g., the model weed Arabidopsis or a tree) reveals immediate differences in form and function. Plants are photosynthetic organisms that are fundamentally nonmotile, whereas animals are heterotrophic and, with exceptions, motile. While animals form a monophyletic assemblage, plants are polyphyletic and include red and brown algae. We recognize that this is important in a phylogenetic sense; however, in the context of the constraints of design, we do not consider this an impediment to our primary arguments.

The evolutionary origin of multicellularity is a key transition in the history of life (Buss, 1987; Maynard Smith and Szathmáry, 1995; Queller, 2000) and ranks among the least controversial examples of an increase in complexity. The fact that multicellularity has arisen numerous times independently indicates that it is more than just a historical contingency peculiar to certain groups. On the other hand, multicellularity leading to large complex organisms has only arisen a few times (Szathmáry and Wolpert, 2003, reviewed in Grosberg and Strathmann, 2007). While many such important evolutionary transitions are shrouded in the past, independent evolution of large multicellular organisms allows for comparisons of relationships between growth/developmental mechanisms and other aspects of multicellular form. Plants; large green, red, and brown algae; metazoan animals; and fungi are the most visible and successful evolutionary "experiments" in multicellularity and therefore make for useful comparisons that may tell us something general about form and how it arises each generation.

Here we limit examples to multicellular plants, animals, and macroalgae. Due to our own bias, we do not treat fungi here. As is common in biological explanations of nature, generalities are easy to create and difficult to defend. While we strive to indicate where exceptions to generalizations lie, various readers will have no trouble finding others. Due to space constraints, we have been selective in our literature cited.

We interpret the concept of "design" for multicellular organisms as the specific distribution and spatial organization of task-specialized cells in an individual or colony of individuals. Any explanation of design requires an attendant explanation of how that particular distribution of cells arises with fidelity from generation to generation; this is the province of development. Thus, development and the evolutionary origin of design in multicellular forms are intrinsically and causally linked.

Hallé (2002) made many insightful observations about similarities and differences in form between plants and animals. Here, because the word "design" is contentious (having been usurped by others for nonscientific explanations of origins), we define design as either the phylogenetic or ontogenetic (or both) emergence of organismal form resulting exclusively from natural selection. For that matter, the word "origin" is also contentious as the origin of evolutionary novelties continues to be a central topic in evolutionary biology (e.g., Moczek, 2008; Shubin et al., 2009). But, since it is reasonable to assume that an ancestral characteristic of organismal design is an initial small size (see Grosberg and Strathmann, 2007), we discuss design of plants and animals with respect to scale and dimensionality. In particular, we consider fractal dimensionality and ask whether there is a necessary relationship between the degree thereof and the corresponding developmental processes. Further, we ask whether in plants or animals there exist developmental constraints that preclude the appearance of particular forms.

A major constraint on growth and form is the dimension of scale. Physical forces including diffusion, gravity, and viscosity impose limitations on morphogenesis (Koehl, 1996) at given sizes. In other words, design in nature is size and context specific. The design of most multicellular creatures adheres to the constraints of scaling relationships during growth and development (e.g., Niklas, 1994 for plants). This response, allometry, can be thought of as a biophysical constraint which is most relaxed in plants and some sessile marine animals (e.g., arborescent bryozoans and branching scleractinian corals). In such cases, the body plan is constructed not from a temporally integrated program of embryonic development resulting in a discrete individual, but rather by an iterative process of growth in which new modules are added sequentially to older ones. This type of growth is associated with departures from determinate growth, in part because each module can maintain consistent surface area to volume relationships (Edmunds, 2006) thus accounting for the weaker constraint of scaling relationships that would otherwise require trade-offs in morphology and behavior. Is design among phylogenetically independent instances of sequential modular growth rooted in convergent developmental processes? We selectively use examples from the animal and plant kingdoms to explore the relationship between morphology and the growth processes from which they are derived.

Beyond the relation between form and growth and development, we discuss the evolutionary consequences of iterative or colonial modular growth versus its alternative, individuated development. Although we have chosen breadth over depth in this review, our hope is that this discussion will further productive comparisons between the evolution and development of plants in comparison to animals, a province with few inhabitants.

## 2. Modularity and the Architecture of Plants and Animals

Biological systems have been to epigenetic networks, cells, morphogenetic fields, animal segments, organ systems, colonial and clonal organisms such as corals, seaweeds such as *Ascophyllum* and *Chondrus*, and flowering plants including strawberries and mangroves. (Bell, 2008; Rosen, 1986; Schlosser and Wagner, 2004; Wagner et al., 2007). Modularity, a term borrowed, coincidentally, by biologists from the architecture and design community, was first used by the botanist Prevost in 1967 and then 4 years later by zoologists (White, 1984). Schlosser and Wagner (2004) write that the cognitive scientist Jerry Fodor first borrowed the term from computer scientists in 1983. Use of the term modularity among biologists may be traceable to multiple origins, a testimony to both its conceptual utility and biological reality. Numerous definitions of the term exist, the most general being that in Schlosser and Wagner (2004) that a module is “a component of a system that operates largely independently of other components.” Plants are interesting, but as we discuss, not unique, developmental models because they are constructed from iteratively added modules that occur at multiple scales (de Kroon et al., 2005). The apical (or subapical) meristematic systems of most plants results in a modular structure observed analogously in the animal world among certain sessile animals. We primarily focus on this mode of modularity as a point of comparison between plant and animal development.

The evolutionary significance of this is seen in terrestrial plants where the fundamental unit of structure is an unbranched unit of stem for which the modern analogue would be the filamentous seta of moss sporophytes (Renzaglia et al., 2000). Subsequent evolution led to now-extinct nonvascular and vascular plants, which produced leafless and rootless forms with dichotomous branching. The basic structural unit was a branch (or telome) that underwent modification through a variety of processes (Kenrick, 2002). These structural units branched in three dimensions lead to more complex morphologies in which specialized stems evolved into leaves, roots, and differentiated reproductive structures (e.g., Stewart and Rothwell, 1993). A few simple patterns of modification, namely, branch reduction, branch fusion, and branch plantation and webbing, produced the complex forms that we see in terrestrial plant biodiversity.

This repeating unit of structure derived from apical meristems allows plant ontogeny to be easily modeled using graph grammars in which the rules for ontogeny can be simply stated and in which groups of rules are repeated as developmental module (meristem) follows module (e.g., Prusinkiewicz and Lindenmayer, 1990). This modeling approach has been used to mimic morphogenesis in red algae, in which the “plants” grow from single cells to large individuals (Garbary and Corbit, 1992), and various plants (e.g., Prusinkiewicz and Lindenmayer, 1990). One might argue, based on the contemporaneous manner in which most animal body plans develop, that in individuated animals the whole organism is the developmental module. Although not a commonly held view, Dewel (2000) proposes that individuated metazoans evolved from colonial ancestors, which supports the idea of individual as module. In contrast to animals, plants are characterized with their repeating modular units in which growth simply adds on new units at terminal (apical) locations, rather than increasing size in all dimensions.

## 3. The Fractal Nature of Plants and Animals

Fractal (or fractional) dimension is a quantitative measure of the space-filling properties of an object. While we normally think of structures as having a single dimension (e.g., a line), two dimensions (e.g., a sheet of paper), or three dimensions (e.g., a sphere), in the natural world, structures or organisms rarely fit perfectly into one of these shapes (Mandelbrot, 1982). Thus, flat organisms rarely completely fill a plane, and marginal branching or lobing or interior holes will reduce the dimension so that it is "fractional" or less than an idealized geometric form of a plane. Similarly, organisms that occupy a three-dimensional morphospace (e.g., a whale) will have a fractal dimension slightly less than 3 as a consequence of surface modifications such as fins. Overall, the exterior surface of motile animals is typically much closer to idealized three-dimensional forms, whereas plant morphologies are typically intermediate with dimensions between 1 and 2 or 2 and 3, depending upon whether they are considered as occupying a flat plane or a three-dimensional volume.

Many fractal forms also have the property of having similar morphologies at different spatial scales. This is most easily seen in geometric forms such as the Koch curves (e.g., the Koch snowflake: see Wikipedia) or Mandelbrot set, in water courses from streams to major rivers, and in biological systems in the branching systems that comprise air and blood passageways in animals and the branching structure of trees. These fractal forms allow us to characterize an important distinction between plants and (motile) animals.

A thallus or blade of a fucoid macroalga is fundamentally filling a plane starting from a small linear structure early in ontogeny to a flattened, dichotomizing structure that is filling a plane (Corbit and Garbary, 1995). Thus, these forms have intermediate dimensions in which the repeated dichotomies fill in a greater proportion of the available plane. In *Fucus*, increases in form complexity (i.e., dimension) are associated with ontogeny and frond size. A similar volume-filling trend is observed in plants (e.g., a tree) which branch in three dimensions but whose fractal dimension will never achieve three because of the huge empty volumes within the canopy. This volume-filling strategy creates turbulent flow, thereby reducing boundary layers so that nutrient and gas exchange between the inside and out of the plant system can be optimized along with propagule dispersal (Niklas, 1992).

This is rarely the case with motile animals. For this argument, we refer to motile animals as those animals for which inertial forces are the principal forces to be overcome in their environment. Much of large animal exterior design deals with reducing turbulence and creating surfaces that reduce drag. While such animals grow, the basic form of a species is typically little changed, notwithstanding allometries. Thus, animals conduct their gas exchange and nutrient absorption internally using lungs, gills, blood circulation systems, etc. The organ systems responsible largely minimize turbulent flow except in the precise areas where absorption occurs. These are organisms that move through their environment to capture prey; capturing materials (i.e., food) via their surfaces is of low importance (an exception are skin-breathing amphibians) and minimization of boundary layers. Most of what is known about developmental mechanisms in animals concerns those forms with high fractional dimensionality.

Plants are fractal on the outside and the inside (e.g., leaf veins), whereas motile animals are fractal only on the inside. The repeating fractal forms of plant interior and plant exterior whether in the roots or shoots may be considered as associated with two different mechanisms. The exterior fractal form is a function of the modularity of the organism and the repeating addition of stem/leaf units. The interior fractal nature of the plant vascular system is a consequence of cell differentiation, i.e., xylem or phloem cells do not form new xylem or phloem cells, instead an undifferentiated plant “stem” cell undergoes a precise morphogenesis to form one of the four major cell types that make up vascular system. This is analogous to the ontogeny of animal fractal structures such as tubes from undifferentiated embryonic cells (Andrew and Ewald, 2009). Some plants have acquired forms that approximate the animal norm of a dimension of 3. These plants belong to the families Aizoaceae and Cactaceae. Here adaptations for water conservation result in shoot structures where leaves are reduced to simple spines and the stems may be largely unbranched or poorly branched cylindrical structures, such as in many cacti. The most reduced of these forms (with the highest fractal dimension) are the stone plants where pairs of succulent leaves are addressed near ground level to form a highly compact shoot. Many Cactaceae (e.g., *Opuntia* spp.), however, retain a fractal form with repeating units where changing axis orientation (i.e., new branches) yields a space-filling architecture.

In the algal realm, some kelp plants (order Laminariales) are nonmodular and may also have fractal dimensions approaching three. Some species (e.g., *Saccharina* spp., *Laminaria ephemera*) are simple strap-shaped fronds borne on a cylindrical stipe that is attached to a holdfast. However, strong currents and wave-swept habitats provide sufficient turbulent flow to supply nutrients and gases to the large (sometimes meters long) fronds to remove the necessity of a treelike space-filling architecture (Koehl, 1996). In addition to their high dimensionality, these organisms all have an intercalary meristem at the base of the blade rather than apical growth as well as a nonmodular, noniterative mode of growth.

In plant systems, one needs to distinguish between primary growth (i.e., growth from plant apices) and secondary growth (i.e., growth in girth or the formation of growth rings in woody plants). Here the cells that make up the fluid- and nutrient-conducting tissues are not derived sequentially in an apical-basal transition but are differentiated in a lateral sequence from newly divided cells. The resulting lateral increments in girth are more akin to the animal growth model than to the primary growth model associated with plant apices. A notable distinction in developmental mechanisms is that in plants, the direction of tissue growth and ultimately plant form is dictated by the orientation of the planes in which the walled cells divide, whereas animal morphogenesis also involves the movement of cells relative to each other, plus cell and tissue deformations.

In primary growth of plants, development of the fractal form results from the sequential addition of new modules separated by time and space. However, in animals, the formation of some structures of low fractal dimensions such as nephritic ducts and other ducts, tubes, and glands indicates that there is no obligatory relationship between such structures and the reiterative, sequential addition of modules. Thus, aortas do not develop sequentially from capillaries, nor bronchi from bronchioles, even though they exhibit an anatomical continuity like that observed in the xylem, the water-conducting vessels of plants, between the apical, youngest cells of a xylem strand and the oldest basal cells.

## 4. Animal Motility as a Fractal Pattern

The physical constraints of animal motility (i.e., the need for speed and reduction of drag) largely constrain animals to forms with a dimension of 3. Free-ranging predators move through their landscape in specialized random walks with, interestingly enough, fractal trajectories (Sims et al., 2008) that optimize searching within their landscapes. Search patterns of animals as diverse as ants (Torres-Contreras and Canals, 2010) and deer (Webb et al., 2009) in terrestrial systems and fish and penguins in marine organisms (Humphries et al., 2010; Sims et al., 2008) show complex branching patterns that are fractal in nature. This is not surprising as such search patterns will optimize area covered during foraging, although the particular pattern will be influenced by the patchiness of resources in the surrounding landscape (Humphries et al., 2010). These search patterns of animals have their analogue in the plant world in the patterns of root growth associated with nutrient foraging (McNickle et al., 2009).

## 5. Nonmotile Animals: Convergence of Plant and Animal Form

So far we have distinguished plants and animals as having different fractal dimensionalities. To some extent, this obviates any comparative discussion about the relationship of their form to their respective ontogenetic mechanisms. However, a major convergence in plant and animal form is observed among some sessile colonial animals. The fractal forms of representatives of plantlike animals have been extensively explored particularly in sponges and corals (e.g., Abraham, 2001; Kaandorp, 1994, 1999). Sessile branching colonial organisms include animals

**Figure 1.** Photograph of a reef community in the vicinity of Bocas del Toro, Panama. The sessile bladed fire coral and the feather duster worm in the foreground are distinctly plantlike in having morphologies with low fractal dimensionality. The form of the motile fish in the background, however, approaches an idealized fractal dimensionality of 3. To what extent is the development of form with low fractal dimensionality comparable between plants and animals?

such as arborescent bryozoans and hydroids, and scleractinian anthozoans (Cnidaria), the latter commonly known as reef-building corals. Scleractinian corals (hereafter referred to simply as corals) build their bodies, and consequently reefs, by secreting a calcium carbonate matrix; the only living part of a coral is the superficial-most layer of tissue.

Corals are exclusively sessile. Like plants, corals must grow in such a way so as to maximize growth in a fluid environment over which the only response to variable incident conditions (either light or planktonic organisms) is through differential growth, much like plants. Scleractinian corals furthermore deposit calcium carbonate as they grow, increasing their structural similarity to plants. Other noncolonial sessile suspension-feeding animals, such as feather duster worms (Fig. 1) and sea lilies, achieve a plantlike low fractal dimensionality, but less is known about their development so we do not formally compare them to plants here.

To what extent is coral growth, particularly the rules that govern branching topology, comparable to plants? We are certainly not the first to wonder about this question, but far from being an idle curiosity (a valid end in itself), the answer to this question may help discern the degree to which terrestrial plants are developmentally and thus evolutionarily constrained in the diversity of forms they can produce.

Rosen (1986) argues that the fundamental module of growth in a branching coral is the zooid, which is composed of the polyp and the calcium carbonate corallite that is deposited by the polyp. Like the stem or branch of a plant which records the historical trajectory of growth from a particular apical meristem, the corallite records the growth history of a polyp and its descendents. Rosen employs the idea of the zooid-as-module to compare the meristematic modular of growth of plants to coral growth and concludes that coral growth is modular, but using a meristematic system that is distributed throughout the colony. For comparative purposes, the designation of the zooid as the module of construction is important because it strengthens the similarity in growth constraints between corals and plants. Namely, the movement of cells relative to each other (cell migration) is a morphogenetic mechanism only available to metazoans. To the extent that the polyp behaves as an irreducible module of growth, coral growth and developmental constraints become more than just superficially plantlike.

Dauget (1991) expanded upon, but also drew implicit distinctions between, architectural similarities of plant and coral growth. The difference in growth habit then between plants and corals can be characterized by the iterative use of a meristem (plants) and the continuous use of one (corals). That is, developmentally, plants are topologically constrained in the production of new growth along an axis by using an iterative apical dominance model for growth. Because coral polyps remain connected by a thin layer of tissue, there is no theoretical restriction on the capacity for regulating subapical growth in response to environmental conditions or gross perturbations (Mackie, 1986). Although intercolonial molecular transport is known to occur (Rinkevich and Weissman, 1987), it is unknown if multipotential cells can migrate among zooids.

What remains to be determined in corals is the basis for restriction of developmental potential along growth axes. In *Acropora pulchra*, differentiation of a radial corallite into an axial corallite determines the future site of lateral branches (Oliver, 1984). Do all radial corallites have equivalent potential to differentiate into axial corallites, or is there a restricted subapical zone of potential, as in plants? To our knowledge, this has not been investigated in these terms. Alternatively, the lateral-branch-forming potential of all radial corallites may be equivalent but become restricted *de facto* by environmental input. Corals are remarkably phenotypically plastic (Todd, 2008), indicating that any genetically determined rules for branching topology include responsiveness to environmental variation (Shaish and Rinkevich, 2009). The extent to which branching rules involve genetically determined spatial restrictions of the developmental potential of individual polyps will determine the extent to which coral plantlike development and actual plant development are comparable and thus genuinely convergent. Genomic approaches to studying coral-specific developmental transitions (Grasso et al., 2008) may shed light on this question.

Some marine invertebrate larvae present an interesting case of motile animals with low fractal dimensionality. Although technically mobile, relative to ambient flow, they are not sufficiently so for effective locomotion. With the exception of crustaceans and tunicates, both having external integuments, most marine invertebrate larvae use cilia as the motive force for locomotion and as a mechanism for suspension feeding. Although not typically expressed this way, feeding larvae typically have a lower fractal dimensionality than larvae that do not feed. The reason for this lower dimensionality stems from the scale at which these organisms are performing. Most larvae are sufficiently small that they are operating at Reynolds numbers below 1. The consequences are that viscous and not inertial forces are dominant aspects of the fluid environment. However, the physical parameter of viscosity is not the only explanation for the lower fractal dimensionality of these larvae because in many cases, when closely related species lose the ability to feed, fractal dimensionality increases (Strathmann, 1978), while size need not. Epidermal outgrowths that decrease fractal dimensionality are branch-like, but the developmental mechanisms by which they form remain to be investigated.

## 6. Cell Movement and Embryogenesis

Animal development differs in one major way from plant development: Animal cells have the ability to migrate from their site of origin in the embryo to another region to undergo differentiation and proliferation. A notable example in vertebrates is the formation of the skull, which involves a massive migration of cells that arise during the formation of the neural tube (Hall, 2009). In plants, the existence of a cell wall precludes this morphogenetic mechanism. The closest analogue is the formation and movement of wall-less plant cells associated with reproduction and embryogenesis. For example, paired sperm cells move within the growing pollen tube of the male gametophyte, although they are attached to cytoskeletal elements in the surrounding pollen tube cell rather than being independently motile. During anther development in some flowering plants, amoeboid cells of the tapetum migrate from the anther wall among the developing pollen grains where they provide a nutritive function (Esau, 1977). In the net-forming green algal genus *Hydrodictyon*, thousands of zoospores form within a mother cell, and these are motile within the cell before aligning to form a new, miniature net which undergoes cell enlargement following release from the mother cell (Pickett-Heaps, 1975). To conclude, whereas the evolution and retention of a cell wall as an integral design element of plants and algae afford great structural support and osmotic tolerance, it clearly reduces the diversity of developmental strategies available to these organisms.

## 7. Relative Use of Programmed Cell Death

Morphogenesis of multicellular organisms requires the regulated deaths of many cells during development to achieve, and often maintain, the adult form. Here we refer to programmed cell death or cell death without specifying the type, which is still a subject of intense discussion (Kroemer et al., 2009; Reape et al., 2008). Metazoan development is often described as a "sculpting" process (e.g., Montero and Hurlé, 2010), ranging from the minimalist "whittling" away of specified cells in nematode embryos to the almost complete destruction and replacement of the larval form during fruit fly metamorphosis (Meier et al., 2000). "Molding" or "modeling" better reflects the rapid interplay of cell proliferation, motility, shape change, and the seemingly wasteful death of cells in metazoan development. Yet, similar outcomes can be achieved by nonmotile plant cells through the slower interplay of cell proliferation and death with the highly controlled and coordinated events of oriented cell divisions, cell expansion, and shape changes, such as those required to generate the jigsaw puzzle-like interdigitation of leaf pavement cells (Kotzer and Wasteneys, 2006).

Broadly speaking, cell death in both plant and animal development modifies tissues and structures and removes redundant or obstructing cells. But a closer look reveals considerable differences. Consider strategies for internal tube and cavity formation, which contribute to internal transport and distribution in all larger multicellular organisms. Andrew and Ewald (2009) identify several mechanisms for generating tubes from epithelial cells, only one of which involves programmed cell death. All involve changes in cell shapes, locations, and cell-to-cell interactions that are impossible for plant cells. For example, a sheet of cells may deform into a furrow (protruding into adjoining tissue), which then detaches to form a separate tube lying parallel to the original sheet, or alternatively the furrow may deepen to form a branch perpendicular to the original sheet (Andrew and Ewald, 2009). Even in cavity formation, the hollowing out in a tissue or primodium can be accomplished by the cells in the middle either dying or simply migrating away into the epithelial "wall" of the tube (Andrew and Ewald, 2009). Thus, cell death is just one tool among many for creating structures. Notable examples of tube formation via cell death occur in salivary gland development and during cavity formation in the inner cell mass during mouse embryogenesis (Coucouvanis and Martin, 1999; Jacobson et al., 1997). In contrast, plants rely on two mechanisms for generating internal cavities and tubes: by cell separation during growth or by programmed cell death (Dahiya, 2003; Evans, 2003; Jarvis et al., 2003; Kozela and Regan, 2003; Raven, 1996).

The networks of tubes that transport water and minerals throughout the plant body (the xylem) form through programmed cell death involving autophagy and the release of degradative enzymes (Bassham, 2009). In animals, the cell "corpses" resulting from embryonic modeling are cleared away by phagocytosis (Savill and Fadok, 2000), whereas in plant xylem, it is the cell corpses, specifically the cell walls which remain following cytoplasmic degradation, that actually form the walls of these tubes (Dahiya, 2003; Gunawardena, 2008; Kozela and Regan, 2003). In plants and many algae, unlike animals, intercellular spaces are abundant, especially in mature tissues. In the absence of integrated pump-based circulatory and respiratory systems, this is the only way to ensure satisfactory gas exchange. The largest and most organized spaces occur in aquatic plants, such as the gas bladders of marine macroalgae, or the aerenchyma system of plants growing in waterlogged (hypoxic) conditions, where these spaces facilitate buoyancy and/or gas transport and gas exchange (Evans, 2003; Jarvis et al., 2003; Raven, 1996). Such spaces may be formed by cell separation, cell death, or a combination of both (Gunawardena, 2008; Evans, 2003; Kozela and Regan, 2003). In intercellular spaces formed by programmed cell death, it is remarkable that cell corpses including cell walls are completely removed despite the absence of phagocytic cells (Evans, 2003). This is attributed to the release of degradative enzymes that nevertheless leave neighboring cells unaffected (Evans, 2003).

Cell death in development not only modifies tissues and structure as outlined in the above examples, it also removes redundant or obstructing cells (Jacobson et al., 1997; Meier et al., 2000), such as those located between developing digits at the ends of tetrapod limbs (Montero and Hurlé, 2010). There are no obvious limits to the location or extent of cell death in developing animals. In contrast, plants and algae tend to discard discrete sets of cells or whole organs and appendages such as leaves and petals (Lewis et al., 2006), or hairs (as in red algae, Garbary and Clarke, 2001) often located in terminal or peripheral locations. An example of a discarded terminal structure is the suspensor, an extraembryonic structure derived from the basal cell of the two-celled embryos that, like the placental mammalian trophoblast, attaches the embryo to maternal tissues in the seed (Kawashima and Goldberg, 2010). Cell death normally occurs throughout trophoblast development and function (Huppertz et al., 2006), whereas all seed plant suspensor cells die in a progressive fashion within a short period late in embryogenesis (Lombardi et al., 2007). Roots provide many examples of sloughing peripheral cell layers or structures, but programmed cell death has been implicated in only some cases (Shishkova and Dubrovsky, 2005 and references therein). A notable exception is the programmed death of epidermal cells that would otherwise block the emergence of specialized lateral roots (adventitious roots) which replace the primary roots during the normal development of rice plants (Mergemann and Sauter, 2000).

Finally, it is evident that developmentally regulated cell death can alter the external surface area of organisms, thus altering their fractal dimensions. It is clear that some plants have deployed cell death specifically to increase surface area to volume ratios. For example, certain cacti establish a large seedling root surface area for water absorption by a program of limited primary root growth, followed by programmed death of root cap and root hair cells and then by the sequential formation of lateral roots upon lateral roots (Shishkova and Dubrovsky, 2005 and references therein). Most dramatic and rare are the systematic formation of leaf perforations in certain monocotyledons like lace plants, the purpose of which remains to be established (Gunawardena, 2008). Analogous holes form in the blade of several kelp genera (i.e., *Agarum* and *Thalassiophyllum*, Guiry and Guiry, 2010), and the function in these algae is equally unclarified.

This brief survey of cell death in multicellular organisms highlights the similar roles for cell death in all multicellular organisms but, at the same time, reveals special roles for cell death in the development of organisms with nonmotile cells, where death is essential for creating spaces, transforming surface areas, and deleting structures to facilitate the modular growth of plants into the space around them.

## 8. Evolutionary Mechanisms and Phenotypic Plasticity

It is beyond the scope of this review to consider evolutionary processes in any detail. Here we highlight some well-known evolutionary processes in plant systems that are rare to absent in animals. Plant systems (i.e., flowering plants and ferns) are extremely prone to interspecific, intergeneric, and even interfamilial hybridization. The resulting hybrids are often viable and, if initially only possessing vegetative reproduction, may form seeds asexually (Niklas, 1997). In some groups, interspecific hybridization is so rampant that it is surprising if it does not occur (Grant, 1971). Following chromosome doubling, such entities may then return to sexual reproduction. Thus, plants may commonly undergo "instantaneous" speciation and saltational changes that are rare to absent in animal systems (Bateman and DiMichele, 2002). A classic example that includes many of these phenomena is the evolution of new species of the salt marsh grasses, *Spartina townsendii and S. anglica.* One of these species (*S. townsendii*) was a diploid, asexual hybrid that originated from the hybridization of a native European and an introduced (from North America) species. *S. anglica* originated following chromosome duplication in the first and was sexually reproductive (e.g., Chelaifa et al., 2010).

A key difference in evolutionary mechanisms between plants and animals is a consequence of the underlying developmental differences in the formation of gametes. Whereas many animals segregate the germ line once (but see Extavour and Akam, 2003), early in development, plants do so postembryonically and repeatedly. Such ontogeny reflects the underlying modularity of plants in which many independent, spatially discrete modules are capable of producing reproductive structures (e.g., flowers). Since each plant axis has its own meristem (vascular plants) or apical cell (many red, brown, and green algae and bryophytes), mutations are possible in individual meristems that are expressed in subsequently developed cells and modules and therefore potentially passed on to the subsequent reproductive structures – whether vegetatively, asexually (via apomixis), or sexually. While the neo-Darwinian synthesis has excluded Lamarkian evolutionary mechanisms, plant (and modular animal) development is intrinsically compatible with Lamarkian evolutionary processes (see Jablonka and Lamb, 2006 for discussion of mechanistic explanations).

## 9. Conclusion

Independent origins of complex multicellular organisms offer ongoing opportunities to compare aspects of form in relation to development and evolution. Unambiguous similarities and differences between plant and animal forms can be readily observed, but less obvious is any predictable relationship of those different forms to the developmental mechanisms that generate them. The extent to which comparable morphologies between plants and animals are generated by comparable developmental processes and mechanisms provides potential to illuminate basic principles and limitations governing the ontogenetic and evolutionary origins of organismal design.

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Biodata of **Natan Gadoth** and **Eliyahu Mass**, authors of "***The Lingual Taste Papillae: A Delicate and Complicated Nature's Design for Taste Modalities Perception***."

**Natan Gadoth, M.D.** is currently the chairman of the Department of Neurology at the Mayanei Hayeshuah Medical Center, Bnei Brak (Israel), and professor of Neurology (Emeritus) at the Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel. He obtained an M.D. degree from Hadassah Medical School, The Hebrew University, Jerusalem, in 1969. He has trained in Neurology at the Johns Hopkins University Hospital in Baltimore, USA (1972–1975). His scientific interests are in the areas of neurogenetics, clinical neurophysiology, the autonomic nervous system, neuromuscular disorders, sleep medicine, and epilepsy in children and adults. His interest in taste and tasting stems from his long-term research in familial dysautonomia, a genetic disorder affecting Ashkenazi Jewish children and causing, among other abnormalities, a pronounced taste deficiency associated with degeneration and disappearance of the tongue fungiform papillae. Part of this particular research was done in collaboration with Dr. E. Mass, the coauthor of this chapter.

E-mail: **gadoth@post.tau.ac.il**

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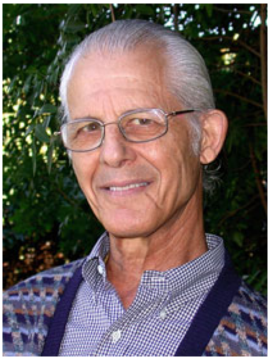
**Eliyahu Mass**, **D.M.D** is at present the director of Postgraduate Specialty Program in Pediatric Dentistry, at the Pediatric Dentistry Unit, Barzilai Medical Center, Ashkelon, Israel, and a senior lecturer (Emeritus) in Pediatric Dentistry, the Pediatric Dentistry Department, Maurice and Gabriela Goldschleger School of Dental Medicine, Tel Aviv University, Israel.

He received his D.M.D. degree from the Faculty of Dental Medicine at Hadassah Medical School, The Hebrew University, Jerusalem, in December 1966. Three years thereafter, he has been employed partly as a dentist at the School of Dental Services of the Copenhagen municipality in Denmark and, partly, as an instructor in the Pediatric Dentistry Department of the Royal Dental School in Copenhagen. Upon his return back to Israel, he joined the Pediatric Dentistry Department at the Tel Aviv University.

His scientific interests are hereditary disorders, dental materials, dental pulp, orodental developmental disturbances and syndromes, and children with special needs.

Working together with Prof. N. Gadoth, they have investigated and published on the orodental aspects of familial dysautonomia and especially taste and taste organs. Parts of this information are incorporated in the present chapter (see biodata of Prof. N. Gadoth).



# THE LINGUAL TASTE PAPILLAE: A DELICATE AND COMPLICATED NATURE'S DESIGN FOR TASTE MODALITIES PERCEPTION

**NATAN GADOTH**[1,2] **AND ELIYAHU MASS**[3,4]
*[1]Department of Neurology, Maynei Hayeshuah Medical Center, 17, Povarsky St., Bnei Brak 51544, Israel*
*[2]Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel*
*[3]The Pediatric Dentistry Unit, Barzilai Medical Center, Ashkelon, Israel*
*[4]The Maurice and Gabriela Goldschleger School of Dental Medicine, Tel Aviv University, Tel Aviv, Israel*

> Taste is the fundamental quality which sums up all the other qualities.
>
> – Isidore Ducasse Lautreamont (1846–1870)

## 1. Introduction

The sense of taste is essential for survival. In animals, the ability to distinguish between nutrient and toxic substances is the final defense mechanism after these materials have been scrutinized by their smell and appearance. In humans, there are additional features of taste, such as hedonism, which gave this sense a leading role in determining our life quality. At present, in the eyes of the western society, famous chefs enjoy a higher social position than the most talented performers, surgeons, scientists, top politicians, and even distinguished writers and poets. In our modern era, getting a seat in a prestigious French restaurant seems to be the fulfillment of one's whole life.

Tasting is not only recognizing the taste itself but also preferring a single brand of coffee from many others and telling a specific Chianti wine from tenths of others.

It is not surprising that wine tasting specialists are a rare brand of professionals who are paid a fortune for their special talent. After a first visit to a Chinese herbal and spices store, one will immediately realize that taste is more than recognizing the five traditional taste modalities, i.e., sweet, sour, bitter, salty, and *umami*, a name given by Japanese researchers to describe the taste of meat. Indeed, this still-debated "fifth modality" refers to the taste of glutamate in the form of disodium glutamate and other amino acids. Many young researchers who spend long hours in the lab without a chance to get a decent meal will take a small bite from a stick of *Marmite,* which is a glutamic acid-rich yeast extract, that has a meat like flavor, and "kill" their gnawing hunger.

Tasting is not just another special sense but is also the initiator of characteristic and meaningful facial and mouth reflex motor activity such as folding the lips reflecting acceptance behavior for sweet, umami, and low salt concentration and pursing the lips and protruding the tongue to avoid bitter, sour, and high concentration of salt (avoidance behavior). Such behavior patterns are shared by all mammals and surprisingly even by human anencephalic newborns (Steiner, 1973).

Although highly sophisticated in its development, anatomy, and neurophysiology, the ability to taste is inferior to the ability to smell, at least in mammals, as they are unable to distinguish different chemical cues within a taste modality but are capable to do so by smelling (Spector and Kopka, 2002).

This chapter will deal with the peripheral system enabling taste modality recognition in mammals and will concentrate on the sophisticated anatomical and molecular design of the tongue fungiform papillae and its central neural pathways.

## 2. Nature's Design: The Fungiform Papillae

A simple glance on the surface of the mammalian protruded tongue will disclose a velvety surface formed by numerous tiny somewhat bulging structures known by the name *papillae*. There are four types of papillae, which were given descriptive names after being seen by the naked eye or aided by a conventional magnifying glass. The most numerous are tiny hairlike projections called the *filiform* papillae (Latin: *phylum*-thread). This type of tongue papillae is the only one without taste buds and, thus, serves as primary sensory tactile organ. All other three contain taste buds and function as primary taste organs. The *foliate* ("leaflike" shaped) papillae are located in small trenches on the sides of the rear of the tongue. Nine to twelve relatively large and prominent *circumvallate (wall-like*) papillae are arranged in an inverted V form with its sharp edge located at the midline of an imaginary line drawn between the anterior two thirds and the posterior third of the tongue, with both arms facing backwards.

The *fungiform* (*mushroomlike*) papillae (FP) are located on the dorsal surface of the anterior two thirds of the tongue, mainly at the tip and the lateral margins, and are significantly fewer than the filiform papillae. Estimates on their total number vary due to differences in age and techniques of counting. As early as 1967, one of us (*N.G.* [*N. Jagoda*]) found an average of 60 FP in 20–30-year-old healthy volunteers using an illuminated magnifying glass (12×). The total number decreased with age to an average of 30 in 50–60-year-olds (Moses et al., 1967). Those numbers were confirmed more recently by video microscopy (Segovia et al., 2002).

These pinkish rounded structures bulge out from the multiple, crowded, tiny filiform papillae. They are not uniform in size and shape. Some are flattened, while others have a short base (Figs. 1 and 2). Each FP is surrounded by a shallow

**Figure 1.** Normal tongue without magnification. Note multiple bulging reddish fungiform papillae (*arrow*).

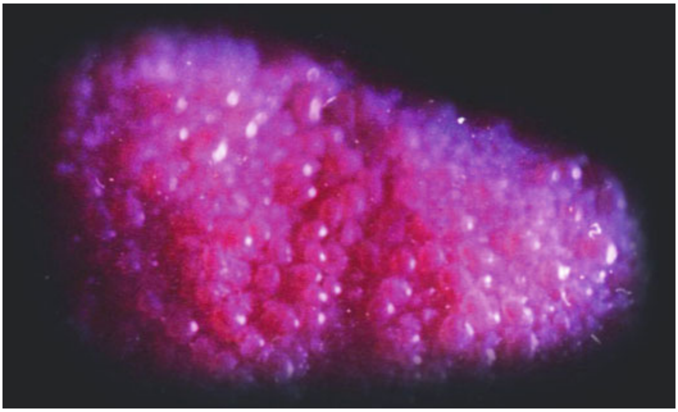


**Figure 2.** Normal tongue viewed with an ophthalmological slit lamp (×20). The fungiform papillae are seen here as a bunch of grapes. The vesicles with a red vascular core are single FP.

groove separating it from the adjacent filiform papillae. It is coated by keratinized or nonkeratinized epithelium and contains a core of connective tissue with its blood and nervous supply. Two to five specialized organs, the taste buds, are embedded in the squamous epithelium of a single papilla (Paran et al., 1975). The taste buds are onion-shaped structures, containing 50–150 cells which are

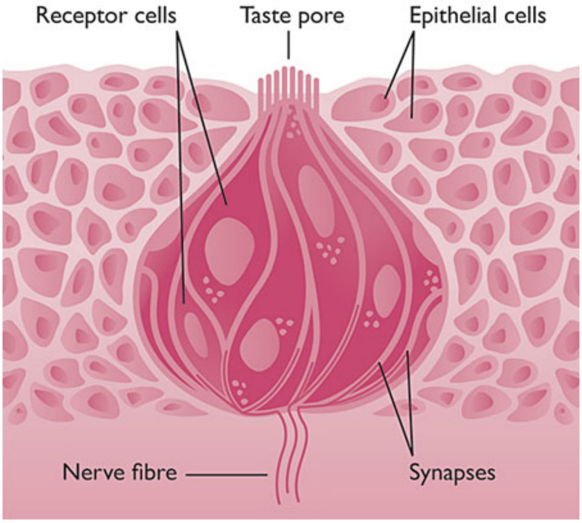


**Figure 3.** A schematic view of a fungiform papilla.

classified according to their function as precursor, support, and taste receptor cells. The narrow and elongated cells extend from the base of the bud to its distal part, reaching the surface of the tongue, thus creating a channel-like structure. At the distal part, these cells "send" slender fingerlike projections called microvilli which reach the surface of the tongue through the opening of the taste bud called the *taste pore* (Fig. 3). Each FP contains roughly 4–5 of such pores in adults and some more in children (Segovia et al., 2002). Through this pore, tastant chemicals which are dissolved in the saliva reach the taste cells to start a cascade of reactions resulting in taste recognition.

Three cell types are present in the human taste buds.

*Type I cells* are the majority. These cells which are located near the base of the taste bud terminate distally by short lateral projections called microvilli. The microvilli intermesh with corresponding projections from adjacent taste cells at the apex of the bud and surround the pore.

Close contacts frequently occur between type I cells and nerve fibers. The plasma membrane of the cells often appears deeply indented by the nerve fibers, which run alongside the cells from the base of the bud to the apical pore.

*Type II cells* are similar to *type I* in their distribution and show great variability in their morphology. The cells are characterized by densely stained cytoplasm, with numerous vacuoles of varying size and shape. Many mitochondria, glycogen, and vacuoles are the dominant cytoplasmic structures in their apical portion. Other *type II* cells, in which the apical mitochondria are not so numerous, may be found. Nerve fibers are in intimate contact with those cells, although the contact is not characteristic of a typical synaptic junction. While there may be more nerve fiber contacts with the basal halves of *type II* cells, such contacts with the nerve fibers may be made near the apical portions and even near the pore.

*Type III cells* are characterized by dense-cored granules and clear-cored vesicles largely in their basal region. The granules and vesicles are especially numerous in the vicinity of nerve fiber contacts. Those cells are believed to act as true receptor cell, in which the cytoplasm represents the presynaptic portion.

It is virtually impossible to distinguish between *type I* and *type III* cells in the bud's apex since neither contain unique cytoplasmic constituents in this region. Therefore, it is not possible to determine whether or not the *type III* cells extend all the way to the pore or to establish the way they terminate.

## 3. Mechanisms of Taste Recognition

The ability to recognize more than one taste modality is mediated by specialized epithelial cells (the taste cells within the taste buds) containing specific transmembrane domain taste receptors, which are either specific proteins expressed on the surface of the cell or "pore-like" proteins known as ion channels. The isolation of two novel G-protein-coupled receptor (GPCR) genes, which encode specific receptors for sweet and bitter, enabled detailed studies of their physiological and molecular characteristics (Hoon et al., 1999).

It is now well recognized that there are different receptors for particular taste modalities. In mammals, there are two receptors for sweet (T1R2; T1R3)-[T1R: *taste receptor type 1*, etc.], one for bitter (T2R), and two for amino acids (T1R1; T1R3). Although the precise mechanism of sour and salt perception is still not fully revealed, there is solid evidence that the perception of those two taste modalities involves ion channels. As mentioned in the introduction, the recognition of salt and sour is essential for survival. Salt perception plays a critical role in maintaining ion and water homeostasis, and sour perception enables to reject immature fruit, toxic materials, and spoiled foods.

## 4. Salt Perception

The ability to recognize salt involves ion flux. Salty substances initiate the flow of $Na^+$ via cation channels located at the apical membrane of the taste cells, which leads to membrane depolarization, generation of action potentials, and concomitant release of neurotransmitter onto the afferent nerve fiber. The generation of action potentials is associated with activation of voltage-gated $Na^+$ and $Ca^{2+}$ channels causing inward $Na^+$ and $Ca^{2+}$ currents. Those events cause depolarization and activation of the voltage-gated $K^+$ channels, which are associated with repolarization and hyperpolarization phases. This cascade of ion flux events elicits $Ca^{2+}$ inflow which leads to synapse exocytosis and neurotransmitter release.

To maintain a continuous inflow of $Na^+$, the membrane-bound $Na^+$-$K^+$-ATPase, which pumps out intercellular $Na^+$, must be intact. There is evidence for additional $Cl^-$ transport involved. A selective anion transport via the tight junction of taste bud cells' basal membrane contributes to the distinct taste of various sodium salts (Elliott and Simon, 1990).

## 5. Sour Perception

In contrast to salt recognition which is dependent on ion flux, sour perception is mediated by protons. Acid-elicited sour taste was found to be proportional to proton concentration. In the taste cells, there are *proton-gated* and *proton-conducting* channels, as well as pH-dependent ion exchangers. These membrane-bound organs are believed to be either *transducer* or *receptors* for sour perception. Protons can reach the taste cells via the tight junctions. By permeating through the taste cells, they modify the extra- and intracellular activities of ion transporters localized at the apical and basolateral regions of the taste bud. In response to acidic stimulation, the activated proton or modulated channel activity depolarizes the membrane. This is caused either by direct current flow or by indirect pH-regulated ion exchanges/transporters which modulate the intercellular $Na^+$, $K^+$, and $Cl^-$. The net result of this modulation is a change in the equilibrium potential of those ions, causing current flow via the already opened channels, resulting in membrane depolarization. This leads to activation of voltage-gated channels, production of action potentials, and release of neurotransmitter onto the afferent nerve fibers.

There are several channels such as *acid-sensitive ion channel* (ASIC), *apical* $K^+$ *channel*, and others, which are known to be associated with sour perception. However, the exact contributory role of those channels to sour perception is yet unknown. Recent observations suggest that ASIC or ASIC-like channels may play an important role in sour taste transduction. Another point of interest is the fact that taste receptor cells express VR1 (vanilloid receptor-1) known also as variant mammalian salt taste receptor. VR1 and its variants are permeable to $Na^+$, $K^+$, and $Ca^{2+}$. At body temperature, extracellular acidification stimulates VR1 channel activity (Jordt et al., 2000). The possibility that changes in intracellular pH may be involved in sour transduction has yet to be proven.

## 6. Sweet, Bitter, and Amino Acid (Umami) Perception

The sweet and bitter taste modalities evoke acceptance and aversive facial and oral motor responses which are retained even in human anencephalic newborns that lack cerebral hemispheres. This surprising observation suggests that these are primitive survival reflexes controlled by neurons located outside the cerebral hemispheres, probably at the level of the motor nuclei of the pons and medulla oblongata, brain regions which are essential for survival.

Both receptors for sweet (T1R2; T1R3) detect all natural sugars and artificial sweeteners. Indeed, mice lacking either receptor are able to detect only very high concentrations of sugar (Zhao et al., 2003). The fact that mice lacking both receptors are unable to detect normal concentrations of sugar implies that presence of both receptors is essential for sugar detection. Another support for the critical role of both sweet receptors for sweet perceptions is the well-known fact that cats avoid sweet food. Indeed, domestic as well as wild cats lack a functional T1R2 receptor due to a microdeletion in the coding sequence of the T1R2 gene (Li et al., 2005). Similarly, the presence of T2R is vital for bitter perception and that of both T1R1 and T1R3 for umami.

The above-mentioned receptors are expressed at specific taste cell in a programmed arrangement. Thus, using immunohistochemistry and antibodies against receptor proteins enabled the mapping of those receptors to specific regions and structures on the tongue surface.

The presence of textbooks' "Taste Maps," which were drawn by applying the four classical tastants (sucrose, NaCl, citric acid, and quinine) in various concentrations over the tongue, has been challenged by single-cell recordings. The lack of proof to the presence of such maps was nicely summarized by Smith and Margolskee which states that *"at present, we have no evidence that any kind of spatial segregation of sensitivities contribute to the neural representation of taste quality"* (Smith and Margolskee, 2001). However, in mice, T1R2 (the sweet receptor) is expressed in fungiform papillae while T2R (the bitter receptor) is expressed in foliate and circumvallate papillae, as well as in the palate (Kim et al., 2003). This suggests that the different expression of specific receptors may still form a topographic map of taste sensitivity.

## 7. The Topical Arrangement of the Taste Receptors of the G-Protein-Coupled Variety

Both T1R and T2R are located in the same taste bud but are not co-expressed in the same taste cell (Nelson et al., 2001). The same goes for T1R1 and T1R2 (Hoon et al., 1999).

This arrangement implies that sweet, umami, and bitter tastes are encoded separately by activation of distinct cell types. It should be noted in this context that most members of the T2R receptor family (T2R variants-T2Rs) are co-expressed in the same subset of taste cells. This implies that a particular subset of taste cells is capable of responding to a wide range of bitter compounds without the ability to discriminate between them (Spector and Kopka, 2002). The simple view that there are five different types of tastes cells, each responding to a single taste modality, lacks biological proof as salt and sour taste recognition occurs in the same subsets of cells that mediate sweet, bitter, and umami. However, there is no cross talk between the specific signaling pathways. Each modality-specific pathway maintains a characteristic temporal firing pattern of action potentials. Thus, the temporal distribution of the firing, its rate and its intensity, may determine the central recognition of the particular taste modality as will be mentioned later.

## 8. The Programmed Development of the Fungiform Papillae in the Rodent Model

The embryonic programmed development of rodent fungiform papillae is an excellent example of the way nature designs sophisticated peripheral sense organs. Histological methods reveal the presence of early taste buds on embryonic day 20–21 (E20-E21). The taste papilla epithelium differentiates first and only later taste bud progenitors differentiate within the papilla epithelium (Mistretta and Hill, 1995). The development of the papilla is regulated by specific molecular signaling. Those "growth molecules" include the following: (1) Sonic hedgehog (Shh); (2) Wnt signaling pathway proteins, which play a key role in regulating vertebrate organogenesis; (3) LEF1, a cell-type-specific transcription factor that mediates the Wnt signaling pathway; (4) bone morphogenic proteins (BMP); (5) the antagonist *noggin*; and (6) SOX2, a transcription factor, which is essential to maintain self-renewal of undifferentiated embryonic stem cells. Those molecules are distributed uniformly in the lingual epithelium at E13. Their expression undergoes significant progressive distribution restriction until E16 when a dense expression in the epical part of the papilla epithelium is present. Other factors, such as epithelial growth factor (Egf), are distributed and expressed heavily throughout the papilla epithelial placode, while epithelial growth factor receptor (EgfR) is progressively distributed in the margins of the placode.

It is essential that the morphological developmental changes in the tongue epithelium will be precisely time-locked with the development of their sensory innervations for the normal functioning of taste perception and recognition. The morphological and molecular differentiation of the placode occurs before the nerves are in close vicinity with the epithelium. Parallel to the process of molecular restriction at the apical papillary epithelium described above, the nerves approach the connective tissue core of the papilla epithelium. Then, the papilla grows and the nerves start to penetrate the apical epithelium. When taste cell progenitors are formed as a result of further differentiation of the apical papilla epithelium, the nerves penetrate the apical epithelium. Later, with molecular support to the taste cell progenitors and molecular signaling innervating ganglion cells, the nerves are capable of "supporting" the papilla and enable the specification of the apical epithelium. The final stage is reached when the taste receptor cell types differentiate and are capable of signaling upon the innervating fibers, which support and regulate the receptor cell differentiation (Mistretta and Liu, 2006).

## 9. Taste Signaling

The initial event in taste is the perception by taste receptor cells of chemical signals generated by taste compounds. Those signals produce changes in membrane potentials and/or intracellular free $Ca^{2+}$ concentration. Such changes evoke neurotransmitter release which stimulates the gustatory afferent nerve fibers. Five different neurotransmitters are now recognized as involved in peripheral taste perception, i.e., glutamate, serotonin, norepinephrine, acetylcholine, and GABA (Herness et al., 2005). Interestingly, more than 30 years ago, we have suggested that acetylcholine plays a role in tasting, based on simple observational neurophysiologic study (Steiner et al., 1973).

The complicated cascade of chemical and bioelectrical events, which was described above in some detail, was discovered only recently and involves several G-protein subunits. The first to be discovered was *gustducin*, a G-α protein subunit, which is expressed in subpopulations of taste receptor cells of all taste buds, partially overlapping the distribution of T1Rs and T2Rs. This arrangement implies that there is a downstream transduction of sweet and bitter receptor activation (Hoon et al., 1999). The critical role of *gustducin* as a transducer of sweet, bitter, and amino acid taste signaling is evident by the reduced behavioral and physiological responses to sweet, bitter, and amino acid-containing compounds given to mice with *gustducin* deficiency (Glenndinning et al., 2005).

The enzyme *phospholipase 2B* and the cationic channel TRPM5, which are selectively expressed in taste cells, are also vital for transduction of taste stimuli. Mice lacking those compounds fail to detect sugars, amino acids, and bitter taste and are left with only a residual ability to recognize sweet, bitter, and umami. The fact that their ability to detect salty and acidic compounds is retained indicates that other G proteins may play a role as signal transducers for the perception of those taste modalities (Zhang et al., 2003).

## 10. The Central Organization of Taste Afferents

The taste information obtained by the lingual neural epithelium of the taste buds within the fungiform papillae is transmitted by the chorda tympani and superficial petrosal nerves, respectively, which accompany branches of the facial nerve. The taste buds of foliate and circumvallate papillae are innervated by the glossopharyngeal nerve, and those located at the epiglottis, by the superior laryngeal branch of the vagus nerve. All those ascending nerve fibers synapse with second-order cells within the tract of the solitary nucleus (TNS) of the medulla oblongata. A second synapse is located in the thalamus, and the third, in the gustatory cortex. In the TNS, there is a “somatotopic” representation of the specific taste receptors. Neurons that synapse on TR1 cells project to the rostral TNS, while those that synapse on T2R cells project to more caudal parts of the tract (Sugita and Shiba, 2005).

This arrangement may be explained either by the location of specific receptor cells in the TNS or by the fact that the chorda tympani nerve fibers, which innervated the TR1 receptor containing fungiform papillae, terminate in the rostral TNS.

Even in the gustatory cortex, there are neurons with different sensitivities to different taste compounds (Yamamoto et al., 1989). Recent evidence suggests that gustatory neurons in the TNS, the parabrachial nuclei, thalamus, and the gustatory cortex may be organized with rostral (sweet/umami) inputs and caudal (bitter) inputs, except for bitter quality in the parabrachial nuclei external medial subdivisions (Sugita and Shiba, 2005).

## 11. How Do We Know What We Taste?

Three models have been suggested:

1. The brain detects (*knows*) which taste cells have been activated.
2. Multiple taste stimuli reach the brain and cause a variety of neuronal activities. The brain, then, compares the relative activity of a population of neurons to determine the most active and thus "senses" the particular taste.
3. The brain analyzes the precise firing pattern of the active potential conveyed from the periphery to "*recognize*" the nature of the particular sensory (taste) input.

## 12. Taste and Its Appreciation

Certain universal facial expressions can be associated with different taste modalities. The young mother as well as a bystander will look intensively at the baby's facial expression when fed. Both will share a smile if the baby's facial expression is one of pleasure (hedonic). Both observers will be unhappy and the mother even alarmed if the baby's facial expression is one of aversion. In addition to the typical facial expressions, associated universal motor behavior such as lip smacking or finger licking is associated with sweet taste, while grimacing, lip pursing, and even spitting accompany the taste of bitter, sour, and concentrated salt. Let's imagine that we are participating in a TV chef competition show. We would watch tensely the facial expressions of the judges who had just tasted the special dish we have prepared. We and those who watch the show at home will know immediately if the judge liked it or not.

The repertoire of this particular behavior pattern which is shared by babies and their grandparents is another "nature's design."

Tasting is not just another special sense but is also the initiator of characteristic and meaningful facial and mouth reflex motor activity (the gustofacial responses), such as folding the lips reflecting *acceptance behavior* for sweet, umami, and low salt concentration and pursing the lips and protruding the tongue to avoid bitter, sour, and high concentration of salt (*avoidance behavior*). The gustofacial responses are shared by all primates and are present at birth. The response has a developmental hierarchy. Steiner et al. (2001) have undertaken a detailed and cumbersome study of the gustofacial responses to the four basic taste modalities in humans and primates. They found that human infants and great apes belonging to the Hominoidea superfamily (chimpanzees, gorillas, and orangutans) have similar and appropriate responses (acceptance and avoidance) to the taste stimuli used. In contrast, Old World monkeys of the Cercopithecoids superfamily, New World monkeys of the Platyrrhini superfamily, and the mongoose lemur monkey of the Lemuroidea superfamily had responses which were inferior in their detailed expression due to activation of a lesser number of facial expressive muscles. Human infants were the only ones who had the full-blown hedonic “flashbulb smile” (when the whole face “lights up”) to sweet tastes. Those findings could not be fully correlated with the different diets of the human infants and the various monkeys examined. Together with Professor Steiner, we have observed many years ago the classical gustofacial responses in healthy newborns and could easily and precisely identify the solution given to babies just by looking at their facial expression. We were astonished to see and correctly identify the solution applied on the tongue of three anencephalic newborns (Steiner, 1973, 1974).

The work of Steiner and coinvestigators established the fact that basic hedonic (acceptance) and aversive (avoidance) behavioral responses to various taste stimuli are shared by primates and humans from day of birth, as well as by anencephalic newborns. The fact that those behavioral responses are present in anencephaly is intriguing and implies that those responses are *not* mediated by the cerebral hemispheres.

The gustofacial response may be looked at as a “survival” reflective response which gets rid of “dangerous” foods by *avoidance* facial expression and allows palatable foods by the *acceptance* response. Theoretically the amygdale could be the initiator for the avoidance behavior and the fronto-orbital cortex could be the site of hedonic experience and mediate the acceptance response (Kringelbach, 2005). However, those anatomical sites are *absent* in anencephaly.

One should assume that a neural circuit outside the cerebral hemisphere is responsible for the gustofacial responses which are indeed true reflexes. A possible neuroanatomical circuit for this reflex may be a reflex loop starting with the afferent fibers of the chorda tympani nerve, which conveys taste from the tongue to the tract of the nucleus solitarius (TNS), located in the medulla. From the TNS, there are fibers reaching several motor nuclei, among them is the motor nucleus of the facial nerve located in the caudal part of the pontine tegmentum. Such a pathway may be left intact in the anencephalic brain.

## 13. Closing Remarks

In spite of the recently discovered detailed information regarding the structure and function of the fungiform papillae, many features of taste are still unrevealed. Why are we so different in appreciation of flavors and how do we distinguish between our “morning coffee,” which we prepare, and that same brand with identical amount of coffee cream and sugar, which is served in the restaurant. Those additional wonders/gifts of mother nature are yet to be understood.

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Biodata of **Joseph Seckbach**, co-editor of this volume and author of "***Divine Genesis, Evolution, and Astrobiology***."

**Professor Joseph Seckbach** is the founder and chief editor of *Cellular Origins, Life in Extreme Habitats and Astrobiology* ("COLE") book series. He has coedited other volumes, such as the *Proceeding of Endocytobiology VII Conference* (Freiburg, Germany) and the *Proceedings of Algae and Extreme Environments meeting* (Trebon, Czech Republic). See http://www.schweizerbart.de/pubs/books/bo/novahedwig-051012300-desc.ht. He edited the recent volume (with Richard Gordon) entitled *Divine Action and Natural Selection: Science, Faith, and Evolution* published by World Scientific Publishing Company (2009). Beyond editing academic volumes, he has published scientific articles, edited and translated several popular books. Dr. Seckbach is the coauthor, with R. Ikan, of the Hebrew language *Chemistry Lexicon* (Deveer publisher, Tel – Aviv, Israel).

Dr. Seckbach earned his Ph.D. from the University of Chicago (1965) and did a postdoctorate in the Division of Biology at Caltech, in Pasadena, CA. He was appointed to the faculty of the Hebrew University (Jerusalem, Israel). Dr. Seckbach spent sabbaticals at UCLA and Harvard University and DAAD-sponsored periods in Tübingen, Germany, and at LMU, Munich. Professor Seckbach served at Louisiana State University, Baton Rouge, as the first chair for the Louisiana Sea Grant and Technology transfer. His recent interest is in extremophiles and astrobiology.

E-mail: **joseph.seckbach@mail.huji.ac.il**

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# DIVINE GENESIS, EVOLUTION, AND ASTROBIOLOGY

**JOSEPH SECKBACH**
*P.O. Box 1132, Efrat 90435, Israel*

> *How Abundant Are Your Works, God; With Wisdom You Make Them All.*
>
> – Psalm 104

## 1. Introduction

Did the universe come about by random blind chance or was it contemplated and implemented by an intelligent being ("intelligently designed")? Science deals with observables, while God does not fit into such equations. The Torah is not a scientific record of creation of Earth and life, but rather deals with the history of and morals for the chosen nation. For science, divine creation is outside the framework of the physical and chemical laws. Since the creation occurred only once, therefore it could not be treated for repeated observations by science.

Life exists on Earth in almost every environment, even in habitats with very severe physical and atmospheric conditions. Living forms that have been observed in harsh habitats are called *extremophiles*. They grow in various ranges of temperatures (from very low to extremely hot niches). Other microorganisms live in very acidic areas or in alkaline waters. At the bottom of the ocean are hydrothermal vents gushing out via volcanic activities, and around these hot, subsurface, steamy waters, under high hydrostatic pressures, are various types of organisms. The extremophiles expand our knowledge about the diversity of life forms and serve as candidates or models for microorganisms thriving in extraterrestrial places. These severe conditions are considered extreme from our anthropomorphic point of view. We assume that the extremophiles feel in their habitats like in Garden of Eden, with "normal" habitats potentially lethal for them, while for the other "common" organisms, such extreme habitats are deadly locations. The tree of life shows three domains of organisms: Archaea, bacteria (both groups are simple-structured microbes), and Eukarya (higher forms with advanced complex cells, including a nucleus and membrane-surrounded organelles). The scientific approach assumes that the first primordial cell was formed in specific habitats by spontaneous chemical reactions and subsequent genetic mutations, either on Earth or elsewhere (Hoover et al., 2007). Then this protocell gave rise to all other organisms on the tree of life. This theory is based on nucleic acid sequences, on genetic mutations over the generations, on the microfossil record, and on Darwinian natural selection. Like all scientific theories, Darwinism is subject to improvement whenever additional data is available from the fossil record or from new experiments or observations. Outside the frontiers of science, in the domain of faith, the existence of the universe and life is of paramount relevance.

The 6 days of creation in Genesis do not necessarily mean exact periods of 24-h units. Remember the first three "evenings and days" were mentioned in the first chapter of Genesis book prior to the setting out of the sun and moon.

These illuminators were brought forth only on the fourth day, so the biblical first days were not similar in their duration to our "days." Both schools may agree that every Genesis "day" might have been an era of millions years. It has been stated in the Bible that human one "thousand years" by the divine scale is equal to one divine single day (Psalms 90:4). The steps of creation according to the book of Genesis are a part of basic faith (that we cannot comprehend and should not deal with), as this divine action stands outside the natural laws (of physics and chemistry), while scientific random generation is a theory. It is interesting that science's steps of evolution run almost parallel and follow those of the first chapter of Genesis. The sequences of formation of mammals and man started with the commandment of the creation of light (perhaps referring to the Big Bang, although we do not have any intention to endorse or question it) → sky and land → the botanical world → illuminators (sun, moon, and stars) → aquatic animals → amphibian, reptiles → birds → mammalians and finally man.

The questions of this chapter are the following: How does religious faith relate to the scientific assumptions of "blind" chance in the formation of the whole universe, emergence of life, evolution of organisms via natural selection and other scientific issues based on random permutations and probabilities? Also, could an observant Jew accept the Darwinian evolution theory as a whole? The observant Jew has a few choices regarding this theory: rejecting, accepting, or accepting with reservations. Our reply would be that theology should not "en bloc" invalidate the findings of science, since the Torah's is a moral message and should not be influenced by some of these scientific points. Furthermore, science cannot cross its own boundaries and venture into the domain of philosophy and religion. Neither should religion mingle into the precincts of science. As Stephen Jay Gould stated, they are both sovereign nonoverlapping domains.

*Astrobiology* is a new multidisciplinary branch of science that deals with many aspects of biological disciplines, ranging from origin of life to fossil records, evolution, diversity of organisms, space, and research on the solar system and beyond in the universe. Astrobiology concentrates also on the possibilities of life on moons, planets of the solar system, and bodies further away.

## 2. Question About Religion Versus Science

Jewish faith has a religious tradition that runs from father to son to grandson and so on, that is, from generation to generation – in most cases, without any doubt. The question is what should be the religious approach toward scientific statements and theories (with respect to the universe formation and evolution of life on Earth as well as to extraterrestrial biology). The following are the three possibilities.

## 2.1. REJECTION

Several theological proponents would reject scientific theories, which seem to contradict established faith. According to scientific theory, all universe components came to existence randomly by blind chance or spontaneous physical and chemical reactions until the first biocell showed up. From this protocell, all the other living forms have derived. There are differences in both disciplines' attitudes toward the 6 days of divine creation, length of the day, origin of the man, and other issues. Under such circumstances, traditional religion avoids or does not address questions inside the scope of science and conceives divine creation as in the Torah.

## 2.2. ACCEPTANCE

Others would claim that there is no conflict between the ideas of science and religion. The aim of the Torah and specifically the first chapters of Genesis was not to compile and supplant a scientific book. Moreover, we might not take the first Genesis chapters as literal; they might be recorded as an allegory. The Torah speaks to each generation in its own language.

## 2.3. QUALIFIED ACCEPTANCE

Halperin (personal communication, and in 2008) stated:

> There is no reason for a religious person to be afraid of exact science that deals with mutations and the laws of selection. On the other hand, there is no reason for an atheist to treat the theory of the origin of species as proven scientific fact, which it is not. One who wishes to believe in Darwinism may do it only on his own responsibility.

We should also add that no scientific discipline is ever final; it always strives for improvement with the confrontation with additional experimental data. A strongly devoted religious person might tolerate and even embrace the theory of evolution. There are issues for discussion that should not stand in contradiction between Torah and science. For example, the number of years that the world exists: the Jewish count gives a figure of ~6,000 years (to be exact it is 5,771 years [for 2011] since the creation), while the scientist's view of the origin of life is in a magnitude of ~4 billion years since the appearance of life. The Jewish idea is that there were indeed other worlds prior to our present world. It has been already quoted over a 1,000 years ago (Gensis Rabbah-Hebrew) that:

> The Holy One, blessed be He, went on creating worlds and destroying them until He created these [heaven and earth], and then He said: "These please Me; those did not please Me."

On the other hand, our religion does not need to prove or disprove all the scientific “evidence.” We might even accept all the scientific ideas of origin of life and the formation by “chance” of the universe and evolution of organisms, yet understand that all these stages followed the design of God.

Rabbi Kook (Letters of Ha-Raya, (igrot Ha-ReaYaH, 1962)) pointed out the above nonconflict between religion and science, see also Shuchat (*Torah u-Mada*, 2005). Let us remember that after all, origin of life is one of science’s mysterious events, a challenge that has not been solved. We might accept the idea of formation of matter and the universe by scientific “chance,” all which have been under the umbrella of the divine providence that created the universe and consequently also life *ex nihilo* (see Fain, 2004, 2009).

## 3. Genesis: Origin of Life

The appearance of the galaxy occurs according to the secular nonbeliever scientists through “nature” or a “chance cosmic event.” Since the genetic code is almost identical in all living things (there were recorded some variation as in the ciliates), it leads scientists to conclude that all organisms evolved from a single primordial “mother” cell. On the other hand, these creative forces are considered by the believers as the deed of Almighty God alone. Furthermore, the formation of the universe (Big Bang) and the miracles via natural or nonnatural occurrences in the past and present, claimed by scientists to have occurred by “random chance,” are actually performed and guided by God, for the believing Jew.

Most evolutionary scientists accept the idea that initial life most probably began in hot or warm liquid environments (so that the first organisms were thermophiles, namely, lovers of heat). A few voices propose that life started in ice-cold areas. We know that some microbes currently grow in extreme temperature habitats, the hyperthermophiles in very hot niches (such as in hot springs). On the other side of the temperature scale are the psychrophiles flourishing in extremely low temperatures. There is a proposal claiming that the initial steps of life were imported from space (“panspermia”). This “seed of life theory” claims that components of life elements and liquid water, or even bacteria, were imported from space to Earth by comets and meteorites. This exogenesis source makes no proposal for the initial origin of the existing life in space before it arrives (supposedly) to Earth.

Supporters of the origin of universe and life, whether by divine creation or via a natural self-change, might consider a famous theoretical situation. Let us assume that Neil Armstrong on his first steps on the moon (1969) finds on the dusty ground a clock. The question is how does it get there? Logically, one might assume that before the astronaut’s visit, somebody placed it there and not that it was assembled in spontaneously. Likewise, if a tornado should run over the area and afterward a complete vehicle or airplane would be found, would anyone think that this new complex product was assembled by itself by chance during the storm? This argument was already raised over 960 years ago by the Jewish philosopher Rabbi Bachya ibn Pakuda (author of *Hovot ha-Levavot*, c. 1040). Bachya wrote that every vessel has a producer and is not produced by itself. He emphasized that the entire universe, too, was not formed by a chance but has a (divine) creator. In the Mishnah (Ethics of the Fathers 5:8), it states, “Tongs too made with tongs,” meaning that every vessel and item in the universe has its producer. We have to remember that the biological cell is quite a complex microstructure. Organs such as the eye, brain, internal organs, and so on are all very complicated, and no one in the laboratory has been ever able to build even a simple, primitive cell. Over 50 years ago, Stanley Miller (Seckbach et al., 2004) succeeded to synthesize from simple gases (with electric sparks sent through a mixture of methane, hydrogen, ammonia, and water) three amino acids (out of the 20 that are the building blocks of protein). These “Miller experiments” were an important step to the simultaneous chemical reactions of initial biological compounds and astrobiology. However, since Miller’s discovery, nobody has been able to proceed and synthesize a living cell in a test tube. Also, from the statistical point of view, there are almost no chances of realizing self-production of life without a divine designer.

In the next section, we will discuss a new branch of biology that demonstrates the hidden diversity of the living world.

## 4. The Extremophiles

> You, only you, are Lord; you made heaven, the heaven of heavens, with their entire host; the earth, and everything that is in it; the seas, and everything that is in them; and you preserve them all; and the host of heaven prostrate themselves to you. (Nehemiah 9:6)

Over the past dozens of years, many microorganisms have been observed hidden outside the “normal” habitats (Seckbach, 1999, 2000, 2007; Seckbach and Chela-Flores, 2007, 2012). They were found in stressful environments that are far away from the known habitats of organisms we are more familiar with. The following are the main factors of the severe environments.

### 4.1. TEMPERATURE

Microorganisms are able to grow in very low temperatures (greater than −20°C), such severe conditions occur in the permafrost of the Antarctic and Arctic regions. These cold-loving microbes are the cryophytes or psychrophiles. At the other edge of the temperature scale are microorganisms that thrive in high-temperature ranges (from around and over water’s boiling point up to 113°C). These thermophiles and hyperthermophiles are present in hot springs, in the hydrothermal vents at the bottom of oceans, and in areas where volcanic streams gush from the ground.

### 4.2. ACIDIC VERSUS ALKALINE (THE PH EFFECTS)

Acidic and alkaline solutions (pH ranges) both have microbial inhabitants. The acidophiles grow in acidic places, such as in ubiquitous hot acidic springs and in abandoned coalmines, while alkaliphiles grow in soda lakes, such as those located in Africa.

### 4.3. SALT STRESS AREAS

The halophiles grow in salty areas, which may contain high concentrations of salt (up to saturated solutions). They occupy ubiquitous salty soils and also lakes of high salt concentrations (such as in the Dead Sea in Israel and the American Great Salt Lake in Utah).

### 4.4. THE EFFECT OF PRESSURE

Some barophiles occur at high hydrostatic pressures in the depth of the oceans. The pressure there could reach 1,000 atm(vs. 1 atm at the sea level). Other microbes can be found in the depths of the Earth's subsurface.

### 4.5. EXTREMOPHILES SHOW LIFE DIVERSITY AND LEAD TO ASTROBIOLOGY

The extremophiles could serve as good examples for the ubiquitous distribution and diversity of life. In addition, these organisms may serve as candidates for or analogous to extraterrestrial life in celestial bodies, such as on some moons or satellites in the solar system and beyond.

## 5. Astrobiology

> Lift high your eyes and see: Who created these? He who sends out their hosts by count, Who calls them each by name: Because of His great might and vast power, Not one fails to appear. (Isaiah 40: 26)

Astrobiology is a new scientific branch dealing with origin of life, evolution, fossil records, physical and atmospheric condition of the universe, biology of space and planets, and possibilities for life in extraterrestrial lands (Chela-Flores, 2001). We have to keep in mind that the main elements required for life (possibilities) are liquid water, carbon compounds, and energy sources. Wherever liquid water is found, there are some good chances for life (as we know it). Reports have been published that there are some worlds outside the solar system that may support life. Such a habitable zone is the best place to look for exobiological life. The problem is that these extraterrestrial bodies are many astronomical light years away from our mother Earth. Other extraterrestrial worlds have not been strange to ancient Jewish scholars. It is mentioned (Songs of Songs Rabbah) that Rabbi Acha said that *"The Holy One, blessed be He,* ***had other worlds*** *upon which He went forth to reveal Himself."*

## 5.1. MAN ON THE MOON

The moon has hardly any atmosphere, so there are no weather effects even to erase the footprints of the 1969 astronauts. Without an atmosphere on the moon, the temperatures there are very hot during the day (100°C) and very cold at night (−173°C).There is no evidence of any life form on the moon.

## 5.2. MARS

This red planet is the most promising target for possible extraterrestrial life among the other celestial places. On this planet, microorganisms should have good chances to survive and grow on the surface or in subsurface layers. The Martian images taken by NASA show on its surface images of dried river contours, gullies, canyons, and lakes, contours of ancient running water (from when this planet was warmer and wetter). These "green fields" vanished in the distant past. Mars contains a high level of $CO_2$, it receives UV radiation, and its surface is cold (from −101°C to 21°C) and desert dry. Some extremophilic microorganisms, however, could live under such conditions as exist on Mars. Recently, a couple of spacecrafts discovered signs of liquid water and evidence of underground fluids as well as the presence of a biological source of methane on Mars. Until now, spacecraft or rovers that landed on Mars did not find any sign of life on its surface at the sites they analyzed. The newly spotted caves on the slopes of Martian volcano may indicate potential underground habitats and may provide a protected niche for past or present life. So perhaps life could be hiding away, having found a subsurface shelter from external hostile Martian surface environments. Or perhaps these caves could even serve as shelter for visiting human beings in the future.

## 5.3. EUROPA

In Vostok station (Antarctica), radar observation discovered a large subsurface lake of liquid salty water (at a depth of 4 km) under the ice. This body of water is warmed by heat radiation from Earth's interior. This lake is trapped under the thick, insulating ice sheet, and the pressure from the weight of all the ice above it lowers the melting point of the ice at the bottom. Drilling down to the lake level of Vostok's icy layer reaching almost to that subsurface lake brought out cores with various microbes. It has been proposed (as analogous to Vostok) that on Europa, the satellite of Jupiter, there also exists an ocean of salty liquid water underneath the heavy frozen crust. It is assumed that microbes could find shelter there from the harsh surface conditions. Images of Europa's icy surface patches show lines that are not stable but constantly moving. That fact led to the idea that the upper ice layer floats on top of water (Seckbach and Chela-Flores, 2007).

## 6. Conclusions

We believe that the rabbis and the other religious authorities should consider the new branches of science (extremophiles and astrobiology) and establish a constructive dialogue within the Jewish thoughts. The author, as a man of Jewish faith, can accept that our entire universe and its inhabitants on Earth and extraterrestrial possibilities of life have been created and guided by divine action. Scientific theories of formation of the galaxy and Earth with its life could also be adopted by observant Jews as the creation, in the humanistic sphere of religion of products of Almighty God.

There is a story of scientists who climb up a tall mountain and when they reach the top are welcomed by (Jewish) scholars who are sitting there and dealing with all universal issues.

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Biodata of **Yury Kamenir**, author of "***Consistent Patterns of Statistical Distributions in Natural Ecological Communities: Lake Phytoplankton***."

**Dr. Yury Kamenir** is currently a researcher fellow of the Mina and Everard Goodman Faculty of Life Sciences in Bar Ilan University, Israel. He obtained his Ph.D. from the Institute of Biology of Southern Sea of National Academy Science of Ukraine in 1991 and continued his studies and research at the Haifa University, Israel. Scientific interests of Dr. Yury Kamenir are in the areas of theoretical and applied ecology, natural taxonomical structure, and marine and freshwater systems.

E-mail: **Yurykam@gmail.com**

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# CONSISTENT PATTERNS OF STATISTICAL DISTRIBUTIONS IN NATURAL ECOLOGICAL COMMUNITIES: LAKE PHYTOPLANKTON

**YURY KAMENIR**
*The Mina and Everard Goodman Faculty of Life Sciences,*
*Bar-Ilan University, Ramat-Gan 52900, Israel*

## 1. Introduction

Environmental protection and management is hindered by the pronounced time-space heterogeneity of natural communities. A possible solution of this problem can be suggested by the so-called "typical" (Schwinghamer, 1981; Sprules and Munawar, 1986; Kerr and Dickie, 2001) patterns and descriptors. Such typical patterns and well-established quantitative relations provide support to reliable mathematical models and analyses of the natural-community structural changes (Peters, 1983; Kerr and Dickie, 2001). A new branch of ecological studies – macroecology (Brown, 1995), aimed at comparative studies of large-scale datasets – has emerged. Such comparative studies have already produced a number of very efficient empirical generalizations and theoretical models connected with the living organism body-size effects, species number, community biomass, and abundance distributions (Peters, 1983; Brown et al., 2001; Kerr and Dickie, 2001).

The abundance distributions of species in natural communities tend toward characteristic patterns, which can be represented as frequency-abundance or abundance-rank models (Fattorini, 2005). Species abundance distributions appear to share similar shapes in numerous ecosystems, leading to operational applications and theoretical generalizations. Therefore, theoretical ecologists have proposed numerous models to fit the data, the most common ones being the geometric series, the broken stick, and the lognormal distribution (Fattorini, 2005). Some consistent, i.e., predictable, taxonomic structure patterns of phytoplankton have been established through long-term monitoring of lakes from several regions characterized by considerably different environments. A very consistent pattern of the phytoplankton species-number distribution to size classes, based on algal cell volume, was found for several lakes, including such contrasting ones as meso-eutrophic, subtropical Lake Kinneret, and mountainous, oligotrophic Lake Tahoe (Kamenir, 2008; Kamenir et al., 2008). A very close size-distribution pattern resembling the sum of several lognormal bells and the same level of consistency was found for marine phytoplankton (Kamenir et al., 2010).

Very consistent patterns were also established for rank distributions of species and other levels of taxonomic hierarchy. Natural communities can be seen as mixtures of species that are unequally successful (Whittaker, 1965). Therefore, the species can be arranged in a sequence ranging from the most to the least important (according to their number of individuals, biomass, etc.). In that case, they form a progression with a specific curve shape. Such dominance-diversity curves represent a range of intergrading types. Nevertheless, this lack of uniformity does not reduce their significance, or the generation of ideas about community organization (Whittaker, 1965). Most often, resource division among natural-community species has been studied using the rank-abundance distributions (RAD). Such distributions were assumed to reflect the underlying pattern of resource allocation. Different distribution patterns can provide support to different theoretical models and processes influencing resource sharing and species coexistence. Hence, such analyses are typically based on two methods, specifically, statistical descriptions and theoretical derivation of the observed distributions (Whittaker, 1965; Thibault et al., 2004).

As a rule, studies of natural communities are hindered by very complicated community time-space structure (Begon et al., 1996). Stochastic dynamics of lacustrine phytoplankton is a well-known problem that often emerges in studies involving a small number of interacting species. Stochastic dynamics of species biomasses was found in long-time mesocosm experiments (Heerkloss and Klinkenberg, 1998) and in theoretical mathematical models (Huisman and Weissing, 2001). Such dynamics hinders prediction not only of community species abundances but even of their competitive exclusion results (Huisman and Weissing, 2001). In such a gloomy situation, it is very important that some of the natural-community features (e.g., total organism abundance, biomass, and energy flux) are resistant to environmental impacts. The RAD shape is also discussed often as one such resistant property of community structure. Unfortunately, RAD dynamics is very seldom assessed quantitatively. Quantitative comparisons would allow testing the idea that a consistent pattern of resource allocation, a general division rule, prevails in a natural community. This division rule has been proposed to explain the stability of species richness through time or in response to environmental disturbances (Brown et al., 2001; Thibault et al., 2004).

Progress in the search for such division rules has been hindered by problems of interpretation and the practical difficulty of testing for the best fit (Begon et al., 1996). In long-term experiments, phytoplankton cell abundance seems to be a very dynamic and heterogeneous property (Heerkloss and Klinkenberg, 1998). Natural communities often encompass a very broad size range of organisms, while organism abundance depends strongly on its body size (Odum, 1971; Peters, 1983). Therefore, highly dynamic abundances and biomasses of populations can mask more stable patterns to be sought and applied in the forecast. For this reason, it is desirable to exclude such descriptors (Kamenir, 2011). The abundance exclusion leads to incidence-based comparisons (Chao et al., 2005), so we proceed from the organism numbers to the species occurrence frequencies (McGeoch and Gaston, 2002) reflected in the ecosystem-monitoring database.

While the species number in natural ecosystems is often measured in the hundreds and thousands, many of them are overlooked, ignored, or lost in some artificial blocks. Traditionally, even the rank distributions often consider only a few dozen species (e.g., Begon et al., 1996; Thibault et al., 2004; Fattorini, 2005). The distribution-plot ability to encompass the whole community or assemblage is important in such conditions.

In this chapter, we provide a review of some consistent and ubiquitous distribution patterns produced by taxonomic units. Such patterns were obtained from long-term monitoring of phytoplankton in Lake Kinneret (Israel) and several other aquatic ecosystems. While hardly predictable changes are characteristic of small-scale experiments (small regions, short time intervals, low species number), some predictable patterns of the aquatic assemblage structure emerge from datasets describing taxonomically rich assemblages at large time-space intervals. Such common patterns of taxonomic structure are connected with resource sharing by the aquatic-community taxonomic components and, therefore, can lead to insights into the natural-community organization and self-maintenance mechanisms.

## 2. Methods

With the help of long-term monitoring, we studied phytoplankton of Lake Kinneret (Israel). Kinneret, situated ca. 210 m below mean sea level at 32°45′N, 35°30′E (Serruya, 1978), is a warm monomictic lake with a surface area of 170 km$^2$, maximum depth of 44 m, and mean depth of 26 m. A routine program monitoring numerous biotic and abiotic parameters has been carried out at Lake Kinneret since 1969 (Zohary, 2004). During this monitoring, phytoplankton samples were collected at 2-week intervals from a fixed pelagic station at the deepest part of the lake. Lugol-preserved samples were brought to the lab for inverted-microscope analysis. Sample processing was described in detail in Zohary (2004) and Kamenir et al. (2008).

A mean biovolume (Vj) of the individual cell of each species, or size category for species counted under several size categories, was calculated from linear microscope measurements and the closest geometrical shape. This cell volume was the parameter used for biomass calculations and for allocating a taxonomic unit to a size class. Sometimes, our individual taxon is not strictly a species. In some cases, a size category within a species is registered; hence, we refer to each as an operational taxonomic unit (OTUj; Sneath and Sokal, 1973). The species biomass (Bj) was calculated for each sample via multiplication of the cell abundance (Nj) by its typical cell volume (Vj) (Zohary, 2004). Size classes were created by cell-size logarithm increments of 0.301. The Vxx notation is used throughout this chapter for size classes, where xx is the logarithm of the class' right boundary (Kamenir et al., 2008).

A traditional taxonomic size spectrum (TTSS) was built from each annual OTU list as the discontinuous frequency distribution (histogram) of the total number of OTUs to size classes. We also applied a rank-frequency model, where the rank of each species reflected its share in the total dataset, and each unit of information (a database record here) described one species presence in one sample of water. The frequency rate (FRj) was estimated for each OTUj as the number of samples containing that OTUj. Each OTUj list was sorted according to the OTUj-dominance criterion (e.g., Bj, FRj) descending order. A logarithmic transformation – $\log_{10}$ (Y) – was applied to the ranking criteria (Vj, Nj, Bj, and FRj), producing log *V*, log *N*, log *B*, and log FR estimates, respectively. The curve-fitting procedure was applied to estimate parameters of linear approximation. The histogram procedure with log FRj and log Vj increment of 0.1 was applied to produce respective graphical representations. The statistical package SPSS 15.0 (SPSS Inc., Chicago) was used for all statistical computations.

## 3. Results

The long-term biomass dynamics of analyzed species has demonstrated quasi-periodic peaks and troughs (Fig. 1). While the dominant 12-month periodicity is evident, each annual curve demonstrated different shapes, especially evident as the main peak height and time-position variability (Fig. 1).

Pronounced variability also characterized the RAD curves obtained from 1-day and monthly pooled samples (Fig. 2a, b, respectively). Each curve had a complicated shape composed of 2–3 regions of considerably different slopes (Fig. 2). The rank distributions of species abundance, biomass, typical cell volume, and frequency rate (Fig. 3a–d, respectively), produced by large-scale (here, annually pooled) datasets, also demonstrated pronounced curve-slope changes. However, in strong contrast to the small dataset results (Fig. 2), each of the large-scale dataset (Fig. 3) panels demonstrated a pronounced variability only in its extreme-right region. On the opposite (i.e., left) side of each graph, including the dominant species, and in the central part, encompassing >50% of the species, we see almost the same pattern each year, despite the fact that the length of each

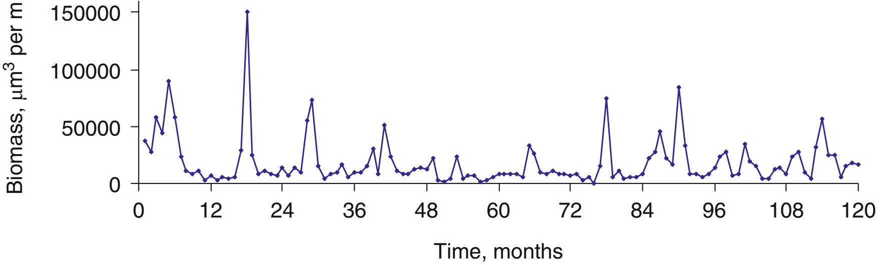

**Figure 1.** Annual dynamics of one species (*Tetraedron minimum*) biomass of Lake Kinneret phytoplankton during 10 consecutive years.

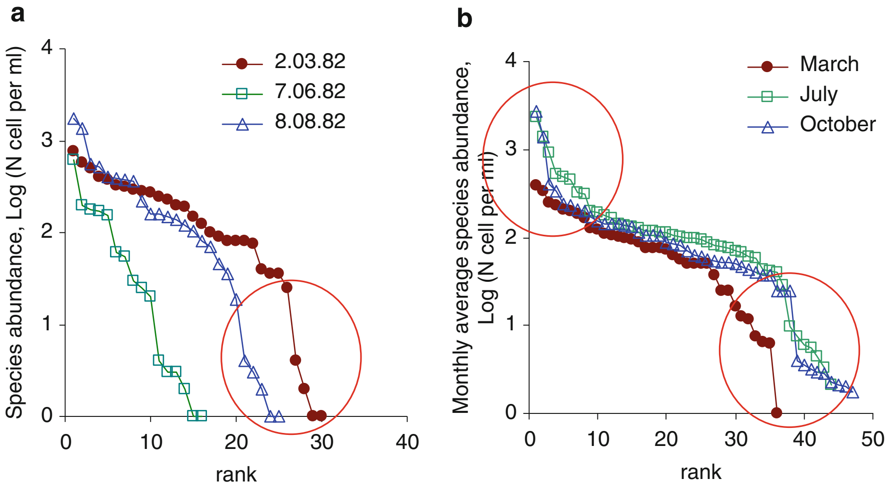

**Figure 2.** Rank-abundance distribution curves of the Lake Kinneret surface-layer phytoplankton for specific water samples (**a**) and for monthly pooled data (**b**), year 1982. (After Kamenir, 2011.) The curve slope changes are marked by *ovals.*

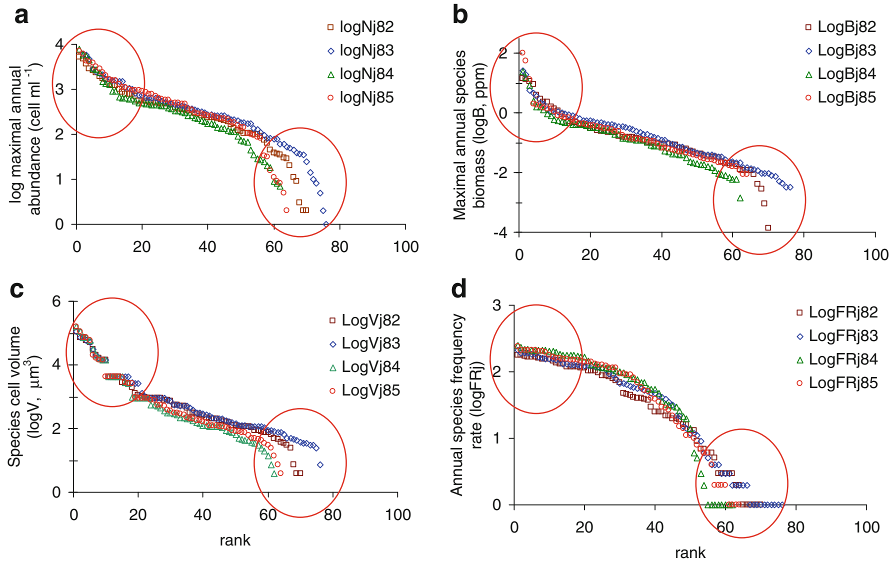

**Figure 3.** Four types of rank distributions of Lake Kinneret phytoplankton taxonomic units. Maximal abundance (cell ml$^{-1}$), maximal biomass (ppm), typical cell volume (µm$^3$), and annual frequency rate (FRj) registered for each species during each of four annual periods (1982–1985) (**a**–**d**), respectively. Logarithmic transformations were applied to *y*-axes of each graph. (After Kamenir, 2011.) Important regions are marked by *ovals.*

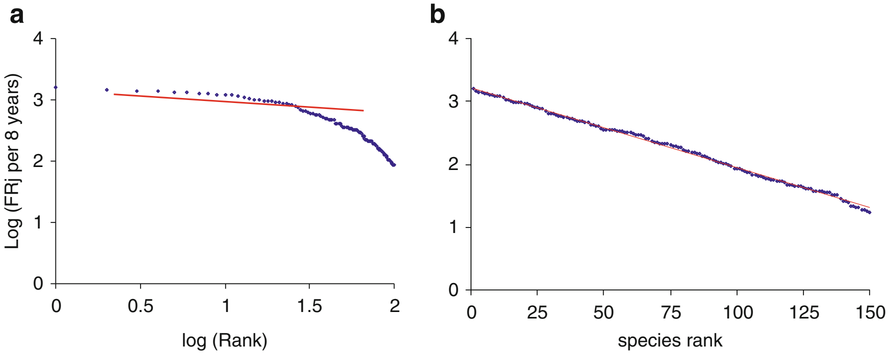

**Figure 4.** (**a**) Zipf's approximation of Lake Kinneret phytoplankton taxonomic rank-frequency distribution for the 100 first species. (**b**) A geometric-series approximation for the first species obtaining FRj > 1% of the maximal FRj. Note the very high coefficient of determination ($r^2 = 0.998$) of the linear regression. (After Kamenir, 2011).

region is visibly different each time. Rather similar distribution forms for the first 40–50 ranks, contrasting much more pronounced variability of the following tail (some 20–30% of taxonomic units), are notable for annual RAD curves (Fig. 3a).

This division to the consistent beginning and more variable tail also characterizes three other types of rank distributions (Fig. 3b–d). For each distribution (Fig. 3a–d), the tail (ranks >40–50) has a varying length (i.e., species number), slope, and linearity each year. While a pronounced slope change within the first 10–15 ranks is clearly seen for the biomass and cell-volume distributions (Fig. 3b, c), the frequency distribution has a smooth beginning part up to ranks 40–50 (Fig. 3d). This smooth part is broader when the species number grows, e.g., for long-term datasets (Figs. 3 and 4). Three types of distribution panels (Fig. 3a–c) demonstrate the slope change in both the left and right peripheries. At the same time, the FR distribution (Fig. 3d) has a smooth left part (the dominant species) suitable for a linear-model approximation.

The Zipf's (i.e., power law) model provides a good linear regression approximation for the first 20 ranks (Fig. 4a).

A slight change in the slope can be assumed at both its left and its right extremities. This change becomes obvious when considering a much larger number ($n = 100$) of ranks. This property of the Zipf's model application is known and has been widely discussed (Caldarelli, 2007). A better fit was obtained using a geometric-series model (Fig. 4b).

A power model for FRj rank-frequency distribution (RFD) has produced good results when a small number (30–40) of the leading species was considered. Its fitting quality considerably declined when all species were included. While numerous "rare" species (FRj = 1) were encountered, their exclusion considerably upgraded the linear-model fitting quality for the log-transformed FRj rank distribution. A geometric-series approximation of Lake Kinneret phytoplankton

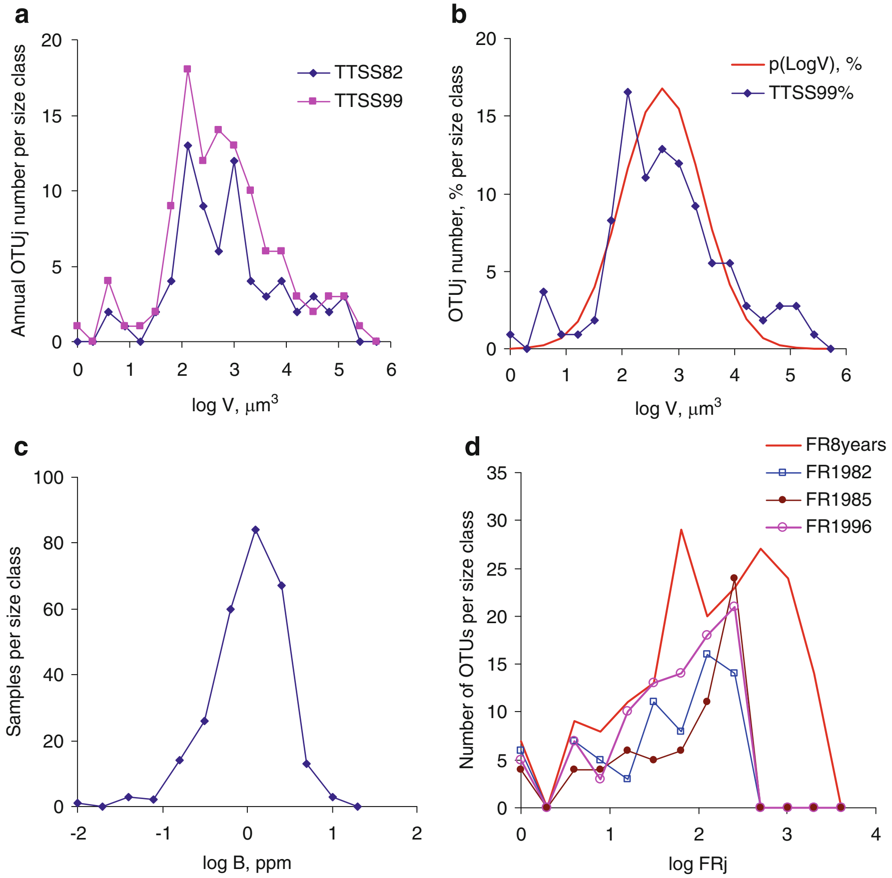

**Figure 5.** (**a**) A traditional taxonomic size spectrum (TTSS) comparison: the first and last years (1982 and 1999) of the studied period. (**b**) The lognormal approximation of TTSS shape and the distribution parameters ($X = 2.72 \pm 0.01$, $SD = 1.01 \pm 0.01$) are estimated from the first year (1982) distribution. (**c**) The species biomass sampling distribution. (**d**) the frequency-rate (FR) histogram for the annual and multi-annual (8 years) datasets produced by Lake Kinneret phytoplankton monitoring. (After Kamenir, 2008, 2011.)

taxonomic RFD of the first 100 species was produced with a very high coefficient of determination ($r^2$) of the linear regression: log (FRj) = 3.22–0.013 rank; $r^2 = 0.998$; $n = 150$; and $p < 0.001$ (Kamenir, 2011). This linearity seems especially interesting when compared with more traditional (Whittaker, 1965; Begon et al., 1996) rank-abundance models. These curves have a less orderly shape that varies from sample to sample (Fig. 2a).

The frequency-rate (FRj) logarithm histograms, produced from annual and multi-annual pooled datasets of Lake Kinneret phytoplankton, had slightly different shapes (Fig. 5a, b). While the linear FRj scale produced a highly asymmetric distribution with a very long right tail, the log-transformed estimates (log FRj) showed a steep right slope and a light leftward skewness. The long-term (8-year pooled) histogram was especially close to a lognormal distribution. The OTUj-number, biomass, and frequency-rate (FRj) logarithm histograms, produced from annual and multi-annual pooled datasets of Lake Kinneret phytoplankton, had slightly different shapes (Fig. 5). While the linear FRj scale produced a highly asymmetric distribution with a very long right tail, the log-transformed estimates (log FRj) showed a steep right slope and a light leftward skewness.

While the species number registered during 1 year was >60 (Kamenir, 2011), we have selected the first 40 ranks as the "beginning part." The curve fitting shows that the slopes of this part of the RFD do change; however, a narrow interval of the slope estimates encompasses all these changes (Kamenir, 2011).

## 4. Discussion

### 4.1. CONSISTENT PATTERNS

The main phenomenon demonstrated and discussed here is evidence of a very high orderliness in the natural aquatic assemblage structure. Ubiquitous statistical distributions of species in natural communities have already emerged in numerous empirical studies. Later, elaborate mathematical models appear, leading to theoretical discussions and redefinition of terms (Preston, 1962; Brown et al., 2001). While such studies most often consider terrestrial animals, aquatic ecosystems deserve no less attention. Such zoological studies consider mostly paleontological data, i.e., huge time-space scales are analyzed. Our experience demonstrated that the invariant statistical patterns emerge from numerous analyses of much smaller objects and periods. Such studies demonstrate rather uniform and consistent patterns found via long-term water-body monitoring. The pattern shape and its approximation-model quality depend strongly on monitoring-period length and assemblage taxonomic richness.

While the shape of the curve is conserved from year to year, the species list and their ranks vary. This property can be interpreted as a specific aspect of the community's adaptation mechanism. This mechanism achieves a stabilization of one property of the aquatic assemblage (i.e., its species rank distribution) via changing of another property, namely its species composition and the dominance changes. Distribution-shape survival can be interpreted as a definite success in community self-maintenance.

An important property of community structure, as reflected by the frequency-rank distributions, is a number of "rare" species that have FRj estimates approximately two orders lower than the dominant species FRj (Figs. 3d and 5d). An advantage of the linear models discussed here is that an approximation, excluding the rare-species region, is based on a high species number ($n = 100$ here) and ignores only a very small part of the monitoring dataset (some 2% of all registration records). The high-quality fitting of the left part of the curve by the Zipf's and geometric-series models supports the application of very simple (linear) regressions. Such simple and precise models can be valuable for the purposes of community-structure modeling and forecasting. Several types of rank distributions have this long linear region, if they are produced from large datasets (Figs. 3 and 4). Comparing four types of rank distributions described above (Fig. 3), we can note that the rank-frequency curves had an especially short tail in the left part and an especially long main linear region (Fig. 3d). The higher the species richness, i.e., the species number, the longer is this linear region (Figs. 2, 3 and 4). Hence, it is short for small datasets obtained from one sample (Fig. 2a). As the four types of distributions describe different properties of the total assemblage (biomass, abundance, size composition, time-spatial structure), they complement each other and, being applied together, provide a more comprehensive analytical tool (Kamenir, 2011). The frequency distribution is especially interesting as being less dependent on several types of errors, including cell counting and cell-volume estimation.

While two types of approximation models (Zipf's and log-linear) seem to be applicable, the experience obtained from studies of scale-free networks recommends to also consider the lognormal model, as typical (Caldarelli, 2007) of the curve types discussed here (Figs. 3 and 4). The lognormal model of the natural assemblage species distribution has been discussed for a long time (Preston, 1962; Whittaker, 1965). The distributions of FRj come closer to a symmetric bell if a logarithmic transformation is performed. Especially small skewness was observed for the long-term (8-year pooled) histogram (Fig. 5d). An almost-symmetric distribution was also evident for species cell-volume logarithm of Lake Kinneret phytoplankton (Fig. 5b). The difference of each annual size-frequency distribution of species (Fig. 5a) from the lognormal one was not significant (Kolmogorov-Smirnov test; $p = 0.238$–$0.892$, $n = 62$–$110$). The first year (1982) distribution produced the lognormal approximation parameters ($X = 2.72 \pm 0.01$, $\mathrm{SD} = 1.01 \pm 0.01$) that suit rather well all other annual distributions, even those obtained 17 years later (Fig. 5b). This size distribution enhances the understanding of the rank-size curves presented above (Fig. 3). While almost all species follow the lognormal distribution (Fig. 5b, $\log V$ from 1.5 to 4.5), we see a good linearity in the central region of the rank-size distribution (Fig. 3c). At the same time, a rather small number of species in the left and right peripheral regions are spread over the other half of the total $\log V$ range (Fig. 5b). They produce much steeper tails on the rank-size curve (Fig. 3c). While the Gaussian bell and its deformations explain here the rank-size curves (Fig. 3c), the lognormal distribution might explain the other three rank distributions described above (Fig. 3). Such analysis gives a sound reason to "censor" some 10% of the species in each tail region of the rank distributions to obtain more precise slope estimations for the main region. The slope variation can be applied as a measure of an integral community's structural change.

## 4.2. CONCEPTUAL MODELS

Theoretical models and empirical results show that numerous processes can generate very similar-looking distributions. Very often, such distribution models can be separated only on the basis of large, complete datasets of high quality (Caldarelli, 2007). Large-scale studies providing detailed information on the species distributions are necessary. An important distinction of our approach is that we consider OTUs, i.e., groups of cells suitable to be discerned from other such groups (Sneath and Sokal, 1973) by computerized tools (Kamenir et al., 2008). OTUj methodology, providing conditions for computer-based methods of particle classification, opens the way to apply automated means (e.g., flow cytometers and image analyzers). Flow cytometry becomes more and more helpful to obtain more comprehensive spectra, as picoplankton – a prominent component of phytoplankton assemblages – takes ever rising importance. Thanks to the growing automation level, such studies can be performed in large aquatic ecosystems using realistic time intervals, work force, and other resources. The resulting datasets can provide high-quality mathematical approximations. Therefore, they allow us to distinguish between the distribution-generating mechanisms. Such mechanism selection is essential for the progress of theoretical ecology.

The best models can serve for ecological diagnostics and forecasting. We find a plausible explanation in the dissipation-structure theory (Nicolis and Prigogine, 1989) and, preceding it, ideas of G. Cuvier and V. Vernadsky. These concepts were applied to develop the model we apply, i.e., the ideal minimal ecosystem (IMES). IMES (Kamenir, 1986, 2011) is a closed volume protecting a closed recycling flow of replaceable flow-through elements. Such flow-through elements, reiterating the whirl-like structure, implement the quasi-cyclic process of the assemblage renewal. The model considers a hierarchical structure (Fig. 6) and supports the analogy between mechanisms functioning at multiple levels of biological hierarchy, from intracellular metabolic cycles to global biogeochemical cycles.

The self-stabilizing renewal process is maintained within a closed envelope or specific membrane protecting a volume of inner medium. The most notable property of this whirl-like structure is a hierarchy of cyclic flows of different time-space scales. The main property of this ideal object is its ability to exist eternally, i.e., to maintain its essential functional characteristics, while withstanding changes in the environmental characteristics and faults in all important components, structures, and subsystems. This ability is implemented through continuous replacement of numerous flow-through elements of the demonstrated above hierarchic structure.

Such an object (i.e., an ecosystem) can be considered a *system*, i.e., "a regularly interacting or interdependent group of items forming a unified whole" (Webster, 1961). This unified whole has new (emergent) properties inherent to none of the items that compose the whole. Some of these properties (e.g., the energy-dissipation spectra, the distribution functions of the flow-through elements) should be analyzed with the help of statistical methods. The sets of such elements

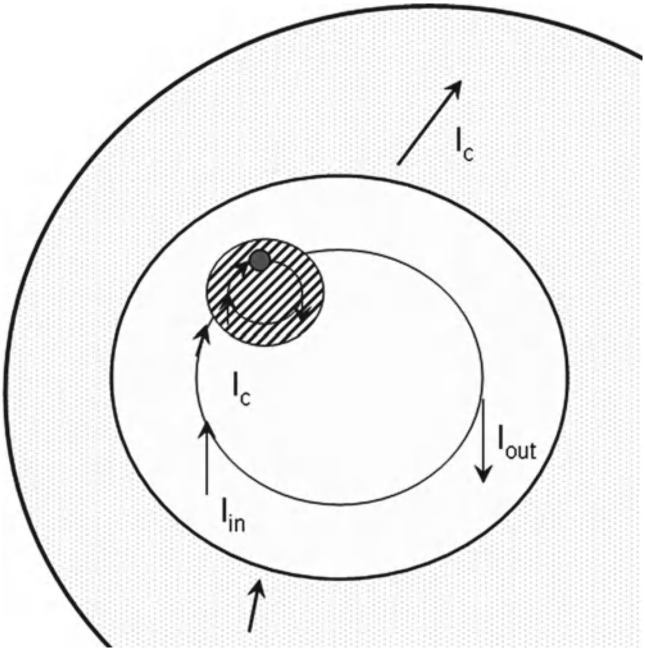

**Figure 6.** Ideal minimal ecosystem (IMES) is a volume protecting a closed recycling flow. This flow implements the quasi-cyclic process of renewal of flow-through elements which reiterate further the hierarchical structure. $I_{in}$, $I_{out}$, $I_c$ are the inflow, outflow, and recycling flow, respectively. (After Kamenir, 1986, 2011).

describe not single elements, but large ensembles creating a whole. The parameter estimates obtained from mathematical approximations of such spectra (e.g., temperature) characterize the state of the system, and not the state of some its elements (Nicolis and Prigogine, 1989).

An ecosystem is definitely a *dissipative structure*, as it has all the main dissipative-structure characteristics. It is far from equilibrium. It exists only due to a continuous flow of energy. Its emergence and destruction can be seen through changes between chaos, correlated processes, and ordered structures. Such structures are created by huge numbers of much smaller particles. Some of the characteristics of these structures (e.g., distribution functions) depict only the macroscopic object, and not some its elements or particles. It adapts itself to the surrounding environment and can have several different states and means of adaptation (Odum, 1971).

An ecological community is a coherent structure of processes that are interdependent and correlated, i.e., it consists of parts that "hold together firmly as parts of the same mass" (Webster, 1961). Especially important are recycling fluxes providing different resources for the maintenance of numerous new flow-through elements.

Such a model necessitates the existence of numerous, heterogeneous, and very big populations of flow-through elements that exist thanks to the incessant replacement of their numerous components. Those flow-through elements go through fission, development, death, and replacement processes. Such multi-stage cycles of processes can explain the long-term existence of the geometric-series distributions. When a population is engaged in tasks whose completion requires the successful conclusion of many independent subtasks, the distribution function for success in the primary task is lognormal (Montroll and Shlesinger, 1982).When dispersion of the lognormal distribution is large, the distribution is mimicked by a $1/x$ distribution over a wide range of $x$ (Montroll and Shlesinger, 1982). Such reasoning supports the necessity to carry out large-scale analyses of the wide-range FRj distributions, providing precise estimations of the fitted-curve parameters describing the shape of the distribution curve and its tails. The necessary datasets can be produced with the help of the OTUj approach supported by automated OTUj-classification tools. The hierarchical structure of such a model is important, as it should be reflected in similarities of mechanisms and structural patterns across the global taxonomic hierarchy, in hierarchies of ecological systems, and across other types of biological structures. While considering an ecosystem as a self-maintaining, highly branched feedback loop produced by the closed recycling web (Kamenir, 1986, 2011), we turn to the dissipative-structure science as the leading methodology needed to select the investigative methods and the model optimization criteria. Energy inflow (hence, the number of points occupied by each species) seems to be the main and universal limiting factor in such closed recycling web (Kamenir, 1986, 2011).

The incessant, self-maintaining whirl-like movement of flow-through elements was described almost two centuries ago by the great French biologist G. Cuvier as a fundamental property of living systems. His concept of “tourbillon vital” (i.e., a living whirl) describes a set of the most important properties needed “to form the just idea of the nature of life” (Cuvier, 1827). Life (according to his definition) is a whirl, the action of which is constant. All its particles are in a state of perpetual motion, constantly coming and going. Life consists of combinations existing in one determined form. Such combinations exist for a limited interval of time. The existence of such combinations is supported by the continuous attraction of substances from without the living structures. At the same time, they return their own particles to the surroundings. The system is alive only while this movement continues. This “vital motion” prevents the system’s dissolution due to the chemical affinities of the chemical elements composing it. A change in any of the partial movements inevitably leads to cessation of life (Cuvier, 1827). Hence, we see huge mobs of relatively small particles and a set of interdependent fluxes. The above concept of G. Cuvier was further developed by V. I. Vernadsky (1978). Vernadsky suggested the “living matter” – the whole ensemble of living organisms – as a concept appropriate for studying the biosphere and ecosystem-level phenomena. Inspired words of Vernadsky (1978), referred to herein our free translation, look as the best summary of the phenomena considered in this chapter: The rules describing living matter, being the rules governing the multitudes, may be analogous to the rules of gas, while are essentially different from the rules governing a living organism. A single organism looks here as a molecule of this gas.

Therefore, not only various molecules or organisms, but even specific populations of plants and animals, look as rather small components of natural ecosystems. Applying a long-term monitoring, large-scale datasets can be collected, and some rules governing the whole living community may be found. Such rules can be very different from the rules governing a specific population. Consequently, specific properties of the whole living assemblage can exist. Some properties can be suitable for quantitative estimation and forecast. At the same time, it can be unrealistic to forecast the destiny of its numerous specific components.

## 5. Conclusion

In spite of the very high time-space heterogeneity of phytoplankton, a high level of orderliness of the phytoplankton assemblage taxonomic structure was found with the help of several statistical models. Very simple models, with an extremely small number of parameters can be found applicable as good approximations for the annual and multi-annual taxonomic-unit rank-frequency distributions of phytoplankton. Empirical results show a fine-tuning of the phytoplankton dominant distribution region with the help of the Zipf's models. A geometric-series approximation model seems to be preferable to the Zipf's model when considering larger numbers of taxonomic units. The lognormal distribution produced by the scale-free food web seems promising as a possible explanatory model. Concepts of the living whirl (G. Cuvier), living matter (V. Vernadsky), and dissipative structures served to develop a minimal model of the self-maintained living assemblage. With the help of operational-taxonomic-unit methodology and automated tools, applied for the data collection in aquatic ecosystems, the large-scale datasets allow us to select the best explanatory models.

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Biodata of **Vincent Fleury** and **Richard Gordon**, authors of "***Coupling of Growth, Differentiation and Morphogenesis: An Integrated Approach to Design in Embryogenesis***."

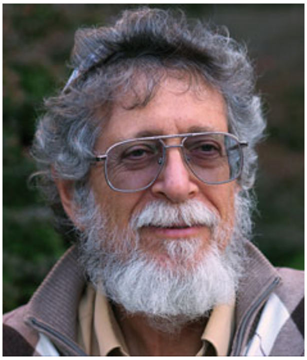
**Vincent Fleury** is "Directeur de Recherches" in the French research agency CNRS. He works in Paris in the "Complex matter and systems" laboratory. After graduating from the Ecole Polytechnique, and completing a Ph.D. in electrochemical growth, he turned progressively to morphogenesis in biology. He has developed several models and experiments in the field of vascular morphogenesis and embryo development. He is also the author of several popular science books and a few detective novels.

E-mail: **vincent.fleury@univ-paris-diderot.fr**

**Dr. Richard Gordon** is an itinerant theoretical biologist with B.Sc. (Math) from the University of Chicago and Ph.D. (chemical physics) from the University of Oregon. He is retired from the University of Manitoba and Scientist at the Gulf Specimen Marine Laboratory (http://www.gulfspecimen.org/). He organized Books With Wings (http://bookswithwings.net) which sends books to universities in Afghanistan, and the Embryo Physics Course online in Second Life® (http://embryogenesisexplained.com/course). He writes a blog in Science 2.0 (http://www.science20.com/cosmic_embryo) and is principal scientific advisor for the EvoGrid project (http://www.evogrid.org/), an attempt to simulate the origin of life. He has also worked in diatom nanotechnology, HIV/AIDS prevention, and algorithms for computed tomography.

E-mail: **GordonR@cc.umanitoba.ca**

**Vincent Fleury**



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# COUPLING OF GROWTH, DIFFERENTIATION AND MORPHOGENESIS: AN INTEGRATED APPROACH TO DESIGN IN EMBRYOGENESIS

**VINCENT FLEURY**[1] **AND RICHARD GORDON**[2,3]
[1]*Laboratoire Matière et Systèmes Complexes,*
*Université Paris-Diderot, 10 rue alice Domon et Léonie Duquet,*
*75013 Paris, France*
[2]*Department of Radiology, University of Manitoba, Winnipeg, MB*
*R3A 1R9, Canada*
[3]*Gulf Specimen Marine Laboratory, Panacea, FL 32346, USA*

## 1. Introduction

In this chapter, we propose a scheme that allows one to couple growth, differentiation and morphogenesis. On fundamental grounds, it is obvious that embryogenesis is a process of motion and reorganization of biological material. All known examples of animal morphogenesis involve large-scale movements. Since there cannot be any mass movement without a force, embryogenesis is, deeply, a dynamic phenomenon (Gordon, 1999, 2006; Beloussov et al., 2006; Kornikova et al., 2010). However, it is also obvious that animals are, in the end, made of several cellular types, over 2,000 for a typical animal (Ibelgaufts, 2011), and many intermediate cell types en route to the adult form (Björklund and Gordon, 1994; Gordon, 1999, 2011). Finally, considerable information has been obtained recently about genetic determinants of morphogenesis, especially by the interplay of the Hox genes (Alexander and Krumlauf, 2001). However, there still exist logical inconsistencies in the genetic description. The two major ones are, first, that mappings of gene expression (we think especially of transcription factors) make the implicit assumption of an underlying cellular "morphogenetic field" (Waddington, 1934; Davidson, 1993; Beloussov, 2001) or "compartment" (Lawrence and Struhl, 1996) where the genes are expressed. Since the boundaries of a morphogenetic field contribute to fixing the absolute values of presumed diffusion fields, it is inconsistent to ascribe morphogenesis to genetic expression, which is calculated inside an already assumed domain. From a mathematical point of view, embryogenesis should be boiled down to what are called "free boundary problems" (Pelcé, 2000) in mathematics: the boundaries are not known, and they are the result of the dynamics of the problem (as, for example, in snowflake, diatom (Gordon and Drum, 1994) or electrodeposition (Fleury, 1997; Gordon and Tiffany, 2011) growth). Cf. (Gordon et al., 1975; Gordon and Jacobson, 1978; Nouri et al., 2008).

The second logical problem with genetics is that gene expression is a scalar quantity (concentration), while the actual morphogenetic event is a deformation.

Therefore, gene expression is at best a vector field of scalar quantities (the concentrations of $n$ specific molecules), coupled to spatial tensorial quantities (Hay, 1953), which themselves lead to equations for displacements. This coupling was not addressed by Turing in "The chemical basis of morphogenesis" (Turing, 1952), who presumed that "…the characteristic action of the genes themselves is presumably chemical", even though he was fully aware of the "…interdependence of the chemical and mechanical data…". Morphogenesis is the integral during the time of the displacement rate. Therefore, understanding morphogenesis requires forming a system in which mechanics and genetics feedback one onto the other in a closed framework, whose output is an animal or plant. While this may seem a formidable endeavour, actually, recent scientific progress in all aspects of this problem let us believe that the moment is arriving when complete organisms may be numerically generated, with a clear understanding of how differentiation, growth and morphogenesis are coupled, and possibly with a reduced number of parameters.

In this closed framework, genetic expression is induced, at least in part, by mechanical stresses. Mechanical stress has been recognized recently as an important factor in biological morphogenesis and in cell differentiation (Gordon, 1999). For example, insect gastrulation is tied to pressure maps (Farge, 2003). But the cell types themselves, which appear dynamically during the morphogenesis process, are also dependent on the same mechanical field, as, for example, in vascular morphogenesis (le Noble et al., 2005). Stem cells show a marked sensitivity to the mechanical environment (Tenney and Discher, 2009), which may allow us to manipulate their course of differentiation (Gordon, 2006). It is even recognized that mechanical stress may play an important role in apoptosis, not only in the well-known cardiovascular system (Wernig et al., 2003) but also in cartilage formation and degradation (Setton and Chen, 2006).

Therefore, in order to form a closed model of growth, differentiation and morphogenesis, one needs a viscoelastic model of development, in which cellular forces act as source terms for deformations, acting upon a continuous material. Then, the properties of this material, or the force terms themselves, will be dependent on mechanical set points (e.g. thresholds for contraction or cell death). An important issue in this respect is what is the physical nature of the living material when it is undergoing the important morphogenetic movements that set its global shape? On fundamental grounds, it is expected that living material is akin to a foam (Stein and Gordon, 1982; Setton and Chen, 2006; Cheddadi et al., 2011) because of the cells' membranes well-known foam-like geometry (Dormer, 1980). This may be particularly true for epithelial sheets, which often have a cuboidal or polygonal aspect, especially in insects (Hayashi and Carthew, 2004); nevertheless, it seems that chordate embryos are close to a classical viscoelastic material. In epithelial sheets, viscous shear involves the so-called T1 mechanism of cell boundary shift (Prud'Homme, 1995), which allows cell laminae to slide onto each other in the direction of the shear (Fig. 1) (cf. model for tissue viscosity in Gordon et al., 1972, 1975) and, by rosette formation, allows even larger shears by cell reorganization (Blankenship et al., 2006; Zallen and Blankenship, 2008).

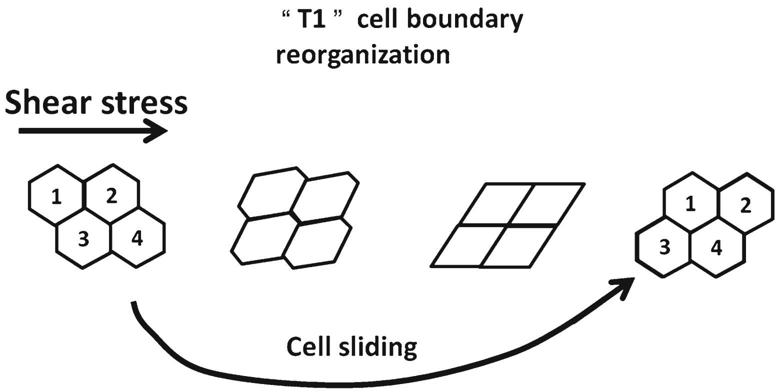


**Figure 1.** "T1" mechanism by which cell laminae slide onto each other, thus accommodating viscous-like shear.

So despite a small-scale cellular reorganization, the tissue behaves globally as a fluid. This may have a more fundamental meaning because, in polyploid vertebrates, which have fewer, larger cells, the animal size and its morphogenesis seem independent of cell size, except for subtle effects in the nervous system (Fankhauser et al., 1955; Snow, 1975; Gordon, 1999), i.e. morphogenesis is roughly independent of the scale of cell organization.

We have previously modelled the flow of extirpated vertebrate embryonic tissues as viscous fluids (Gordon et al., 1972, 1975), and the shaping of the vertebrate neural plate as a motion of a viscoelastic material (Jacobson and Gordon, 1976; Gordon and Jacobson, 1978). Here we demonstrate the latter property experimentally (cf. Beysens et al., 2000). Anecdotally, it is a common observation that dejellying of early amphibian embryos greatly distorts them, but they quickly resume their spherical shape, illustrating the elastic component of their viscoelasticity. This is also true of chicken embryos at the blastula stage, when cultured without a shell: when taken out of the egg and laid flat on a petri dish, the embryo first buckles, but it soon flattens off by internal stress.

If a small pressure is applied for a long time to an amphibian embryo, such as via a capillary tube with a slight negative pressure, the embryo is drawn into the tube, illustrating its viscous behaviour. However, if a small force is applied too long, the effects are irreversible (Björklund et al., 1991), unlike simple viscoelastic fluids whose properties do not change with time.

## 2. Material Properties of Embryonic Tissue

As it gets increasingly evident that mechanical stresses play a role in all aspects of embryogenesis, the measurement of mechanical properties of living tissues begin to play a greater role. A considerable number of experiments have been dedicated to the measurement of mechanical properties of single cells such as one-cell embryos (Harvey, 1931a, b; Harvey and Fankhauser, 1933), endothelial cells (Stroka and Aranda-Espinoza, 2010), fibroblasts (Munevar et al., 2004) or even cochlear cells in the context of loss of hearing (Brundin and Russell, 1994), bacteria (Boulbitch, 2000) and diatoms (Hamm et al., 2003). Also, cell response to substrate stiffness has received a great deal of attention (Harris et al., 1980; Choquet et al., 1997; Discher et al., 2005; Evans et al., 2009). Still, in vivo measurements at the tissue level are scarce (Waddington, 1939, 1942; Austman, 2004). In vivo measurements are rendered difficult by the seemingly complex embryonic 3D environment and by the fact that development is rapid. Embryonic physical properties have been measured by many techniques (reviewed in §1.13 in Gordon, 1999) including recently by such experiments as cantilever or plateau experiments (Damon et al., 2008; Agero et al., 2010).

In the search for a more versatile instrument, one of us proposed adapting air-puff tonometry to the study of living tissue (Fleury et al., 2010). In this case, the surface of the embryo is indented by an air jet, and the deformation curvature is followed in time optically. In previous studies, the prototype air-puff tonometer was equipped with a standard black/white analogue camera. In a newer version, the tonometer is equipped with a fast digital camera (Photron Fastcam), which allows one to record tissue behaviour at a rate of up to 1,000 frames per second. We turned to the study of the tissue behaviour on early chicken embryos, at the early gastrula and up to the ten somites stage. Typical data acquisition is shown in Fig. 2.

This figure represents the deformation curve as a function of time, as a response to an instantaneous air puff, started at $t = 1.6$ s. This is the classical response of a viscoelastic material to a stepwise compressive stress (Meyers and Chawla, 2008). We observe first a stepwise elastic response which progressively asymptotes to a small limiting constant creep deformation. The limiting behaviour at long times corresponds to the small viscous creep under a constant force. The rapid exponential response corresponds to the viscoelastic response. From this curve, it is deduced that embryo tissue behaviour is a quite typical viscoelastic behaviour, with a characteristic time constant of about 4 s at the six pairs of somites stage (Hamburger and Hamilton, 1951) shown here.

This confirms previous reports about the viscoelasticity of embryonic tissue (Jacobson and Gordon, 1976; Gordon and Jacobson, 1978; Discher et al., 2005). The important issue is that no odd behaviour is found for this rather high force, which drives the response into the viscous flow regime. Therefore, it is expected that lower forces, as the ones imparted by cell–cell traction, act in a linear viscoelastic regime. Whether there is a threshold to this behaviour is not demonstrated, we found the same behaviour down to all measurable applied forces. In vivo tissue dynamics seems to suggest a possible threshold of shear rate of the order of 0.01/min, separating areas of viscous flow from areas of solid body movement. However, in a few cases, such as rapid contractions that occur during gut pocket growth, intestine growth or lung expansion for example, the forces exerted by the cells are clearly in a more non-linear regime. This is especially obvious on the cardiac time scale, as the cardiomyocytes rhythmically stretch the surrounding

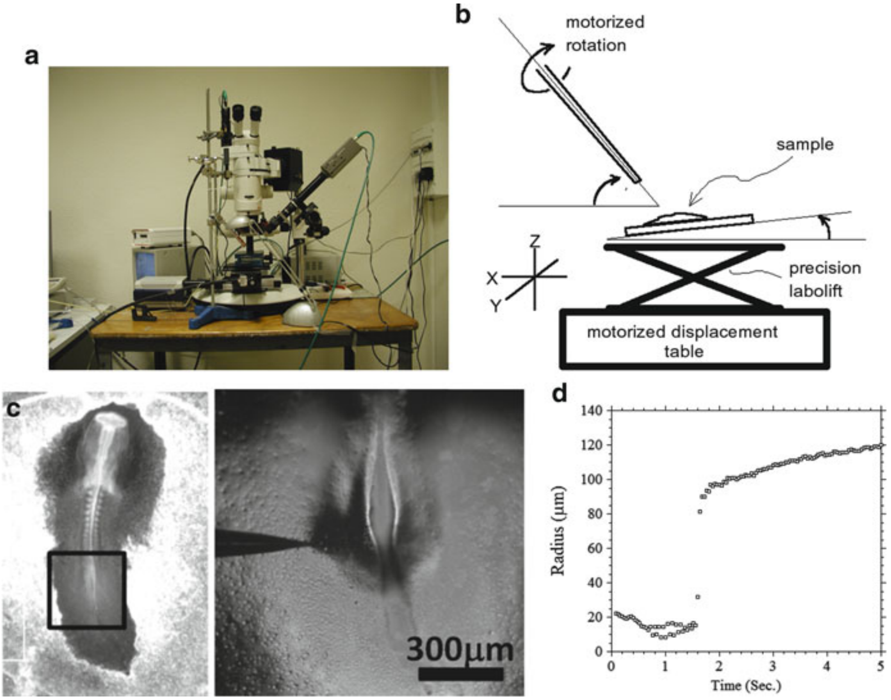


**Figure 2.** (**a**) Picture of the air-puff tonometer. (**b**) Scheme of the set-up. (**c**) Image of an embryo while performing air-puff tonometry, the tip is targeting the hind limb lateral plate. (**d**) In vivo viscoelastic response of embryonic tissue, to a stepwise air puff of 1 mb, corresponding in this geometry to a flux of 1 $cm^3$/min. The simple viscoelastic response is obtained with a viscous creep after about 3 s.

tissue, although the pace of the contraction has a much lower frequency than 1 Hz at early stages of morphogenesis.

One issue that still needs exploring is whether the anisotropic tensions in some tissues, such as amphibian neural plate (Jacobson and Gordon, 1976), where cells align perpendicular to the neural fold anteroposterior direction, reflect or induce anisotropic viscoelastic properties. If so, the constitutive properties of tissues will themselves require a tensor representation or a crystal-liquid approach.

## 3. In-Plane Viscous Flows of Tissue

From the previous data, it is acceptable to consider that early chick embryonic tissue behaves as a viscous material for time scales $>10$ s. Let us observe that during the earliest stages of vertebrate morphogenesis, the cellular movements are locally 2D, with typical speeds of 1 µm $min^{-1}$; this is especially true of amniotes, in particular of the chicken embryo (Fig. 3). Therefore, the first instances of cellular differentiation that interest us should occur along a 2D flow of cells.

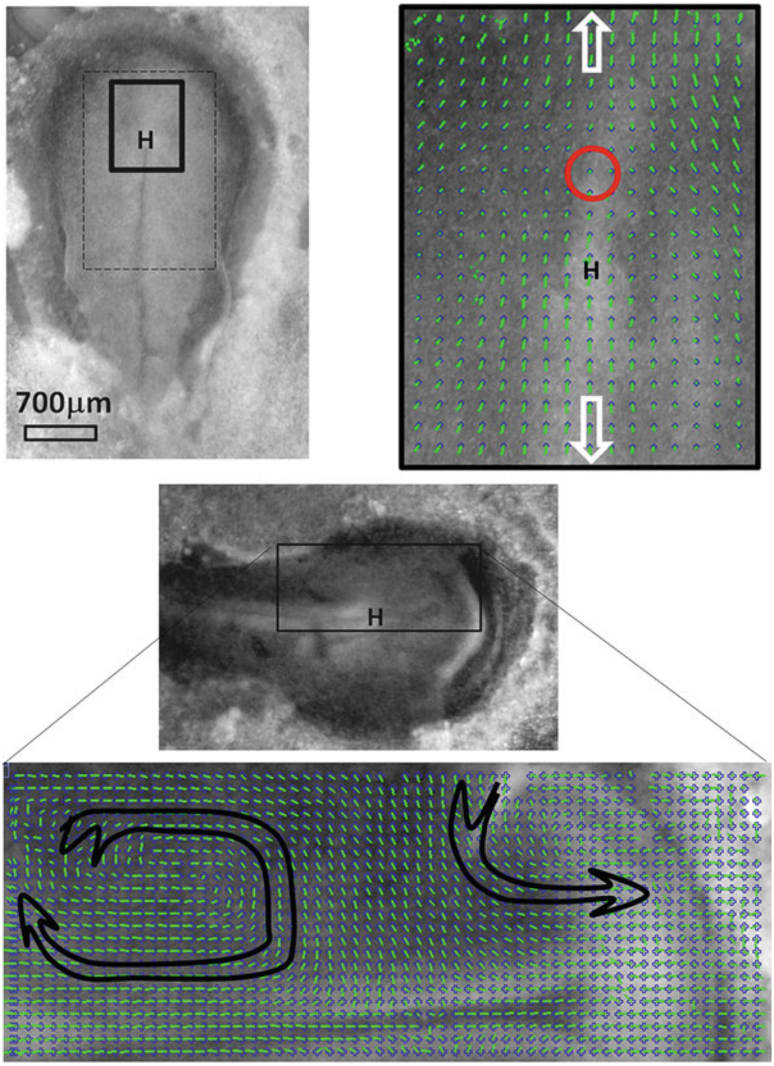


**Figure 3.** (*Top*) In vivo image of a chicken embryo during gastrulation. The embryo has a "keyhole" shape and is almost flat, except along the median axis where invagination of the tissue creates an edge whose radius of curvature encompasses about five cells. *Right*: Particle imaging velocimetry (PIV) of the embryo movements shows a rotational movement of the cells on the ectoderm, which wind towards the anterior part, and towards the posterior part. The apex of the fold is the so-called Hensen's node. *Bottom*: At the start of neurulation, the embryo begins to fold in 3D along the median axis; nevertheless in the lateral tissue, the flow map still shows a massive bidirectional 2D winding, towards the anterior and the posterior areas.

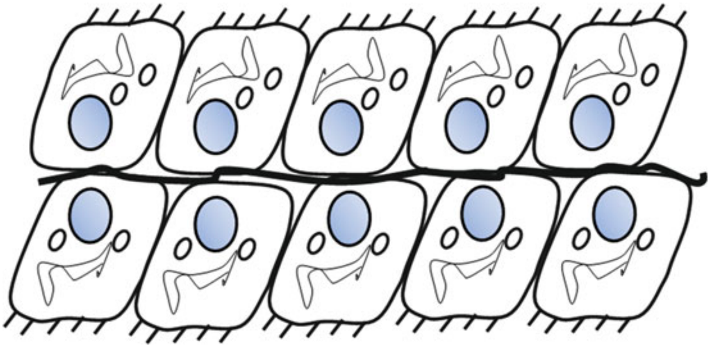


**Figure 4.** Scheme of two thin films of cells sliding past each other. There is a large shear due to out-of-plane gradient of the in-plane speed. This generates an in-plane shear that derives from a gradient of in-plane pressure. This form of the shear is higher than the shear due to tissue flow in 2D because of the small thickness (the shear due to thin-film effect is $\sim V/h$, while the tissue flow shear is $\sim V/D$ where $D$ is the diameter of the gastrula).

In general terms, viscous materials may have a dilational viscosity (also known as volume viscosity or second viscosity), in addition to a shear viscosity (Happel and Brenner, 1991). However, if we restrict ourselves to early stages of chick embryonic development, the embryo sheets are indeed sheets, i.e. they are thin in the dorsoventral direction. The size of the blastula in the case of a chicken is 4 mm at the moment of gastrulation. This corresponds to about 20,000 cells in-plane at the start of the gastrulation movements. The thickness is 2 cells or 0.2–0.4 mm. *Ambystoma mexicanum* (the axolotl) at gastrulation has a cellular monolayer of 0.04–0.08 mm thickness covering a 2-mm diameter sphere, with 113,000 cells (Gillette, 1944). (The much lower cell numbers of (Valouch et al., 1971) warrant explanation.)

As embryonic sheets slide past each other, shears are developed in the dorsoventral direction, parallel to the surfaces of the sheets. In such a situation, the main terms in the stress tensor are the out-of-plane shear terms (Taylor, 1969; Boudaoud and Chaieb, 2001; Fleury, 2005) (Fig. 4). This is true not only for sheets sliding on each other but also for single sheets sliding on or across extracellular matrix (ECM), or above or below a fluid or a membranous layer.

In such a geometry, the tissue flow will behave as a Poiseuille flow (Taylor, 1969). This is to say that the average in-plane flow will derive from a potential that is a compressive stress. This compressive stress is generated by cell traction forces. In terms of physics, the localized vector force is a stress dipole. Traction forces amount to volume forces that correspond to pressure stresses. The traction forces are exerted by membrane protrusions (filopodia, lamellipodia) connected to extracellular matrix integrin foci, and also by cell cytoskeletal conformational changes which pull directly on neighbouring cells by cell–cell junctions. Each individual cell traction is a dipole of compressive stress, and dipoles add up to form a long-range pressure drop. If we imagine the abstract case of a one dimension line of cells, if each cell exerts a traction equal to d$P$ by which it moves forward with a speed $V=-a$ d$P$, limited by viscous drag, the total pressure drop is just equal to the integral of d$P$ over the cell line, such that there exists a macroscopic pressure drop across a line of moving cells: they all move at a constant uniform pace, like a flow in a tube, and there is a pressure $P_0$ at one end and a pressure $P_1$ at the other end, associated with the fluid movement of the cell flow. This is sometimes found in the literature as "cell population pressure". Of course, such lines of individually moving cells exist only *in abstracto*, but similar concepts generate gradients of pressure in 2D sheets of cells. Cellular monolayers support such pressure gradients to the extent that they may start to deform in the perpendicular direction and buckle.

To avoid confusion, a distinction must be made between continuous unicellular sheets in which cell–cell traction generates convergent flows, such as towards the blastopore in frogs or along Koller-Rauber sickle in chicken. In this instance, cell–cell pull suffices to induce the movement although the global average is zero (the forces sum up to a quadrupolar flow). However, after ectoderm invagination (and formation of the mesoderm), cell traction occurs also by the edge of the moving mesoderm, which has a divergent movement instead of a convergent movement. But a divergent movement of the mesoderm results in a convergent movement of the ectoderm by the action and reaction principle. The only caveat to be underlined is that in the absence of any substrate such as ECM or other cell layers, a cell can only exert a quadrupolar force (its average is zero, but a zero average may emerge from an inhomogeneous distribution of tractions). However, in presence of a substrate or of another cell layer on which to crawl, a cell can exert dipolar forces.

In two dimensions, the conservation law for a cell flow is still written div $\boldsymbol{V}=0$. The pressure pattern will depend on the singularities of the vector field. Indeed, the flow field will be found at first order by writing $d_x v_x + d_y v_y = 0$ (conservation law) around the said singularity. The classical examples are the hyperbolic flow, for which the singularity is hyperbolic (Fig. 5), in this case $V=0$ at the hyperbolic point in all directions and the speeds are $V=(-k_x, k_y)$ away from the singularity located at (0, 0). In the linear expansion, around the fixed point $k$ is a constant. The other classical example is the solid vortex core for which $V=(0, 0)$ in the centre (Fig. 6), and the velocity is linear with distance from the centre. In other instances, fluid velocities may often be found to be divergent in the centre of the vortex cores. These classical singular vortices are rarely evidenced in real systems because of the so-called Stokes-Whitehead paradox: actually, when the speeds diverge in the centre of the core, a different physics will be at play at some scale (high Reynolds limit); in other cases, a shear threshold (shear banding) may be reached or any other typical length scale in the system (e.g. cell scale). The vortex core is generally associated with a low pressure area, while the hyperbolic point is generally associated with a high pressure area.

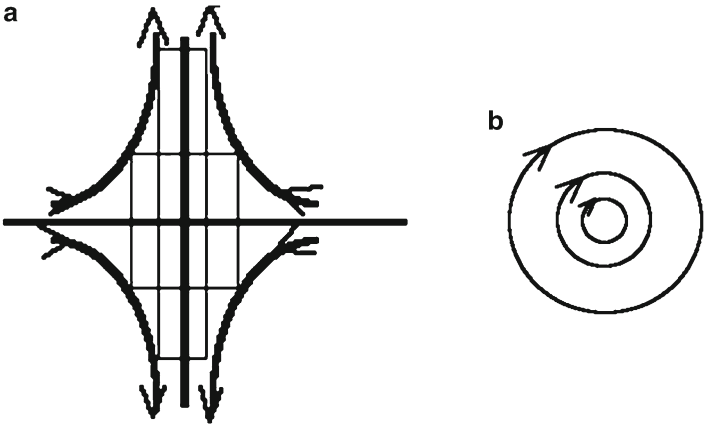


**Figure 5.** (**a**) Streamlines of the hyperbolic flow in 2D. There exists a central singularity with a flow that is convergent along the horizontal axis, and divergent along the vertical axis, by conservation laws. (**b**) The solid vortex core corresponds to a revolution at a constant angular speed of the flow, which then revolves like a "merry-go-round". The velocity at a given point is linear with distance from the centre. In the centre, there is a singularity whose velocity is zero. Both flows satisfy conservation laws, around different topological singularities.

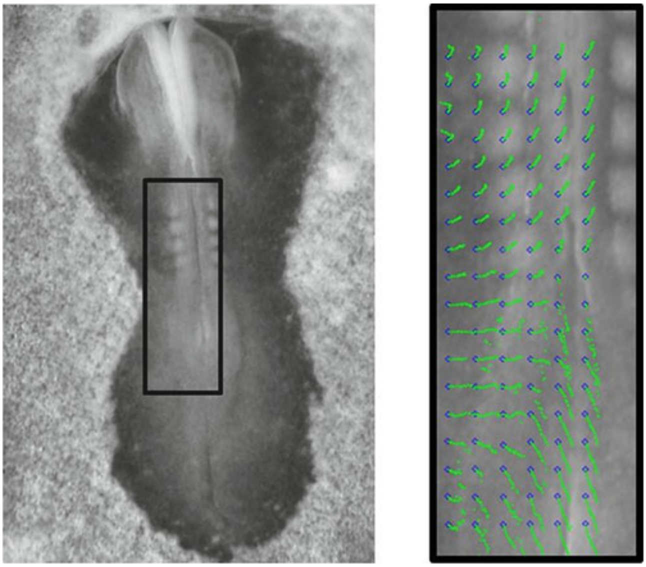


**Figure 6.** Hyperbolic singularity observed in a tetrapod, by in vivo time-lapse microscopy. The image shows a chicken embryo, at the four somite stage. The short tracks correspond to 50 min of tissue tracking. The crosses correspond to the starting point of the tracks. The tissue winds towards posterior, and anterior, there is a point of neutral speed.

The existence of such singularities is compulsory in flat domains with a circular perimeter or on spherical shells. Stated otherwise, fundamental laws of nature imply the existence of a finite number of singularities of the developmental field. This is a consequence of the fixed point theorem, in the version demonstrated by Luitzen Egbertus Jan Brouwer (Brouwer, 1910; Adams, 1962). This is to say that, in principle, the early embryonic movements can be characterized by the number of such singularities. Such singularities are indeed observed in biological systems with cells behaving as crowds forming long-range coherent flow patterns. As a matter of fact, Brouwer himself was inspired by the observation of vortices on the pattern of hair implantation, which is another biological example (Wang et al., 2006). We discussed fixed points in the context of amphibian neurulation (Jacobson and Gordon, 1976). Typical observed topologies are the circular topology (also known as "target pattern") observed in radiates and the hyperbolic topology observed in bilaterals (Fig. 5) (especially tetrapods). In tetrapods, the hyperbolic flow topology is found around the point where gastrulation is triggered, and later in the umbilical area (Fig. 6) (Fleury, 2005). It is also referred to as "convergent extension" (Keller et al., 1985; Zajac et al., 2003; Brodland, 2006; Schiffmann, 2006). Its cause was attributed to elongation and narrowing of the attached, underlying notochordal region of the mesoderm in urodele amphibians (Jacobson and Gordon, 1976; Gordon and Jacobson, 1978). These deformations are rendered possible by cellular wall reorganization. However, the effect actually feeds back on the cause exerting a topological constraint. The initial cause of the presence of the hyperbolic point is in the asymmetries of the first cell cleavages (Danilchik et al., 2006).

Also, during later stages of development, the hyperbolic point continues to be evidenced in the central part of the embryos (Boryskina et al., 2011), around the presumptive navel (Fig. 6) (or rather around the presumptive yolk stalk of birds and reptiles, which is the analogue of the umbilical area of mammals). Now, concomitantly with the hyperbolic pattern, when inspected carefully, the mesoderm lateral to the forming neural plate exhibits a striking pattern of differentiation: the mesoderm differentiates to form haemangioblasts. These haemangioblasts are the precursors of the blood vessels but follow a very conspicuous convergent pattern of differentiation towards the hyperbolic point. On the lateral plates, it can even be seen that they follow deterministic lines of clusters (Fig. 7) exactly parallel to the movement lines (streamlines).

Eventually, these haemangioblasts will form the initial blood capillaries by coalescence, and next, these blood vessels mature to form the vitelline arteries. Therefore, the entire pattern of omphalomesenteric arteries seems to be a direct consequence of the tissue flow field in the high pressure area (the presumptive navel/yolk stalk). As it is known independently that, in vitro, precursors of endothelial cells proliferate and differentiate in response to shear stress (Wang et al., 2005), it is natural to think that the tissue flow, by shearing the endothelial precursors cells (EPC), which are mesenchymal cells, generates organized pools of capillary precursors following streamlines. In such a case, it is possible to

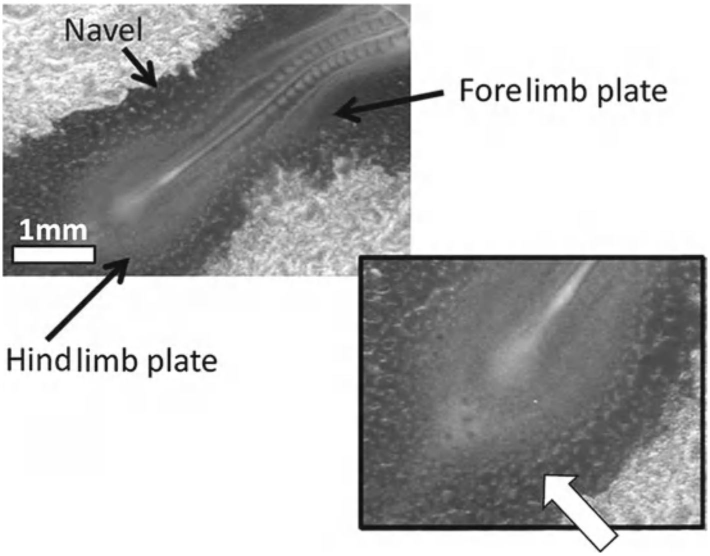


**Figure 7.** Image of a chicken embryo showing lower right (*arrow*) the ordered clusters of haemangioblasts which follow the pattern of tissue winding around the hindlimb plate during the establishment of the body plan.

ascribe the morphogenesis of the yolk sac vasculature, and of the entire navel area to the stress field around the hyperbolic point, which simultaneously induces EPC differentiation and properly aligns the blood islands into deterministic paths. Why the pools of capillary islands should indeed form dot-like islands may be a self-organized consequence of the fact that the differentiation of one capillary island reduces the shear in its neighbourhood by forming locally a plasma pool, thus inducing a small zone of reduced shear around itself, a classical phenomenon in material science known as an “exclusion zone”. When a phenomenon is triggered by a threshold of some quantity, the first consequence of the trigger is to reduce the triggering signal around the nucleation site and prevent the formation of other nucleation sites in the neighbourhood (Fleury, 1997), as, for example, in polycrystalline growth. This is why polycrystals may form gusts of separated crystals.

Therefore, it seems that, in vertebrates, the hyperbolic pattern of flow, and its central singularity, is associated with morphogenesis and differentiation, with a typical flow pattern converging towards the umbilical region located spontaneously in the high pressure region, itself fixed by the singularity in the vector field. This relates deep mathematical properties of space to crucial anatomical facts. It has also been shown independently that the vector field of development is associated with stress gradients (Boryskina et al., 2011). How the actual singularity is related, in each animal species, to its genetics, and then passed to offspring, is an important question which we can hardly discuss here, but there is a convergent effort by several authors which suggests a form of self-organization of the collective motion of cells, at very early stages (Newman, 2008; Chuai and Weijer, 2009; Fleury, 2009), which is scaled up in the adult animal. This is especially obvious in *Xenopus*, for which the directions of flow of the blastula at the moment of gastrulation are clearly defined by the early cell cleavage pattern and then upscaled by self-organization.

## 4. Out-of-Plane Biomechanical Buckling

In the previous section, we addressed only the localization of high compressive stress areas (by viscoelastic flow cell migration). However, it is an obvious observation that living tissue also grows, and that growth must be consistent with morphogenesis and differentiation. To our knowledge, this issue was never addressed in closed form, i.e. there exists no closed model of tissue expansion leading to biological pattern formation and differentiation. The primitive streak and median axis of, say, the early chicken embryo forms the main folds of the animal, and the next regular folds generate cell clusters, somitomeres (Jacobson, 2001) and somites (Gilbert, 2003) which segment the tissue. A considerable effort has been dedicated to analysing observed molecular oscillations that are correlated with segmentation (Pourquié, 2003). However, the exact molecular mechanism remains elusive. In addition, folds, and even segments, occur at other places than at somites. Along fin folds of fish, regular rays form with obvious mode-lockings between thick and thin areas (Fig. 8), which locks the number of rays onto the number of vertebrae, as also known for ribs and possibly fingers (Fleury, 2009). It suffices to count the number of cartilage rays in Fig. 8, stained in blue, to notice that it is twice the number of cartilage stems on the vertebrae. Such period doubling is a classical phenomenon in free boundary and other problems (Rossi, 1998).

**Figure 8.** Mode-locking between backbones of a fish, and lateral fin rays. A count of the number of wavelengths inside the backbone, and along the fin yield 8 and 16, respectively. This doubling is a classical situation in physics, while it is difficult to explain by genetic induction (Photo M.C. Davis, with permission © Nature).

In addition, inside all animals, there exist many organs with some form of folding or regular instability (branching organs, villi folds, brain folds, etc.). In the case of "branching morphogenesis", a growing pouch is unstable at its apex and generates fingering patterns of a formidable complexity and surface area (Warburton et al., 2005). It is a classical observation that the bottom of the "valleys" of these instabilities is associated with some form of tissue differentiation. For example, Langerhans islands will be found in the bottom of the valleys in the pancreas (Davies, 2006). In many glandular organs, there exist "interstitial cells" different from the duct cells. In the lungs, cellular differentiation at the valleys stabilizes the clefts of the bifurcations (Nakanishi et al., 1986). In friction skin, while sweat pores form at the crests of dermatoglyphic ridges, these crests actually open in the valleys of the underlying deeper ridge pattern which is of a halved wavelength as compared to the outer visible layer which generates the "fingerprints" (Hale, 1952) (Fig. 9). Recent work has shown that stem cells of dermis differentiate as they travel from the bottom to the top of the valleys and terminate differentiation in the bottom of the dermis valleys (Blanpain and Fuchs, 2009). Another classical observation is that blood vessels tend to follow the valleys of rhombomere boundaries during early embryonic development. We have hypothesized that "the boundaries (grooves) for each level of segmentation are launching domains for differentiation waves" (Proposition 263 in Gordon, 1999), which partly meshes with these ideas.

These observations all fit into the concept that a localized increased stress will trigger differentiation in localized areas forming a mechanical niche, which we have previously assigned to the trajectory of differentiation waves (Gordon, 1999). However, in the situation described here, this niche is 3D, as valleys and folds generate complex patterns, as opposed to the previous in-plane case. This niche is self-organized by the stress field as an out-of-plane instability develops.

While a flat biological tissue admits regimes of instability, the features generated by the folding process are themselves stable. For example, while it takes 90 min to form a well-defined chick somite, the somites themselves are stable entities. Also, these instabilities can be induced or triggered, above some experimental or natural threshold – hence the word "induction". However, this may be a mechanical, not primarily chemical, induction (Gordon and Brodland, 1987). Also, these instabilities are related to animal development and *growth*. Any reasonable model of this phenomenon must therefore naturally include growth, folding, non-linear induction by artefacts or self-organized physiological induction. Also, the geometry of the problem must be preserved: the folds are formed by sheets that fold out-of-plane as a consequence of in-plane motion and growth.

Growth implies increase in mass and/or transfer of mass from one part of an embryo to another. Mammalian and bird embryos grow in total mass during their development, while amphibian embryos do not (Jacobson, 1991). The evidence suggests no increase in neural plate volume during neurulation in an amphibian

**Figure 9.** Fingerprint formation is related to the shrinking of volar pads, by the 10th week of gestation (*Left*, from Cummins, 1926). Sweat pores open "naturally" in the bottom of the valleys of the underlying pattern of the folds (in the epidermis). Right sweat pores cast by Hale of volar skin in the human fetus (Hale, 1952).

(Jacobson and Gordon, 1976). However, later stages in amphibians may involve mass transfer:

> It is doubtful that there is any transfer of material needed for growth from one cell to another until the heart begins to beat. That first occurs at larval stage 34. Then, certainly, many regions of the embryo begin to grow at the expense of food stuffs transferred from the large endodermal cells that line the gut. (Jacobson and Gordon, 1976)

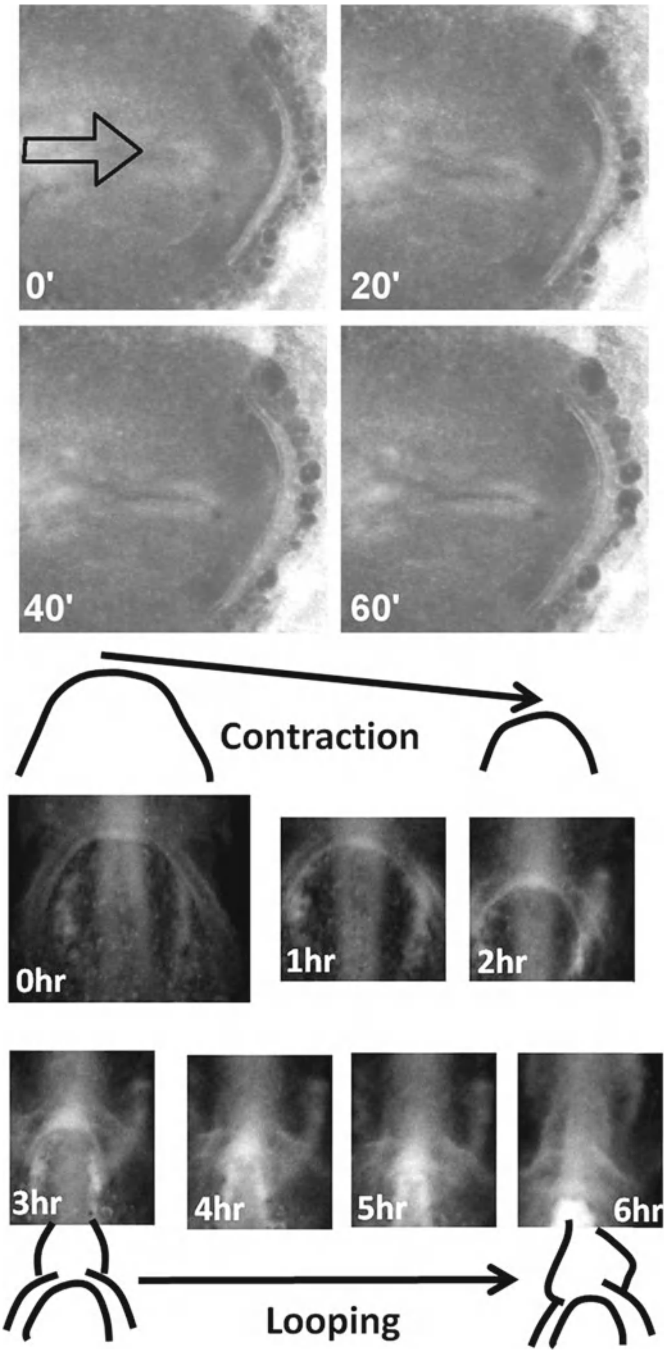
Such transfer may be the basis for observations of "internal resource-competition" during development (p. 305 in West-Eberhard, 2002). The amount of mass transferred could alter stresses and trajectories of differentiation waves. To address these issues, we must go in more detail into the biology of tissue expansion. It has long been known that, at the tissue level, animals have a dipoblastic or tripoblastic organization (Gilbert, 2003), i.e. they are made of cell layers (generally three layers of cells). The upper layer is called ectoderm, the lower layer endoderm and the middle layer mesoderm. From a physics point of view, a layered material has a natural tendency to fold, when in-plane stresses are generated.

Therefore, out-of-plane folds of the layers in biological tissue have been ascribed to buckling, and such buckling modes have been invoked for brain convolutional development (Richman et al., 1975; Armstrong et al., 1995), for neural tube formation (Gordon, 1985, 2006), for fingerprint formation (Kücken and Newell, 2005; Kücken, 2007) and even heart and gut pocket formation (Fleury, 2011) (Fig. 10). Buckling may also function in single cell morphogenesis (Gordon and Tiffany, 2011). The original hypothesis of buckling of laminates as a model for embryogenesis goes back to the founding father of embryo physics (His, 1888).

However, these models are so far *elastic* models of deformation, and they generally lack the viscous component and coupling to growth factors; also, differentiation is not assumed. They either assume uniform growth rates, or purely physical elastic deformation modes, or pre-patterns of growth independent of tension, and they assume uniform physical parameters. In these models, the mechanical non-linearities suffice to induce instabilities.

However, be it lung growth, fingerprint formation or any other instability phenomenon in biology, each aspect of morphogenesis generally correlates with genetic pathways, growth factors, cell division and differentiation, such that a complete description of the phenomenon is still lacking. Especially, the biological parameters of growth are actually not uniform. In the case of fingerprints, it was recognized long ago that actual biological growth, with differential growth rates between valleys and bumps, is an issue (Hale, 1952), but "…to our knowledge, no mechanism based on pure cell proliferations of the basal layer leading to fingerprint patterns has ever been suggested" (Kücken and Newell, 2005).

In the case of brain development, it has been observed that mitotic rates and cleavage orientations of RG-stem cells and cell migration varies from gyri to sulci, with a corresponding variation of cortex thickness, such that there is a lateral expansion force which may explain brain gyrification (Kriegstein et al., 2006). In the case of branching morphogenesis, there is in situ evidence that growth factors correlate with local expansion forces (Unbekandt et al., 2008). In the more specific example of lung growth, it has been shown that fibroblast growth factor FGF10 is in fact mechanosensitive (Unbekandt et al., 2008), and since lung expansion varies linearly with pressure (Kitano et al., 2001), it is reasonable to deduce that the entire morphogenetic process, including any hypothesized morphogen expression, is linearly slaved to pressure. Still, FGF10 is crucial both for lung and limb extensions (Sekine et al., 1999). Other growth factors of the same family, like FGF8, show a very strong spatial correlation to force maps at the blastula and early gastrula stage (Fleury, 2009); this is also true of FGF2 which is an important heart growth factor, and which is known to correlate with mechanical load (Schultz et al., 1999). Also, genes coding for transcription factors, like Twist (Farge, 2003) and Tbx5 (Krause et al., 2004), are mechano-sensitive. The production of growth factors in the case of the lung seems to vary linearly with mechanical force, up to the point that staining maps may be viewed as strain maps (Unbekandt et al., 2008). This fact allows one to couple growth factor production in "the bulk" to the interfacial growth field itself (the stress field) and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to form a closed mathematical system, leading to differentiation in localized areas since convoluted surfaces generate strong stress singularities, as we now show.

The model is as follows. First of all, let us consider the geometry of the problem. We have to address a system formed of a sandwich of ectoderm and mesoderm (or epithelium-mesenchyme for a description of villi, lung growth, etc.). We consider that the ectoderm is hooked to the mesoderm through a thin basement membrane. The mesoderm is supposed to have a finite thickness $h_0$. (Additional tissue layers could be incorporated; we will limit ourselves to two layers, new layers could even be induced dynamically by out-of-plane division in response to stress, the stress orienting the mitotic spindles.) We shall assume that ectoderm expansion is associated with forces (cell division being in plane, prior to differentiation) and neglects the forces related to mesoderm expansion. In other words, we assume that the disordered nature of mesoderm makes it more fluid.

Epithelia (or ectoderm) grow in response to growth factors of the FGF family (Bellusci et al., 1997). This is now well established. But FGFs are produced by fibroblasts present in the *other* layer, the mesoderm. This is also well established. FGFs are diffusible molecules. Let us consider the diffusion of FGF (or any other mechanosensitive molecule) with diffusion constant $\Xi$ across mesoderm cells and their membranes of thickness $h_0$, produced at rate $\alpha$. Let us assume that it is not degraded, except at the upper boundary, where it is captured by the basal layer of the epithelium via receptors such as FGFR2b, in the case of FGF10. We write $F(h)$ to represent the concentration of growth factor at position $h$ across the mesoderm. Because of the diffusion equation, we have across the mesoderm layer:

$$\partial F(h) / \partial t = \Xi \partial^2 F(h) / \partial h^2 + \alpha \tag{1}$$

In steady state, considering that the layer is very thin, this equation has a solution:

$$F(h) = (\alpha / \Xi)(h_0 + h)(h_0 - h) \tag{2}$$

One can represent the profile of growth factor, in cross section, from top to bottom as shown in Fig. 11. In this model, the internal tissue "informs" the epithelial layer via a vertical gradient of FGF, which is consistent with biologists' observations and common knowledge; and the ectoderm expands laterally (cells divide in-plane).

**Figure 10.** The vertebrate heart is formed dynamically by a fold of the endoderm, which takes a pocket like shape, and progressively rakes the visceral mesoderm into a tubular form. *Top*: In vivo time-lapse imaging of the formation of the early cardiac fold territory. The median folds of the body axis push on the endoderm of the gastrula, thus generating a crescent-shaped fold. This shape is initially formed from the forward movement of the median axis, which buckles the gastrula surface. *Bottom*: While the crescent shape constricts, it descends along the body and collects the lateral visceral mesoderm that will form the heart chambers. The heart folds are a consequence of the constriction dynamics.

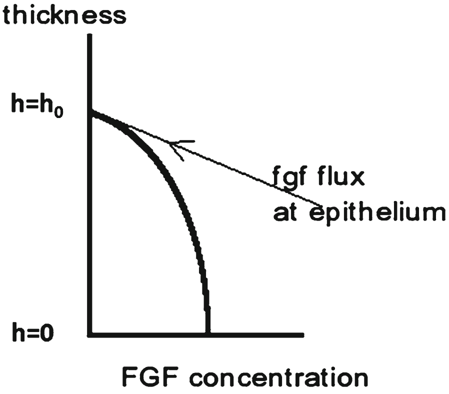

**Figure 11.** If we consider an epithelium resting over a mesoderm of thickness $h_0$, the production of FGF has a parabolic profile, with a value 0 at $h = h_0$, (the epithelium at the top is a sink) and a zero flux at $h = 0$ (at bottom, no escape or reflecting boundary condition). Then, there is a net flux at $h_0$ that depends on the production factor and on the layer thickness.

However, fibroblasts are *mechanosensitive*; this has been recently established in vivo for FGF10; we assume it to be more general. We also assume a linear production of FGF with the mechanical stress, which is likely (Sekine et al., 1999), although detailed in vivo experiments are extremely difficult, albeit desired. The layer of mesoderm may be considered as a viscoelastic material. When the epithelium descends during segmentation (we will see below why it does so), the fibroblasts underneath undergo a squeeze that we assume will enhance the production of FGF. Therefore, the actual flux at the epithelium is proportional to $h(h_0 - h)$, where $h_0 - h$ is the squeeze of the tissue. This function takes the value 0 at $h = 0$ (no cells), and at $h = h_0$ (no stress). This will be the origin of a fundamental instability. Stated simply, undeformed living material will not undergo morphogenesis, neither differentiation; deformed material will continue to deform until valleys of quite deformed areas appear, which are very stressed and deformed, separated by non-deformed areas (i.e. the tissue tends to fold and segment, if it receives a non-linear trigger), in which the stress is small. In the very stressed areas, the total growth factor production will be small, so cells will not tend to grow, but the stress will induce differentiation above some biological threshold. This is the meaning of the product $h(h_0 - h)$: for small deformation $h \sim h_0$, there is little production rate per unit cell; for large deformations $h \sim 0$, although cells should individually produce a lot of FGF, there are fewer cells there, and although these are very stressed, the net flux of FGF is small. In general terms, a non-linearity of the form $h(A - h)$ will imply the existence of a maximum of *deformation times thickness*, somewhere between the non-stressed regions. The origin of the instability is therefore in the fact that the non-linear function $h(h_0 - h)$ presents an unstable maximum at $h = h_0/2$ and will therefore tend to

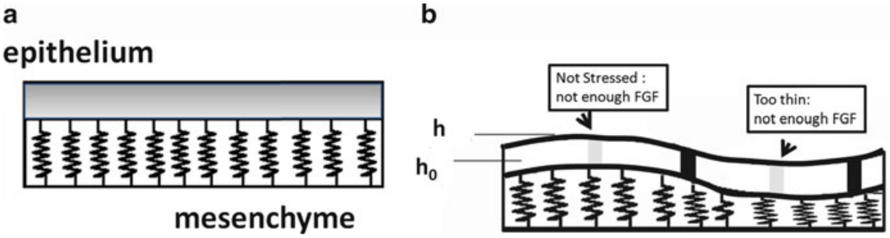

**Figure 12.** (**a**) The mesoderm (mesenchyme in case of lung growth) is modelled as an elastic layer located underneath a shell of epithelium. (**b**) The elastic component of the deformation of the layer stimulates the production of the growth factor FGF. Calculations show that if the thickness is large, the mesenchyme cells are not stressed: the production of FGF arriving at the upper epithelium (*light grey*) is small. If the tissue is very thin, the production of FGF is small. The maximum of FGF production is for deformations in between, in this case, a larger quantity of FGF arrives at the epithelium (*black*).

destabilize under stress and split the domain into areas of $h = 0$ and areas of $h = h_0$, which are two static equilibria.

Stated otherwise, the inhomogeneity of growth factor flux is transferred to the surface where in-plane differential surface tension will act to generate a wavy pattern. This in turn changes the pressure map, which self-consistently changes the flux. Therefore, the entire morphogenesis can be rewritten in terms of a free surface deformation, bulk pressure acting as a mechanical "morphogen" inducing all the others and lateral epithelial growth acting as an inhomogeneous surface tension with a negative term related to pressure, which is the driving force for morphogenesis and differentiation. In general terms, sheet growth and folding amount to a surface increase; therefore, some equivalent to a negative surface tension should appear in the problem, which is actually the compressive stress state of dividing cells (a similar effect exists in physics of negative surface tensions, known as Lippmann effect) (Fig. 12).

More precisely in this simplified flat situation, the FGF flux serves the purpose of extending the epithelial layer, such that the epithelial layer exerts an in-plane stress proportional to $\alpha h(h_0 - h)/\Xi$. We neglect other components of the force for now, and the lateral diffusion of FGF. Let us consider that the epithelial layer is much stronger than the fibroblasts (this is ascribed to the fact that the mesoderm is rather loose, while epithelial cells are connected to each other and to a basement membrane), such that the epithelial layer deforms following a mode of shell flexing under the action of this stress. This is modelled by the von Karman equation for thin shells, as known, for example, for the buckling of epidermal ridges (Kücken and Newell, 2005), except that we keep only the effect of the lateral stress exerted by cells under the influence of the growth factor, which is formally a surface tension, although not derived from an interfacial free energy. The first term in the right-hand-side represents the response to bending of the shell, the second term the out-of-plane component of the in-plane stress associated with a curved surface. The term in the left hand side represents viscous damping of a dashpot component attached to the more fluid mesenchyme:

$$\kappa\partial h(x)/\partial t = D\partial^4 h(x)/\partial x^4 - (2\alpha h\ (h-h_0)/\Xi)\ \partial^2 h(x)/\partial x^2 \tag{3}$$

with $D$ = the bending modulus; remember that $h$ is oriented upwards with $h=0$ at the bottom; therefore, the stress is compressive for $h<h_0$, (i.e. as soon as the mesenchyme is squeezed).

We look for static equilibrium solutions. We assume a profile of the form $h(x,\ t)=h_0+\eta\ \exp(i\omega x)$; with $\eta$ small we get a relationship:

$$D\eta\omega^4 \cos(\omega x) + (2\alpha\eta^2 h_0/\Xi)\omega^2\cos^2(\omega x) = 0$$

This equation is different from the usual buckling equation (Bloom and Coffin, 2000). By the presence of the $\cos^2(\omega x)$ term, sinusoidal solutions associated with a wave vector $k_x$ do not show up directly. In classical buckling, one finds the latter by setting to zero the coefficient of the cosine function (Bloom and Coffin, 2000). In fact, we understand that around $h=h_0$, there is no such buckling solution, because the compressive stress is not sufficient and, in addition, zero on average. However, we see that the maximum of compressive stress is actually found at $h=h_0/2$. We therefore *change variables* and define a new variable $z$, which is related to $h$ by $z=h-(h_0/2)$. It represents the distance to the middle of the layer. The static equilibrium equation now becomes:

$$0 = D\partial^4 z(x)/\partial x^4 - ((2\alpha z^2 - h_0^2/4)/\Xi)\partial^2 z(x)/\partial x^2$$

Around $z=0$, i.e. around the position where the layer is one half of the initial layer, we are able to perform a linear analysis by neglecting the $z^2$ term. We find a buckling problem, associated with a maximal value of the stress, corresponding to the middle position of the layer. Since this stress is a maximum stress value, the spatial derivative is flat, and this contribution vanishes at first order at $h=h_0/2$. We then end up with the classical buckling equation:

$$0 = D\partial^4 z(x)/\partial x^4 + \left(\alpha h_0^2/2\Xi\right)\partial^2 z(x)/\partial x^2. \tag{4}$$

It classically exhibits buckling modes of wavelength $k=\alpha h_0^2/(4D\Xi)$ if the stress exceeds a critical value $C_{cr}=(\pi^2/4)D/L^2$. The form of the growth-induced stress as a function of geometry is important in that it shows that the same effect (transition from non-segmented to segmented with differentiation in the valleys) may be obtained in different situations: either the tissue is soft (small $D$), or the flux of growth factor is less rapid (large $\Xi$), or the initial mesoderm is thick (large $h_0$), or the mechanotransduction is very sensitive (high $\alpha$), etc. This shows that physical parameters exist, which drive the formation of segments, in the presence of a mechanosensitivity, and these may have different values at different places in the body because of the global morphogenesis history. One need not expect the segmentation process to happen with the same values of the genetic parameters, in different animals, nor, in the same animal, in different places with the same wavelength, etc. Stated otherwise, there may not be a single gene, nor a single boundary condition associated with the formation of segments, and with differentiation niches.

We therefore see that the system may be absolutely stable around $h=0$, for which the niche is too small (in this case, the tissue has thinned down, and the total amount of FGF is not enough for generating an instability), and absolutely stable around $h=h_0$ (because if the cells are not deformed, they are not producing enough FGF to generate a deformation), but the system starts to become unstable, if a large enough deformation is imparted on it but not too large ("induction"), such that the system is stressed down enough to arrive to the thickness $h_0/2$. This is to say that if we compress the system enough, as, for example, in Farge's experiment (Farge, 2003), at some point the system becomes unstable and reacts. However, prior to reacting, the system is stable, and after the reaction, the system is split into two stable domains, one highly stressed at $h \sim 0$, the other not stressed, and at $h=h_0$. It makes sense, indeed, that a segmented animal, with its segments separated by a furrow has to be stable: the segments themselves, stress-free, are stable, and the region of the furrow being very thin cannot segment any further. In this crude model, the two equilibrium states are $h=h_0$ and $h=0$; however, in a real system, it is likely that the equilibrium state corresponding to $h=0$ will not be observed, and instead, the instability will cease to develop due to a minimum located at some critical value of the stress, generating a cell phenotype change, since cells cannot be squeezed forever. If staining of cells is performed, it is likely that some contrast will be seen either because of the gradient of cell density, of cell stress state or of possible differentiation induced by stress, and this contrast will map the stress/deformation field.

## 5. 1D Numerical Integration

In its simplest form, the mathematical system shown above leads to a self-consistent non-linear equation of the von Karman type, with an in-plane inhomogeneity of the surface tension, which is *parabolic* with the field $h$ (the thickness). This means that the mechanotransduction, and *the entire phenomenon of morphogenesis with differentiation, is intrinsically non-linear*. This is deeply rooted in the fact that if stress induces differentiation waves associated with growth factors signalling, as modelled here in a closed fashion, the trigger for these waves is not just the stress but the product of the stress by the volume of the stressed cells, and this is at the origin of the non-linearity. Stated otherwise, the flux of growth factors is never linear, in the presence of mechanotransduction, because mechanical stresses not only modify chemical production but they also deform the "space" or the "geometry" in which the chemicals are produced. The coupling, of the change in geometry and of the increased chemical concentrations, is the cause of the non-linearity in morphogenesis. It is classical in physics that non-linearities generate multiple steady states, each with its basin of attraction. In the case shown here, differentiation emerges from the presence of two distinct mechanical states, which spatially segregate the differentiation pathways. This may explain logically how spatial inhomogeneities relate to dichotomous differentiation. This may also be related to the mechanics of cell division, stress state inducing the choice of cleavage plane (possibly inducing differentiation or stratified growth or both).

This equation exhibits a triggering mode of instability, which can be interpreted as *biomechanical induction* of trains of folds. Between the folds, there exist thin valleys corresponding to the "interstitium" which is so often found between villi, ducts, acini, etc. This interstitium will serve as a template for other morphogenetic processes, such as deposition of islets, or vascular growth, or neural growth, the two latter progressing with the same traction mechanism (Gerhardt et al., 2003; Lu et al., 2004) and altering the outer surface of the organs, as in mesenteric vascularization or gut innervation, etc.

This instability generates an avalanche of segments, from an initially featureless structure, one segment inducing the next one non-linearly. This may, then, be the fundamental cause of meristic characters and their variation (Lindsey, 1962; Depew et al., 2005; Asher et al., 2011). Such avalanches of folds are clearly seen also in *Drosophila* germ-band extension, although the ectodermal movements in insects and in vertebrates occur in opposite directions. In insects, the germ-band extension winds away from the median area and returns towards the anal pole, while in vertebrates, the ectoderm converges towards the umbilical region and winds caudally and rostrally, as we have observed. This may be related to the debate about the evolutionary split between insects and vertebrates (Travis, 1995; Van Den Biggelaar et al., 2002), and the fact that tissue stratification is reversed in arthropods and in chordates.

Variation is expected because a spatially linear sequence of non-linear events that depend on one another consecutively is likely to accumulate deviations. A typical numerical, dynamical integration of the equation shows that above a threshold of the ratio of deformation at one edge, an instability indeed propagates (Fig. 13). This instability is limited by the limited thickness $h_0$ of the layer. Therefore, in this simplified model, the increase of surface area is limited by what happens in the deep grooves at the depth level $h=0$, where some differentiation stops the process. The valley of the instability is characterized by high stress whose magnitude is proportional to the depth of the valley. This is why differentiation will occur first in the valleys. This gives a natural explanation to such self-organized processes as vasculogenesis occurring in valleys of embryonic material, or sweat pores opening along dermatoglyphs, or lacrimal glands forming in the bottom of the conjunctival fornix (external fold of the eye ectoderm, see below). Differentiation, especially of blood vessels, will so to speak "decorate" with blood islands the topographical features of the embryo, for example, the interstitial space between somites, which will eventually be remodelled into vessels. For *Xenopus*, we have estimated that the speed of propagation of somite formation

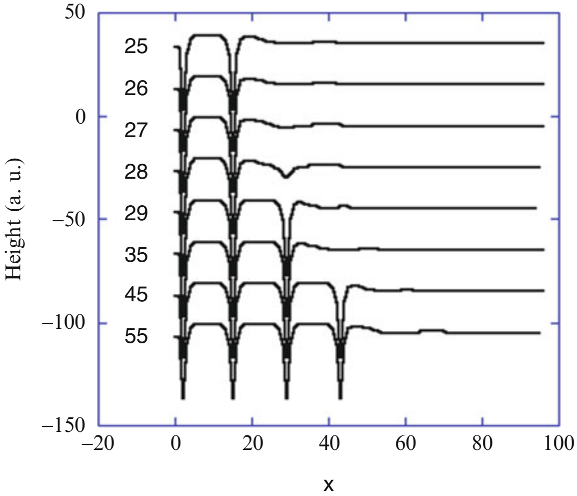

**Figure 13.** Height profile as a function of time (here number of iterations). Regular segments propagate from left to right, after an initial step of deformation to the left. For the sake of clarity, the curves were shifted downwards as a function of time. The segmentation may describe a typical somitogenesis process as observed in vertebrates or fold formation on villi, lung branching, etc. The important issue is that higher stresses are found in the bottom of the furrows, such that these areas will be prone to differentiation. The equation was solved with a 1D explicit scheme, in C++, along a segment of 100 grid points.

is 3 μm/min, about the same speed that we observe for earlier differentiation waves in axolotls (§9.20 in Gordon, 1999). This is also the magnitude of morphogenetic movements in the chicken embryo.

## 6. Complete Models

Complete models of viscoelastic deformation coupled to differentiation, with a feedback of differentiation appearing as source terms of the viscoelastic equation, require a formalism that can at this stage only be addressed numerically, with such tools as finite element methods (Gordon, 1983, 1985; Allena et al., 2010) or cellular models (Graner and Glazier, 1992). Global models of gastrulation, so far restricted to *Drosophila* germ-band extension, are appearing (Pouille and Farge, 2008; Allena et al., 2010), which could be expanded to include feedback loops of differentiation and thereby become realistic developmental models. A proof of principle in the case of tetrapods is found in Fleury (2009), in which out-of-plane buckling is coupled to in-plane flow. In summary, as shown in the buckling model above, and as classical in mechanics, when a stressed mechanical state is unstable, the reference configuration destabilizes towards a new configuration in which domains appear with more stressed areas separated by less stressed areas (forming stripes or hills). This is a consequence of the integral of the elastic energy: in the reference homogeneous state, the elastic energy (product of deformation by stress) is higher than in the new deformed and inhomogeneous state, although the stress and deformations are distributed along a more convoluted surface (actually, it is favourable to have highly stressed areas, if these are very narrow). This is how morphogenesis will be coupled to differentiation splitting. However, one interesting observation is that, in the specific case of biological growth, the morphogenetic chemicals produced by cells are related to mechanical stresses, while the geometry (deformed state) is also related to stress, thereby making the system unstable.

We shall not present here "models of everything" but rather a simple discussion of two celebrated cases: one which is that of the eye and the other is that of the heart.

## 6.1. THE EYE

The morphogenesis of the eyes is a well-known problem. On the one hand, a lot is known about the genetics of induction of the eyecup, and especially the eye lens placode (Lamb et al., 2007). Genes such as *pax* are known to be conserved across species and play an important role in the formation of light-sensory organs, in very different genera (Lamb et al., 2007; Suga et al., 2010). On the other hand, a lot is known about the anatomy of the early neural tube of vertebrates, especially in the area of the eyes placodes (Gordon et al., 1994; Ladher and Schoenwolf, 2005). The scenario of eye formation, starting from a completely flat blastula, can now be understood as follows.

First, the blastula winds rostrally and caudally. This generates elongated folds along the anteroposterior axis (neural folds, Fig. 14a). These folds move forward under the stress gradient that they impart onto themselves. The collision and fusion of the left half and right half of the neural plate generates the neural tube (Fig. 14b). In the anterior part of the embryo, the neural tube is open. The lips of this open area will be the eye placodes. How the eye placodes form from a neural tube is an interesting but complex 3D viscoelastic problem. In chick, we show that it occurs in the neural tube. As the left and right lips of the neural tube collide against each other, the eye territory expands laterally by viscoelastic deformation. However, in amphibia, initiation of the eye placodes (optic cups) may happen in the open neural plate (Sarasin and Sarasin, 1889; Gordon et al., 1994):

> The eye anlage contraction wave begins as a circle on the edges of the rising neural ridges of the anterior neural plate at stage 14. Upon reaching the central area of the anterior neural plate, the circle breaks into an arc and the two ends close into two separate circles corresponding with the two eye rudiments. The circle vanishes and the region disappears laterally under the rising neural ridges. (Gordon et al., 1994)

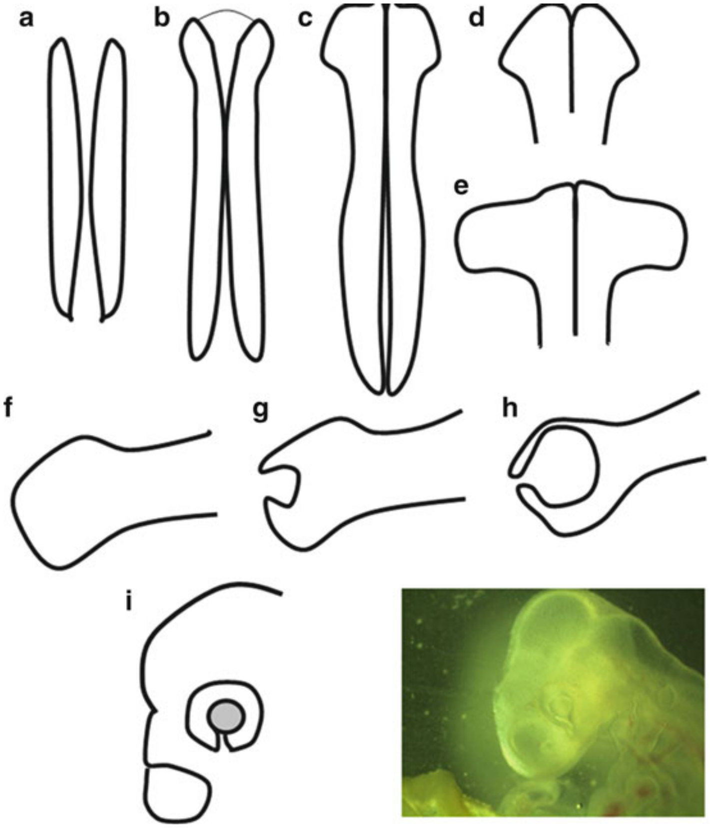

**Figure 14.** Scheme of different stages in eye development. The dorsal folds (**a**) form; as they collide against each other, (**b**) the neural folds evaginate sideways. As the apex of the folds moves forward, the nasal pit closes as a consequence of ventral traction of the gut pocket (**c**). As the dorsal folds move more forward, the eye primordia evaginate because they are squeezed between the nasal pit and the brain rudiments (**d**). The eye primordia push strongly on the ectoderm, which induces the eye placode (**f**–**i**).

In chick, first the neural tube is flexed forward. When the flexure of the neural tube is followed simultaneously ventrally and dorsally, it is observed that the flexure of the neural tube is "induced" by the traction of the gut pocket (Fig. 15).

This flexure closes the neural tube in the anterior area that will be the nasal pit (arrow in Fig. 15, and sketch in Fig. 14c). As a consequence, the eye-competent region is squeezed between the nasal area, which is the (closed) very end of the neural tube, and the brain vesicles (esp. mesencephalon). As development continues, the edge of the neural fold has no other means than expanding laterally, forming progressively the evagination of each eye territory (Figs. 14d, e and 16).

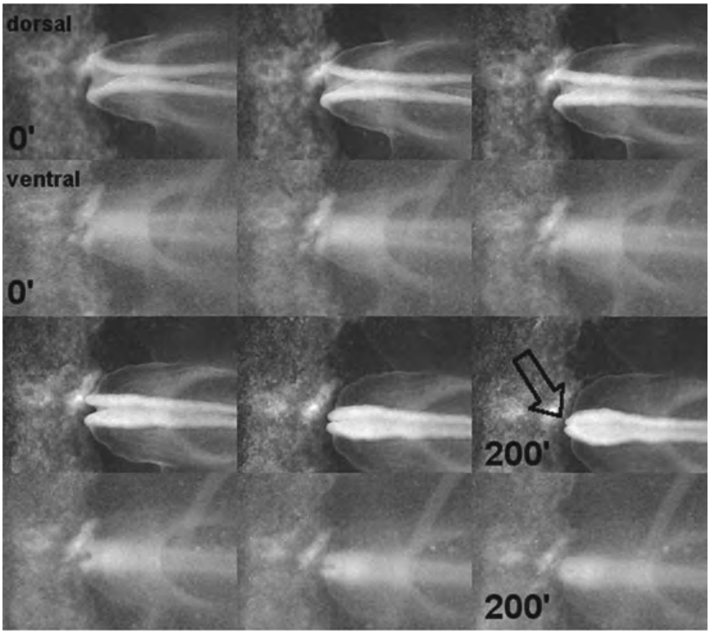

**Figure 15.** This plate shows 200 min of development of the anterior opening of the neural tube. Simultaneously, an underneath view of the gut pocket is obtained on the same embryo. It is observed that the anterior end closes, as the gut pocket moves posteriorly. The eye bulges (and their eyecups) will form posterior to the nasal pit. The nasal pit is obtained by the collision of the two halves of the anterior opening of the neural tube, as the gut pocket pulls it posteriorly.

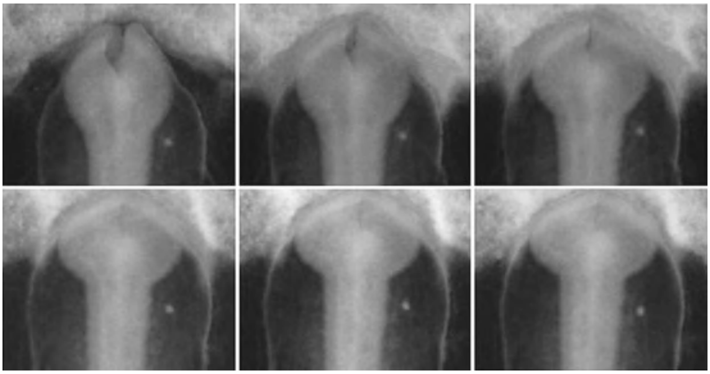

**Figure 16.** In vivo time lapse of the closure of the nasal pit, showing the early evagination of the eyecups (at 30-min intervals). Transiently, the eye mass has a rather round shape. However, as the median axis extends forward, it pushes on the posterior part of the eye mass, which then evaginates sideways.

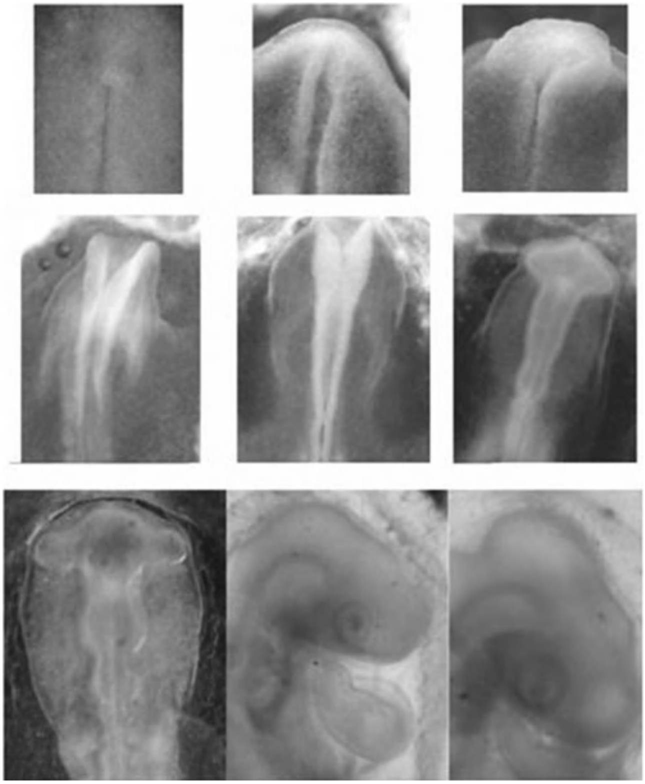

**Figure 17.** Summary of the formation of the eyes, as followed in vivo. The entire eye mass is competent to yield eyes, although only the two evaginations on the lateral sides of the head will actually become, eventually, the two eyes known in most vertebrates.

As the eyecups grow more, they evaginate sideways, in what may be called "the trail" of the movement. This trail occurs on an embryo that is flexing forward; therefore, the brain progressively rocks over the eye forming the frontal features (Fig. 17).

Now, here comes the coupling with differentiation: as the eyecups evaginate sideways, the contact of the superficial ectoderm with the invaginated ectoderm (apico-basal contact with itself so to speak) is known to "induce" the lens placode (Lamb et al., 2007). This discontinuity occurs rapidly (in about an hour) and can be observed dynamically by time-lapse microscopy in an HH stage-16 embryo (Hamburger and Hamilton, 1951; Anonymous, 2010). This causes a retro-evagination of the eyecup around the recently induced lens placode (Fig. 18). This creates the well-known structure of the eye, which is a spherical ball, surrounded by a spherical "orbit" with a lens at the exterior surface of the sphere and the retina at the internal surface of the sphere. It is a classical result that the

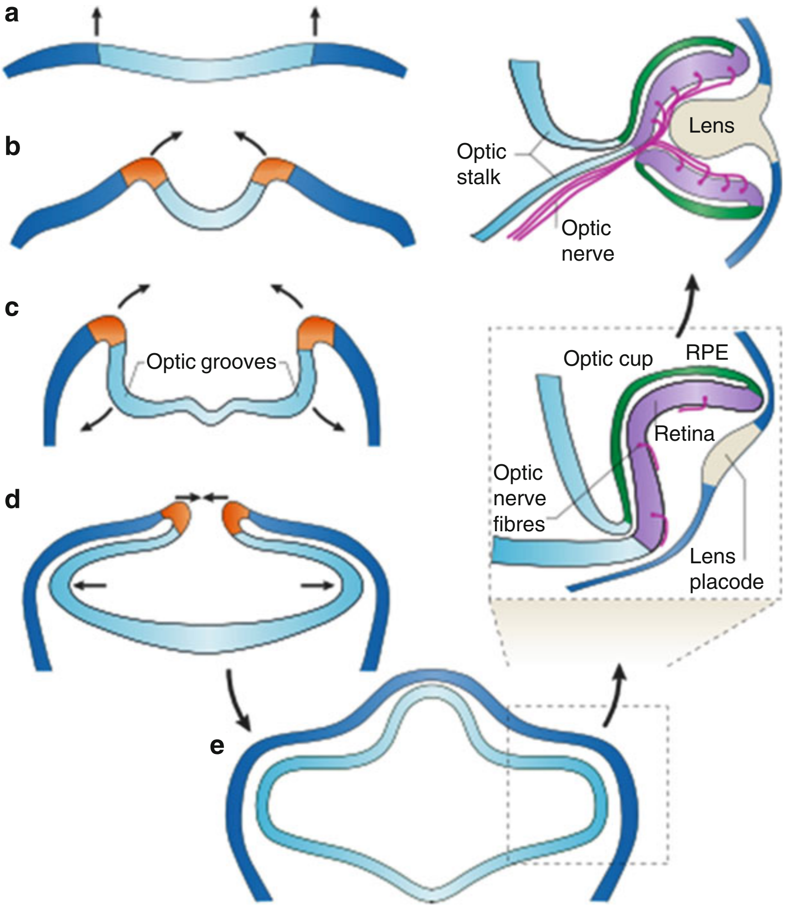

**Figure 18.** The formation and development of the vertebrate eyecup (Reprinted from Lamb et al., 2007 with permission © *Nature Reviews*). After a movement of evagination, the differentiation of the lens tissue occurs, as a consequence of the direct contact between ectodermal layers at the apex of the evaginated eye primordium. Here, the two layers start to induce the lens placode at drawing (*e*).

entire area between the eyecups is considered as "competent" to give eyes. This may be a misconception, in that the "competence" to give eyes is in fact intrinsic to the physics of the contact between the two ectoderms. It is not that the tissue is already prepared to make an eye everywhere, at early stages. It has even been shown recently that the retro-invagination of the eyecup, at the point of contact, is intrinsically related, via apical contraction, to the process of lens placode formation (Plageman et al., 2010). This is to say that the differentiation of the lens placode is related to the mechanics of the retro-invagination of the eyecup itself related to the force of evagination created by the trail of the eyes. An alternate view, given in the conclusion, is that all the cells in the tissue are indeed

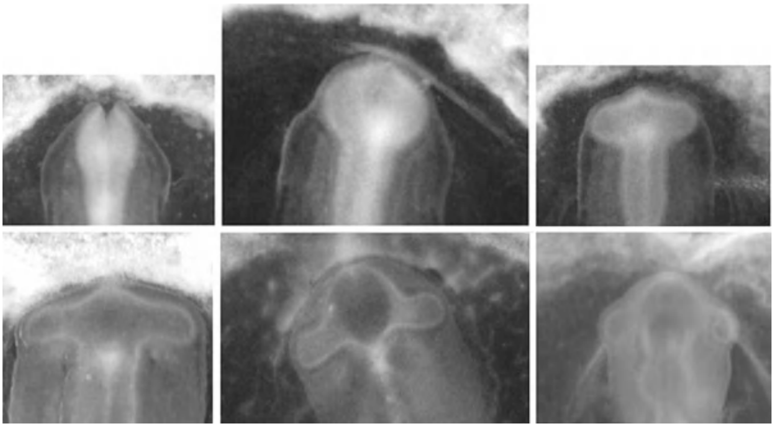

**Figure 19.** A focus on the eye evaginations shows that the eye primordia evaginate and rock posteriorly, to become incorporated to the lateral sides of the head. This happens as a consequence of forward movement of the median axis, which deforms the eye mass viscoelastically in the shape of a "trail" of tissue.

biochemically competent to produce eyes but only those that happen to have physical contact do so.

This gives sense to a long line of well-documented data that indeed bilateral animals may have a single eye instead of two, in the celebrated condition of cyclopia. Even so, early chordates, which do not have eyes, like cephalochordates, have some sort of an eye spot along the median axis; tunicates or hagfish have also a single "eye" or ocellus in the anterior area, in between brain rudiments (Lamb et al., 2007). Cyclopia can be induced in vertebrates by adjunction of cyclopamin, or even ethanol (Dubourg et al., 2007), in low concentrations, and there exists a continuum of conditions between almost normal facial structures to fully cyclopic, associated with holoprosencephaly in humans (Blader and Strahle, 1998). Although very rare in newborns (~1/20,000), this condition is actually frequent in conceptuses (1/300) and somehow is associated with early miscarriages, which is why it does not appear as statistically significant.

It makes complete sense that during the formation of the eyecups, a stronger or weaker forward push of the tissue in the anterior part of the neural tube, against the nasal area, will generate a more or less evaginated T-shaped eye presumptive area. In this respect, mutants that simply have a weaker convergent extension movement at the moment of eyecup formation evidently result in cyclopia (Marlow et al., 1998; Dubourg et al., 2007).

Especially, during early stages of eyecup evagination, the eyes area has transiently a roundish shape corresponding to a single mass, from a point of view of physical tensions (Figs. 17 and 19).

Progressively, this mass evaginates, up to the point that it exhibits a "peanut" shape, with two distinct lobes. Therefore, it makes complete sense that the cascade

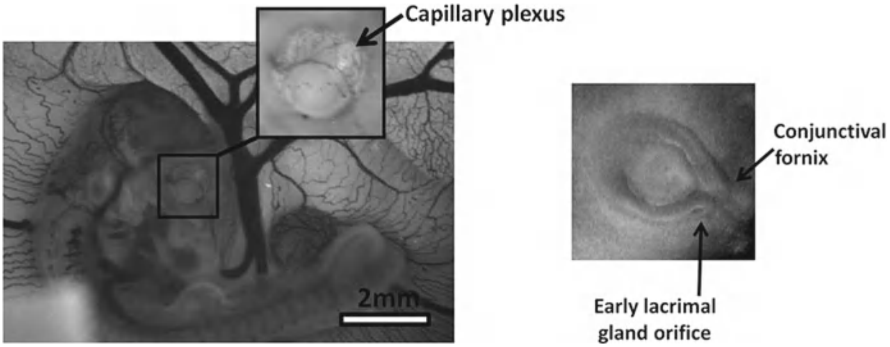

**Figure 20.** *Top*: The endothelial cells form a capillary plexus that propagates along the eye ball, until it arrests itself at the border of the iris. Here, a day-5 chicken embryo is shown. Capillaries invade all organs, and they cover the retinal area (*magnified image*). The capillary plexus does not propagate to the lens likely because of the gap separating the boundary of the ectodermal fold of the eye ball and the lens. Therefore, lens transparency is in part a consequence of eye geometry. Bottom: in vivo image of a day-4 chicken eye showing the fold of the edge of the eyecup. The lacrimal orifice finds itself in the deep groove of the conjunctival fornix, where the ectoderm is folded on itself.

of inductive events will either remain inside a single mass (leading to one single eye but a bigger eye), located along the median axis, or be split into two masses, depending on the viscoelasticity of evagination, coupled to the timing of the ectodermal contact leading to the differentiation of the lens placode. But this is of course a very complex 3D problem, with ectoderm so much folded that it acquires this “peanut” shape, that it cannot be treated exactly without finite elements or the like. It will require doing an entire 3D simulation of the several ectodermal shells, themselves folded, including the differentiation feedback at the point of contact of ectodermal layers, with apical constriction occurring at the point of differentiation.

The entire transition, between a cyclopic animal and a stereoscopic ocular system on a bilateral animal, seems deeply rooted in the viscoelasticity of tissue flow, and the induced mechanotransduction and differentiation at the growing interfaces.

Still, the mechanotransduction event does require that the inductive event, although mechanical in nature, triggers the formation of lens tissue with specific optical qualities, as we know them. The lens is transparent, thanks to the absence of extracellular matrix (ECM), absence of blood vessels, “crystalline” order of cells and production of a protein “crystalline” (Piatigorsky and Wistow, 1989). It is possible that the formation of a spherical placode from an invaginating ectoderm automatically separates blood vessels and ECM by the formation of a topological boundary, and that there is a deep link between eyecup folding and lens transparency. In effect, the eye choroid plexus of endothelial cells reaches the eye from the back and progressively covers the eye ball starting from the optic nerve area, arresting itself around the lens boundary (Fig. 20).

There is therefore a geometrical contribution to the arrest of endothelial cells around the lens. However, in addition, evidence exists that the differentiation pathway for endothelial cells is specifically inhibited in the eye, to keep them transparent (Cursiefen et al., 2006). Therefore, the transparency of the eye is the result of both physical, material issues and of localized differentiation pathways (with Pax6 as main master gene), but these differentiation pathways would not be localized, in the absence of the physical movements which created a local niche, in the form of a round cavity. Recent large-scale DNA-chip analysis of 24,000 genes (Wolf et al., 2009) has revealed 559 genes related to Pax6, and about 10 genes directly controlled by Pax6. Nevertheless, in situ immunohistology clearly shows that the Pax6 gene is expressed in conjunction with the invagination dynamics, therefore coupling the apical constriction wave to the differentiation wave. This differentiation wave, in this specific case, seems to have a very narrow bottleneck, through the Pax6 pathway.

## 6.2. THE HEART

In the previous part, in Fig. 10, we prepared the reader for the complex problem of heart morphogenesis and differentiation. The presumptive territory for the heart is a so-called cardiogenic territory or “heart-forming field” (Hoogaars et al., 2007), which progressively takes the shape of a folded and twisted set of tubes. However, it is not so clear how this set of tubes forms, and how the form is related to the function. It has long been known that heart development goes hand in hand with its contractile behaviour (Taber, 2006). It is even known that important growth factors for heart formation are mechanosensitive (Schultz et al., 1999). At the same time, the spatial and temporal organization of the important transcription factors of the heart, especially Tbx5, has been obtained (Liberatore et al., 2000). However, it is only recently that the dynamics of heart formation has started to be understood, and it shows a remarkable interplay with the differentiation of the heart transcription factors.

In brief, the cardiogenic territory would never form a heart without the complex folding, twisting and looping movements of the tissue. However, in vivo time-lapse microscopy shows that these movements originate in the overhang of the gut pocket over the blastula plane (Boryskina et al., 2011). When the bidirectional movements of embryo extension occur, the median axis shears the underlying endoderm and starts to overhang over the blastula plane. This forms the edge of the so-called gut pocket. As this edge constricts, it moves posteriorly and rakes progressively all the tissues along the median axis, and especially the visceral mesoderm (Figs. 10 and 21).

The movies for this phenomenon, as obtained in vivo, are quite spectacular. Figure 21 shows a 90-min time lapse of the constriction of the edge of the gut pocket. This phenomenon is very dynamic, and the pattern of expression of transcription factors cannot be understood, if one neglects the quite rapid

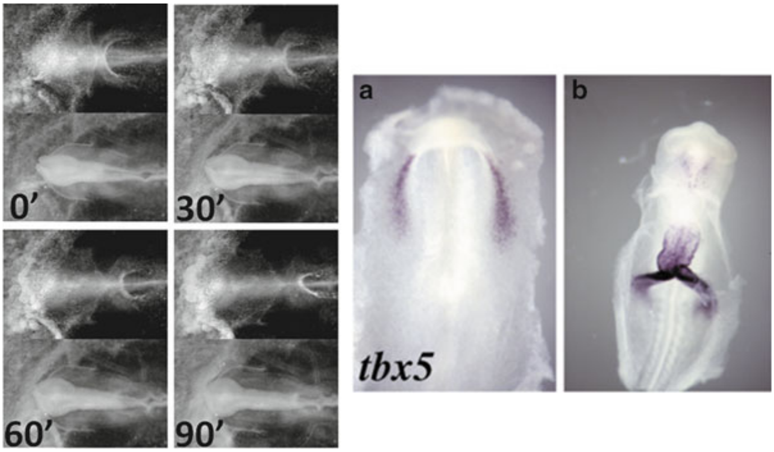

**Figure 21.** *Left*, in vivo time lapse of the constriction of the edge of the gut pocket. The dorsoventral imaging allows one to observe the concomitant closure of the nasal pit on the other side and the evagination of the eyecup. In the meantime, the heart forms by constriction of the ventral endoderm that wraps the visceral mesoderm. To the *right*, staining of the important cardiac transcription factor Tbx5 at different stages (about 5 h apart) shows that it is associated with the dynamics of the constriction (From Liberatore et al., 2000, with permission).

constriction "like a purse" of the edge of the gut pocket. As it constricts, the edge of the gut pocket rakes the visceral mesoderm towards the median axis and rolls it up into the heart itself and its omphalomesenteric veins. Again, it is an instance where the spatial expression of transcription factors cannot be understood without addressing the displacement field which positions the material of the heart. But this displacement field is itself a consequence of the pattern of forces, which is in turn dependent on the genetics of the contracting cells. A remarkable fact in this context is that the constriction of the gut edge, which generates the heart, occurs at a constant speed (Fleury, 2011). Therefore, given the topology of the gut pocket, it is possible that by simply changing the magnitude of the contraction forces, different organs, more or less twisted, are generated (think of the string of a purse).

The study of the interplay of heart mechanics and differentiation will certainly be an important topic in the forthcoming years.

## 7. Conclusion

We have come to the problem of embryogenesis from two different points of view: mechanics of morphogenesis first, with differentiation as an afterthought (VF), and differentiation first, driven by an observable but unexplained mechanics (RG).

Now, we will attempt to put these ideas together. The result will be tentative because we have worked on mostly different stages of different vertebrate organisms (VF: chick; RG: urodele amphibian).

First, then, let us consider the view summarized as "The Hierarchical Genome and Differentiation Waves" (Gordon, 1999). A differentiation wave is an easily observable (Gordon and Björklund, 1996) wave of contraction or expansion of the apical surface of an epithelial tissue. We found a nearly one-to-one correlation between differentiation waves and the classically defined differentiated embryonic tissues, in investigations carried up to neural tube closure (Björklund and Gordon, 1994; Gordon et al., 1994). We concluded that each tissue at a given stage of embryogenesis is split by a pair of waves, one contraction wave and one expansion wave, into two new tissues. Each cell in that tissue then becomes one of two new cell types, triggered by participation in the particular wave type. We identified a cytoskeletal apparatus at the apical end of each epithelial cell, consisting of a microfilament ring, a coplanar microtubule mat (Gordon and Brodland, 1987), and an intermediate filament ring (Martin and Gordon, 1997), that we called the cell state splitter. We assigned two roles to the cell state splitter: (1) propagation of the waves of contraction (driven by the microfilament ring) or expansion (driven by the microtubule mat) and (2) sending a one-bit signal to the nucleus indicating that the cell had just participated in a contraction or expansion wave. Our working hypothesis is that, at a given stage in embryogenesis, the nucleus has two pathways available, and that a contraction wave triggers one of these pathways, while an expansion wave triggers the other. One of two new subsets of genes is thus made available for gene expression, while all other genes are sequestered. We called this process, and the readiness of the nucleus, the nuclear state splitter (Björklund and Gordon, 1993). Now, except for syncytial cells such as striated muscle, all the cells in the body can be traced back to the fertilized egg in a bifurcating tree called the cell lineage tree. These are somehow bundled into tissues (Gordon, 2011), which are like cells. Our hypothesis is that it is the differentiation waves that accomplish this bundling, spatially determining which cells become which kinds. This bundling results in what we call the differentiation tree for an organism (Gordon et al., 1994).

What we could not explain is how differentiation waves are initiated and terminated. In the case of the neural plate, the pharyngeal endoderm makes contact underneath the monolayer ectoderm, doubling its thickness and, we could hypothesize, creating a spot of mechanical imbalance, launching a differentiation wave (Gordon and Brodland, 1987). Termination of this contraction wave was observed to be by self-annihilation, as it closed down to a point roughly opposite to the launching point (Brodland et al., 1994). This led us to suggest that differentiation waves act precisely as waves in active media, but since they change the state of the material through which they travel, they are also kink waves (Gordon, 1999).

In order to bring our disparate approaches together, we need to explain at least the following:

1. Can the launching of differentiation waves be attributed to singularities in the mechanics of morphogenesis?
2. Can the propagation of differentiation waves be fit into the formalism developed here for the propagation of viscoelastic, morphogenetic waves?
3. Can the speed of differentiation waves (around 3 μm/min) be reconciled with morphogenetic waves?
4. Can the halting of differentiation waves be predicted as mechanical phenomena?
5. What is the role of mechanical stress, if any, in determining the trajectory of a differentiation wave? For example, the ectoderm contraction wave that leaves the axolotl neural plate in its wake travels faster at the edges than the middle, perhaps due to increased stress caused by the continuing involution of ectoderm over the dorsal lip of the blastopore (Fig. 22).
6. Is it part of the behaviour of differentiated cells to alter their mechanics, perhaps by setting up a new metastability of their cell state splitters, so that they "prepare" for the next round of differentiation?
7. The model based on differentiation waves does not invoke gradients or growth factors at all, each cell acting autonomously in its response to participating in a contraction or expansion wave. Changes in gene expression (transduction factors, etc.) are caused by the waves in a one-bit signal from the cell state splitter to the nucleus. Can we sort out whether gradients play any role?
8. The ectoderm contraction wave in axolotls traverses a monolayer of cells overlaying the archenteron, and thus, there is no mesoderm beneath them. Does this mean that the role of growth factors such as FGF is secondary, in the sense that it applies only to later tissues? If so, do cell state splitters exist in those later tissues or is their function replaced by growth factors?
9. Is competence merely mechanical or is there a nuclear state splitter ready in each cell that is in a specific state of differentiation that, under the right mechanical conditions, transitions to one of two possible new states of differentiation?
10. The mechanics view of differentiation focuses on singularities (0D) and lines (1D) of stress, which led to our conclusion that undeformed living material will not undergo morphogenesis, neither differentiation. Perhaps, a differentiation wave should be looked upon as a propagating deformation that permits a 2D region of tissue to differentiate, not just 0D and 1D regions.

One of us faced this situation before, in an attempt to reconcile the morphomechanics of Lev Beloussov (Beloussov, 1998) with differentiation waves (Gordon, 2006). Now, we have three approaches to embryo physics that need to be reconciled. Part of the difficulty is that each group chose a different model organism: *Xenopus laevis*, an anuran amphibian (LB); chick (VF) and *Ambystoma mexicanum*, a urodele amphibian (RG). Future work had best proceed by focussing

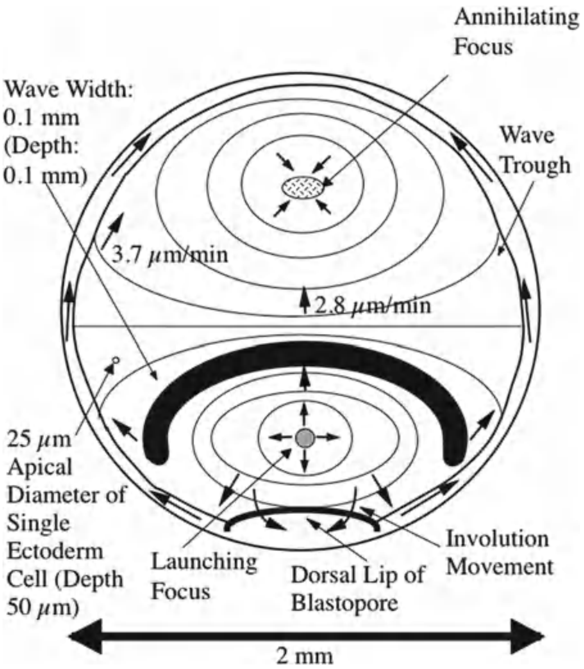

**Figure 22.** The ectoderm contraction wave in the axolotl takes about 12 h to traverse the dorsal ectoderm, starting at the end of gastrulation. The tissue it passes through differentiates to neuroepithelium (neural plate). The wave travels as a furrow from one focus to another, 0.1 mm wide and deep, across the 2-mm diameter embryo, as if it were bent by gradient index optics. It is launched or initiated at one focus where the ectoderm is touched by the involuting pharyngeal endoderm and self-annihilates at the other focus. *Curved lines* show the bottom of the furrow at 1-h intervals. The *curved, black bar* shows the width of the furrow at 3 h after it started. Most of the dorsal ectoderm is underlain by a water-filled chamber called the archenteron and so is not in contact with mesoderm. It is one-cell layer thick (Redrawn from Gordon et al., 1994).

on one model organism. Imaging approaches that permit the position, shape and mitosis history of every cell, such as Google Embryo (Gordon, 2009; Gordon and Westfall, 2009), may help unravel these questions.

## 8. Origin of Design

The self-construction of organisms is the quintessential design problem. It is the heart of the conflict between creationists and anti-creationists (Gordon, 2008; Seckbach and Gordon, 2008), going back at least to William Paley (Paley, 1802). Although the apparent number of taxa is high in the biosphere, the number of phyla is small (Valentine, 2004). Darwin himself considered that all animal plans could be boiled down to about “4 or 5” plans. The typical form or organization plan of an animal might be fixed by the topology of the singularities in the early movements occurring on the fertilized ovocyte, such as a hyperbolic point for tetrapods, a hedge-hog point for radiates, etc. The number of such singularities is finite.

Next, the convergence of the biomechanical study of embryo folding and of the cellular study of differentiation is encapsulated in the dichotomous nature of differentiation, and the dichotomous nature of viscoelastic buckling. During buckling, the tissue is split into stressed and non-stressed areas. This locks the states of differentiation spatially to corresponding areas, also with the help of mechanically oriented cell division. The intrinsic coupling of morphogenesis and differentiation is deeply rooted in the fact that stress has an impact on geometry *and* on gene expression. This renders the problem of development intrinsically non-linear. If we are right in thinking we are hot on the tail to the problem of how an embryo builds itself, "the miracle of birth" (Bryan et al., 1994), we may bring the question of design to the same status as the "breath of life", which was reduced to respirology (Sebel, 1985).

## 9. Acknowledgements

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Biodata of **Joel K. Yisraeli**, author of "***Interior Cell Design: VICKZ Proteins Mediate RNA Localization and Cell Function***."

**Joel K. Yisraeli** is currently the chair of Undergraduate Studies for Biomedical Sciences, Institute for Medical Research Israel-Canada, Hebrew University–Hadassah Medical School. He obtained his Ph.D. from the Hebrew University in 1986 and did a postdoctoral fellowship at Harvard University. Professor Yisraeli is interested in the fields of RNA localization, generation of polarity and axis formation during embryonic development, cell motility, and the role of RNA binding proteins in cancer.

E-mail: **yisraeli@cc.huji.ac.il**

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# INTERIOR CELL DESIGN: VICKZ PROTEINS MEDIATE RNA LOCALIZATION AND CELL FUNCTION

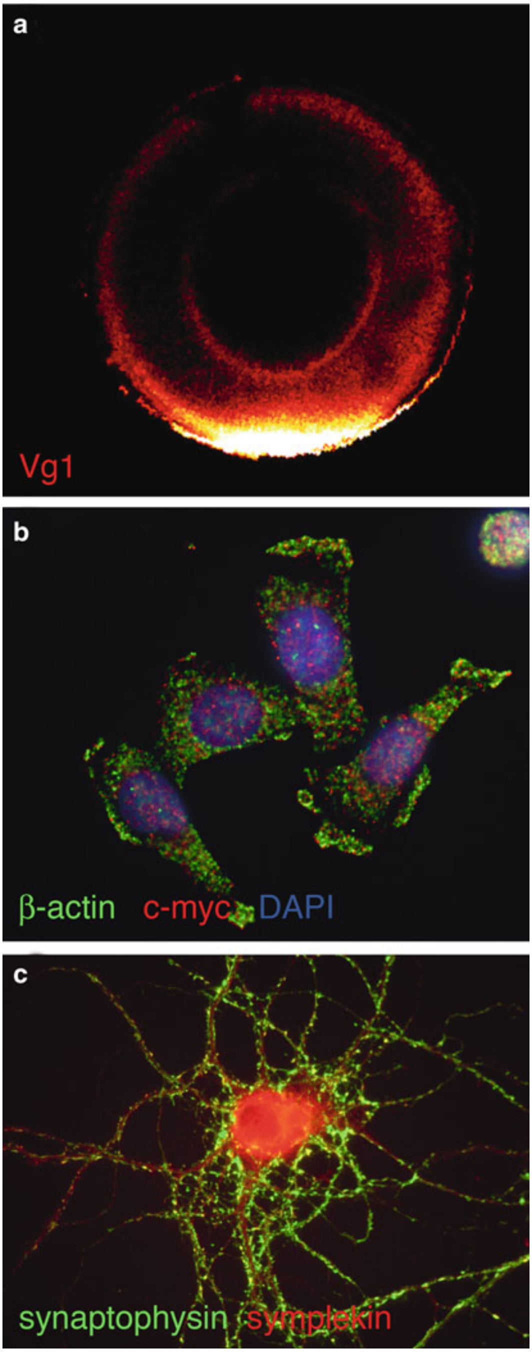
**JOEL K. YISRAELI**
*Department of Developmental Biology and Cancer Research, Institute for Medical Research – Israel-Canada, Hebrew University-Hadassah Medical School, Jerusalem, Israel*

## 1. Introduction

As methods for examining the inner structure of the cell improve, the exquisite organization present in every cell becomes even more pronounced. Not only is the position of organelles within the cell carefully regulated, but compartmentalization and trafficking of many different molecules also play a critical role in the proper function of the cell. Most cells demonstrate some sort of polarity (see Fig. 1). For example, in the epithelial cells of the gut, the apical surface faces the lumen, forms microvilli, and functions in the carefully controlled uptake of nutrients; the basal-lateral surfaces contain unique molecular markers and form cell–cell junctions. Migrating cells demonstrate a very different polarity, generally forming a leading edge with a broad lamellipod and a ruffled membrane, while the trailing edge detaches from its contact with the substrate. This polarity tends to be very dynamic, but nevertheless, localization of molecular markers at one side of the cell or the other can be clearly observed.

Localization of molecules within a cell can be achieved in different ways. Vesicles, containing various cargoes, are trafficked, based on the molecules on their surface, either inwards from the plasma membrane or outwards from endoplasmic reticula (ER) to Golgi and then to the plasma membrane. Proteins can be shuttled to various intracellular sites within the cytoplasm, as well as into and out of the nucleus. RNA molecules are initially transported from their sites of transcription out of the nucleus, and then can be localized to specific cytoplasmic organelles or targets. All of these movements involve the use of various elements of the cytoskeleton, generally coupled with molecular motors and coupling proteins that help mediate the association between the localized molecule and the cytoskeletal elements being used. Thus, the interior design of the cell is a result of a large number of mechanisms occurring more or less independently and in a very dynamic fashion.

In this chapter, I will focus on one family of RNA binding proteins, termed the VICKZ proteins, as a paradigm for understanding how molecules can be localized within cells and how this localization can affect cell function. Although most of the work mentioned here will be from vertebrate systems, many of the


a
Vg1
b
β-actin c-myc DAPI
c
synaptophysin symplekin

ideas apply to a large number of invertebrate systems as well. Many of the design principles at work in somatic cells appear to be very similar to those in germ cells and in the cells of developing embryos from virtually all species examined, perhaps reflecting an underlying conservation of the cytoskeletal elements and molecular mechanisms involved.

## 2. Discovery of the VICKZ Proteins

As is often the case, a number of different groups, interested in very different questions, independently discovered proteins that were all members of the same family, in a short space of time. The first member of the family to be reported was the ZBP1 protein (*z*ipcode *b*inding *p*rotein 1), which was identified on the basis of its specific binding to the element in β-actin mRNA (termed the zipcode) previously shown to be responsible for directing the localization of the RNA to the leading edge of migrating chick embryo fibroblasts (Ross et al., 1997). Within the space of a few months, a group looking for proteins overexpressed in pancreatic carcinomas reported cloning a protein they called KOC (*K*H domain containing protein *o*verexpressed in *c*ancer) (Mueller-Pillasch et al., 1997). This protein turned out to be the first human paralog of the family to be cloned, but the connection was not realized initially due to the inadvertent omission of the ZBP1 protein sequence from the GenBank. The following year, in two almost simultaneous publications from different groups, a *Xenopus* RNA binding protein, termed Vg1 RBP (*Vg1* mRNA *R*NA *b*inding *p*rotein; Havin et al., 1998) or Vera (*V*gLE binding and *ER a*ssociation; Deshler et al., 1998), was shown to be a highly conserved homolog of both ZBP1 and KOC, thus placing all of these proteins into the same, highly related family. In rapid succession, other members of the family were identified, based on different screens. A mouse homolog, CRD-BP (c-myc *c*oding *r*egion *d*eterminant-*b*inding *p*rotein) stabilizes c-myc mRNA by binding to a sequence within the coding region of the transcript (Doyle et al., 1998). Three highly related human paralogs, termed IMP1, 2, and 3 (*I*gf2-like *m*RNA binding *p*rotein), were identified by their ability to inhibit the translation of Igf2 mRNA (Nielsen et al., 1999). Sera from patients with various kinds of cancer were found to contain antibodies against one or more of the human homologs (Zhang et al., 2003; Zhang et al., 1999a). All of these proteins were highly related to each other (78% amino acid identity from frogs to humans), indicating that these proteins all

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**Figure 1.** Examples of polarized cells. (**a**) Stage IV *Xenopus laevis* oocyte hybridized with a probe for Vg1 mRNA. The RNA is localized at the vegetal cortex of the oocyte (at *bottom* in figure). (**b**) Fluorescence in situ hybridization of TSU-Pr bladder carcinoma cells using a β-actin probe (*green*) and a c-myc probe (*red*). The nuclei are labeled with DAPI (*blue*). β-Actin mRNA localizes to the leading edge and periphery of cells. (**c**) A rat primary hippocampal neuron stained for synaptophysin, a presynaptic marker (*green*), and symplekin, a scaffold protein for the cytoplasmic polyadenylation machinery (*red*). (Courtesy of Joel Richter, University of Massachusetts Medical School.)

belong to one evolutionarily conserved family. In this chapter, I will refer to this family as the VICKZ proteins, based on the first letters of the founding members of the family (Yaniv and Yisraeli, 2002); the NCBI refers to these proteins as Igf2bp (Igf2-like mRNA RNA binding proteins) 1, 2, and 3.

## 3. Molecular Functions of VICKZ Proteins

It is clear from the above description that the VICKZ proteins can interact in several different ways vis-à-vis their target RNAs. In a number of systems, such as embryonic fibroblasts, oocytes, and neurons, VICKZ proteins bind to specific mRNAs and help localize these RNAs to particular sites within the cell (Eom et al., 2003; Leung et al., 2006; Lewis et al., 2008; Oleynikov and Singer, 2003; Yao et al., 2006). Generally depending on the size of the cell, different cytoskeletal elements are employed. In large cells, such as oocytes and neurons, VICKZ proteins associate their RNA targets with microtubules, in complexes that contain microtubule motors. In smaller cells, such as fibroblasts, the VICKZ-RNA complexes associate with microfilaments, and their movement is mediated by myosin. Although VICKZ proteins clearly play a role in the directed transport of these RNAs, whether or not these proteins are involved in anchoring the mRNAs at their sites of localization remains an open question.

By virtue of their ability to bind to cis-acting elements in transcripts, VICKZ proteins can also stabilize RNAs. Mouse VICKZ1 was cloned through its ability to stabilize c-myc mRNA via binding to an element in the coding region (Doyle et al., 1998), and siRNA-mediated knockdown of VICKZ1 in MCF-7 breast cancer cells as well in ES-2 ovarian carcinoma cells indeed reduces the stability or half-life of c-myc mRNA (Ioannidis et al., 2005; Kobel et al., 2007). The stability of CD44 mRNA, as well as a number of other mRNAs encoding molecules associated with cell adhesion, invasion, and migration, was downregulated by knocking down VICKZ1 and VICKZ3 in HeLa cells (Vikesaa et al., 2006). VICKZ1 was also shown to stabilize βTrCP1 mRNA, which encodes an E3 ubiquitin ligase, in colorectal carcinoma cells (Noubissi et al., 2006). Recently, the mechanism for this stabilization was described; VICKZ1 binding of βTrCP1 mRNA in its coding region prevents the hybridization of miR-183 to its target region, which overlaps the VICKZ1 binding site (Elcheva et al., 2009). This may be a general mechanism by which VICKZ proteins can upregulate stability.

Translational regulation is a third way in which VICKZ proteins can interact with their targets. VICKZ binding to multiple sites in the 5′UTR of Igf2 mRNA inhibits translation of the message in rhabdomyosarcoma cells as well as NIH 3T3 cells (Nielsen et al., 1999). Localization and translational control may also be coordinated by VICKZ proteins. In a series of elegant experiments in neuroblastoma cells, β-actin mRNA translation initiation was shown to be repressed by VICKZ1 binding, and this inhibition was released by Src phosphorylation of VICKZ1. Src and VICKZ1 interact at the cell periphery near sites of filopodia formation, suggesting that β-actin mRNA is translationally silenced by VICKZ1 while being transported to the periphery of the cell, where its translation is then activated by Src phosphorylation of VICKZ1 (Huttelmaier et al., 2005).

It should be noted that the cellular context may play a very important role in determining which of the various molecular functions of VICKZ proteins is active on a given mRNA. In addition, the proteins may combine more than one function. Thus, the same mRNA may be stabilized by VICKZ proteins in one cell type but not in another, and its translation may also be regulated or not, independent of the effects of VICKZ binding on its stability. As mentioned, intracellular localization can be coupled with translational control, and regulation of turnover of the message can be combined with trafficking, as well. Also, much of the work that has been done until now has not compared the potential differences among the three paralogs. The fate of an mRNA that is a target of the VICKZ proteins is therefore a complicated function involving a large number of parameters, only some of which are currently understood.

## 4. Cellular Functions of VICKZ Proteins

Given the complexity of molecular functions that are associated with VICKZ proteins, it should come as no surprise that there is an ever-growing list of cellular functions with which VICKZ proteins are involved. Mainly through the use of RNAi-mediated knockdowns, and embryonic knockouts, it has been possible to identify a number of different cellular processes in which VICKZ proteins play a role.

### 4.1. CELL MOTILITY

One of the first indications that the intracellular localization of RNA molecules could be involved in helping regulate cell movement came from the seminal observation that β-actin mRNA is localized to the leading edge of migrating chick embryo fibroblasts (Lawrence and Singer, 1986). Disruption of the localization of β-actin mRNA to the leading edge, using antisense oligonucleotides directed against the zipcode sequences in the message, causes a loss of persistence of motion of the cell (Shestakova et al., 2001). These, and many other, experiments gave rise to the hypothesis that the continued movement of a cell in a particular direction could be enhanced by increasing the amount of β-actin mRNA, and hence, β-actin protein, at the leading edge – a sort of mass action effect (Condeelis and Singer, 2005). A corollary of this hypothesis is that interfering with the mechanism of localizing the RNA, such as by inhibiting the binding proteins that help mediate localization, would also cause a similar effect on cell movement.

In vivo evidence for the importance of VICKZ proteins in cell movements came from work with *Xenopus* embryos. A single VICKZ paralog (xVICKZ3) is present in frog embryos (Deshler et al., 1998; Havin et al., 1998) and expressed in many different cell types (Zhang et al., 1999b). In particular, neural crest cells are among the first cells expressing zygotic VICKZ protein, and these cells are characterized by extensive cell migrations throughout the embryo. Injection of antisense morpholino oligonucleotides (AMO) directed against VICKZ mRNA into both blastomeres at the 2-cell stage frog embryo caused a striking inhibition of movement of the neural crest cells (Yaniv et al., 2003). Although the cells expressed differentiated neural crest markers, they were unable to either delaminate from the neural tube or migrate after they were out. When neural tube segments were explanted at stages prior to neural crest migration from embryos injected with AMO, the few cells capable of exiting the tube were those neural crest cells that escaped the AMO knockdown. Thus, VICKZ protein appears to be required for migration of neural crest cells in *Xenopus* embryos.

In vitro experiments have demonstrated the importance of VICKZ proteins in the motility of a variety of different cell types and have provided some insights into what aspects of movement are involved. Invadopodia, protrusions of the cell through the extracellular matrix (ECM), are strongly correlated with cell invasion and metastasis in cancer cells and require expression of the hyaluronan receptor, CD44, for their formation (Bourguignon et al., 1998). When VICKZ1 and 3 are knocked down in HeLa cells (no VICKZ2 was detected in these cells), a reduction in cell adhesion and invadopodia is observed (Vikesaa et al., 2006). CD44 mRNA contains sites for VICKZ binding, and the VICKZ1,3 knockdown causes a reduction in the half-life of CD44 mRNA. Furthermore, VICKZ proteins and CD44 mRNA colocalize to invadopodia. Taken together, these data suggest that VICKZ proteins help stabilize CD44 mRNA and localize it to the site of invadopodia formation, enhancing invasion through the ECM. Overexpression of VICKZ1 in NIH-3T3 cells has been reported to increase invasion potential, as measured by a matrigel filter assay (Kato et al., 2007). A dominant negative construct of VICKZ has been generated, which lacks the last KH RNA binding domain and inhibits RNA binding of each of the three paralogs when expressed in the same cells (apparently as a result of forming an inactive heterodimer). This construct strongly inhibits cell movement in vitro when expressed in Tsu-Pr1 bladder carcinoma cells, using several different parameters (Oberman et al., 2007). All three paralogs were also inhibited in SW480 colorectal carcinoma cells using inducible shRNA constructs against the three genes; in this case, lamellipodia and ruffle formation, required for cell movement, were downregulated almost threefold (Vainer et al., 2008). In general, these experiments suggest that expression of VICKZ proteins, in a variety of transformed cells, is positively correlated with motility and invasion and that reduction of VICKZ protein expression can inhibit cell movement.

In this regard, however, there is an important caveat. In the case of the metastatic rat mammary adenocarcinoma cell line, MTLn3, the correlation between VICKZ expression and motility/invasiveness/metastasis appears to be reversed. These cells normally express very low levels of VICKZ1 and demonstrate high levels of chemotaxis towards an EGF-secreting pipette when viewed in vivo in primary tumors using a sophisticated multiphoton imaging system (Wang et al., 2004). Overexpression of VICKZ1 in these cells reduces their ability to invade into the collecting pipette or to metastasize from the primary tumor, leading these researchers to propose that VICKZ1 is suppressing metastasis and invasion in these cells. VICKZ1 does appear capable of inducing a persistence of motion in these cells, but this is postulated to work against the ability of these cells to respond to a chemotaxic gradient during invasion or metastasis (Lapidus et al., 2007). It remains to be seen how to understand these data in light of a large body of literature demonstrating strong correlations among VICKZ expression, poor prognosis, increased metastasis, and reduced survival (Findeis-Hosey and Xu, 2011; Findeis-Hosey et al., 2010; Hammer et al., 2005; Kato et al., 2007; Kobel et al., 2007; Schaeffer et al., 2010; Vainer et al., 2008; Yu et al., 2010).

## 4.2. NEURONAL FUNCTION

There is probably no cell in the body that demonstrates the importance of design and compartmentalization more than neurons. With axons that can extend more than a meter from the cell body, it is clear that there must be an elaborate mechanism for allowing functions to occur locally in a decentralized fashion. By trafficking mRNAs, proteins, and vesicles to specific locations along axons and dendrites, the neuron generates localized regions of autonomy.

VICKZ proteins play a central role in helping to direct mRNAs to particular locations in developing embryonic neurons and in regulating several different functions. In mice, as in frogs, VICKZ3 is expressed throughout much of the developing CNS in early neurulas, and its expression declines as neurons mature (Mori et al., 2001; Zhang et al., 1999b). Localization of β-actin mRNA into dendrites and at dendritic spines is activated by neuronal depolarization and is dependent on VICKZ1, and the VICKZ1-β-actin mRNA RNP is required for proper dendritic morphology and synaptic growth (Eom et al., 2003; Tiruchinapalli et al., 2003).

Perhaps the most striking example of the importance of VICKZ1 proteins in “cellular design” is in the role they play in regulating axon guidance. In embryonic chick forebrain neurons, VICKZ1 and β-actin mRNA localize in ribonucleoprotein (RNP) particles into axons and growth cones following NT-3 stimulation, and this localization is dependent on the presence of the zipcode sequence in the β-actin 3′UTR (Zhang et al., 2001). In growth cones of retinal axons, the VICKZ proteins present in β-actin mRNA-containing RNPs repress β-actin mRNA translation. When the axons are asymmetrically stimulated by attractive cues, such as netrin-1 or BDNF, these VICKZ–β-actin mRNA-containing RNPs are transported into filopodia on the near side of the stimulus, and translation is activated asymmetrically on that side, creating a local source of β-actin protein that triggers directed turning (Leung et al., 2006; Yao et al., 2006). More recently, localized Src phosphorylation of VICKZ1, on the BDNF-stimulated side, has been shown to be responsible for the localized release and translation of β-actin mRNA (Sasaki et al., 2010). Thus, VICKZ proteins play a pivotal role in patterning the nervous system through their intracellular functions of trafficking and translational regulation.

## 4.3. CELL VIABILITY AND PROLIFERATION

An additional cellular role for VICKZ proteins that has surfaced over the last few years is in helping regulate cell viability and proliferation. Although this role may not be directly connected to "design" principles, at least in a spatial sense, given its importance to the overall functioning of the cell, it is included here as well.

Knockdown experiments, particularly of VICKZ1, have demonstrated an important role for this protein in cell viability and growth. Decreased colony formation in soft agar, reduced uptake of $^3$H-thymidine, reduced cell number, and a reduction in the expression of a number of cell cycle regulator genes have all been attributed to reduced VICKZ1 expression in different neoplastic cell types (Boyerinas et al., 2008; Ioannidis et al., 2005; Kato et al., 2007; Kobel et al., 2007). Of particular interest is the observation that VICKZ1 mRNA is a target of the miRNA let-7g (miR-98) and that let-7g expression in A549 lung carcinoma cells induces growth reduction that is mainly mediated by VICKZ1 (Boyerinas et al., 2008).

A complicated network of potential significance has been described that involves the stabilization of βTrCP1 mRNA by VICKZ1 (Noubissi et al., 2006). βTrCP1 is an E3 ubiquitin ligase that recognizes, among other ligands, β-catenin and IkB, the inhibitor of NFkB. When IkB is degraded, NFkB enters the nucleus, is transcriptionally active, and inhibits apoptosis. These researchers found that β-catenin activates VICKZ1 transcription in colorectal carcinomas, triggering this cycle that leads to inhibition of apoptosis. As mentioned above, VICKZ1 can also stabilize c-myc mRNA, further enhancing cell viability and potential transformation. VICKZ1 appears to function in melanomas in a similar fashion (Elcheva et al., 2008). It is worthwhile remembering, however, that although transgenic mice overexpressing VICKZ1 in the mammary fat pad developed primary tumors at relatively high frequencies (95% and 60%, depending on the level of exogenous VICKZ1 expression), very few metastases formed, and no change in c-myc expression was detected above wild-type levels (Tessier et al., 2004). Therefore, the relative importance of this network remains to be determined.

It has been postulated that much of the effect on cell viability seen in the VICKZ knockdowns may be due to effects on Igf2 expression. In this regard, a VICKZ1 knockdown in human K562 leukemia cells has been reported to cause an increase in cell proliferation due to an increase in Igf2 expression (that is mediated by increased Igf2 mRNA but not increased translation rates) (Liao et al., 2004). The same group has also reported that a VICKZ3 knockdown in the same cell line causes a decrease in cell proliferation due to reduced Igf2 mRNA translation (Liao et al., 2005). Clearly, work still needs to be done to understand the cell-specific effects of the various VICKZ knockdowns, especially given the apparently large number of potential VICKZ targets (Hafner et al., 2010; Jonson et al., 2007).

## 5. VICKZ Proteins as Interior Designers: Integrating Molecular and Cellular Functions

A general model is emerging for how mRNAs are trafficked within cells and achieve their ultimate destinations. From their site of transcription, nascent transcripts appear to diffuse through channels within the nucleoplasm until they come to a nuclear pore through which, if the pore is available (i.e., not in use), the transcript will pass in under a second (Mor et al., 2010). Once in the cytoplasm, if the RNA needs to be transported over a large distance, such as in neurons or oocytes, microtubule-mediated transport via motor proteins is usually involved (Kiebler and Bassell, 2006). Shorter distances, however, appear to be transversed by a facilitated diffusion in which mRNAs may exhibit short, directed runs and then random walk kinetics; the presence of cis-acting localization sequences in the RNA appears to enhance the directed runs (Fusco et al., 2003). Most of the transcripts in the cytoplasm, however, exhibit predominantly diffusive behavior, and by a purely stochastic model, this can also account for the translocation of mRNAs to their site of translation (Ben-Ari et al., 2010). Cis-acting localization sequences, however, are also required for this movement (Shestakova et al., 2001). All in all, from the start of transcription until the mRNA reaches its cytoplasmic target, the process takes about 20–30 min (Ben-Ari et al., 2010).

By virtue of accompanying mRNAs throughout this process, VICKZ proteins assist in the interior design of cells and thereby play a role in their physiology. VICKZ proteins are recruited to the transcription site of nascent transcripts in the nucleus, where they appear to be loaded onto the transcript, most likely in conjunction with other proteins (Oleynikov and Singer, 2003). Once in the cytoplasm, VICKZ RNPs may undergo remodeling, with changes or reorganization of the RNA-protein interactions (Lewis et al., 2008). Through their regulation of RNA stability, translation, and localization, VICKZ proteins help determine where and when the proteins encoded by their cargo mRNAs are expressed. Thus, compartmentalization of protein expression, an essential component of functioning cells, is achieved, at least in part, through the action of VICKZ proteins.

## 6. Final Comments

The VICKZ protein family is a paradigm for how RNA binding proteins in general can play a crucial role in regulating cell function. Given the large number of RNA binding proteins present in the genomes of both invertebrates and vertebrates, and that any mRNA transcript is likely to be a target for at least several different proteins, one can envision a complex, combinatoric network of RNA-protein interactions throughout the cell. During *Drosophila* development, it is estimated that almost 70% of all RNAs demonstrate some sort of asymmetric distribution within cells (Lecuyer et al., 2007). Cells, therefore, appear capable of intricate levels of organization, combined with delicate, compound local control of expression. The final, functional output for each mRNA (e.g., translation, stability, localization) then becomes a complicated function reflecting the array of binding proteins with which it is associated and the signals that are received from its local environment, a concept that has been termed a “post-transcriptional operon” (Keene and Tenenbaum, 2002).

As any good theory does, this model opens up as many or more questions than it answers. Focusing just on the VICKZ protein paradigm, the catalog of mRNAs empirically shown to be bound by each VICKZ paralog remains a matter of some debate, and if, and how, this may vary in different cells. In light of the “promiscuity” of VICKZ binding, it has been very difficult to determine the precise mechanism by which a given VICKZ paralog affects the function encoded by a particular mRNA target. It remains a fascinating question to understand how the mechanisms for RNA localization can yield such highly asymmetric, well-defined distributions when the translocation process appears to be so stochastic (Messitt et al., 2008; Zimyanin et al., 2008). Interactions among the VICKZ paralogs, as well as with other RNA binding proteins, need to be well understood in order to begin to predict, for any given mRNA, where it will go within the cell and what will be its fate. Posttranslational modifications of VICKZ proteins resulting from extracellular signaling represents a powerful way of integrating external cues with regulation of expression, and these changes are only beginning to be understood.

Understanding the principles of interior cell design is at once awesome, intimidating, and challenging but is likely to hold the keys for discovering important solutions to diseases and syndromes in which the design has somehow gone awry.

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Biodata of **Marcello Barbieri**, author of "***Organic Codes and the Origin of Language***."

**Marcello Barbieri** (born 1940) is professor of embryology at the University of Ferrara, Italy. He has conducted research on embryonic development and ribosome crystallization at the Medical Research Council in Cambridge, UK; the National Institutes of Health in Bethesda, USA; and the Max-Planck-Institut für Molekulare Genetik in Berlin. He has published books on embryology and evolution and has taught biophysics, molecular embryology and theoretical biology, respectively, at the Universities of Bologna, Sassari and Turin. His research interests include embryology, evolution and biosemiotics. He is editor-in-chief of the journal *Biosemiotics*, co-editor of the Springer Book Series in Biosemiotics and president of the Italian Association for Theoretical Biology. His major books include *The Semantic Theory of Evolution* (1985), Harwood Academic Publishers, New York; *The Organic Codes. An Introduction to Semantic Biology* (2003), Cambridge University Press; *Introduction to Biosemiotics (ed.)*, 2007, Springer; *The Codes of Life (ed.)*, 2008, Springer.

E-mail: **brr@unife.it**

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# ORGANIC CODES AND THE ORIGIN OF LANGUAGE

**MARCELLO BARBIERI**
*Dipartimento di Morfologia ed Embriologia, Via Fossato di Mortara 64-A, 44121 Ferrara, Italy*

## 1. Introduction

There is a large consensus, today, on two general conclusions about language. One is that language is a biological phenomenon. The other is that language has been a product of evolution. As soon as we move beyond these preliminaries, however, the consensus immediately breaks down, and what we have is a bewildering variety of hypotheses, models and scenarios on virtually every issue concerning language. The nature of language, to start with, is still the object of endless controversies; the origin of language continues to be the target of free-ranging speculations, and the debate on the evolution of language remains locked into the *nature-nurture* contraposition. Here it is shown that some progress can be made in all three issues. On the nature of language, we can combine the insights provided by Biolinguistics and Biosemiotics and, in particular, by Noam Chomsky and Thomas Sebeok. On the origin of language, it will be shown that the very considerable evidence which has been gathered on human *anatomy* leads inevitably to a specific scenario and makes it no longer true that '*anything goes*' in this field. Finally, it will be shown that the discovery of many organic codes in life has direct and radical implications on the evolution of language. These points will be developed in stages, and to this purpose, this chapter has been divided into three parts, dedicated respectively to the nature, the origin and the evolution of language.

## 2. Part 1

### 2.1. ON THE NATURE OF LANGUAGE

#### *2.1.1. The First Step*

The idea that man is different from animals is present in all cultures and is generally expressed by saying that only man has 'higher' faculties like consciousness, free will, morality and the creative power to produce art, religion, science and poetry (together with torture, mass murder and environmental disasters). Today, we have a shorter explanation for all that. All we need to say is that only man has 'language'. The rest is just a consequence of that one faculty, so it is the origin of language that we need to understand if we want to find out what made us human.

Anything in science, however, must be accounted for, including the sweeping generalization that we have just encountered. Are we really sure that 'only man has language' and that animals do not have simpler forms of language? Granted that animals do not talk like we do, they are certainly capable of communicating with each other, often in highly sophisticated ways, so it seems reasonable to conclude that language is just an evolved form of animal communication. More powerful, yes, but not *qualitatively* different. This is indeed a possibility, but we should not take it for granted because we have learned that genuine novelties did, occasionally, appear in the history of life.

We have therefore a first problem before us: is there a qualitative difference between language and animal communication? And if the answer is yes, what does the difference consist in? This is the first question that we need to address about language. There are many other queries after that, but we must deal with that issue first because it is a precondition for all the other steps.

### *2.1.2. The Uniqueness of Language*

Animals receive signals from the world, transform them into mental (or neural) images and perform operations on these images that allow them to mount a reaction. When the signals come from other animals, the reactions can start new rounds of processing and give origin to an exchange of messages that we call 'communication'. The key point is that animal communication usually depends on context, learning and memory, which shows that animals are capable of interpreting the incoming signals. Interpretation, in turn, is an act of semiosis, i.e. an activity based on signs, because the link between signals and responses is not determined by physical necessity but by a looser connection, by a less deterministic relationship.

According to Charles Peirce, there are three main types of signs in the world, and therefore three types of semiosis (Peirce, 1906). The three types of signs are referred to as *icons*, *indexes* and *symbols*, and the processes that are based on them are known respectively as iconic, indexical and symbolic processes. In animals, they can be described in the following ways:

1. A mental image is an *icon* when it is associated with another mental image because a *similarity* is established between them. All trees, for example, have individual features, and yet they also have something in common, and this leads to a mental generalization that allows us to recognize as a tree any new specimen that we happen to encounter. Icons, in other words, lead to pattern recognition and to mental categories, and these are the basic tools of perception.
2. A mental image is an *index* when it is associated with another mental image because a *physical link* is established between them. We learn to recognize any new cloud from previous clouds, and any new outbreak of rain from previous outbreaks, but we also learn that there is often a correlation between clouds and rain, and we end up with the conclusion that a black cloud is an index of rain. In the same way, a pheromone is an index of a mating partner, the smell

of smoke is an index of fire, footprints are indexes of preceding animals, and so on. Indexes, in short, are the basic tools of learning, because they allow animals to infer the existence of something from a few physical traces of something else.

3. A mental image is a *symbol* when it is associated with another mental image because a *conventional link* is established between them. There is no similarity and no physical link between a flag and a country, for example, or between a name and an object, and a relationship between them can exist only if it is the result of a convention. Symbols allow us to make arbitrary associations and build mental images of future events (projects), of abstracts things (numbers) and even of non-existing things (unicorns).

The idea that language is based on arbitrary signs, or symbols, is, in our times, the legacy of Saussure, whereas the idea that animal communication is also based on signs has been introduced by Sebeok and is the main thesis of *zoosemiotics*. This extension of semiosis to the animal world, however, has not denied the uniqueness of language. On the contrary, it has allowed us to reformulate it in more precise terms. Such a reformulation was explicitly proposed by Terrence Deacon in *The Symbolic Species* with the idea that animal communication is based on icons and indexes whereas language is based on symbols (Deacon, 1997).

Today, this is still the best way to express the uniqueness of language. It is true that some examples of symbolic activity have been reported in animals, but in no way, they can be regarded as simple languages or intermediate stages towards language. Deacon's criterion may have exceptions, but it does seem to contain a fundamental truth. A systematic use of symbols at the basis of our behaviour is indeed what divides human language from animal communication, and we need therefore to account for that divide. Why were animals unable to go beyond icons and indexes? Why did not they learn to make an extensive use of symbols?

### *2.1.3. Two Modelling Systems*

All animals build internal representations of the world, and this is usually expressed by saying that they have a 'modelling system', a means of constructing mental (or neural) images of the surrounding environment. The discovery that our perceptions are produced by our brains implies that we live in a world of our own making, and this has led to the idea that there is an unbridgeable gap between mind and reality. Common sense, on the other hand, tells us that we better believe our senses, because it is they that allow us to cope with the world. Our perceptions 'must' reflect reality; otherwise, we would not be able to survive. François Jacob has expressed this concept with admirable clarity: '*If the image that a bird gets of the insects it needs to feed its progeny does not reflect at least some aspects of reality, there are no more progeny. If the representation that a monkey builds of the branch it wants to leap to has nothing to do with reality, then there is no more monkey. And if this did not apply to ourselves, we would not be here to discuss this point*' (Jacob, 1982).

Any animal has a modelling system that builds internal images of the world, and we have learned from Darwin that natural selection allows organisms to become increasingly adapted to the environment, i.e. increasingly capable of reducing the distance that separates them from *reality*. Natural selection, in other words, is a process that allows animals to catch increasing amounts of reality. This is because mental images are not about things, but about *relationships* between things, and have been specifically selected so that the relationships between mental images represent at least some of the relationships that exist between objects of the physical world. To that purpose, natural selection can definitely use relationships based on icons and indexes, because these processes reflect properties of the physical world, but it cannot use symbols, because symbols are arbitrary relationships and would increase rather than decrease the distance from reality. Natural selection, in short, is actively working *against* the use of symbols as a means to represent the *physical* world.

The world of an animal, on the other hand, does not consist only in the physical environment but also in other organisms, and its modelling system contains therefore models of physical relationships as well as models of psychological relationships. As we have seen, the models of the physical world are necessarily based on icons and indexes because these signs provide the means by which organisms adapt to the environment. The models of the psychological world, in turn, are also based on icons and indexes because these signs lead to pattern recognition, mental categories and learning, which are the basic tools of animal communication. This tells us that icons and indexes are all that was needed to build the physical and the psychological modelling system of animals, and natural selection favours both types of signs.

The animal modelling system, in short, is entirely based on icons and indexes, and the system that we have inherited from our animal ancestors has been referred to as the *primary modelling system* of our species. In addition to that, however, we have also developed a modelling system that is based on symbols and that has been referred to as the *second modelling system* of our species. It is precisely this second system that gave us language, and it is this system therefore that we need to understand.

### *2.1.4. The Semiotic Approach to Language*

Language is based on signs and is therefore an example of ‘semiosis’, or sign production. The study of language as semiosis – language is in fact the quintessential example of semiosis – started at the beginning of the twentieth century with two independent approaches, and for many decades, it has remained split into two separate schools. One was the school of the Swiss linguist Ferdinand de Saussure, who gave the name *semiology* to the study of signs and described it as a branch of psychology. The other was the school of the American philosopher Charles Sanders Peirce, who adopted the name *semiotics* and regarded it as part of philosophy, more precisely as a branch of logic.

The main difference between the two schools is that Saussure defined the sign as a dual entity, a combination of *signifier* and *signified*, whereas Peirce insisted that it is a triadic relationship between a *representamen*, an *object* and an *interpretant*. According to Peirce, any elementary act of signification, i.e. any *semiosis*, cannot involve less than three parties because there must necessarily be a process of interpretation between sign and meaning.

The semiological tradition of Saussure was followed by Roman Jakobson (1896–1982), Louis Hjelmslev (1899–1966), Claude Lévi-Strauss (1908–2009), Roland Barthes (1915–1980), Yuri Lotman (1922–1993), Umberto Eco (1932) and in general by the supporters of structuralism. The main followers of Peirce were Ivor Richards (1893–1979), Charles Ogden (1989–1957), Charles Morris (1901–1979), Thomas Sebeok (1920–2001), John Deely (1942), Marcel Danesi (1946) and in general the proponents of pragmatism. The split seemed to cut also between Europeans (largely on Saussure's side) and Americans (generally pro-Peirce), and within each camp, there seemed to be a wide variety of individual approaches.

By the 1990s, however, the situation was totally different. The most authoritative treatise of semiotics, published in four volumes between 1997 and 2003 by Roland Posner, Klaus Robering and Thomas Sebeok, makes it clear that at that time semiotics had become a virtually unified field, and that semiosis was defined in unmistakably Peircean terms. This result had largely been engineered by Thomas Sebeok, who promoted it with all the academic and editorial power he could muster as editor-in-chief of *Semiotica* and founding member of the International Association for Semiotic Studies.

Sebeok adopted the Peirce model of semiosis, and since this is explicitly based on interpretation, he concluded that semiosis is quintessentially an *interpretive* activity. The Peirce model was formally described in the *Treatise of Semiotics* with the following statement: 'The necessary and sufficient condition for something to be a semiosis is that A interprets B as representing C, where A is the interpretant, B is an object and C is the meaning that A assigns to B' (Posner et al., 1997).

Sebeok underlined that concept on many other occasions and in no uncertain terms: 'There can be no semiosis without interpretability, surely life's cardinal propensity' (Sebeok, 2001). In addition to this idea, however, Sebeok introduced two other far-reaching innovations, and we can say therefore that he engineered three major changes in semiotics:

1. In 1963, he founded the new research field of *zoosemiotics* by proposing that semiosis takes place not only in our species but also in all animals (Sebeok, 1963, 1972).
2. In the 1980s and 1990s, he led the movement that recognized the existence of semiosis in all living systems (*biosemiotics*) and formulated the foundational principle of biosemiotics with the idea that 'life and semiosis are co-extensive' (Sebeok and Umiker-Sebeok, 1992; Sebeok, 2001).
3. Throughout his academic life, Sebeok promoted the revolution in semiotics that eventually replaced the dualistic model of Saussure with the triadic model of Peirce (Sebeok, 1979, 1988, 1991).

That was Sebeok's revolution, and it is largely because of it that semiotics became identified with Peirce semiotics, which implies that any sign-activity, including language, is assumed to be an interpretive activity, a process based on interpretation, and an extended form of 'cognition'.

### *2.1.5. The Chomsky Approach to Language*

In modern linguistics, any verbal communication system (English, Russian, Chinese, etc.) is often referred to as *External Language* (E-language), whereas the faculty that is responsible for it is called *Internal Language* (I-language). In everyday life, the term 'language' is normally used in the first sense, whereas in academic life and in scientific research, it is mostly used in the second sense and has become virtually synonymous with I-language (Bever and Montalbetti, 2002).

Another important distinction is between language and *speech*. Speech is the actual verbal activity that takes place between individuals, whereas language is the faculty, or the 'organ', that makes speech possible. Ever since Aristotle, speech has been regarded essentially as an activity that links *sound and meaning*, and requires therefore the coordination of two distinct systems: a phonetic system that receives and produces sounds (the *sensory-motor* component of language) and a cognitive system that gives meaning to sounds (the *semantic* component of language). Recently, however, it has been widely acknowledged that a third system must exist in order to perform an additional type of processing. This third component of the faculty of language is the system responsible for *syntax*, the set of rules that all combinations of sounds must follow to be accepted as valid linguistic expressions.

It is largely thanks to the work of Noam Chomsky that syntax has become the key component of language. Chomsky repeatedly underlined that syntax and semantics are intimately interrelated but, at the same time, he showed that they are distinct entities. He demonstrated this point with the classical sentence *'colorless green ideas sleep furiously'*, which is nonsense in terms of meaning and yet it is correct in terms of syntax. Most importantly, Chomsky recognized that it is this third component of language that is capable of generating an unlimited number of expressions from a finite set of elements. It is syntax, in other words, that is responsible for *recursion*, and for that reason, one can rightly regard it as the generative engine, or the computational machine, of language.

In addition to this seminal idea, Chomsky introduced two other major concepts, and his contribution too can be summarized by three great innovations:

1. His review of Skinner's *Verbal Behavior* overturned the behaviourist paradigm and fuelled the 'cognitive revolution' in psychology (Chomsky, 1959).
2. He made universally familiar the idea that language depends on an innate generative mechanism called 'Universal Grammar' (Chomsky, 1957, 1965, 1975).
3. His campaign for the *Principles and Parameters* programme led to a huge explosion of inquiry into different languages and then to an investigation into the architecture of language that has become known as the 'Minimalist Program' (Chomsky, 1995, 2005, 2006).

The very special role that syntax plays in language has induced Hauser et al. (2002) to propose two distinct definitions of language. The faculty of language in the broad sense (FLB) is formed by all three systems mentioned above (phonetics, semantics and syntax), whereas the faculty of language in the narrow sense (FLN) contains syntax alone.

The rationale of this proposal is that 'FLN is the only uniquely human component of the faculty of language', whereas the other two come from our animal ancestors. According to this proposal, in short, all animals are capable of communication, but language exists only in our species because only humans have evolved the generative engine of syntax.

### *2.1.6. Sebeok's Definitions of Language*

Thomas Sebeok reached his conclusions on language by elaborating the concepts proposed by two Estonians, Jakob von Uexküll (1864–1944) and Juri Lotman (1922–1993).

Von Uexküll was regarded by Sebeok as a precursor of biosemiotics (a 'cryptosemiotician') because he had shown that all animals are capable of interpreting the world and that they do it in species-specific ways. According to Uexküll, every animal perceives the external world with internal means and lives therefore in a subjective environment of its own making that he called *Umwelt*. The mental images of the external world, in turn, are built by an internal system that Uexküll called *Innenwelt*, so it is this 'inner world' that is ultimately responsible for what an animal regards as its surrounding environment (von Uexküll, 1909).

Juri Lotman gave the name *semiosphere* to the world of culture and regarded that term as the cultural equivalent of the name *biosphere* that is often used to describe the biological world. But Lotman was also a follower of Saussure and inherited from him the idea that language is made of two distinct components: an abstract-universal system called *Langue* and a concrete-individual entity called *Parole*. Langue, according to Saussure, is the system that lies at the very heart of culture, and for that reason, Lotman called it *'the primary modelling system'* of our species (Lotman, 1991).

Thomas Sebeok accepted both the idea of a modelling system proposed by Lotman, and the concept of Umwelt proposed by Uexküll, and argued that there must be a deep relationship between them. Any Umwelt is produced by an Innenwelt, according to Uexküll, and Sebeok realized that the Innenwelt of any animal is essentially what Lotman called a modelling system. From this, he concluded that the primary modelling system of man is his ancestral animal Innenwelt, not language. In that case, language was a later evolutionary addition, and Sebeok described it as *the secondary modelling system* of our species.

The concept of modelling system has acquired an increasing importance in semiotics, and Sebeok continued to develop it throughout his life. His last book on that concept, *The Forms of Meaning*, written with Marcel Danesi, appeared just 1 year before his death (Sebeok and Danesi, 2000).

It is worth noticing that the 'primary modelling system' of Sebeok is the whole set of brain-modelling faculties that we have inherited from our animal ancestors, and is therefore more general than the 'faculty of language in the broad sense' (FLB) defined by Chomsky. In the same way, Sebeok's 'secondary modelling system' includes all modelling faculties that evolved only in our species and is slightly more general than Chomsky's 'faculty of language in the narrow sense' (FLN). There is, however, no contrast between the definitions of language proposed by Chomsky and by Sebeok, and all we need to keep in mind is that they use different terminologies for largely similar purposes.

### *2.1.7. The Bone of Contention*

Chomsky's most seminal idea is the concept that our ability to learn a language is *innate*, the conclusion that children are born with a mechanism that allows them to learn whatever language they happen to grow up with. That inner generative mechanism has been given various names – first *universal grammar*, then *language acquisition device (LAD)* and finally *faculty of language* – but its basic feature remains its *innateness*. The mechanism must be innate, according to Chomsky, because it allows all human children to master an extremely complex set of rules in a very limited period of time. The faculty of language, furthermore, is acquired in a precise sequence of developmental stages like all biological faculties of our body and can be regarded therefore as a new organ that for some reasons evolved only in our species.

At the very heart of this new organ, or faculty, is the mechanism of recursion, the apparatus that is capable of generating an unlimited number of structures from a finite set of elements, and it is to this inner generative mechanism that Chomsky gave the name first of 'universal grammar', and then of 'faculty of language in the narrow sense' (FLN). According to Chomsky, in short, the generative engine of syntax has the characteristics of a physiological organ, and in this respect, it is similar to the sensory-motor component of language. There is, however, one important difference between these two components. The sensory-motor apparatus has an extremely long history behind it and that made it possible that its features were shaped by natural selection (what Chomsky called 'Jacobian bricolage'), whereas the apparatus of syntax could not have evolved by that mechanism for at least two reasons. The first is that language appeared only recently in the history of life, and there simply was not enough time for natural selection to produce extensive changes. The second reason is that the principles of syntax are regarded as general constraints, like those dictated by logic, mathematics and physics, and natural selection can do nothing about them.

Chomsky concluded that language probably evolved as an exaptation of processes that originally evolved for different functions, and this is a conclusion that Thomas Sebeok did support. He did so by repeatedly underlining that language is first and foremost a modelling system and that only in a second stage it has been redeployed as a verbal communication system.

There is, however, an issue about which Chomsky and Sebeok reached two very different conclusions. They never had a public debate about it, but that issue has been, and continues to be, the bone of contention between Biolinguistics and Biosemiotics. The issue is the mechanism that lies at the heart of language. Is the mechanism of recursion a product of universal laws or the result of interpretation?

The crucial point here is that Sebeok adopted the Peirce model of semiosis and concluded that semiosis is always an interpretive activity. In such a framework, one is bound to conclude that the generative mechanism of language is an interpretive process, and this is incompatible with the idea that it is the result of universal principles or physical constraints.

This is therefore what divides Biosemiotics from Biolinguistics. As long as semiosis is based on interpretation and the generative mechanism of language is based on universal laws, the divide is incommensurable. And yet they are studying the same phenomenon, so there must be a way of bridging the gap. This is indeed our goal, but it requires, as we will see, a new theoretical framework, and in order to have that, we must first take a new look at the origin of language.

## 3. Part 2

### 3.1. ON THE ORIGIN OF LANGUAGE

#### *3.1.1. A Juvenile Ape*

In 1926, Luis Bolk, professor of anatomy at Amsterdam university, proposed the ‘fetalization theory’, the idea that the origin of man was due to the extension of foetal or juvenile features to the adult phases of life (Bolk, 1926). The idea was not new (Geoffroy Saint-Hilaire had mentioned it in 1836), and the phenomenon had been described in many other species with names such as *paedogenesis* (von Baer, 1866), *neoteny* (Kollmann, 1885) and *paedomorphosis* (Garstang, 1922). But it was Luis Bolk who turned that idea into a compelling doctrine by the sheer number of data with which he supported it.

In all primates, the foetus and the newborn child have big brains in respect to body size, flat faces, thin brow-ridges, small teeth and jaw, light skin and sparse body hair, but only man retains all these features in adult life. Similarly, the front-to-back axis of the head is perpendicular to the axis of the trunk in the foetus and in the newborn child of all primates, but only man maintains that angle of the cervical flexure throughout his life, and that is what allows him to have a horizontal line of sight while standing erect, whereas all primates can look around while walking on all fours (Bolk, 1926; Gould, 1977).

Big brains, flat faces, reduced body hair and upright posture are unmistakable marks of humanity and are undeniably present in the foetal stages of all primates, so there is little doubt that an extension of these juvenile features, i.e. a process of fetalization, did take place in our ancestors.

Today, the role of embryonic development in evolution has been documented in so many species and with so many examples that an entirely new science – familiarly known as *Evo-Devo* – has been built to study it. It is known, furthermore, that there are genes specifically dedicated to embryonic development and that a few changes in them can have enormous consequences on adult bodies. The increase in size of the human brain, for example, can be accounted for by the activity of just a few homeotic genes (Gilbert, 2006).

It is also known that environmental changes can affect development and produce either a retardation or an acceleration of sexual maturity in respect to body growth. In axolot, for example, an abundance of water favours an unlimited extension of the larval stage, whereas a dry climate induces a quick metamorphosis to adult stage (Gould, 1977). It is likely, therefore, that changes in the environment provided the initial pressure for changes in the embryonic development of our ancestors, and we know that vast climatic changes did take place in Africa in the past 10 million years.

We conclude that the fetalization theory, or its modern versions that come from Evo-Devo, provides a sound theoretical framework for the origin of man. At the same time, however, we must not forget that neoteny and many other processes of heterochrony (changes in timing) have taken place in countless animal species but have never produced a modelling system based on symbols. Our problem, therefore, is to find out what was it that made the difference in our species. More precisely, among all the evolutionary processes that shaped the human body, we are looking for those that created the conditions for the origin of language.

### *3.1.2. Fetalization and Brain Wiring*

In the 1940s, Adolf Portmann calculated that our species should have a gestation period of 21 months in order to complete the processes of foetal development that occur in all other mammals (Portmann, 1941, 1945). A newborn human baby, in other words, is in fact a premature foetus, and the whole first year of his life is but a continuation of the foetal stage.

This peculiarity of human development is due to the fact that fetalization leads to an extended foetal period and therefore to a greater foetus at birth, but this process is severely constrained because the birth canal can cope only with a limited increase of foetal size. During the evolution of our species, therefore, any extension of the foetal period had to be accompanied by an anticipation of the time of birth. The result is that the foetal development of our species became divided into two distinct phases – intrauterine and extrauterine – and eventually the extrauterine phase came to be the longest of the two.

It is not clear why this evolutionary result is uniquely human, but it is a historical fact that it took place only in our species. In all other mammals, foetal development is completed in utero, and what is born is no longer a foetus but a fully developed infant that can already cope with the environment.

The crucial point is that the last part of foetal development is the phase when most synaptic connections are formed. It is a phase of intense ‘brain wiring’.

The fetalization of the human body has produced therefore a truly unique situation in our species. In all other mammals, the wiring of the brain takes place almost completely in the dark and protected environment of the uterus, whereas in our species, it takes place predominantly outside the uterus, where the body is exposed to the lights, the sounds and the smells of a constantly changing environment. In our species, in short, the difference between intrauterine and extrauterine foetal development created the conditions for two distinct types of brain wiring, and this did have far-reaching consequences.

The brain wiring that occurs in the last phase of foetal development provides the neurological basis for the mental models that the organism is going to use throughout its life. If that phase occurs in the highly stable and reproducible environment of the uterus, the operations of brain wiring follow a pre-established sequence of steps and generate a modelling system that has been highly conserved in evolution. In our species, however, the last phases of foetal development have been progressively displaced outside the uterus, in a radically different environment, and that created the opportunity for a radically new experiment in brain wiring. That was the precondition for the evolution of a uniquely human modelling system, but let us not forget that a precondition for language was not yet language. It was only a potential, a starting point.

### *3.1.3. The Body-Plan of Language*

The human brain is about three times larger than the brain of any other primate, even when body weight is taken into account. This means that the primary modelling system that we have inherited from our animal ancestors required, at most, a third of our present brain size. The other two-thirds could be explained, in principle, by a further extension of our animal faculties, but this is not a satisfactory solution. We have not developed a sharper eyesight, a more sensitive olfactory system, a more powerful muscular apparatus, and so on. As a matter of fact, our physical faculties are in general less advanced than those of our animal relatives, so it was not an improvement of the primary modelling system that explains our increased brain volume. It is highly likely, therefore, that the brain increase that took place in human evolution was largely due to the development of those new faculties that collectively make up our second modelling system, the system that eventually gave origin to language.

The main point is that this new system was a genuine novelty, something that no other species managed to evolve. We are facing therefore the same problem that we encounter in all great events of macroevolution: How did living systems give origin to real novelties? A useful clue comes from another macroevolutionary event: the origin of the first animals. In that case, the starting point was a population of cells that could assemble themselves in countless different ways, so how did they manage to generate those particular three-dimensional structures that we call animals?

The solutions were obtained by three types of experiments, more precisely by the attempts to form multicellular structures with one, two or three different types of cells. The experiment with one cell type produced bodies that have no symmetry (the sponges), two cell types generated bodies with one axis of symmetry (the *radiata* or diploblasts, i.e. hydra, corals and medusae) and three cell types gave origin to bodies with three axes of symmetry (the *bilateria* or triploblats, i.e. vertebrates and invertebrates) (Tudge, 2000).

It turns out that animal cells arrange themselves in a three-dimensional pattern because they receive instructions which tell them that their position is anterior or posterior, dorsal or ventral and proximal or distal in respect to the surrounding cells. These instructions are carried by genes and are molecules which are referred to as the molecular determinants of the body axes. The crucial point is that there are countless types of molecular determinants and yet all triploblastic animals have the same body axes. This shows that there is no necessary correspondence between molecular determinants and body axes, and that in turns means that the actual correspondence is based on conventional rules, i.e. on the rules of an organic code.

That is what we learn from the origin of animals, and that lesson can illuminate many aspects of the origin of language. The number of three-dimensional patterns that the first animal cells could form in space was potentially unlimited, and the same was true for the brain-wiring patterns of the neural cells that generate a modelling system in the brain of an animal. It was imperative to adopt a set of pattern constraints in order to generate real bodies, and the same was true for the generation of a real modelling system out of countless different possibilities. The constraints that gave origin to animals are their body-plans, and in a similar way, the constraints that gave origin to language can be regarded as the neural body-plan of language (Barbieri, 2003). There is no way of building a body without a body-plan, and in a similar way, there is no way of building a modelling system without the neural equivalent of a body-plan.

The second modelling system that gave origin to language, in short, was the result of an evolutionary process that was similar, in principle, to the building of a neural body plan, and the most likely solution was, as in many other cases of macroevolution, the development of a new organic code.

### *3.1.4. The cerebra bifida Model on the Evolution of Man*

There is no general agreement on the definition of the genes of language, but it seems reasonable to say that they are genes whose mutations produce heritable changes in the faculty of language. There are many examples of such genes, and the outstanding conclusion that has come out of their study, so far, is that virtually all of them are present also in animals. All known genes of language, in other words, are genes of the primary modelling system that we have inherited from our animal ancestors. Future discoveries may well modify this conclusion, of course, but not much. The reason is that we share 98.8% of our genes with the chimps, so the number of uniquely human genes is bound to be small.

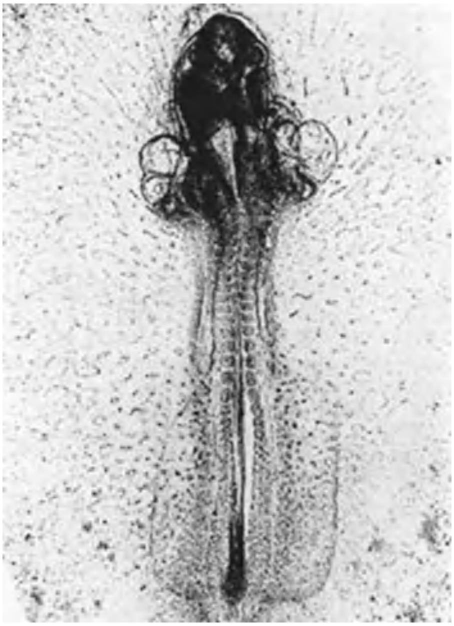

**Figure 1.** The heart arises from left and right cardiac primordia that move together and fuse in the midline. If fusion is prevented, each half forms a complete and fully functional heart, as seen in this 2-day-old chick embryo, a condition that is known as *cardia bifida.* (DeHaan, 1959).

The experimental evidence, in short, tells us not only that the genes of language do exist but also that virtually all of them exist also in animals, and this means that our second modelling system was built with the genes of the animal modelling system, not with uniquely human genes. This, in turn, implies that language was the result of epigenetic processes that operated on animal genes and produced a uniquely human result. That may look like a far-fetched speculation, at first, but let us take a closer look and examine, as a first step, the result of a classic experiment.

In vertebrate embryonic development, the heart arises from two primordia that appear on the right and left side of the developing gut, and then migrate to the centre and fuse together in a single median organ. If fusion of the two primordia is prevented by inserting an obstacle between them, each half undergoes a spectacular reorganization and forms a complete and fully functional beating heart (Fig. 1). The formation of the two hearts, furthermore, is followed by the development of two circulatory systems, and the animal goes through all stages of life in a double-heart condition that is known as *cardia bifida* (DeHaan, 1959).

This classic experiment shows that two profoundly different bodies, one with a single heart and the other with two hearts, can be generated *without any genetic change at all*. A modification of the epigenetic conditions of embryonic development is clearly an extremely powerful tool of change and may well be the key to human evolution. The gradual extension of our foetal period together with the constraint of the birth canal has split the foetal development of our brain into two distinct processes, one within and one without the uterus, whereas in all other mammals it has remained a single process that takes place entirely within the uterus. This splitting of the foetal development of our brain into two distinct processes is a condition that can be referred to as *cerebra bifida*, in some ways analogous to *cardia bifida*, except that in the case of the heart the two organs arise from a separation in space whereas in *cerebra bifida* the two developments are produced by a separation in time.

The *cardia bifida* experiment is illuminating because it shows that no new genes are required for the duplication, and that may well explain why no new genes were necessary for building the second modelling system of our species. The same set of genes could well have produced two different modelling systems simply by operating in two different environmental conditions, a conclusion that can be referred to as 'The *cerebra bifida* model' on the evolution of man.

The faithful reappearance of parental features in the descendants, in other words, can be ensured not only by genes but also by epigenetic processes. It is possible of course that new genes of language did evolve in the course of time, but they were not *essential*. Our two modelling systems could well have been built from the same set of genes that we have inherited from our animal ancestors, and that is probably what did happen because there does not seem to be any other explanation that fits with all known experimental facts.

### *3.1.5. A Community Code*

The classical studies of Jean Piaget on postnatal development have shown that our cognitive faculties (the concepts of object, space, time, causality, number, word, etc.) arise step by step throughout infancy in a sequence of four distinct periods (sensory-motor, preoperational, operational and formal), each of which is subdivided into stages (Piaget, 1954, 1960). New neural connections are formed in all periods, and in this respect, the cognitive stages are a continuation of the extra-uterine phase of foetal development, except that the intensity of brain wiring tends to decrease with age.

The development of human cognition, in other words, is based on neural connections that are formed *outside the uterus*, where the child is directly exposed to the environment, and this raises immediately a problem: what precisely are the environmental factors that have an influence on our cognitive system? This is a crucial point because one of the major functions of the brain consists precisely in *ignoring* most incoming signals. What are therefore the few signals that are allowed into the system and have the power to shape the development of our cognitive faculties? There are many clues on these issues, but two of them are particularly important. One comes from the study of children raised in the wild by animals (the so-called wolf children or feral children). Their primary modelling system is perfectly normal, but their potential to learn a language is highly compromised (Maslon, 1972; Shattuck, 1981). This shows that language is critically dependent upon *human* interactions that take place in the first few years of postnatal development. The second clue comes from the studies of the 'creole' languages and is the fact that the major role in the making of new linguistic rules appears to be played by children (Bickerton, 1981).

We have learned in this way that the development of language crucially depends on interactions that take place first between child and mother and then between child and other children. It is these interactions that induce the brain-wiring operations that build our cognitive system, but how can they do it?

It is known that the wiring of the nervous system is achieved by an overproduction of neurons followed by the elimination of all those that do not come in contact with nerve growth factors (Changeaux, 1983; Edelman, 1987). The death of these cells, however, is not due to injuries or starvation because in every region of the developing embryo, there are cells that must die and others that must live. It is due to processes of active suicide (programmed cell death or *apoptosis*), but all cells contain the genes of apoptosis, and these are activated by different molecules in different tissues and in different stages of development, so there must be rules that control their expression.

The wiring of the nervous system, in short, is achieved by the rules of a code, and the results obtained from wolf children and creole languages suggest that this may well be true for the wiring of our cognitive system, except that the rescuing role is exercised not by growth factors but by human interactions. In the case of language, in other words, the brain-wiring rules are provided not by *internal* but by *external* factors, and this may well be the crucial difference that exists between our two modelling systems.

The genes of language are probably the same genes of the modelling system that we have inherited from our animal ancestors, and their expression is again controlled by the rules of a code, but the codemaker of language is not the single individual brain. It is a community of interacting brains that together generate the rules of a new brain-wiring code.

This conclusion is a version of what has become known as *Distributed Language*, the idea that language is not inside the individual head but is 'distributed' in a population (Cowley, 2007). Here it is underlined that what is distributed is the *codemaker* of language, and this of course implies the existence of a code. More precisely, it implies the idea that language is based on a community code of brain-wiring rules. What is particularly inspiring about this idea is that it brings the origin of language in line with the other great events of macroevolution because all of them, as we will see, are associated with the appearance of new organic codes.

## 4. Part 3

### 4.1. ORGANIC CODES AND MACROEVOLUTION

#### *4.1.1. Life is Artefact-Making*

Codes and conventions are the basis of all cultural phenomena and from time immemorial have divided the world of culture from the world of nature. The rules of grammar, the laws of government, the precepts of religion, the value of money, the rules of chess and countless other stipulations are all human conventions that are profoundly different from the laws of physics and chemistry, and this has led to the conclusion that there is an unbridgeable gap between nature and culture. Nature is *governed* by immutable laws, whereas culture is *produced* by the mutable conventions of the human mind.

In this century-old framework, the discovery of the genetic code, in the early 1960s, came as a bolt from the blue, but strangely enough, it did not bring down the barrier between nature and culture. On the contrary, a 'protective belt' was quickly built around the old divide with an argument that effectively emptied the discovery of the genetic code of all its revolutionary potential. The argument is that the genetic code is fundamentally a *metaphor* because it must be reducible, in principle, to physical quantities. It is a secondary structure like those computer programs that allow us to write our instructions in English, thus saving us the trouble to write them in binary digits. Ultimately, however, there are only binary digits in the machine language of the computer, and in the same way, it is argued, there are only physical quantities at the most fundamental level of nature.

This conclusion, known as *physicalism*, is based on one fact and one assumption. The fact is that all spontaneous reactions are completely accounted for by the laws of physics and chemistry. The assumption is that it was spontaneous reactions that gave origin to the first cells on the primitive Earth. According to physicalism, in short, genes and proteins are spontaneous molecules that evolved into the first cells by spontaneous processes.

This, however, is precisely the point that molecular biology has proved wrong. Genes and proteins are *not* produced by spontaneous processes in living systems. They are produced by molecular machines which physically stick their subunits together in the order provided by *external* templates. They are assembled by molecular robots on the basis of outside instructions, and this makes them as different from ordinary molecules as *artificial* objects are from *natural* ones. Indeed, if we agree that objects are natural when their structure is determined from within and artificial when it is determined from without, then we can truly say that genes and proteins are *artificial molecules* and that they are *artefacts made by molecular machines*. This, in turn, implies that all biological objects are artefacts and that the whole of life is *artefact-making*.

Even this insight, however, has not reduced the gap between nature and culture. Modern biology continues to hold the view that semiosis exists only in culture, not in nature, and the main reason for this is that it does not realize that the cell is a semiotic system. The cell is the unit of life, and if semiosis did not exist in it, we would indeed have to conclude that all systems made of cells are not semiotics systems. They would be based on physics and chemistry alone, not on semiosis, and the divide between nature and culture would remain intact. This is therefore the problem that we have before us: is the cell a semiotic system? Does the existence of the genetic code imply also the existence of semiosis at the molecular level?

### *4.1.2. The Code Model of Semiosis*

The discovery of the genetic code has thrown a completely new light on the cell, but is it enough to conclude that the cell is a semiotic system? The answer clearly depends on the definition of semiosis and in particular on the minimal requirements that allow us to recognize the existence of a semiotic system in nature.

Semiosis is usually referred to as *the production of signs*, but this definition is too restrictive because signs are always associated with other entities. A sign, to begin with, is always linked to a *meaning*. As living beings, we have a built-in drive to make sense of the world, and when we give a meaning to something, that something becomes a sign for us. Sign and meaning, in other words, cannot be taken apart, because they are two sides of the same coin. The result is that a system of signs, i.e. a *semiotic system*, is always made of two distinct worlds: a world of entities that we call *signs* and a world of entities that represent their *meanings*.

The link between sign and meaning, in turn, calls attention to a third entity, i.e. to their *relationship*. A sign is a sign only when it stands for something that is *other than itself*, and this *otherness* implies at least some degree of *independence*. It means that there is no deterministic relationship between sign and meaning. Different languages, for example, give different names to the same object precisely because there is no necessary connection between names and objects. A semiotic system, therefore, is not any combination of two distinct worlds. It is *a combination of two worlds between which there is no necessary link*, and this has an extraordinary consequence. It implies that a bridge between the two worlds can be established only by *conventional* rules, i.e. by the rules of a *code*. This is what qualifies the semiotic systems, what makes them different from everything else: *a semiotic system is a system made of two independent worlds that are connected by the conventional rules of a code*. A semiotic system, in conclusion, is necessarily made of at least *three* distinct entities: *signs*, *meanings* and *code*.

Signs, meanings and code, however, do not come into existence of their own. There is always an ‘agent’ that produces them, and that agent can be referred to as a *codemaker* because it is always an act of coding that gives origin to semiosis. In the case of culture, for example, the codemaker is the human mind, since it is the mind that produces the mental objects that we call signs and meanings and the conventions that link them together. The crucial point is that *signs and meanings simply do not exist without a codemaker and outside a codemaking process*. The codemaker is the *agent* of semiosis, whereas signs and meanings are its products. We conclude that signs and meanings are totally dependent on codemaking, i.e. they are *codemaker-dependent entities*. This is their qualifying feature, and we can say therefore that signs and meanings exist whenever there are codemaker-dependent entities.

We come in this way to a general conclusion that can be referred to as 'the Code Model of semiosis': *a semiotic system is made of signs, meanings and code that are all produced by the same agent, i.e. by the same codemaker* (Barbieri, 2003, 2006). This tells us precisely what we need to prove in order to show that a system is a semiotic system. We need to prove that there are four distinct entities in it: signs, meanings, code and codemaker.

### *4.1.3. The Cell as a Trinity*

The idea that life is based on genes and proteins is often expressed by saying that every living system is a duality of *genotype* and *phenotype*. This model was proposed by Wilhelm Johannsen in 1909 but was accepted only in the 1940s and 1950s when molecular biology discovered that genes are chemically different from proteins and, above all, when it became clear that genes carry *linear information* whereas proteins function by their *three-dimensional structures.* The genotype-phenotype duality is therefore a dichotomy that divides not only two different biological functions (heredity and metabolism) but also two different physical quantities (information and energy). It is the simplest and most general way of defining a living system and has become the foundational paradigm of modern biology, the scheme that transformed the *energy-based* biology of the nineteenth century into the *information-based* biology of the twentieth.

In the 1950s and 1960s, however, the study of protein synthesis revealed that genes and proteins are not formed spontaneously in the cell but are manufactured by a system of molecular machines based on RNAs. In 1981, the components of this manufacturing system were called *ribosoids*, and the system itself was given the collective name of *ribotype* (Barbieri, 1981, 1985). The cell was described in this way as a structure made of genes, proteins and ribosoids, i.e. as a trinity of *genotype*, *phenotype and ribotype*.

This model is based on the conclusion that the ribotype had a historical priority over genotype and phenotype. Spontaneous genes and spontaneous proteins did appear on the primitive Earth, but they did not evolve into the first cells, because spontaneous molecules do not have biological specificity. They gave origin to *molecular machines*, and it was these machines that evolved into the first cells. The simplest molecular machines were *bondmakers*, molecules that could join other molecules together by chemical bonds. Among them, some developed the ability to join nucleotides together in the order provided by a *template*. Those bondmakers started *making copies* of nucleic acids and became *copymakers*. Proteins, on the other hand, cannot be made by copying, and yet the information to make them must come from molecules that can be copied, so it was necessary to bring together a carrier of genetic information (a messenger RNA), a peptide bondmaker (a piece of ribosomal RNA) and molecules that could carry both nucleotides and amino acids (the transfer RNAs). The outstanding feature of the protein makers, however, was the ability to ensure a one-to-one correspondence between genes and proteins, and that means that the evolution of the translation apparatus had to go hand in hand with the evolution of the genetic code. Protein synthesis arose therefore from the integration of two distinct processes, and the final machine was a *code-and-template-dependent-peptide-maker* or, more simply, a *codemaker*.

The RNAs and the proteins that appeared spontaneously on the primitive Earth produced a wide variety of ribosoids, some of which were synthetizing ribosoids whereas others were ribogenes and others were riboproteins (or ribozymes). The systems produced by the combination of all these molecules, therefore, had a ribotype, a ribogenotype and a ribophenotype. Eventually, evolution replaced the ribogenes with genes and the riboproteins with proteins, but the synthetizing ribosoids of the ribotype have never been replaced. This shows not only that the ribotype is a distinct category of the cell but also that it is a category without which the cell simply cannot exist.

The ribosoids of the ribotype are the oldest phylogenetic molecules that exist on Earth (Woese, 2000), and they firmly remain at the heart of every living cell. Genes, proteins and ribosoids are all manufactured molecules, but only the ribosoids are also *makers* of those molecules. This concept can perhaps be illustrated by comparing the cell to a city where proteins are the objects, genes are the instructions and ribosoids are the ‘makers’ of genes and proteins, i.e. the inhabitants of the city.

It is an experimental fact, at any rate, that every cell contains a system of RNAs and ribonucleoproteins that makes proteins according to the rules of a code, and that system can rightly be described as a ‘codemaker’. That is the third party that makes of every living cell a trinity of genotype, phenotype and ribotype. The genotype is the seat of heredity, the phenotype is the seat of metabolism and the ribotype is the codemaker of the cell, the seat of the genetic code.

### *4.1.4. Signs and Meanings at the Molecular Level*

All biochemistry textbooks tell us that there is a genetic code in protein synthesis, but none of them mention the existence of signs and meanings. At first sight, in fact, these entities do not seem to exist at the molecular level. The translation apparatus can be regarded as a codemaker because it is the seat of the code that creates a correspondence between genes and proteins, but these molecules appear to have only ‘objective’ chemical properties, not the ‘codemaker-dependent’ properties that *define* signs and meanings. A messenger RNA, for example, appears to be a unique and objective sequence of molecules, but let us take a closer look.

A messenger RNA is certainly a unique and objective chain of *nucleotides*, but in no way it is a unique sequence of *codons* because different codemakers could scan it in different ways. If the nucleotides were scanned two-by-two, for example, the sequence of codons would be totally different. The same chain of nucleotides, in other words, can give origin to many sequences of codons, and it is always the codemaker that determines the sequence because it is the codemaker that *defines* the codons. A linear sequence of codons, in short, does not exist without a codemaker and outside a codemaking process. It is totally dependent on codemaking and is therefore a *codemaker-dependent entity*, which is precisely what a sign is.

In the same way, the linear sequence of amino acids that is produced by the translation apparatus is also a codemaker-dependent entity, because only a codemaker can produce it. Any spontaneous assembly of amino acids would *not* make linear chains, and above all, it would not arrange the amino acids in a specific order. Specific linear sequences of amino acids can be produced only by codemakers, but different codemakers would arrange the amino acids in different ways, which shows that the sequence of a protein is only one of the many possible 'meanings' that could be given to a string of nucleotides.

The sequence of a gene and the sequence of a protein, in conclusion, are not *objective* properties of those molecules. They are codemaker-dependent properties because they do not exist without a codemaking process and because they would be different if the codemaker had a different structure. The sequences of genes and proteins, in short, have precisely the characteristics that define signs and meanings. They are codemaker-dependent entities made of organic molecules and are therefore organic signs and organic meanings. All we need to keep in mind is that *signs and meanings are mental entities when the codemaker is the mind, but they are organic entities when the codemaker is an organic system* (Barbieri, 2003).

We reach in this way the conclusion that every cell contains all four components of semiosis (signs, meanings, code and codemaker) and is therefore a real semiotic system.

### *4.1.5. The Organic Codes*

According to modern biology, the genetic code is the only organic code that exists in life, whereas the world of culture has a virtually unlimited number of codes. We know, furthermore, that the genetic code came into existence at the origin of life, whereas the cultural codes arrived almost four billion years later. This appears to suggest that evolution went on for almost the entire history of life on Earth, without producing any other organic code after the first one. According to modern biology, in short, the genetic code was a single extraordinary exception, and if nature has only one exceptional code whereas culture contains an unlimited number of them, the real world of codes is culture and the barrier between the two worlds remains intact.

At a closer inspection, however, we realize that many other organic codes exist in life and we can actually prove their existence. Any organic code is a set of rules of correspondence between two independent worlds, and this requires molecular structures that act like *adaptors*, i.e. that perform two independent recognition processes. The adaptors are required because there is no necessary link between the two worlds, and a set of rules is required in order to guarantee the specificity of the correspondence. The adaptors, in short, are necessary in all organic codes. They are the molecular *fingerprints* of the codes, and their presence in a biological process is a sure sign that that process is based on a code.

The existence of organic codes, in short, is documented by the presence of molecular adaptors, and these molecules have been found not only in protein synthesis (where the adaptors are the tRNAs) but in many other cellular processes. This has revealed the existence of the *splicing codes*, the *signal-transduction codes*, the *cytoskeleton codes* and the *compartment codes* (Barbieri, 1998, 2003), whereas similar arguments have brought to light the *metabolic code* (Tomkins, 1975), the *sequence codes* (Trifonov, 1987, 1989, 1996, 1999), the *sugar code* (Gabius, 2000; Gabius et al., 2002), the *histone code* (Strahl and Allis, 2000; Turner, 2000, 2002) and many others (Barbieri, 2008).

What is particularly interesting is that the origins of the organic codes were closely associated with the great events of macroevolution. Any time that a new organic code came into being, something totally new appeared in nature, something that had never existed before.

The origin of the genetic code, for example, produced *biological specificity*, the most fundamental of life's properties. The signal-transduction codes allowed primitive systems to separate their interior space from the outside environment. That was a precondition for the origin of *individuality* and, in particular, for the origin of the cell. Another great innovation was brought about by the codes of splicing because this process requires a separation in time between transcription and translation and that was a precondition for their separation in space, i.e. for the *origin of the nucleus*, and therefore for the origin of the eukaryotes (Barbieri, 1998, 2003).

Many other eukaryotic innovations were brought into existence by other organic codes. The cytoskeleton codes, for example, allowed the cells to build their own scaffoldings, to change their own shapes and to perform their own movements. The origin of embryos was also associated with organic codes because typical embryonic processes like *cell determination*, *cell adhesion*, *cell migration* and *cell death* are based on molecular adaptors and have all the qualifying characteristics of codified phenomena (Barbieri, 1998, 2003).

The major events in the history of life, in short, went hand in hand with the appearance of new organic codes, from the first cells all the way up to multicellular life, and this suggests a very deep link between codes and evolution. It suggests that *the appearance of new organic codes was the key to the great events of macroevolution.*

### *4.1.6. Two Types of Semiosis*

Thomas Sebeok adopted the Peirce model of semiosis, and since this is explicitly based on interpretation, he concluded that semiosis is quintessentially an *interpretive* activity. This conclusion is undoubtedly valid in animals, but not in all living systems. It is not applicable, in particular, to the cell, where the genetic code has been virtually the same for billions of years, which clearly shows that it does not depend on interpretation.

The idea that the cell is capable of interpretation has been re-proposed time and again by the followers of Peirce with the argument that the behaviour of the cell is context-dependent, and this is assumed to be a sure sign of interpretive ability. But let us take a closer look. The genetic code and the signal-transduction code consist of context-free rules, but what happens when they work *together*? The answer was provided by the classic experiments of Jacob and Monod on the regulation of protein synthesis: the cell uses the genetic code to make proteins according to the inputs of the transduced signals, and its behaviour becomes context-dependent. That is all we need to explain the context-dependent behaviour of the cell: two codes working together, two integrated activities of coding-decoding. But there is more than that. In addition to the above two codes, the eukaryotic cells have many other organic codes, and each of them brings an additional level of complexity into the system. The extremely complex behaviour of the eukaryotic cell, in short, is but the natural result of the presence of many organic codes in it, and does not require interpretation.

For the first 3,000 million years – almost 80% of the entire history of life – our planet was inhabited only by single cells, and the behaviour of these cells is fully accounted for by *code semiosis*, i.e. by a form of semiosis that relies exclusively on coding and decoding. With the origin of animals, however, a new type of semiosis came into being, a type that is rightly referred to as *interpretive semiosis* because it is specifically involved in the process of interpretation.

Can we justify this conclusion? Can we say that there has been a real macroevolutionary discontinuity between single cells and animals? To this purpose, let us underline that animals do not interpret the world but only *representations* of the world. Any interpretation, in other words, is always exercised on internal models of the environment, never on the environment itself.

Single cells, on the other hand, do not build representations of the outside world. They decode the signals from the environment but do not build internal models of it and therefore cannot interpret them. They are sensitive to light, but do not ‘see’; they react to sounds but do not ‘hear’; they detect hormones but do not ‘smell and do not ‘taste’ them. It takes the cooperation of many cells which have undertaken specific processes of differentiation to allow a system to see, hear, smell and taste, so it is only multicellular creatures that have these experiences. Only animals, in short, build internal representations of the outside world, and only these representations allow them to *perceive*, to *feel* and to *interpret* the world.

The evolution from single cells to animals was far more than an increase in growth and complexity. It was a true macroevolutionary event that gave origin to absolute novelties, to entities that had never existed before such as perceptions and feelings. Interpretation had an origin and a history, like everything else in life, and arose only in multicellular systems. That is what divides animals from single cells, and that is why we need to acknowledge that there are two distinct types of semiosis in living systems: one that depends on coding and one that relies on interpretation.

### *4.1.7. The Code Model on the Origin of Language*

The origin of language has undoubtedly its own unique features, but the origin of previous biological novelties can help us to understand its underlying mechanism. In particular, there is an important lesson that we can learn from single cells and animals.

The fact that virtually all cells have the same genetic code but belong to three distinct domains – Archaea, Bacteria and Eucarya (Woese, 1987, 2000) – strongly suggests that the genetic code appeared in precellular systems and that the cell organization arose afterwards in three different ways (Woese, 2002). We know furthermore that Archaea, Bacteria and Eucarya have different signalling systems on their membranes, which suggests that each cell domain arose by the combination of the genetic code with a different signal-transduction code.

At a very early point in the history of life, however, the cells adopted two divergent strategies and that channelled them into two very different evolutionary directions. Archaea and Bacteria chose a streamlining strategy that prevented the acquisition of new organic codes and have remained substantially the same ever since. The Eucarya, on the contrary, continued to explore the 'coding space' and developed new organic codes (splicing codes, compartment codes, histone code, etc.) throughout the whole 3,000 million years of cellular evolution. This turned the eukaryotic cells into increasingly more complex systems, and eventually some of them became complex enough to generate three completely new forms of life, the great kingdoms of plants, fungi and animals (Barbieri, 1981, 1985, 2003).

If we now look at the history of life from the organic codes' point of view, we realize that the same pattern is appearing all over again. Any new organic code brings a genuine novelty into existence, but the origin of *a new integrated system* always requires more than one code. A cell requires a genetic code plus a signal-transduction code, whereas a triploblastic animal requires at least three distinct codes, one for each body axis (top and bottom, back and front, left and right). This initial set of codes, furthermore, has two outstanding properties: (a) it is limited and (b) it is strictly conserved in all descendants. From this general pattern, we obtain three main concepts:

1. The origin of a new integrated system in the history of life (the first cells, the first plants, the first animals, etc.) is produced by a limited set of new organic codes (the foundational set).
2. The further evolution of the system (eukaryotic cells or multicellular organisms) does not take place by a mere increase of components, but by a step-by-step addition of new organic codes.
3. The appearance of new organic codes is essential to the further evolution of the system, but equally essential is the *conservation* in all descendants of the foundational codes.

With this in mind, let us now go back to the origin of language. If we accept that it was a biological event, it is not unreasonable to think that it had the same underlying pattern of the other events of macroevolution. This gives us *the code model on the origin of language*, a model that consists of three points:

1. The *origin* of language was due to a small set of new codes (the foundational event).
2. The *evolution* of language was due to the appearance of other codes at various stages of development.
3. The foundational set of codes has been strongly conserved and remains at the heart of the language faculty in all human beings.

## 5. Conclusion

The existence of many organic codes in nature casts a completely new light on living systems and leads to a theoretical framework that can be referred to as 'the Codes View of Life'. This view, or framework, consists of three distinct concepts (Barbieri, 2003, 2006):

1. We can prove the existence of many organic codes by the presence of molecular adaptors. This means that organic codes are *normal components* of living systems, not extraordinary exceptions, and that they appeared throughout the whole history of life and not just at the beginning and at the end of evolution.
2. The presence of two or more organic codes is enough to explain the context-dependent behaviour of the cells, and there is no need of interpretation at the cellular level. This means that there are two distinct types of semiosis in life: one that depends of coding and one that depends on interpretation.
3. Any new great step of macroevolution was associated with the appearance of new organic codes.

Biolinguistics and Biosemiotics have both been built without these concepts, and it is largely because of this that a divide has existed between them. As soon as we introduce the idea of the organic codes, in fact, we find that the two main obstacles that so far have divided them can be removed:

(a) The major claim of Biolinguistics is that the development of the faculty of language must be precise, robust and reproducible like the development of any other faculty of the body, and therefore, it cannot be left to the vagaries of interpretation. The ontogeny of language, in other words, cannot be explained by interpretive semiosis. Clearly, this obstacle can be removed only by showing that there are two distinct types of semiosis in life, and that one of them does not require interpretation.

(b) The major claim of Biosemiotics is that life is based on semiosis, and this is not compatible with the idea that the rules of syntax are based on universal laws. The ontogeny of language, on the other hand, would be precise, robust and reproducible even if it were based on organic codes rather than universal laws. The genetic code, for example, guarantees precise, robust and reproducible features in all living system and has properties that are even more universal than those attributed to universal grammar. Language does require rules, but the rules of universal grammar, or the principles and parameters of syntax, are much more likely to be the result of organic codes rather than the expression of universal phenomena like the Periodic Table or the Principle of Least Action. This is because the rules of life are produced by living systems and evolve with them, whereas the rules of mathematics and physics are not subject to historical change.

The Codes View of Life, in short, removes the two main obstacles that have divided Biolinguistics from Biosemiotics and gives us a unified approach to the study of language. More than that, it allows us to prove that the cell is a semiotic system and therefore that there is a real bridge between nature and culture. It makes us realize that semiosis appeared on Earth in the form of organic codes and later evolved into two types of interpretive semiosis: first the iconic and indexical semiosis of animals and then the cultural semiosis of our species. Finally, the Codes View of Life tells us that the organic codes are the great invariants of evolution, the entities that remain constant when everything else is changing. The genetic code has been conserved ever since its first appearance, and the same is true for the organic codes that came later and gave origin to the great events of macroevolution. But this is not because their rules are mathematical principles or universal laws of nature. They are conserved because living systems actively and continuously eliminate the changes that appear in them, and reconstruct their original components in every new generation.

Life is essentially about creating new organic codes and conserving those which have been created. This is what we learn from macroevolution, and this is what we should always keep in mind, even when the issue in question is the origin of language, the last episode of macroevolution.

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Biodata of **Emmanuel Farge**, author of "***Mechano-Sensing in Embryonic Biochemical and Morphologic Design: Evolutionary Perspectives on Emergence of Primary Organisms***."

**Emmanuel Farge** researches focus on the involvement of soft matter physical properties of living systems coupled to biochemical activities of the cell in the generation of functional and vital *in vivo* physiological processes since 1989. Trained as a physicist (U-Paris7 Magistère, 1984–89), **Emmanuel Farge** switched to biophysics in the Physico-Chemistry Biology Institute Paris, in 1989 in Ph.D. where he worked on the soft matter elastic response of biological membranes to biochemical active transmembrane translocation of phospholipids ("flippase"), leading to endocytic-like vesiculation on liposome model systems (Ph.D., 1993). In 1994, he joined the Pasteur Institute in Paris (as assistant professor of physics U-Paris 7, 1993), where he revealed the motor role of the "flippase" in the endocytic vesiculation in living cells. He then moved on to head his own group at the Curie Institute in Paris in 1997 (Institut Universitaire de France, 99–04), modelling the mechanics of endocytosis in quantitative relation to living cells experiments, and demonstrating the mechanical induction of transdifferentiation gene expression though the mechanical inhibition of morphogene endocytosis. In parallel, the Drosophila embryo was introduced to study the feedback role of the mechanical strains developed by gastrulation morphogenetic movements into the regulation of patterned gene expression, through the discovery of the mechanical induction in Twist expression in the future anterior gut track cells, specifically strain compressed by the morphogenetic movement of convergent extension, and vital in functional anterior gut track development. Currently, the Farge (Research Director Inserm, 2006) group combines the tools of genetics, experimental and *in silico* biomechanics to unravel the underlying mechanisms of biological molecular to mechanical multicellular phenotype interplay during embryonic morphogenesis and tumour development, *in vivo*.

E-mail: **emmanuel.farge@curie.fr**

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# MECHANO-SENSING IN EMBRYONIC BIOCHEMICAL AND MORPHOLOGIC DESIGN: EVOLUTIONARY PERSPECTIVES ON EMERGENCE OF PRIMARY ORGANISMS

**EMMANUEL FARGE**
*Mechanics and Genetics of Embryonic and Tumoral Development Group, UMR168 CNRS, Institut Curie, 11 rue Pierre et Marie Curie, F-75005 Paris, France*

## 1. Introduction

The diversity of morphological shapes generated in living systems is a recurrent issue of fascination for any observer of nature. It is therefore a continuous issue of investigation of science from antiquity to the present, having more recently been studied alternatively by physical or molecular biology-based approaches.

The mechanisms through which living systems' geometrical morphologies are designed will here be stated from the molecular to the multicellular organism levels, on a few specific but vital cellular and tissue morphogenetic processes. We will focus on both the underlying molecular mechanisms of living systems morphogenesis and on the feedback function of the cell and multicellular morphologies on the biochemical activities of the tissue cells. We will learn from these examples how vital physiological functions emerge from the coupling of the biochemical and physical properties of living matter, with objectively no dominant effect of any of the molecular biology or physical aspects of such seminal interaction.

At the cellular level, we will first briefly describe the biochemical origins of the cell membrane shape changes leading to inward vesiculation budding (referred to as endocytosis budding), allowing exchanges of biochemical signals from the outside to the inside of the cells (Sect. 2.1). We will describe the physiological function associated to the mechanical modulation of these mesoscopic morphogenetic events into the mechanical activation of biochemical transduction pathways, leading to gene expression events, like BMP morphogenetic pathways (Sect. 2.2).

At the multicellular level, secondly, we will focus longer on embryonic development, which represents a coordination of tissue biochemical patterning and morphogenetic movements (Sect. 3). Last decades revealed the close control of the molecular motor Myosin-II-dependent biomechanical morphogenesis by patterning gene expression, with constant progress in the understanding of the underlying molecular mechanisms. Reversed control of developmental gene expression and of Myosin-II patterning by the mechanical strains developed by morphogenetic movements was recently revealed at Drosophila gastrulation, through mechano-transduction processes involving pathways such as Armadillo/β-catenin or the downstream of Fog/Rho pathways. We will present the theoretical (simulations integrating the accumulated knowledge in the genetics of early embryonic development and morphogenesis) and the experimental (genetic and biophysical control of morphogenetic movements) tools having allowed the uncoupling of pure genetic inputs from pure mechanical inputs in the regulation of developmental gene expression and Myosin-II patterning. Specifically, we will describe the innovative magnetic tweezers tools we have set up to measure and apply physiological strains and forces *in vivo*, from the inside of the tissue, to modulate and mimic morphogenetic movements in living embryos. We will also discuss mechanical induction in tumour development. This will concretely show the integrative role of mechanical strains in directly regulating the reversal molecular to multicellular scale interplay that coordinates multicellular active events in embryogenesis. We will specifically see how the endocytotic budding morphogenesis at the cell scale discussed in Sect. 2 can mediate the molecular to multicellular interplay in such *in vivo* process.

We will ultimately discuss the associated perspectives in evolution in terms of putative emergence of earliest organisms in response to external mechanical stimuli though the appearance of a putative primitive motor-sensorial system based on mechano-transduction (Sect. 4).

## 2. Cell Membrane Morphogenesis

### 2.1. ENDOCYTOSIS VESICULATION MEMBRANE MORPHOGENESIS AS A RESPONSE OF ELASTIC MEMBRANES TO ATP-DEPENDENT TRANSMEMBRANE TRANSPORT OF PHOSPHOLIPIDS

The internal medium of living cells (cytosol) is separated from the outside by a membrane. This membrane exchanges with internal cytosolic membranes by budding-trafficking-fission of 100-nm vesicles (Fig. 1a). Membranes are composed of two liquid coupled leaflets made of phospholipids. Because the structure of this bilayer is maintained by hydrophobic interactions without covalent interactions between phospholipids, it is highly deformable, with bending energies on the order of 10 times the molecular thermal energy $kT$ only. The membrane thus belongs to soft matter physics (Fig. 1b) (Helfrich, 1973).

Across these membranes exist ubiquitous transmembrane proteins called “flippases” (Seigneuret and Devaux, 1984). These are phospholipid translocases that specifically pump phospholipids (phosphatidylserine and phosphatidylethanolamine) – from the external leaflet to the internal leaflet of the phospholipid bilayer. Because the bilayer is highly deformable, the production of a phospholipid number asymmetry leads to an inward bending deformation,

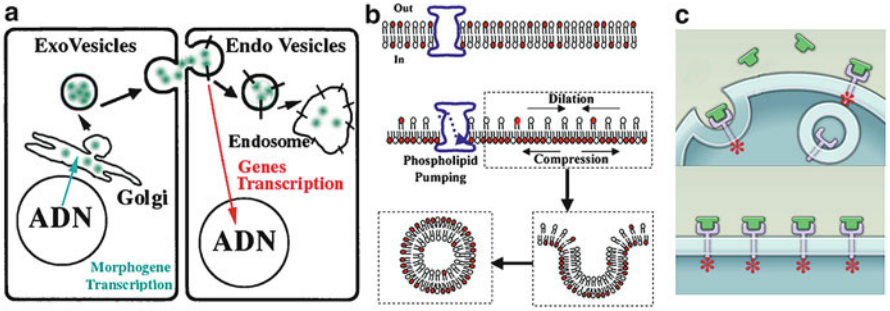


**Figure 1.** Vesiculation budding of cells plasma membrane: a functional morphogenetic process and genetic mechano-sensor at the cell scale. (**a**) Signalling proteins (morphogenes) are secreted by exocytosis, namely, by the formation of 100-nm-size vesicles from the Golgi and their fusion with the plasma membrane (*left cell*). The signalling protein forms a complex with its specific receptor at the target cell membrane (*right cell*). This activates both a cytosolic transduction pathway that can lead to gene transcription and a signal of concentration of the complex into privileged domains of endocytosis (clathrin domains), leading to its internalisation into acidic endosomes after 2, 3 min. This generates the separation of the complex and the inhibition of the transduction pathway activation. (**b**) The driving force of the budding as an elastic response of the soft matter membrane to the transmembrane active transport of phospholipids. (**c**) Membrane mechanical tension inhibits endocytosis by membrane flattening. Without tension (*up*), endocytosis is allowed, with less receptors activated at the plasma membrane (*red stars*) and more degradation of their interactions with the signalling protein (*in green*) into the cytyosol, than for the membrane mechanically flattened by tension (*down*) blocking of endocytosis. (Adapted from Fernandez-Gonzales and Zallen, p. 78.)

generating internal vesicles at the 100-nm length scale (Farge, 1995). Unless other molecular mechanisms are also found to trigger internal budding (Huttner and Schmidt, 2002), the stimulation of flippases activities effectively leads to an increase of budding activities, from liposome artificial systems to living cells (Farge and Devaux, 1992; Farge et al., 1999). Conversely, mutants of flippases in yeast definitively lead to the inhibition of any endocytosis activities (Pomorski et al., 2003). Therefore, budding morphogenesis at the 100-nm mesoscopic length scale in 10-μm cells appears to be generated by the elastic response of membrane bilayers to the ATP-dependent biochemical activity of transmembrane phospholipids pumping.

Note that regarding the role of flippases in endocytosis, the involvement of local polymerization of specific proteins like clathrin or bars in driving endocytic budding was proposed as molecular alternatives (Wu et al., 2010). On the other hand, mutants of flippases completely block any type of endocytosis in yeast (Pomorski et al., 2003). Therefore, flippases activities could generate a non-local-budding driving force that would nucleate at positions energetically favoured by local pre-bending of the membrane in the presence of polymerised coats like clathrin or bars complexes.

In this specific case, the morphogenetic process of budding is thus an emergent physiological property of the cell at the mesoscopic scale, resulting from the symmetric interaction of a biochemical activity at the molecular scale (the "flippase" activity) with the soft matter physics properties of membranes at the larger cell scale.

In this process, neither the biochemical nor the physical properties are dominant players in the interaction. And the elastic properties of the membrane directly allow the emergence of a physiological function of budding endocytosis at the mesoscopic scale from a biochemical activity at the molecular scale. This trans-scale integration is here simply due to mechanical interactions allowed by the fact that soft matter physics structures of biological membranes are deformable by the characteristic energies of protein molecular activities, which are on the order of several 10 $kT$ only.

Vesiculation budding morphogenesis is functional in the sense that it regulates the interactions of the cells with its neighbouring cells through internalisation of secreted signal proteins. Cells secrete signalling proteins that interact with specific receptors on their surface and the surface of neighbouring cells. This generally activates a transduction signal into the target cells, leading to internal protein activations and/or gene expression. But this also activates a signal, triggering the signalling protein concentration in membrane domains of endocytic vesiculation, leading to the internalisation of the receptor-signal protein complex after budding and to the separation of the complex in internal compartments only 2.5 min after the formation of the complex (Fig. 1a) (Dautry-Varsat et al., 1983). This thus generally plays the role of a negative feedback rapidly blocking the activation of the pathways before saturation of signalling. In some cases, the endocytosis of the signal protein is on the contrary necessary for the activation of the pathway (Vieira et al., 1996). Therefore, and interestingly, membrane budding morphogenesis possesses a physiological function of regulating negatively, and sometimes positively, the activation of the pathways triggered by secreted signals, thereby regulating biochemical cytosolic and genomic cell–cell interactions.

## 2.2. MECHANICAL MODULATION OF MEMBRANE ENDOCYTIC VESICULATION MORPHOGENESIS AS A MECHANO-SENSOR OF THE MACROSCOPIC MECHANICAL ENVIRONMENT

Strikingly, such physiological function appears to also be central in the mechanosensing of the cells in response to its mechanical deformation due to macroscopic mechanical perturbation of the environment. Indeed, applying a pressure on a cell triggers mechanical tension in its membrane, which flattens the membrane and prevents inward budding and endocytosis (Raucher and Sheetz, 1999; Rauch and Farge, 2000). Therefore, secreted signals remain coupled to their receptors and blocked outside the membrane, with no possibility of internalisation and of inhibition of the interaction, which, in the general case, means an inhibition of the negative-feedback endocytic-dependent process and therefore to an amplification of the downstream signalling pathway (Fig. 1c). It is effectively possible to dramatically accelerate the myoblast-osteoblast transdifferentiation process of C2C12 cultured cells by mechanically blocking the endocytosis of BMP2, the secreted signalling determinant triggering the transdifferentiation, as well as to mechanically trigger the transdifferentiation at subcritical concentration of BMP2, not allowing the differentiation within unstrained conditions (Rauch et al., 2002).

Therefore, the changes of morphologies of the plasma membrane at the 100-nm scale, due to remarkable soft matter physics elastic properties of membranes, are privileged mediators of the reciprocal interactions between the molecular scale (here flippases activities or gene expression driving transdifferentiation) and the macroscopic scale (concentration of signal proteins secreted by tissues or the tissue mechanical strain state).

Regarding membrane tension as physico-biochemical mechano-transduction sensor, we will see in Sect. 3.3 that it appears to be recruited in a major event of embryonic morphogenesis: the mesoderm invagination initiating early Drosophila embryo's gastrulation, with a speculative implication in the major evolutionary event of emergence of motor-sensorial system and of primary organisms as defined by multicellular systems characterised by the existence of a primitive functional organ.

## 3. Embryonic Morphogenesis

The most ancient known scientific report on embryonic morphogenesis is by Aristotle, four centuries BCE (Aristotle II). In his report, Aristotle emphasises that the different parts of the body of the chicken embryo form in a sequential process rather than all at the same time. This seminal observation led to the so-called "epigenetic" conception of embryogenesis, through which the existence of the structure of the embryo of a given stage conditions the emergence of the structure of the next stage. This conception does not require a pre-existent body plan, in opposition to the earlier platonic preformationist conception of morphogenesis. Much later, the progresses of optical microscopy from the seventeenth to beginning of the twentieth century allowed increasingly accurate observation of embryonic development. While the preformationists initially thought they could detect the existence of small preformed human shapes in the head of the male spermatozoid (called the "homunculus" by Leeuwenhoek) (Leeuwenhoek, 1683), the epigenetic view of development was rapidly confirmed by the observation of morphogenetic movements of tissues that correlate to growth, which progressively shape the embryo from ovoids to complex body shapes in a step-by-step sequential process. At that time, the privileged observable feature of embryogenesis was thus the morphogenetic movements, which appeared as hydrodynamic fluid movements. After the Newtonian evolution of physics, these observations were naturally interpreted by many of the embryologists of that period, like His and Leduc (His, 1875; Leduc, 1912), as passive flows exclusively governed by the Newtonian laws of hydrodynamics. One of these embryologists, D'Arcy Thompson, worked within this context of passive dominating view of tissue deformation of this century to explain the different shapes produced by evolution even though suspecting the existence of still unknown hidden underlying additive physiological factors driving the morphogenetic processes (Thomson, 1917; Fox-Keller, 2003).

The discovery of the genome and the emergence of molecular biology and the genetics of developmental biology in the middle of twentieth century revealed the nature of these factors, both genetic and biochemical in nature. From this evolution of biology, developmental biology focused most of its efforts on the study of the genetic control of the elaboration of the biochemical differentiation of the tissues designing the body plan of the future organism (Lewis, 1978; Nusslein-Volhard and Wieschaus, 1980; Garber et al., 1983; St Johnston and Nusslein-Volhard, 1992). However, the end of twentieth century (at the onset of the 1990s) was marked by a return to geometrical morphogenetic considerations, with the discovery of master developmental gene, regulating the generation of morphogenetic movements in embryogenesis (Sweeton et al., 1991). Today, our understanding of the molecular mechanism linking patterning gene expression to the production of mechanical forces that shape the embryo increasingly progresses (Martin, 2009). More recently in the beginning of the twenty-first century, reverse signals were discovered, showing the mechanical control by the morphogenetic movements of the expression of patterning and developmental genes, based on biochemical mechano-transduction processes (Farge, 2003; Brouzes and Farge, 2004).

In this chapter, we will describe the state of the art in this emerging field reciprocally coupling genetics to mechanical physics. The study of such coupling necessarily requires the establishment of new methods, allowing the uncoupling of pure genetic inputs from pure mechanical inputs in the regulation of patterning gene expression. After the first part, describing our knowledge on the genetic control of morphogenetic movements in embryogenesis, we will review today's knowledge of the mechanical control of patterning and developmental gene expression, and the distinct genetic and biophysical methods which have been set up to uncouple mechanical inputs from biochemical inputs in the control of developmental gene expression *in vivo*. Specifically, we will describe the innovative tools we have set up to measure and apply physiological strains and forces *in vivo*, from the inside of the tissue, to inhibit or quantitatively mimic morphogenetic movements. We will report our understanding of the underlying molecular mechanisms that translate mechanical strains applied to cells and tissues *in vivo* into the activation of transduction pathways connected to major developmental biochemical events during embryogenesis. Next, we will describe the influence of such mechano-transduction processes in medicine and more specifically in carcinogenesis. Finally, we will speculate on evolutionary perspectives potentially related to the emergence of such mechano-transduction processes.

## 3.1. GENETIC CONTROL OF MORPHOGENETIC MOVEMENTS

Embryogenesis is composed of two major morphogenetic processes: the biochemical patterning of the embryo and the mechanical morphogenetic movements that geometrically shape the embryo. Starting 20 years ago, experiments initiated in early Drosophila embryos have shown that the morphogenetic movement sequence is tightly controlled by patterning gene expression (Sweeton et al., 1991). For instance, embryonic mesoderm invagination requires the expression of the Fog (expressed under the control of Twist) and Snail zygotic proteins in the mesoderm (Seher et al., 2007), whereas the germ-band extension movement (i.e. the anterior-posterior elongation of the invaginated embryo) requires the expression of the bicoid, nanos and torso-like maternal proteins, which control the anterior-posterior polarity of the embryo (Irvine and Wieschaus, 1994) (Fig. 2). However, the elucidation of the relationship between gene expression and the generation of strains leading to the tissue shape changes remained until recently largely unknown. The key role of cell polarities, in terms of the cortical (sub-plasma membrane) concentration of the molecular motor Myosin-II protein (Myo-II) in generating multicellular morphogenetic movements was first found in the generation of invaginations during Drosophila embryo gastrulation. In this process, the apical concentration of Myosin-II leads to the constriction of cell apexes and generates the trapezoidal cell shape changes, leading to posterior pole cell invaginations (Young et al., 1991). More recently, the role of the dorsoventral and anterior-posterior patterning genes was established, which induce the embryo polarities at the multicellular embryonic scale, in the generation of apico-basal and planar polarities in Myo-II concentration leading to morphogenetic movements (Dawes-Hoang et al., 2005; Bertet et al., 2004).

### *3.1.1. From Genes to Shape: Molecular and Cell Biology of Local In Vivo Force Generation*

Regarding germ-band extension, the bicoid, nanos and torso-like genes establishing the anterior-posterior polarity of the embryo regulate the concentration of Par-3 in plasma membrane surfaces parallel, but not perpendicular to the axis, through a still poorly understood mechanism. As Myo-II interaction with the subcellular cortex is impaired by Par-3, this establishes a high cortical concentration of Myo-II on membranes perpendicular to the axis (Zallen and Wieschaus, 2004). As a consequence, the cortical tension of those cell-cell interfaces increases and relaxes through a decrease of the cell-cell surface contact perpendicular to the axis, which leads to cell intercalation and extension of the germ band (Fig. 2) (Bertet et al., 2004). Understanding of this process was reinforced by successful *in silico* simulations mimicking germ-band extension with only these ingredients (Rauzi et al., 2008). Interestingly, planar polarity genes also appear to be critical in the generation of convergent extension morphogenetic movements in the embryos of other species, including zebrafish and Xenopus (Roszko et al., 2009; Keller, 2002; Heisenberg and Tada, 2002).

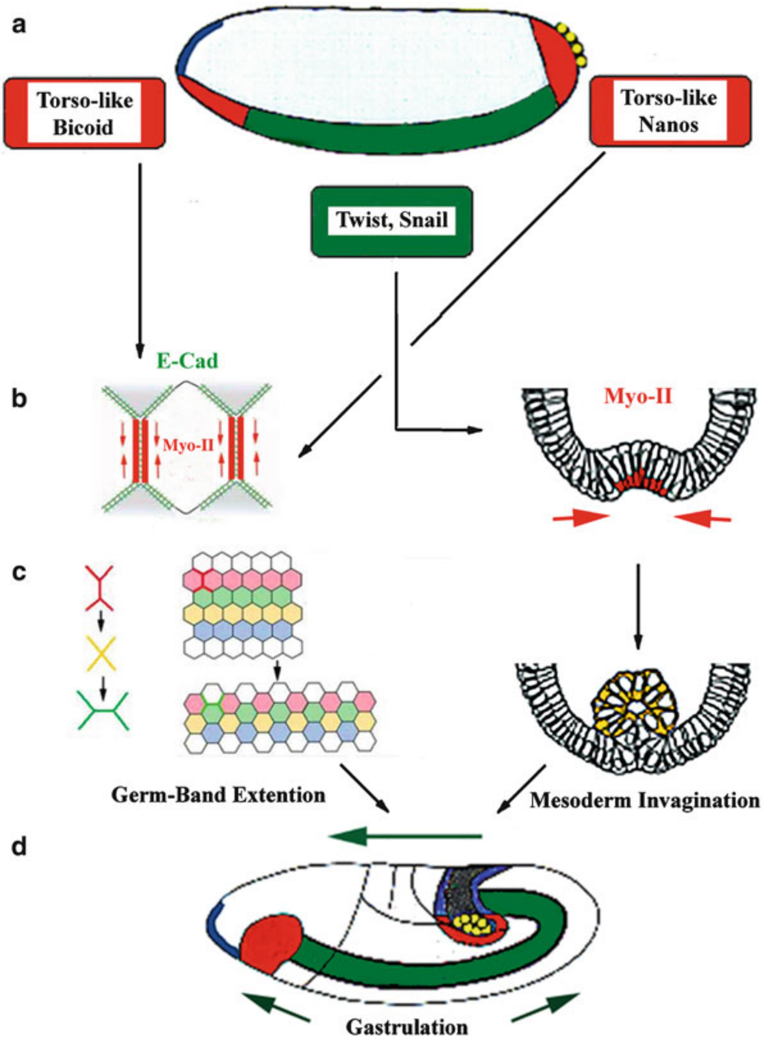


**Figure 2.** Control of multicellular morphogenetic movements in Drosophila embryos gastrulation via genetically controlled intracellular polarities in Myosin-II concentration. *Germ-band extension*. (**a**) Before gastrulation, the pattern of expression of developmental genes determining the anteroposterior polarity of the embryo is controlled by the expression of the maternal gene products bicoid in the anterior and nanos in the posterior (*in red*). (**b**) This combines to the expression of the terminal patterning genes controlled by the maternal gene torso-like, to establish the planar polarity of Myosin-II sub-membranar concentration (*in red, left*). The origin of the underlying molecular mechanism linking anteroposterior patterning gene expression to planar polarity remains to be fully understood. (**c**) The consequence of the polarity is an increase of tension in membranes perpendicular to the anteroposterior axis, leading to a decrease of these surface areas, then to the dorsoventral cell intercalation (adapted from Bertet et al., 2005) extending the anteroposterior length of the tissue at gastrulation (**d**, *green arrows*).

Regarding mesoderm invagination, the Fog signalling pathway has been demonstrated to involve the apical attraction of Myo-II through the activation of a Rho signalling pathway. Fog is a secreted signalling molecule that is expressed under the control of Twist in the mesoderm and in the posterior pole, activating apical redistribution of Myo-II (Dawes-Hoang et al., 2005). *T48*, another gene acting downstream of Twist, cooperates with Fog in triggering the apical attraction of RhoGEF2, a protein required for apical redistribution of Myo-II and for mesoderm invagination (Kolsch et al., 2007). In addition to the Twist-dependent activation of the RhoGEF2 apical redistribution process, Snail is also necessary for stable apical redistribution of Myo-II and mesoderm invagination, through a still unknown molecular mechanism (Fig. 2).

Different simulations were developed to test whether the apical surface tension increase induced by redistribution of Myo-II would be the only genetically controlled active perturbation necessary for mesoderm invagination, or if the invagination would require additive active movements, such as cell shortening. Whereas simulations describing cells as a continuous viscoelastic medium suggest the necessity of an active shortening of mesodermal cells to accomplish invagination (Conte et al., 2008), hydrodynamical simulations describing the tissue as composed of individual cells with individual plasma membranes characterised by an actomyosin cortical tension and contractile apical rings connected by intercellular junctions suggest that the Myo-II-dependent increase of apical surface tension of mesodermal cells is sufficient to trigger the movements observed during invagination (Pouille and Farge, 2008). Simulations of mesoderm invagination were also performed in sea urchins embryos, which have an extracellular matrix that should be specifically compliant to allow gastrulation (Davidson et al., 1995). However, the Myo-II activity was proposed to be not the only player of other early embryonic morphogenesis. Effectively, recent simulations proposed the involvement of the microtubule network within *Caenorhabditis elegans* epithelial cells in redistributing the stress originally produced by actomyosin-oriented actin filaments, thus leading to the elongation morphogenetic movement of the embryo (Ciarletta et al., 2009). Note that in addition to the genetic control of Myosin-II cell polarities, the origin of multicellular morphogenetic movements was also proposed to be driven by the difference of adhesive surface tensions between cells of different differentiation states (Foty and Steinberg, 2005; Graner and Glazier, 1992; Schotz et al., 2008; Krieg et al., 2008; Kafer et al., 2007).

◄

**Figure 2.** (continued) *Mesoderm invagination*. (**a**) Before gastrulation, the pattern of expression of developmental genes determining the dorsoventral polarity of the embryo is controlled by the expression of the maternally induced nuclear translocation of the transcription factor Dorsal, that activates the expression of the ventral mesodermal genes *twist* and *snail* (*in green*). (**b**) These genes are necessarily together to induce the sub-membrane apical accumulation of Myosin-II (*in red, right*) that increases the apical surface tension. (**c**, **d**) This leads to the decrease of apical surface area compared to basal surface areas, triggering the inward curvature and invagination of the mesoderm at gastrulation. The understanding of the underlying molecular mechanisms linking the expression of the patterning genes *twist* and *snail* to apical attraction of Myosin-II are better and better understood (see Fig. 4).

Even though some movement-promoting components necessarily belong to hydrodynamic-like movement of a passive fluid submitted to external macroscopic forces (Zamir et al., 2006), here we see how embryonic morphogenesis is in addition specifically driven by external active microscopic forces developed in any cells of the tissue, due to genetically controlled cell differential adhesions or cell polarities in the distribution of Myo-II.

### *3.1.2. Measuring the Active Forces Developed in Morphogenetic Movements In Vivo*

In the preceding case, the origin of the multicellular morphogenetic movements of the embryonic tissue is the anisotropy of Myo-II concentration within individual cells, leading to both cell migration intercalation movements in response to polar planarity anisotropies and to cell shape changes in response to apico-basal polarities. Even though the link between patterning gene expression and the generation of a three-dimensional embryonic morphology has begun to be understood, the evaluation of the forces developed by these morphogenetic movements has until today been very rarely measured *in vivo*. Looking at Xenopus embryonic explants, the measurement of the deflection of the beam emerging from an optical fibre, of which the bending elastic constant has been calibrated and applied to the tissue submitted to convergent extension, leads to a maximum force of 1 μN (Moore, 1994). Such an apparatus is able to measure forces in the range of 50 nN to 10 μN, but necessitates working *ex vivo* on tissue explants (Davidson and Keller, 2007).

Another extensively studied morphogenetic movement is the Drosophila embryo dorsal closure, which combines the action of a closing purse-string surrounding the amniosera tissue and constricting it, with contractile amniosera cell oscillations, extrusion of cells inside the embryo and cell apoptosis in the amniosera (Tokoyama et al., 2008; Solon et al., 2009; Jacinto et al., 2000). In this case, fine mathematical analysis of the geometry of the tissue elements of dorsal closure, combined with the quantitative analysis of tissue relaxation photo-ablations of specific domains of the dorsal closure, leads to the evaluation of the ratio between the purse-string and amniosera tissue tensions collaborating in the driving of dorsal closure (Hutson et al., 2003). Relative forces can be evaluated directly by studying tissue dynamics, but only a local direct mechanical deformation allows access to the constraints field and the absolute forces.

Measuring the forces associated with morphogenetic movements *in vivo*, within the developing embryo, requires the use of nanotechnologies to mechanically manipulate the living multicellular mechanical medium of the embryo from the inside. Injection of ferrofluids composed of 7-nm magnetic particles into the cytoplasm of Drosophila embryos at the end of cellularisation allows the magnetization of a condensed pack of 50-μm cells, on which a force of 60 nN was applied by using a calibrated magnetic tweezer to quantitatively mimic the rate of deformation of anterior pole stomodeal cells of the embryo normally due to the convergent extension of the mesoderm at gastrulation (Desprat et al., 2008). The difference of two orders of magnitude of these forces is coherent with the fact the Drosophila embryo is typically ten times smaller than the Xenopus embryo, which develops 1-μN forces, as the forces developed are generally proportional to the section of the tissue involved, which is square the size.

## 3.2. MECHANICAL CONTROL OF GENE EXPRESSION

Developmental gene expressions consist in control parameters necessary for both the biochemical patterning and the generation of morphogenetic movements that geometrically shape the embryo. The role of genetically driven physical dynamical modules, such as cadherin-dependent differential adhesion or Wnt-Notch-dependent dynamical oscillations of gene expression, has been proposed to be determinant in the emergence forms in multicellular systems and in its evolution (Newman and Bhat, 2008). Reversely is the state of expression of the genome sensitive to the patterns and shapes it develops? Regarding biochemical patterning, the state of expression of the genome is constantly changing in response to the pattern of expression of developmental proteins through classical biochemical induction: the pattern of expression of the RNAs of a given stage of development is triggered in response to the pattern of expression of the proteins of the previous stage. Because multicellular morphology is not biochemical in nature, the existence of such feedback cannot be based on classical biochemical inductive cues. We proposed that it was rather due to mechanical cues associated to tissue deformation.

Strikingly, looking at endogenous morphogenesis in the early Drosophila embryo, the expression of the Twist protein was found to be strongly amplified in anterior pole stomodeal cells, after 10–20 min of compression of these cells by the morphogenetic movement of germ-band extension. Twist expression being found to be mechanically induced in early Drosophila embryos submitted to global artificial shape changes (Farge, 2003), this suggested that Twist expression might be mechanically induced in the stomodeum at the onset of gastrulation (Fig. 3) (Desprat et al., 2008; Farge, 2003).

However, testing the existence of mechanical cues leading to Twist mechanical induction in stomodeal cells in response to the endogenous morphogenetic movements of germ-band extension requires the elaboration of tools, allowing the inhibition and rescue of the Myo-II-dependent germ-band extension morphogenetic movement, *in vivo*.

### *3.2.1. Genetic Tools to Control Morphogenetic Movements*

Taking advantage of the well-characterised genetics of early Drosophila embryo morphogenesis, one can use the anterior-posterior apolar triple mutant *bicoid nanos torso-like* to block germ-band extension (Irvine and Wieschaus, 1994). In these mutants, anterior stomodeal cells are found to be not compressed, with no amplification of Twist expression in these cells (Farge, 2003). A 50-μm micromanipulated needle was then used to compress stomodeal anterior pole cells in these mutants, with a physiological order of magnitude of deformation. In response

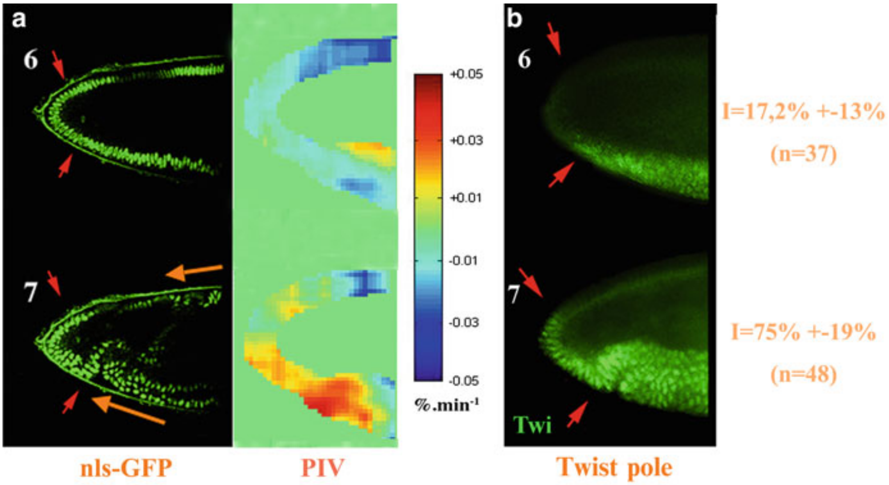


**Figure 3.** Twist expression increase correlates with compression by GBE in stomodeal cells at the onset of gastrulation. (**a**) Nls-GFP nuclear labelling shows the compression of stomodeal cells (in between *red arrows*) in between early stage 6 and late stage 7 due to GBE movements (*orange arrows*). Quantitative PIV analysis shows a 2% $\text{mn}^{-1}$ dynamics of compression during the first 10 min of GBE, encoded in *red*. (**b**) Twist is over-expressed at late stage 7 in stomodeal compressed cells (quantitative mean values combine (Desprat et al., 2008; Farge, 2003) data, and figures adapted from the same references).

to deformation, the amplification of the expression of Twist was rescued in these mutants, suggesting a mechanical induction of Twist by stomodeal cell compression in response to their compression by germ-band extension in wild-type embryos (Farge, 2003). The rescue of the strong expression of Twist in stomodeal cells was also triggered in response to the rescue of germ-band extension by using the *bicoid torso-like* double mutant, in which the expression of the posterior gene *nanos* allows the first 20 min of germ-band extension (Irvine and Wieschaus, 1994), without affecting the genetic background of anterior pole cells (Farge, 2003). All together, these results suggest that the endogenous morphogenetic activity of Myosin-II, leading to germ-band extension (Bertet et al., 2004), mechanically induces the activation of Twist gene expression in stomodeal cells at the onset of Drosophila gastrulation.

### *3.2.2. Opto-Magnetic Tools in Morphogenetic Movement Control*

The ability to use genetics and simple micromanipulated needles to control stomodeal cell deformation suggests endogenous mechanical induction of Twist in stomodeal cells. However, working with non-wild-type embryos using non-physiological forces of tissue deformation prevents the establishment of a definitive conclusion, which would require experiments performed within fully physiologic genetic and biomechanical conditions. One has thus to develop new biophysical tools, allowing control of the deformation of stomodeal cells, with finely controlled physiological forces and within the wild-type genetic context.

### Inhibiting Deformation by Photo-Ablation

Because the germ band largely extends posteriorly, leading to a strong dorsal wave of compression from the posterior to the anterior pole of the embryo (Fig. 2d and 3a), the ablation of the most dorsal tissue of the embryo was inhibited to prevent anterior pole stomodeal cell compression in wild-type embryos (Fig. 4a). In fact, the ablation of the most dorsal part of the embryo blocks the germ-band extension on a timescale largely higher than the characteristic time of stomodeal cell compression during normal development, inhibiting both the posterior extension and the anterior extension which also efficiently compress stomodeal cells (Farge, 2003; Supatto et al., 2005).

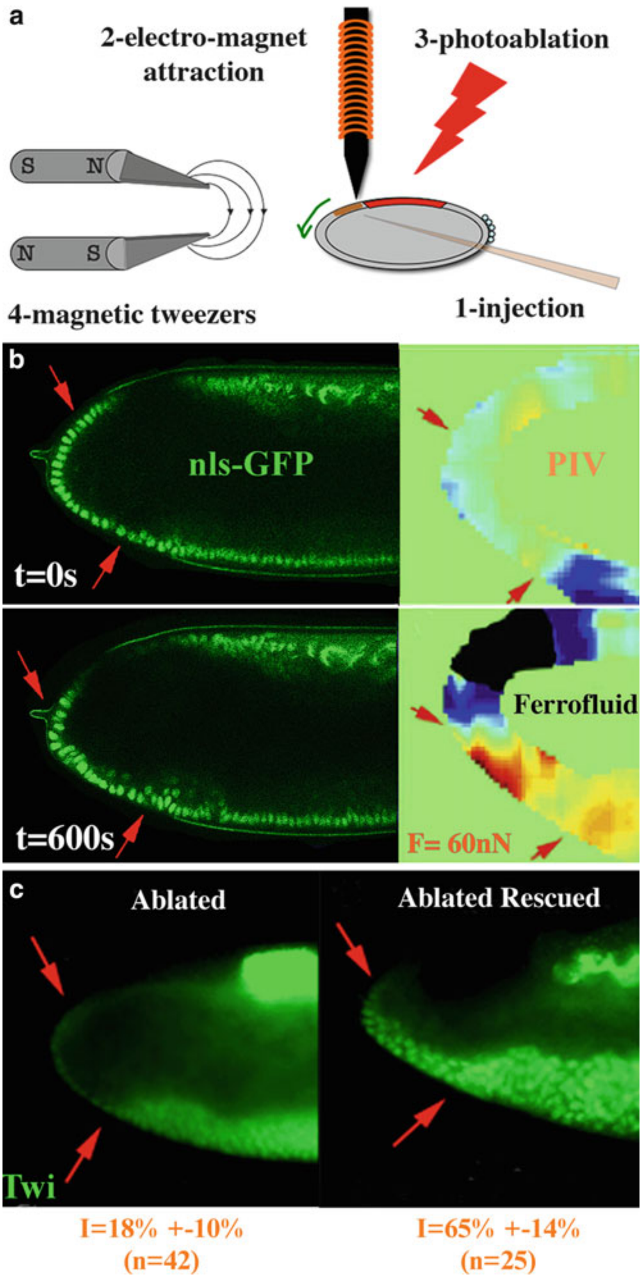
The ablation uses high power two-photon femtosecond microscopy. The two-photon technology allows the generation of a powerful irradiation only at the point of focus of the infrared incident beam. At this point only, the probability of condensing two photons at the same place and time becomes high, leading to a destructive beam whose energy is square the energy of the non-destructive original infrared beam. As a consequence, the incident beam can cross tissues without destroying them and will be destructive only at the point of convergence. In addition, because destructive ablation effects are proportional to the power of the energy of the laser (namely, the energy deposited by unit of time), the fact that the femtosecond laser impulsions are very short ($10^{-15}$ s) means that the energy deposited in the impulses can remain very small in order to trigger a power high enough to generate destruction. Indeed, the heating of the embryos after ablation was evaluated to be on the order of 0.1°C only (Supatto et al., 2005).

As a result of the laser treatment, wild-type ablated embryos showed an inhibition of stomodeal cell compression (Fig. 4b), with an inhibition of the amplification of Twist expression in these cells (Fig. 4c) (Farge, 2003; Supatto et al., 2005).

### Quantitative Rescue of Physiological Deformation by Ferrofluid Injection and Magnetic Manipulation

To rescue the compression of stomodeal cells with physiological dynamics, a magnetic ferrofluid is injected into the anterior dorsal cells neighbouring the stomodeal cells at the end of cellularisation, after the photo-ablation of middle dorsal cells (Fig. 4a) (Desprat et al., 2008). Once cells are magnetised by ferrofluid insertion, cells are subsequently attracted by a calibrated magnetic tweezers (Fig. 4a).

The position of the magnetic tweezer is systematically explored in order to quantitatively tune the dynamics of compression rescue of the ablated embryos to the value of the endogenous compression of the non-ablated wild-type embryos, which corresponds to the application of a force of 60 nN by magnetised cells onto stomodeal cells (Fig. 4b) (Desprat et al., 2008). This compression strain was applied for 10 min in order to mimic endogenous stomodeal cell compression, with immediate subsequent fixation of the embryos and classical labelling with anti-Twist antibodies.


a
2-electro-magnet attraction
3-photoablation
S N
N S
4-magnetic tweezers
1-injection
b
nls-GFP
PIV
t=0s
t=600s
Ferrofluid
F= 60nN
c
Ablated
Ablated Rescued
Twi
I=18% +-10% (n=42)
I=65% +-14% (n=25)

As a result, the strong expression of Twist was rescued in stomodeal cells in response to compression. Quantitative analysis revealed a level of expression rescue of Twist in stomodeal cells normalised to mesoderm cells of 65% ± 14%, which is amplified compared to the 18% ± 10% characterising the ablated embryos (ablated and injected without magnetic field application), and comparable to the value of expression after compression by the endogenous movement of germ-band extension of 71% ± 19% (Fig. 4c) (Desprat et al., 2008).

Thus, rescuing stomodeal cell compression from ablated non-compressed embryos by using the physiological biomechanical deformation of 2% $\text{mn}^{-1}$ (representing of slow movement of 2 $\mu\text{m mn}^{-1}$), within the physiological wild-type genetic background, quantitatively rescues the high level of Twist expression in the stomodeal cells compressed by germ-band extension, which is lost after inhibition of compression due to dorsal cell photo-ablations.

This demonstrates that Twist over-expression is mechanically induced by stomodeal cell compression due to germ-band extension during endogenous development.

### *3.2.3. Underlying Molecular Mechanism of Mechano-Transduction and Physiological Function in Development*

The underlying molecular mechanism of Twist mechanical induction is the mechanically induced release of Armadillo/β-catenin from the junctions into the nuclei. Armadillo/β-catenin is the cotranscription factor of TCF.

Dominant negative mutations of TCF as well as over-expression of Axin (which traps Armadillo/β-catenin in the cytoplasm, preventing any nuclear translocation) are both characterised by a lack of Twist mechanical induction, showing the necessity of the transcriptional activity of the β-catenin in Twist mechanical induction (Farge, 2003). Such release belongs to a mechano-transduction process that is dependent on Src42A, a protein triggering the inhibition of the interaction of β-catenin with E-cadherin in Drosophila embryos β-catenin phosphorylation. Because Src42A is already activated (phosphorylated) before compression, and not over-activated in response to stomodeal cell mechanical strains, Src42A appears to be permissive in Armadillo/β-catenin release form the junctions, and

◄

**Figure 4.** Testing Twist mechanical induction in controlling stomodeal cells compression by combining optics photo-ablation and ferrofluid injected cells magnetic tissue manipulation. (**a**) The dorsal domain of the embryo is photo-ablated to block GBE, after injection and concentration of a calibrated ferrofluid of magnetic nanoparticles into anterodorsal cells. Calibrated magnetic tweezers are positioned in order to attract magnetised dorsal cells to compress anterior pole stomodeal cells with a deformation rate that mimics GBE endogenous compression dynamics. (**b**) Dynamics of stomodeal cells compression (in between *red arrows*) induced by magnetic manipulation mimicking the first 10 min of compression due to GBE during normal development, observed in nsl-GFP and in PIV. A force of 60 nN is applied to stomodeal cells to quantitatively phenocopy the endogenous compression measured by PIV in Fig. 2a. (**c**) Inhibition of Twist over-expression in non-compressed stomodeal cells into the ablated embryo (in between *red arrows*) and recovery in the stomodeal cells of the ablated embryos which the physiological compression is rescued by magnetic manipulation. (Adapted from Desprat et al., 2008.)

not directly involved into the mechano-transduction pathway (Desprat et al., 2008). One possibility, among others, is that mechanically induced conformational changes of junctional Armadillo/β-catenin would open sites of phosphorylation with activated Src42A, leading to the inhibition of its interaction with E-cadherin and to its release into the cytoplasm. Such activated Src-dependent mechanical activation of p130Cas was demonstrated *in vitro*, in response to mechanical induction of p130Cas changes of conformation (Sawada et al., 2006).

Interestingly, mechanical activation of Armadillo/β-catenin was also found to be involved in mouse bone development, through muscle contractions inducing mechanical shocks in between the bone synovial joints. The pluripotency of synovial bone cells, which controls both bone growth and synovial joint differentiation, is indeed maintained by such mechanically induced nuclear translocation of β-catenin (Kahn et al., 2009).

Regarding the physiological function of Twist mechanical induction, the high expression of Twist at stage 7, which is mechanically induced by germ-band extension, was found to be necessary for midgut cell functional differentiation at late embryonic stages 14–16 (11–15 h of development) through the control of Dve expression, as well as for survival of 4–5-day larvae. Effectively, genetically controlled defects in Twist over-expression to the level of expression of non-compressed stomodeal cells (due to patterned and staged expression of Twi-RNAi interfering with Twist expression in stomodeal cells only and during compression only) lead to the loss of Dve expression in anterior midgut cells as well as to lethality in typically 80% of cases (Desprat et al., 2008).

Therefore, in Drosophila embryos, mechanical induction of Twist expression in stomodeal cells during their compression appears to control vital functional differentiation of the anterior midgut cells of the embryo.

Interestingly, mechanical contraction waves of the primary neural tissue were speculated to control differentiation on itself during development in axolotl embryos (Brodland et al., 1994). Here we demonstrate the inductive involvement of the body shape change of the embryo into the developmental gene expression cascade control, through the mechanical induction of anterior gut functional differentiation in response to its compression by the morphogenetic movement of another tissue, the germ band, *in vivo* (Desprat et al., 2008; Farge, 2003). Mechanical induction due to embryonic morphogenesis was also very recently proposed *ex vivo*, on embryonic xenopus explant experiments (Kornikova et al., 2010).

### *3.2.4. The β-Catenin: An Evolutionary Conserved Polarisation Pathway in Early Embryos*

It is interesting to note that the Armadillo homolog, β-catenin, translocates into the nuclei at the dorsal pole of early frog and fish embryos but also in the anterior pole of the bilaterian and non-bilaterian sea urchin and ancient cnidaria sea anemone embryos (Logan et al., 1999; Wikramanayake et al., 2003), where it plays a role in determining both the anetro-posterior and the dorso-ventral embryonic polarities (Logan et al., 1999; Schneider et al., 1996). Furthermore, the ectopic nuclear localization of β-catenin induces the dorsalisation of vertebrate embryos (Schneider et al., 1996). Because the dorsal-ventral axis of invertebrates is inverted with respect to that of vertebrates, this corresponds well with the ventralisation (i.e. Twist expression) observed in Drosophila embryos upon the mechanical induction of Armadillo nuclear localization (De Robertis and Sasai, 1996; Holley et al., 1995). Thus, mechanical compression may reactivate a conserved and ancient pathway for dorsal-ventral axis formation, or more generally, to axis formation in pre-bilaterians embryos like sea anemone that is determined by polar β-catenin nuclear translocation (Wikramanayake et al., 2003).

It is therefore tempting to speculate that a local response of earliest embryos tissues to mechanical contact with the ground after gravity sedimentation could have locally activated the β-catenin, thereby participating in the determination of the primary axis formation of earliest diploblasts common ancestors of both invertebrate and vertebrate species. Then, Wnt ligands expression, leading to β-catenin pathway activation, may have replaced such primitive mechanical signaling, inducing polarization independently of environmental mechanical cues, thereby initiating biochemical patterning embryogenesis. Internal mechanical strains, such as Germ Band Extension induced compression of future anterior gut tissues (see Sect. 3.3.2) may also have replaced such primitive external mechanical cues.

## 3.3. MECHANO-TRANSDUCTION IN THE CONTROL OF THE POST-TRANSLATIONAL MORPHOGENETIC EVENTS TRIGGERING MESODERM INVAGINATION

In addition to controlling the state of expression of the genome, mechano-transduction processes in development can also control post-translational events, involving for instance Myosin-II intracellular behaviours at the onset of gastrulation. In Drosophila embryos, gastrulation begins by a Snail- and Twist-dependent apical redistribution of Myosin-II that leads to a constriction of apical cell surfaces. Such constriction generates a trapezoidal shape change of individual cells, leading to the decrease of the apical surface area of the mesoderm compared to the basal surface area, which induces the inward bending constraints of mesoderm invagination (Sweeton et al., 1991).

Interestingly, there exists two phases of apical constriction. The one occurring during the first 4 min is stochastic, and randomly involves the uncorrelated reversible pulses of constriction and relaxation of individual cells, and is unable to trigger mesoderm invagination (Sweeton et al., 1991). These pulses are associated with reversible pulses of apical spots of Myosin-II (Martin et al., 2009). The second one is collective and involves the constriction of all mesodermal cells (Sweeton et al., 1991), through a process of pulsatile constrictions, including a ratchet process progressively stabilising cell apexes into more and more constricted states. This is

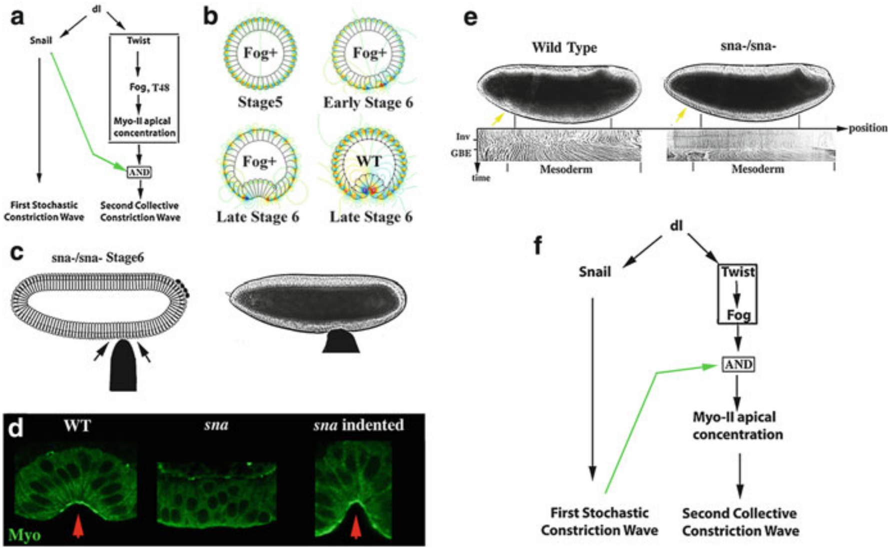


**Figure 5.** Mechanical induction of Myo-II apical redistribution leading to mesoderm invagination. (**a**) The genetic network controlling mesoderm invagination. The mesoderm Snail and Twist/Fog T48 pathways cooperate in triggering the apical constriction leading to mesoderm invagination (*green arrow*). (**b**) Simulating an embryo in which Fog is expressed ectopically and, responding to mechanical strain by mechanical activation of the Fog signalling pathway, phenocopies the experimentally observed propagation of apical Myo-II redistribution and flattening from mesoderm to lateral and dorsal tissues (see text). (**c**) Indenting *sna* mutants to rescue the lack of mechanical strain of *snail* mutants and to test the mechanical reactivation of the Fog signalling pathway controlling both apical redistribution of Myo-II and mesoderm invagination. (**d**) Rescuing apical accumulation of Myo-II and mesoderm invagination, lost in the *sna* mutant, after soft indentation of the mesoderm of *sna* mutants, in a Fog-dependent process. (**e**) Kymographs of the mesoderm constriction movements at earliest stage 6 in the wild type, which is not observed in earliest stage 6 non-constricting *sna* mutant embryos, as a phenotype criteria to select *sna* mutant embryos *a priori*, before indentation. *Sna* mutants are double checked through the delay in anterior midgut formation of *snail* homozygous compared to WT and heterozygous (*yellow arrow*) (Pouille et al., 2009). (**f**) The mechano-genetic network controlling mesoderm invagination. Snail initiates apical constriction fluctuations, which activates the Fog signalling pathway (through the mechanical blocking of Fog endocytosis, see text), leading to the coordinated Myo-II apical stabilisation and coordinated apical constriction of mesoderm cells necessary for mesoderm invagination. (Adapted from Pouille et al., 2009).

associated with the progressive stabilisation of the apical spots of Myosin-II, leading to apical Myosin-II coalescence and redistribution (Martin et al., 2009). Because mutants of *twist* only show the stochastic phase, the collective phase is Twist dependent. In fact, the Fog-secreted factor, which is expressed under the control of Twist, is the key signalling protein triggering the collective phase (Costa et al., 1994). However, the *snail* mutants are defective in both the stochastic and collective phases, indicating that the stochastic phase is indeed Snail dependent but also that the two phases are not independent (Fig. 5a).

Strikingly, a purely biochemical interaction between the Snail and Twist/Fog underlying genetic and biochemical networks can be excluded by the following observations. In mutants of Snail, in which Fog is still expressed in the mesoderm (Morize et al., 1998), no apical redistribution of Myosin-II can be observed in the mesoderm (Martin et al., 2009; Pouille et al., 2009). In addition, the ectopic expression of Fog all around the embryonic tissue does not rescue apical constriction in *snail* mutants' mesoderm, whereas it does in *twist* mutants (Morize et al., 1998). Thus, Fog alone is not sufficient to trigger apical redistribution of Myosin-II and mesoderm invagination, but Fog and Snail together are necessary for Myosin-II apical redistribution (Seher et al., 2007). On the other hand, the ectopic expression of Fog all around the embryo induces an apical redistribution of Myosin-II in all tissues of the wild type embryo, including in ectoderm cells in which Snail is not expressed (Dawes-Hoang et al., 2005). So, contrary to the previous observations, this would suggest that Fog alone is able to trigger the apical redistribution of Myosin-II.

This apparent contradiction can be resolved by considering that the interaction between the two phases is not mediated biochemically, but by cell-cell mechanical interactions via a Fog-dependent mechano-transduction process leading to apical redistribution of Myosin-II (Pouille et al., 2009). Effectively, considering that the mechanical strains (mean surface tension or mean cell pressure) developed by the stochastic phase of constriction could trigger a Fog-dependent mechanical activation of apical redistribution of Myosin-II in the mesoderm, this would mean that stable apical redistribution of Myosin-II would require mechanical strains plus Fog expression. Such mechanical strains being absent in the mesoderm in a *snail* mutant, no mesodermal apical redistribution of Myosin-II is observed, even in the presence of Fog (Morize et al., 1998; Martin et al., 2009; Pouille et al., 2009). On the other hand, if Snail is expressed in the mesoderm, the mechanical strains would activate the Fog-dependent mechano-transduction pathway and lead to the apical redistribution of Myosin-II, then to mesoderm invagination. In turn, mesoderm invagination mechanically strains ventrolateral cells. In the wild type, in the absence of Fog in these cells, apical redistribution of Myosin-II is not induced in non-mesoderm cells and is thus restricted to the Fog expressing mesoderm. On the other hand, in embryos in which Fog is expressed ectopically all around the embryo, the apical redistribution of Myosin-II will be first activated in ventrolateral cells in response to stretching by mesoderm cells, in which apical stress will increase. In turn, these cells will stress more lateral cells and activate apical redistribution of Myosin-II, a process that will propagate from ventral cells to dorsal cells after the initiation of mesoderm invagination of stage 6 (Dawes-Hoang et al., 2005).

### *3.3.1. In Silico Physical Tools to Test Theoretically the Viability of the Mechano-Transduction Hypothesis*

Here such a scenario can be predicted by simulations of mesoderm invagination in which the Snail-dependent stochastic phase is introduced with a Fog-dependent mechanical activation of stable apical redistribution of Myosin-II. The Fog-dependent mechanical activation is first tuned in the mesoderm to mimic mesoderm invagination in the wild type. It is then added all around the embryo to mimic the genetic background associated with the ectopic expression of Fog. The output of the simulation is the production of an embryo characterised by apical accumulation of Myo-II propagation all around the embryo (Dawes-Hoang, 2005), leading to flattening in lateral ectoderm and dorsal cells, to a lateral tension preventing the formation of a complete mesoderm invagination (Pouille et al., 2009) (Fig. 5b), a phenotype characteristic of embryos over-expressing Fog ectopically (Morize et al., 1998). This suggests, but yet does not prove, the possibility of an underlying mechano-transduction mechanism of interaction between the Snail (initiating deformations) and Fog (actively responding to the strain by apical stabilisation of Myo-II) networks, necessary for early Drosophila embryo mesoderm invagination.

### *3.3.2. The Coupling of Mechanical and Genetic Tools to Experimentally Test Mechano-Transduction in Myo-II Apical Redistribution Leading to Mesoderm Invagination*

The core of the model is that Snail expression in itself is not necessary with Fog to trigger apical redistribution of Myosin-II, but the mechanical strains developed by Snail expression with Fog are. Thus, if the model is correct, rescuing the existence of a mechanical strain in the mesoderm of *snail* mutants should rescue both the apical redistribution of Myosin-II and the mesoderm invagination, both of which are missing in these mutants. Embryos of *snail* mutants are thus indented 5 μm (namely, 30% of the thickness of the ectoderm and 2% of the thickness of the embryo) locally in the middle of the mesoderm, with a micromanipulated needle, precisely 2–3 min after the end of cellularisation, which signals the initiation of the stochastic phase in wild-type embryos (Fig. 5c). As a result, both apical redistribution of Myosin-II and invagination were rescued in 67% of the indented *sna* homozygous mutant embryos (Fig. 5d), not only in the indented tissue but also throughout the complete mesoderm, suggesting a propagation of the contractile wave pre-patterned by Twist expression (Pouille et al., 2009). This percentage decreases to 38% when the indentation is realised 10 min after at the onset of GBE, probably because of a competition with the GBE morphogenetic movement (Pouille et al., 2009). Interestingly, *twi sna* double mutants do not show any response of the mesoderm to mechanical indentation, showing that the mechano-transduction pathway is dependent on the expression of Twist in the mesoderm. On the other hand, indenting a *twi sna* double mutant in which Fog has been additionally expressed only in the mesoderm, rescues the apical redistribution of Myosin-II and mesoderm invagination. In contrast, in the absence of indentation, Fog expression alone does not exhibit any rescue in the *sna twi* context (Pouille et al., 2009). Thus, Fog expression alone, without Snail, does not induce apical redistribution of Myosin-II, but rescues apical redistribution of Myosin-II in response to mechanical strains.

Such genetic manipulation can be realised by crossing a *sna twi* double mutant with a *twi PE-Fog* transgenic mutant, in which Fog is expressed under the control of the proximal element of the promoter of Twist (PE) which is known to control the expression of Twist in the mesoderm only. Thus, Fog is expressed in the mesoderm only, within a *sna twi* context (because the single mutation of *snail* adds to the fact that Snail expression is highly deficient at stage 6 within the *twi* mutant context (Leptin, 1991), as confirmed by no effect of mesoderm invagination of the *twi sna/twi, PE-Fog* non-indented embryos (Pouille et al., 2009)).

### *3.3.3. Mechanical Modulation of Fog Endocytosis: A Potential Underlying Molecular Mechanism of Mechano-Transduction*

Fog is a secreted signalling protein that activates the Rho pathway through its interaction with its putative receptor Cta (Costa et al., 1994). The activation of the pathway leads to the apical attraction of Myosin-II, possibly through its release from microtubules and its attraction by Cta, helped by T48 (Kolsch et al., 2007). One of the underlying mechano-transduction mechanisms involving secreted signalling proteins is the mechanical modulation of endocytosis. As described in Sect. 2, cell culture experiments have already shown the possibility of enhancing or triggering the activation of transduction pathways due to the increase of membrane mechanical tension, leading to the flattening of the membrane and thus to the inhibition of endocytosis of signalling proteins (Rauch et al., 2002). Membrane tension can be activated by the increase of the volume pressure in the cells (for instance, due to a mechanical deformation by pressure applied to the cells). Generally, the endocytosis of signalling proteins involves the degradation of the interaction with its specific receptor inside the endosomal compartments and the arrest of downstream signalling pathway inhibition. Therefore, the mechanical inhibition of signalling protein endocytosis leads to the enhancement of the activation of the downstream transduction pathway. It can also lead to pathway activation under subcritical concentrations of the signalling protein unable to activate the pathway within normal conditions of endocytosis (Rauch et al., 2002).

The role of the mechanical strain developed in the mesoderm by the Snail-dependent stochastic phase of constriction, triggering the inhibition of Fog endocytosis, leading to the activation of the downstream Rho transduction can also be investigated by coupling mechanical with genetic tools. Building a double *shi sna* mutant allows blockage of endocytosis, thanks to the temperature-sensitive *shi* mutation of dynamin which inhibits endocytosis within 2 min. Labelling Fog with a specific antibody confirmed the accumulation of Fog at the plasma membrane under conditions of inhibited endocytosis, as compared to the permissive temperature. In *sna* mutants, such plasma membrane accumulation of Fog is only observed in indented mutants of *sna*, showing that the indentation of the mesoderm mechanically induces the blockage of Fog endocytosis. This plasma membrane accumulation is also observed during the first 4 min of Sna-dependent stochastic constrictions in wild-type embryos, showing that Snail induces the inhibition of Fog endocytosis. Finally, the blocking of endocytosis in the *sna shi* double mutant rescues the apical redistribution of Myosin-II and mesoderm invagination, both of which lack in the *sna shi* mutants in endocytosis permissive temperature conditions.

Together, these observations suggest that the mechanical strains developed by sna-dependent stochastic constrictions in the mesoderm lead to the inhibition of Fog endocytosis, in turn leading to the activation of the downstream Rho pathway (Fig. 5f) (Pouille et al., 2009).

### *3.3.4. Incidences of the Mechanical Induction of Apical Redistribution of Myosin-II in Developmental Biology*

Interestingly, Myo-II dynamics was also found to be regulated by tension in actin cables, proposed to be maintained by another positive feedback mechanism to generate efficient germ-band extension tissue elongation in Drosophila embryos (Fernandez-Gonzalez et al., 2009). In Xenopus, the correct spatio-temporal assembly of the fibronectin matrix, a key process in the morphogenesis of the embryo, was suggested to be regulated by a tension integrin-dependent process (Dzamba et al., 2009). A role of mechanical strains in the regulation of microtubules orientation during meristem development was also suggested (Mammoto et al., 2009). Such positive mechanical feedback from strains to tensile or structural molecule redistribution could also be at work in processes of tissue reactive contraction resistance to stress having been proposed to be involved in Xenopus embryogenesis (Beloussov et al., 2006). The role of tensions developed by embryos in activating calcium-dependent processes of contraction has also been theoretically speculated in systems as distinct as sea urchin and Xenopus (Forgacs and Newman, 2005).

Here, the finding of Fog signalling as a mechano-transduction pathway has two distinct possible implications in developmental biology.

#### Long-Range and Rapid Cell–Cell Interactions Through Mechanical Cues

The first implication, very directly addressing the understanding of the respective roles of Snail and Fog in the apical redistribution of Myosin-II, indicates the existence of mechanical cues allowing rapid and long-range interactions between non-adjacent cells mediated by mechanical cues and mechano-transduction. Effectively, the fact that Myosin-II is redistributed apically within the mesoderm in the presence of Fog and Snail, but all around the embryo when expressing Fog ectopically despite the expression of Snail remaining restricted to mesodermal cells, shows that the expression of both Snail and Fog is necessary, but not necessarily within the same cells, to trigger apical redistribution of Myosin-II.

In other words, in embryos expressing Fog ectopically, Snail and Fog interact across very distant cells (mesodermal to dorsal, Fig. 5b), through the lateral propagation of mechanical strains initiated by the stochastic pulses of apical constriction generated by Snail in the mesoderm (Dawes-Hoang et al., 2005).

#### Does Coordinated Constrictions Integrated by Mechanical Cues and Mechano-Transduction Lead to Mesoderm Invagination?

The second implication addresses the question of the detailed mechanisms leading to the coordination of apical constriction which is necessary for mesoderm invagination. It indicates the existence of processes triggering collective-ordered cell behaviours directly by the increase of the stochastic fluctuations of behaviour of individual cells. Effectively, these experiments suggest that the Snail-dependent fluctuations feedback to individual cell states through Fog-dependent mechano-transduction, leading to the activation of a strong constriction of individual cells which is coordinated via mechanical interactions between cells that propagates very rapidly through the mesoderm, via cell surface deformations or possibly via internal cells hydrostatic pressure (Pouille et al., 2009). *In contrast to physical system behaviours, in which fluctuations at a given scale fight against ordered collective behaviours at the same scale, here, fluctuations would trigger ordering and coordination restricted to mesoderm, because of mechano-transduction patterned by Fog expression. Such collective coordination determines the very efficient multicellular morphogenetic movement of mesoderm invagination* (Driquez et al., 2011).

### *3.3.5. Incidences of Mechanical Induction in Tumour Development*

The activation of tumour genetic programmes has long been proposed to be associated with the anomalous reactivation of embryonic programms in adult tissues (Brabletz et al., 2005). Strikingly, the nuclear translocation of β-catenin is a signature of tumour initiation and progression in many tissues and especially in human and mouse colon tumours (Kirchner and Brabletz, 2000; Morin et al., 1997). Because the nuclear translocation of β-catenin from the junctions mediates mechanical activation of Twist in early Drosophila embryos (Desprat et al., 2008; Farge, 2003), we asked the question of a putative mechanical activation of β-catenin nuclear translocation in response to the strains developed by the mechanical pressure associated with tumour growth in the tissue surrounding the tumour (i.e. the stroma) (Brouzes et al., 2004; Whitehead et al., 2008). Following our Drosophila embryo protocols, we began to deform mouse tissues with uniaxial pressures applied to colon tissue explants. These experiments were designed to test the potentiality of an oncogenic biochemical response of the tissue in response to artificial mechanical strains. However, in this specific case, the pressure can be controlled at the level of the intestinal transit pressure of the mice, the colon being submitted to such natural pressure daily. Wild-type tissues did not exhibit any response at all of the β-catenin or of the two target genes Twist-1 (involved in invasivity) and c-Myc (involved in cell division and tumour growth) at the 20 min to 4 hours time scale. Interestingly, regarding the β-catenin pathway, a major difference between the wild-type mouse tissue and the early Drosophila embryo tissue is the state of expression of APC. APC collaborates with the GSK-3 system to send into a degradation pathway the cytoplasmic β-catenin, preventing β-catenin translocation into the nucleus. APC is not expressed in the early Drosophila embryo (Hayashi et al., 1997) but is expressed in mouse colon tissues. To test that the expression of APC in wild-type colon tissues could prevent the nuclear translocation of β-catenin after mechanical strain, we strained heterozygous mutants of APC. In these tissues, some of the β-catenin is translocated into the nuclei, with the observation of the expression of Twist and c-Myc target genes and protein products (Whitehead et al., 2008). Thus, loss of 50% of APC expression leads to a defect of the degradation of the β-catenin released from the junctions to the cytoplasm in response to mechanical strain and to the translocation of a certain pool of β-catenin into the nuclei, where it is able to trigger the activation of oncogene transcription.

Eighty percent of human colon cancer tumours carry APC mutations, of which 10% are hereditary mutations. In these cases, the question of the sensitivity of such pre-tumoural colon tissues to intestinal transit is potentially addressed by our observations. Should *in vivo* studies confirm such behaviour, adopting an alimentary regime regulating the stiffness of the food might decrease the probability of developing tumours in the APC+/− context. The other 90% of cases first develop a sporadic mutation in one cell, leading the natural growth of a clonal APC+/− domain. Inside this domain, a second sporadic event involving loss of the second allele of APC in one cell is thought to trigger the transition to cancer (a cell with complete loss of APC is no longer able to prevent the nuclear translocation of the β-catenin which is constantly produced by the cells). Thus, an APC−/− clonal domain grows within the APC+/− pre-tumoural domain. Our observations thus ask the question of a potential activation of β-catenin nuclear translocation and target oncogene expression in the APC+/− pre-tumoural tissue domain in response to the pressure developed by APC−/− tumour growth, which might amplify tumour progression.

Here, we thus ask the question of the activation of signalling pathways connected to oncogene expression directly, with future investigations designed to probe the involvement of the mechanical induction process in response to tumour growth during tumour progression (Alexander et al., 2008).

## 4. Mechano-Genetics Network in Perspective of Evolution: Mechanical Induction in First Multicellular Organism Emergence?

Coming back to embryonic development, we already discussed the putative involvement of β-catenin mechanosensitivity in the determination of primary axis formation of earliest common ancestors of diploblasts (see Sect. 3.2.4). Regarding Myo-II apical redistribution mechano-sensitivity in the early Drosophila embryo, a last implication relates to evolutionary speculations concerning the emergence of the feeding reflex of ancient embryos in response to touch and its evolution by integration of the underlying mechanisms regulating embryo morphogenesis. The idea that ancient must have first organisms developed a primitive gut has long been suggested and developed by Haeckel (Jaegerstem, 1956; Wolpert, 1992). Here we propose that such phagocytosis could have been a mechanotransduction driven response of tissues to touch due to contact of embryos with the ground after gravity-driven migration. Such contact could have activated a primitive motor-sensorial response of invagination to touch, leading to the phagocytosis of sediments. Strikingly, *sna* mutant embryos react by an active generation of invagination in response to touch in Fog expressing domains (Fig. 5c, d). We thus proposed that we might have reactivated in early Drosophila embryos an ancient feeding reflex response to touch (Farge, 2003; Pouille et al., 2009). In other words, we suggest that the emergence of the Fog/Myo-II mechano-sensitive pathway, or a primitive equivalent, might have been at the origin of the generation of a transient primitive gastric organ in response to external stimuli of touch. This would mean that the emergence of such mechano-transduction pathway would have been the key event leading to the emergence of the first organisms (which, by definition, is a multicellular system with an organ) from the earliest embryos defined as an aggregation of cells without collective functional cell behaviour (Pouille et al., 2009).

Following this view, the "cell aggregate" to "first organism" transition could be thought of as the consequence of the emergence of a mechano-sensitive Myo-II apical redistribution in response to soft external strains.

Then, we speculated that the generation of internal mechanical strains, like those due to Snail-dependent stochastic oscillations developed from the inside of the mesoderm tissue, have replaced the, primitive primary external stimuli, in such a way that a permanent gastric organ evolved to develop independently of the external stimuli.

This could have initiated the process of embryonic morphogenesis by co-opting a favourable response of the embryo to external mechanical stimuli for use in response to the internal mechanical stimuli, leading to the generation of a gastric organ (Pouille et al., 2009). Interestingly, both Twist and Snail are expressed in the endoderm primordia at the onset of its invagination in the sea anemone ancient pre-bilaterian organism (Martindale et al., 2004). Because insect mesoderm is thought to have derived from the common ancestor endoderm (Arendt, 2004), the mechanotransduction process leading to mesoderm invagination experimentally found in drosophila embryos in response to *snail* dependent fluctuations of cell shape, or to external mechanical cues, may well have been involved in the blastuae-diploblast transition having let to the emergence of the first organism.

Finally, one can also speculate that the mechanical strains developed by the invagination have triggered a β-catenin dependent expression of genes like *twist*, in the primitive endoderm, and by the extension in the derived mesoderm. In the case of the endoderm, this would have ensured a functional "digestive" differentiation (Desprat et al., 2008). In the case of mesoderm, this could have ensured the differentiation of the third layer having allowed the emergence of tribloblasts from diploblasts (Fernandez-Sanchez et al., 2010 and Brunet et al. submitted).

If this scenario is correct, primary organism would have been favoured compared to its primitive ancient embryo precursor, thanks to its ability to ingest nutriments by tissue phagocytosis. In other words, the primary organism would have emerged from mechanotransduction processes having allowed its ability to favourably react to its environment by ingesting what it touches.

## 5. Acknowledgements

We thank Joanne Whitehead for her reading of the manuscript. The author's lab is funded by the ANR (ANR Blanc 2011 project MIME and PiriBio ANR-09-Piri-0013-02), the ARC, Microsoft, NanoIdF, the Fondation Pierre Gilles de Gennes, ITMO Biology Cellulaire, Developement et Evolution and the HFSP RGP001-14/2006 grants.

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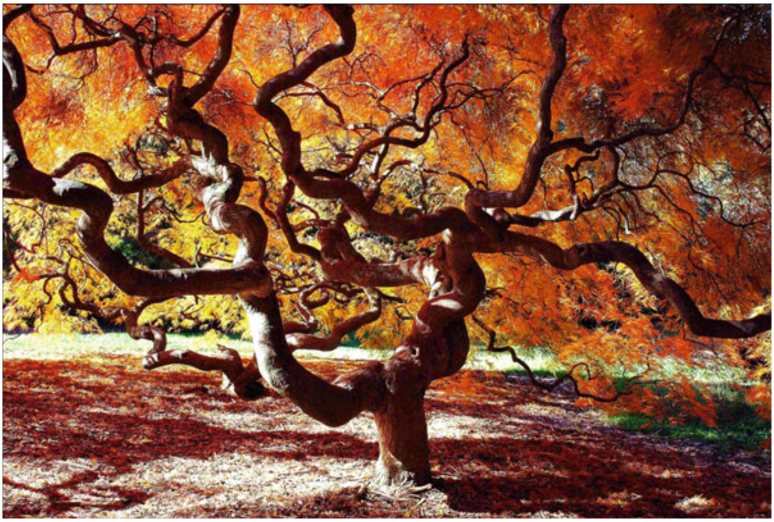
# PART V:
# CRITICAL DISCUSSION OF DESIGN IN WHAT LIES BEYOND DARWINISM

**Gill**
**Luisi**
**Svoboda**
**Barbalet**
**Miran**
**Miran**
**Chen**
**Negrotti**
**Ward**
**Cook**



Japanese maple in November taken at Cylburn Arboretum in Baltimore, MD, USA, by Glen Mendels.

Biodata of **Zann Gill**, author of “***A Response to Darwin’s Dilemma: A-PR Cycles and the Origin of Design in Nature***.”

**Zann Gill**, founding director of the Microbes Mind Forum (M|M) (http://microbes-mind.net), received her M.Arch. from Harvard University Graduate School of Design. Early in her career, she worked for Buckminster Fuller, whose concepts of design science and World Game for environmental sustainability led her to recognize the need for a new discipline of *collaborative intelligence*. Her entry to the international competition, *Kawasaki: Information City of the 21st Century*, sponsored by the Japan Association for Planning Administration and *Mainichi News*, with cooperation of ten ministries and three agencies of the Japanese government, tied with Panasonic (then Matsushita Corp.) for first place and won the Award of the Mayor of Kawasaki. She proposed 16 diverse interlinked initiatives comprising an innovation network, designed to evolve as a collaborative ecosystem. Before starting M|M Forum, as a research scientist for RIACS (Research Institute for Advanced Computer Science) at NASA Ames Research Center, Gill proposed a series of NASA collaboratories, both as technology platforms and as cross-disciplinary, self-improving ecosystems, harnessing principles of self-organization and *collaborative intelligence* found in living systems. Later at NASA, she developed program plans for an Institute for Advanced Space Concepts (IASC), a collaboratory BEACON (Bio-Evolutionary Advanced Concepts), and an astrobiology program for NASA University. Through ecoDESYN lab, she consults on projects, ranging from the Smart Systems–Eco-Cities initiative of Australia’s ICT Center of Excellence to world-class execution and decision support for sustainable remediation. Her book, *If Microbes begat Mind*, proposes the A-PR hypothesis (Autonomy and Pattern Recognition) as the basic unit of creative cognition. A sequel, *What Daedalus told Darwin*, argues that Darwin has been misinterpreted,

L. Swan et al. (eds.), *Origin(s) of Design in Nature*,
Cellular Origin, Life in Extreme Habitats and Astrobiology 23, 507–522
DOI 10.1007/978-94-007-4156-0_26,

drawing evidence from his writing and current debate. Focusing on self-organizing systems, she correlates recent findings about mechanisms of evolution to define the new field of *collaborative intelligence* and develop applications for Planet Innovation, harnessing next-generation collaborative computing.

E-mail: **zg@microbes-mind.net**

# A RESPONSE TO DARWIN'S DILEMMA: A-PR CYCLES AND THE ORIGIN OF DESIGN IN NATURE

**ZANN GILL**
*M|M Forum, NASA Ames Research Center,*
*Moffett Field, CA 94035, USA*

## 1. Introduction: Limits of Language and an "Objective" View

The A-PR Hypothesis aligns with the view of Stephen Jay Gould that Darwin was a victim of a view later ascribed to him that was not his: "Darwin lived to see his name appropriated for an extreme view that he never held—for Darwinism has often been defined, both in his day and in our own, as the belief that virtually all evolutionary change is the product of natural selection" (Gould, 1982).

By making natural selection by the environment the sole arbiter of evolutionary direction and calling the variation that produces design "random," Darwinism and its successor, neo-Darwinism, fail to account for how each living organism affects the design direction of its species' evolution. The A-PR hypothesis proposes that evolution, rather than being life's attribute, may be the process that preceded and invented both life and intelligence. Then all living organisms, in how they lead their lives, are designers—autonomous agents in a complex, multiagent system, their ecosystem (Gill, 2011c). Gould's claim that Darwinism is a misinterpretation of what Darwin himself intended has recently been reinforced by the theory of facilitated variation derived from research on evolutionary mechanisms, providing new evidence of the limits of traditional Darwinism to explain the origin of design in nature (Kirschner and Gerhart, 2005).

The term "design" is commonly used to connote top-down design, raising a red flag by invoking Intelligent Design, a Higher Authority sitting above, and outside, the system He designs. Similarly in the arts, Design is seen as a craft—something a Designer (capital D) does, top down, from outside in. Top-down views of design overlook the emergent mechanisms responsible for design in nature. An object-oriented perspective on design defines design as producing objects that can be preplanned before execution (by a Designer) and/or assessed after the fact (by the Environment). Transposing this view to evolution leads to a focus on genetic inheritance whereby organisms can be assessed after the fact as objects for "survival of the fittest." This limited connotation of design leaves a gap in the English language with no term to describe the origin of design in nature.

In the chicken-egg conundrum, both chicken and egg are objects—hardware. That conundrum dissolves when we move beyond evolution's objects to evolution as a design process that harnesses life's own evolving capacity to select from options in its struggle for existence. The origin of design in nature then offers an explanation of evolution as the means through which potential emerges, from implicit to explicit, converging toward coherent outcomes as organisms respond to contextual needs.

## 2. The Peacock's Tail: Darwin's Design Dilemma

On April 3, 1860, Charles Darwin wrote to his botanist friend Asa Gray, "The sight of a feather in a peacock's tail, whenever I gaze at it, makes me sick!" (Darwin, 1860). The peacock's impractical tail symbolized for Darwin the problem of design, prompting him to write *Descent of Man* where he extended ideas introduced in *Origin* about the role of competition for mates in evolution and acknowledged that environmental selection is not the sole mechanism of evolutionary design (Darwin, 1871). The peacock's tail is large and blows around in the wind. Its bright colors attract predators. The peacock would probably survive better without his tail. But the many peahen mates the peacock's tail attracts far "outweigh" its disadvantages.

The peacock's tail epitomized Darwin's dilemma: He could explain the origin of species through variation and natural selection, but he could not explain the process responsible for the origin of variation, on which his theory depended. The origin of design in nature has remained a dilemma because of the common view that cognition is an attribute of advanced life, rather than of life itself.

*Problem*. Darwin needed to explain the origin of design in nature to complete his theory of evolution and to respond to core questions: How does evolution generate (or design) effective novelty? Is the selecting environment nature's sole designer?

*Question*. Who designed the peacock's tail? The peacock's tail annoyed Darwin because it so flamboyantly symbolized his dilemma. William Paley's simple answer did not satisfy Darwin.

In 1802, William Paley published his *Natural Theology—or Evidences of the Existence and Attributes of a Deity Collected from the Appearances of Nature*, which contained his famous "argument from design," the legacy argument that Darwin set out to revise. Darwin was assigned the rooms at Christ's College that had belonged to William Paley. He carefully studied Paley's *Evidences of Christianity* (Darwin, 1887), even taking Paley's *Natural Theology* aboard the *HMS Beagle* in his scant baggage allowance. Darwin's contemporaries generally believed William Paley's argument that Design, with a capital D, implied Intelligence, with a capital I, which implied that the wonders of nature were produced by an Intelligent Designer (Paley, 1802). Design was an argument for the existence of God. Darwin himself referred to the Creator in *On the Origin of*

*Species*, although the frequency of this reference was reduced in later editions (Darwin 1859–1876, Peckham, 1959, Darwin Online Project).

Darwin responded (November 23, 1859) to comments of Thomas Huxley, after reading *On the Origin of Species*, "You have most cleverly hit on one point, which has greatly troubled me; if, as I must think external conditions produce little direct effect, what the devil determines each particular variation. What makes a tuft of feathers come on a Cock's head; or moss on a moss-rose? I shall much like to talk over this with you" (Darwin, 1892). Darwin never did find the answer. He was convinced that variations make possible the origin of species. But he could not explain the origin of variations—the origin of design in nature.

Darwin's dilemma had two horns: his discomfort with seeing variation as merely random and his inability to accept Intelligent Design. Both explanations of variation were unsatisfactory. The origin of design in nature, upon which his theory of evolution depended, remained unexplained. Darwin needed a third option, beyond Intelligent Design and beyond random variation with environmental selection, both of which describe life as passively designed by an external agent, whether an Intelligent Designer or the selecting Environment.

In Chapter VI, "Difficulties on Theory," Darwin directly addressed his issues with Intelligent Design:

> He who believes in separate and innumerable acts of creation will say that in these cases it has pleased the Creator to cause a being of one type to take the place of one of another type; but this seems to me only restating the fact in dignified language. He who believes in the struggle for existence, and in the principle of natural selection, will acknowledge that every organic being is constantly endeavouring to increase in numbers; and that if any one being vary ever so little, either in habits or structure, and thus gain an advantage over some other inhabitant of the country, it will seize on the place of that inhabitant, however different it may be from its own place. Hence it will cause him no surprise that there should be geese and frigate-birds with webbed feet, either living on the dry land or most rarely alighting on the water; that there should be long-toed corncrakes living in meadows instead of in swamps; that there should be woodpeckers where not a tree grows; that there should be diving thrushes, and petrels with the habits of auks. (Darwin, 1859)

Here Darwin clearly stated his view that life's own struggle for existence and life's habits and behavior affect how each organism responds to its environment, nonrandomly directing the evolution of its species.

To overcome the resistance Darwin anticipated from the religious community, he aligned his theory with the rising star of capitalism. Darwinism was cultured in a capitalist, industrialist hotbed, which rapidly transmuted Darwin's theory of evolution into survival of the fittest objects, through competition and elimination of the least fit. Emphasis on "survival of the fittest objects" forced evolution into a rationalist, materialist, object-focused box. Because the extreme stance of neo-Darwinism seems inadequate to account for the sheer intricacy of evolution's designs, theorists seek complementary hypotheses to account more fully for the origin of design in nature. Iterative self-organization with external guidance, unlike

Paley's theological view, could converge toward coherent design without reference to perfection or purpose, or any Godly role in nature's design process. Theorists seek an unambiguous, documented objective standard to prove that some living systems could not have evolved incrementally, solely by random variation and environmental selection. Efforts to hijack their questions to make a case for Intelligent Design derail and politicize debate. The real questions have been neglected:

- Did life originate and evolve its intricate, well-adapted designs solely through random variation and environmental selection? What role did life itself play in the origin of design in nature?
- Beyond the assumption that mutation produces new objects, from which the Environment alone selects the fittest objects to survive and reproduce, suppose that random variation is not the sole source of life's adaptations, that there is a codesigner, life itself?
- Is there a third option, beyond the extremes of Blind Chance and Intelligent Design?

## 3. A-PR Cycles and the Peacock's Tail

The A-PR hypothesis states that the origin of design in nature rests on iterative A-PR cycles (*A*utonomy | *P*attern *R*ecognition) through which living systems recognize and develop *potential*. In this bootstrapping cycle, an autonomous agent (A) engages in pattern recognition (PR) in order effectively to exercise its autonomy (A) and to select its next steps. The capacity to engage in A-PR cycles evolves, from bacteria to humans, as increasingly sophisticated pattern recognition is achieved.

*Autonomy*. The term *autonomy* traditionally connotes self-control of behavior. The autonomy definition of life implies that the conventional Darwinist view of life as externally designed, solely by environmental selection of the fittest organisms, is insufficient: Life itself engages in iterative cycles of pattern recognition, which enable effective agency during its lifetime.

*Pattern Recognition*. Nobel laureate Emil Fischer coined the key-lock metaphor to describe biochemical pattern recognition and how specificity constitutes information (Lichtenthaler, 1995). The analytic, external, objective, environmental assessment half of evolutionary dynamics is complemented by the synthetic, internal, subjective, pattern-recognizing, self-organizing half through which life "recruits" information from its environment, compiles that information into a message, and recognizes patterns in order to navigate in its struggle for survival. Alfred Russel Wallace made "the importance of recognition-marks for evolution" of new species a cornerstone of his development of the theory (Wallace, 1911) (Fig. 1).

Each pattern recognizer applies unique criteria to interpret the meaning of patterns recognized. A-PR cycles (*A*utonomy | *P*attern *R*ecognition) are not only defining attributes of life. A-PR cycles are also drivers of iterative emergence,

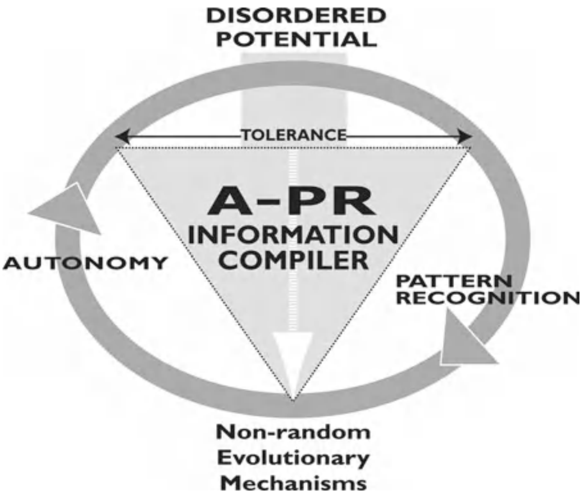


**Figure 1.** The A-PR cycle is a bootstrapping engine: an autonomous agent engages in pattern recognition, which drives agency, processing noise and unfiltered information (disordered potential) in a convergent ecosystem to funnel options toward new capacities and improved fitness.

through which life recognizes and develops partial, blurry patterns as it adapts, self-organizes, and evolves toward increased functional effectiveness. From bacteria to ants to peacocks to us, every living organism navigates through life by means of A-PR cycles: Autonomy enables each organism to engage in pattern recognition to guide its next steps as an autonomous agent (Darwin, 1909). The peahen recognizes the "best possible" tail among her suitors (Petrie, 2004). The chess player recognizes the "best possible" move among his options. The card player recognizes which card to discard. Their criteria are subjective.

Pattern recognizers interact with other pattern recognizers in pattern-recognizing ecosystems. A-PR cycles bootstrap innovation, guiding evolution's arrow toward increased functional effectiveness. For peahens, flamboyant beauty determines increased functional effectiveness of peacock tails in attracting mates. Mate selection guides evolution's arrow, complemented by many other instances of bootstrapping A-PR cycles, from the origin of life to bacterial collective intelligence to ant colony foraging (Ben-Jacob, 2004; Gordon, 2010). Relevant to arguing the logical necessity of the A-PR hypothesis is work on the nature of autonomy and agency, which links biology with artificial intelligence, robotics, and complex systems (Gill, 2011a).

Collectively, organisms participate in multiagent, networked, pattern-recognizing ecosystems, evolving by means of the choices of all players in that network of pattern recognizers. Each player has criteria for its choices. Some "rules of the game" govern all players. Others are individual, subjective styles of play. Collective decisions translate into external, objectively measurable consequences, as in an economic market (Gill, 2012).

The capacity to detect signals, to discriminate among those relevant for survival, and to recognize patterns emerging is critical for survival. A-PR cycles enable life to cope with unpredictability, harnessing tolerance toward improved fitness and emergence of new capacities. Each organism participates in the design of its species, as Darwin acknowledged. Only an autonomous system can interpret information, recognize patterns, manifest behaviors, and select the next moves through which it designs itself. Implicit potential is explicitly actualized through iterative, emergent pattern recognition and self-organization, guided by environmental selection. Fit behavioral choices affect evolutionary direction. Through iterative self-design, embryos and cells develop, and species evolve. Evolution is guided, but not exclusively directed, by natural selection. Feedforward A-PR cycles make prediction active and constructive (Gill, 1986). Overemphasis on evolution as determined exclusively by survival of genetically fittest organisms neglects development, through which life's capacities for pattern recognition and self-organization drive evolution toward increased functional effectiveness. The acceleration of evolution, from the origin of life (c. 3.8 billion years ago) to the first eukaryotic cells (c. 2.8 billion years ago) to multicellularity (c. 2.2 billion years ago) to the Cambrian "explosion" of life forms (c. 600 million years ago) to the origin of *Homo sapiens*, probably less three million years ago, continues in the observable acceleration of technology innovation in this century. If evolution were driven solely by random variation, this acceleration would be difficult to explain. A-PR cycles introduce a nonrandom feedforward accelerator.

Grandpierre proposed a revised Galileo experiment at the Leaning Tower of Pisa. Rather than dropping two weights, suppose that Galileo had dropped one weight and one bird. The weight would fall. The bird would fly. Using Galileo's experiment to frame a new thought experiment, Grandpierre asks how an inanimate object behaves differently from a bird. How is one predictable and the other not? (Grandpierre, 2009). Evolutionary theory describes how the Environment selects. But it cannot explain how each organism selects from among its alternative options. Evolution can explain how the bird acquired its instinct and capacity to fly, but not where it will decide to fly or when, although where it flies and when may impact its survival and the evolution of its species. The randomness of mutation is complemented by life's capacity to design itself through its struggle for existence. To be alive is to be a designer. Life's behavior—its effective performance—drives evolution.

## 4. Who Designed the Peacock's Tail?

Would an indifferent environment select for peacock tails as the most efficient survival mechanism? Few dispute that the male peacock's tail is not the most practical solution to the problem of taillessness. An environmental selection regime would not choose such tails.

*Who are the peacock tail designer suspects?* First, those demure, well-camouflaged peahens. Other suspects include the diversity of the peacock's ecosystem, with varied capacity for pattern recognition down to the cellular, even molecular, level, and other organisms in the peacock's ecosystem, especially his predators.

The peacock's tail evolved because lady peahens liked such tails and chose for mates the peacocks with the handsomest tails. As lady peahens chose peacocks with grander, more unwieldy, but more gorgeous tails, the tails themselves did not make those peacocks more fit. But the bird that could wield its unwieldy tail, and still survive, had made a show of fitness. Peahen preference, internal perception and pattern recognition, guided the evolution of the peacock's increasingly gorgeous tail, complementing random variation and environmental selection, which can only select what will survive from what already exists. Good genes, the traditional view, versus good taste sum up two complementary views (Kampis and Gulyas, 2004). As peahens choose their peacock mates, life discriminates, selecting promising behavioral strategies to pursue. Good taste acknowledges the role of pattern recognition as a driver of design in evolution. Choice of a mate is not the only domain where an individual can exercise discrimination, influencing evolutionary direction. While peahens deserve some credit for peacock tails, pattern recognition also drives evolution across species, as Wallace originally showed in his studies of the importance of recognition marks for evolution (Wallace, 1911). So foxes drive the evolution of their rabbit prey, and vice versa.

How does a peahen choose her peacock? Researchers conclude that a peahen picks her peacock based not on weighing all data but on quick pattern recognition heuristics. One research team reported that the peahen's key heuristic was: How many eyespots does he have in his tail? (Petrie, 1994). Debate among peacock specialists ensued. More experimental research was conducted; eyespots were manipulated and removed. Seventeen years later another research team published their findings: Rarely the eyespot count, spread that matters when a lady peahen sizes up her peacock's tail (Dakin and Montgomerie, 2011). Although details of peacock tail design and peahen preference are debated, all agree that peacocks are a dramatic instance of pattern recognition in mate selection, one of the drivers of evolution. Most agree that the peahen does not perform a detailed "tail design analysis." She has a quick heuristic to decide which peacock suits her fancy. Whether that heuristic is the number of eyespots, or size and spread of her peacock's tail, autonomy and pattern recognition are at work.

## 5. The Origin of Design: Life as an Information Processor

Across a range of prerequisite conditions, tolerance spectra, when overlaid, allow a "window of opportunity" for evolutionary novelty to emerge, whose fitness is tested in context. Selection for fitness computes the integrated synergy of interactions of the organism as it compiles, and responds to, information from its environmental context. Capacity to cope with future unpredictability is an iterative cycle. Life and intelligence bootstrap themselves as a single symbiotic system (Gill, 2011b).

The origin of design in nature is addressed by the emerging field of developmental systems theory (DST), which combines evolutionary and developmental lines of research (evo-devo). This field traces its history to a 1991 meeting called Evolution and Development, a theme proposed by François Jacob, whose book, *The Possible and the Actual*, called for integration of these two fields: "For it is during embryonic development that the instructions contained in the genetic program of an organism are expressed, that the genotype is converted into phenotype. It is mainly the requirements of embryonic development that, among all possible changes in genotype, screen the actual phenotypes" (Jacob, 1982). Jacob, and later J. Scott Turner, argued that evolution retains and reuses old components as does a tinkerer or *bricoleur*, who reuses existing materials to assemble objects for new functions (Jacob, 1982; Turner, 2007).

Work in developmental systems theory (DST) increasingly suggests that at the microlevel of individual cells, and even individual molecules, alternative regimes provide evidence that the origin of design cannot be explained solely as random variation with environmental selection. Questions are raised about the extent to which genes are complemented by other factors in explaining heredity, development, and evolution (Jablonka and Lamb, 2005; Kirschner and Gerhart, 2005). DST views the developmental system as comprised of all components, including genetic, that drive evolution, representing a new synthesis between developmental and evolutionary theory. DST has been proposed as a new way of doing biology, offering both new theoretical claims and new methods, while contributing different approaches toward reframing both developmental and evolutionary biology.

Developmental systems theory (DST) aims to rework central biological concepts in order to extend the neo-Darwinian theory of evolution toward the evo-devo synthesis argued by Jablonka and Lamb (2005). West-Eberhard emphasizes plasticity, proposing the alternative adaptation hypothesis that alternative adaptations can be produced by the same genome (West-Eberhard, 1986). Facilitated variation and its core mechanism weak linkage, discussed below, illustrate how developmental mechanisms nonrandomly impact evolution (Kirschner and Gerhart, 2005). DST offers a constructivist view of biology, examining how living systems construct and reconstruct themselves through time. On this view, genetic and nongenetic factors "collaborate" to constrain design via development and its evolutionary effects. While all biologists admit that the relationship between evolution and development is complex, Kirschner notes that few ask the obvious question: Could this complexity indicate that we have misunderstood something? (Kirschner and Gerhart, 2005).

## 6. Design Mechanisms: Facilitated Variation and Weak Linkage

Evidence for the A-PR hypothesis is provided by recent work in developmental systems theory, particularly by the theory of facilitated variation. The origin of design in nature is implicit in a range of nonrandom mechanisms that drive evolution toward increased functional effectiveness. Cellular biologists Marc Kirschner and John Gerhart propose their theory of facilitated variation to explain how evolutionary drivers operate at the cellular level through nonrandom, adaptive, developmental mechanisms. They define evolvability as the capacity of the organism to generate heritable phenotypic variation (Kirschner and Gerhart, 2005). The theory of facilitated variation exposes our common view of evolution as far too simplistic. The traditional view of selection as nonrandom is turned on its head when Kirschner notes the fortuitous relationship of the phenotype to its selective conditions. The view of variation as random is tempered by recognizing that how an organism accepts and works with variation is nonrandom. Organisms' evolvability (capacity to evolve) is also nonrandom. Kirschner and Gerhart set out to show that phenotypic variation is facilitated by the phenotype itself, that life is its own intelligent designer. Random changes in the genotype produce nonrandom changes in the phenotype.

Kirschner and Gerhart cut that Gordian knot, suggesting that the translation between development and evolution has seemed inexplicably complex because we have neglected to explain how rather few, highly robust, evolvable mechanisms make complex interoperability possible. Rather than rigid planning of complex structures, the origin of design in nature relies on adaptable design processes that enable coordination on the fly.

Kirschner and Gerhart tackle Darwin's difficulties on theory via their theory of facilitated variation, which they define as variation biased toward viability, functional outcomes, and response to environmental conditions, citing many instances of life's capacity for cellular adaptation. In defining design as structure related to function, not implying either a human or divine designer, they acknowledge design as more than an attribute of objects. Design is a process. Facilitated variation is life's developmental capacity to respond to its environment, one core contributor to the origin of design in nature. They focus on how the organism constructs itself (its phenotype) from its genetic instructions, its genotype, and the role of self-design and construction in evolution. Emphasizing adaptive core processes at the cellular level, Kirschner and Gerhart's theory of facilitated variation provides a scientific basis for understanding the origin of design as a nonrandom mechanism of evolution (Kirschner and Gerhart, 2005).

Their theory makes logical sense. Would life design itself through a brittle system where every genetic change is either lethal or produces a highly improbable improvement in fitness? Wouldn't it make more sense to design a tolerant system where many genetic changes can be tolerated with small phenotypic consequences, while those with selective advantage are recognized and integrated into the evolving system? That genetic differences among individuals of the same species enable production of new varieties aligns with the neo-Darwinist view that random variation, competition among those individuals, and environmental selection of the fittest to survive and reproduce explains how life incrementally evolved toward increased functional effectiveness. However, Kirschner and Gerhart go beyond neo-Darwinism to address Darwin's dilemma, the origin of design in nature.

Our typically digital, macro view of evolution assumes that evolution occurs only at the birth and death of each organism, the on-off switch of life and death. Kirschner and Gerhart emphasize the pervasiveness of on-off switches at the microscale in the developmental mechanisms of life itself. Many of the developmental processes they study are simply tripped on and off by switches (Kirschner and Gerhart, 2005). This observation led them to characterize “weak linkage” as a generic, unspecified signal that is interpreted in context. That same signal may have one meaning in one context, another meaning in another context. The hox gene signal to “build an eye” does not say what kind of eye to build; a human hox gene to build an eye, when transplanted into a fruit fly, builds a fruit fly eye because the meaning of the signal is interpreted in context. Weak linkage, a foundation for all mechanisms of facilitated variation, is not instructional: It does not tell a living system what to do. It simply flips a switch to trigger a response, allowing the receiver to determine, via pattern recognition, what the appropriate response should be in context and to select an appropriate response behavior. Signals are interpreted in their receiving context, which specifies how living systems self-organize.

Weak linkage couples potentially complex processes to each other, and to various inputs, such that a minimally informative signal can produce a response that is maximally responsive and adaptive to the context where it is received, providing simple ways for systems to be linked together to be interoperable, such that evolution produces not just objects but behaviors that are responsive to current needs. For example, traditional evolutionary studies have observed finches over time, analyzing changes in finch populations under differing environmental conditions. In contrast, Clifford Tabin argues that because evolution is itself a process of synthesis, to uncover its principles requires synthesis in the laboratory. Beak studies in the Tabin Laboratory illustrate how, through facilitated variation, birds develop uniquely adapted beaks in response to environmental demands. Abzhanov’s experiments suggest that the developmental process is surprisingly adaptable to respond to a single genetic mutation. Every part is constrained to be interoperable with every other. Each genetic change triggers a cascade of developmental, accommodating changes. For example, if a genetic mutation changes the width of a bird’s beak, developmental, relational mechanisms to make beak width and skull width “interoperable” will adjust the width of the skull such that the width of the beak and width of the skull will correspond without requiring additional genetic change (Abzhanov et al., 2004; Kirschner and Gerhart, 2005).

Facilitated variation and its core mechanism, weak linkage, effectively transform the common digital, still-frame view of evolution, seen as operating in digital steps only at birth and death, into an analog view, whereby lifetime adaptation and behavioral choices play a critical role in determining fitness and survival. Physiological adaptability is well recognized. Kirschner and Gerhart’s unique contribution lies in their argument that the same mechanisms that make physiological adaptability possible also serve evolutionary adaptation. An organism does more than survive and replicate (or not) in its environment. Cells adapt. Variations occur during the course of a lifetime, making the organism more or less fit.

By decomposing the tautology that what is fit is what survives and that what survives is most fit, Kirschner topples two traditional misconceptions.

*The first misconception*: Many take for granted that survival of the fittest through natural selection is nonrandom. Instead, Kirschner emphasizes that the relationship of the organism to its selective conditions is fortuitous, i.e., random, making the selection component of evolvability random. The identical twin killed in an automobile accident was unlucky, not less fit than his surviving twin. An organism with tolerance to temperature increase or acidity, if it happens to live in a lake that becomes hotter or more acidic, may survive, though these conditions were not predicted. In contrast to the conventional view that selection is nonrandom, this aspect of environmental selection has a random component since we cannot precisely predict how the organism will relate to its environment or how its environment may change.

*The second misconception*: We assumed that the chance element in evolution was random variation. Instead, Kirschner questions what we took for granted, arguing that facilitated variation is nonrandom. The most important variation component of evolvability measures the intrinsic capacity of an organism to vary its phenotype, its physical self, based upon its genetic makeup and other properties. This capacity to vary contributes to its ability to respond to its environment, which again is nonrandom. In contrast to the conventional view that variation is random, this aspect of variation has a nonrandom component, described by the theory of facilitated variation.

Facilitated variation explains the variation component of evolvability by examining the underlying embryology, cell biology, and biochemistry of organisms. Three key properties of facilitated variation are: first, the capacity to maximize effective phenotypic variation for given genotypic variation, amplifying effective variations; second, capacity to minimize lethality of variation; and finally, capacity to adapt phenotypic variation to environmental conditions, even when those conditions have never been experienced before by the organism's ancestors, making life itself, via its capacity for facilitated variation, the originator of design in nature.

Research on organisms that scientists once thought primitive, such as bacteria and ants, shows them to be far more sophisticated information processors than we imagined. Research increasingly suggests that bacteria have sophisticated capacity to compile multiple signals about their environment into an integrated message to guide their behavior (Ben-Jacob, 1998, 2004; Mehta et al., 2009). This sophistication of single-celled bacteria aligns with Kirschner and Gerhart's findings that life at all levels relies on capacity to adapt at the cellular level.

The origin of design in nature then rests on life's capacity as an information processor, via weak linkage as a basic mechanism enabling facilitated variation.

## 7. Pattern Recognition and the Origin of Design in Nature

The A-PR Hypothesis is proposed to address longstanding debates about the origin of design in nature. Humans are complex autonomous agents and sophisticated pattern recognizers with capacity as designers to solve creative problems through exercising collaborative intelligence, which harnesses the same evolutionary principles that all of life harnesses. Sir Charles Sherrington powerfully characterized how the origin of design in nature is mirrored in human intelligence: "Between [the] perceiving mind and the perceived world, is there nothing in common? We call them disparate and incommensurable. Nature in evolving us makes them two parts of one mind, and that one mind is our own. We are the tie between them. Perhaps that is why we exist" (Sherrington [1937–1938] 1951). I propose that what we easily accept as applying to humans applies to all of life.

If life was externally designed, life is an object, subject to the laws of survival of the fittest objects. In contrast, if life designs itself, harnessing A-PR bootstrapping cycles, although external factors play a role in life's survival, each organism also drives the evolution of its species its capacity for autonomy and pattern recognition, making "fit" or "unfit" behavioral choices: choosing a mate; deciding whether to flee, fight, or hide; or growing toward the light—or, as Darwin noted, being a woodpecker in a place where no tree grows.

## 8. Notes and Acknowledgments

This chapter, dedicated to the late Arthur Loeb, who led the Design Science program at Harvard, anticipates a forthcoming book pair on the origin of design in nature: *If Microbes Begat Mind: from origins of life to emergence of intelligence* and *What Daedalus Told Darwin: from Darwin's dilemma to the struggle for existence*. The first focuses on the origin of mind in nature's capacity for design, manifest at the threshold when the first nonliving system became alive. The second describes how the origin of design in nature is manifest in evolution. This book pair describes principles that govern emergence and self-organizing systems, addressing debates about the origin and evolution of life. I thank Chris McKay, Stuart Kauffman, and J Scott Turner for reviewing my work on the A-PR hypothesis.

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Biodata of **Pier Luigi Luisi**, author of "***The Synthetic Approach in Biology: Epistemic Notes for Synthetic Biology***."

**Pier Luigi Luisi** joined the Biology Department of the University Rome3 in 2003 after 30 years at the Federal Institute of Technology in Zurich (ETHZ). He has been working in the area of surfactant aggregations, developing self-reproducing vesicular systems as models for biological cells as well as synthetic biology projects (the "never born proteins"). Origin of life and the question "what is life?" in general has been his main concern over the years, also from the philosophical point of view. Luisi, a member of the Mind and Life Institute, created the interdisciplinary ETHZ Cortona week since 1985 at the interface between science and humanities.

E-mail: **luisi@mat.ethz.ch**

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# THE SYNTHETIC APPROACH IN BIOLOGY: EPISTEMIC NOTES FOR SYNTHETIC BIOLOGY

**PIER LUIGI LUISI**
*Department of Biology, University of Rome3, Rome, Italy*

## 1. Introduction

There are by now a few definitions of SB, and the common denominator describes a science that aims at synthesizing alternative forms of life or, more generally, biological structures which do not exist in nature. The term "alternative forms of life" should be further qualified by referring simply – for the moment at least – to bacteria, and in fact the most popular version of SB is the construction of bacteria which are supposed to perform novel "useful" tasks, like the production of fuels, hydrogen and other forms of energy. Typical titles are, for example, *Engineering a synthetic dual organism system for hydrogen production* (Waks and Silver, 2009), *Metabolic engineering of microorganisms for biofuels production* (Lee et al., 2008) and *Light-energy conversion in engineered microorganisms* (Johnson et al., 2008). The notion of alternative forms of life is also emphasized; for example, see the paper in Craig Venter's group titled *Genome transplantation in bacteria: Changing one species into another* (Lartigue et al., 2007) or *Engineering microbes with synthetic biology frameworks* (Leonard et al., 2008).

Important in this field is the notion of "bio-bricks", which indicates the genetic elements that can be made available also commercially and that can be used as elements for constructing the novel genetic circuits (see, e.g. *Genetic parts to program bacteria* (Voigt, 2006), and see also the Register of Standard Biological Parts in the MIT web page, http://parts.mit.edu). In the same way as we used to buy chemicals to start the synthesis of more complex organic molecules, or electronic parts to make an electronic gadget, now there seems to be the possibility of buying genetic parts to build up synthetic life. To be noticed, that the traditional approach to learn about life was to dissect the living, and study the single parts one at a time. Now, with SB, we can learn about life by way of synthesis, and this is of course an important conceptual difference – in the chemical sciences, we used to say that we can fully understand only what we can synthesize. It is also interesting to notice that SB has been in full development in concomitance with system biology, namely, with the capability of studying and in part conceiving the living in its entirety – actually even in its social context.

Also, the term "chassis" is used in the field of SB, like the naked chassis of an auto on which you put all parts – wheels and motor and brakes – in order to make the whole. And indeed some of the titles reflect this assembly endeavour, which sounds like the construction of electronic circuits, for example, *An integrated cell-free metabolic platform for protein production and synthetic biology* (Jewett et al., 2008), *Toward scalable parts families for predictable design of biological circuits* (*8*) and *Principles of cell-free genetic circuit assembly* (Noireaux et al., 2003).

The notion of bio-bricks may give lay people the idea that, by buying all components, you can assemble a living organism. Is something like that really possible? The answer really depends on what you mean by the question and by the term life in particular, but the first approximation answer is no. We will come back to this later on in this chapter.

Aside from the big question of making life, the bioengineering applications of SB cover also the field of medicine; see, for example, the work of Benner et al. (2008) (*Synthetic biology for improved personalized medicine*) or the work by Sang Y. Lee (Lee et al., 2009) on the *Metabolic engineering of microorganisms: general strategies and drug production*. Also, see the work by Fussenegger (Weber and Lienhart, 2009) on biotin-triggered genetic switch, which enabled dose-dependent vitamin H control in certain cell lines; the work by Chang and Keasling (2006) on *Production of isoprenoid pharmaceuticals by engineered microbes* and that by G. Stephanopoulos (Ajikumar et al., 2008) on terpenoid synthesis from microorganisms.

## 2. Teleonomy Versus Teleology in SB and Determinism Versus Contingency

Most of this work on this kind of genetic SB follows a classic bioengineering approach, whereby a determined goal is set at the very beginning, and all routes and tools are bent and focussed for obtaining that goal – for example, bacteria to make hydrogen, or a particular drug.

Beginning with epistemic terminology, we can then say that we are dealing with a classic *teleological* enterprise, where teleology means that the purpose is defined at the very beginning – as engineers do when they have to construct a bridge or an airplane. It is worthwhile reminding that teleology is not the way by which nature and biological evolution in particular are supposed to proceed. The function (e.g. the sight, the spinning flagellum, the wings) in nature's evolution is never set a priori but is the result and the consequence of the contingent structure's development. There is no programmer or intelligent designer in the plans of nature: the amoeba, the bees or the ants move about and do what they do obeying more or less blindly to a genetic programme, borne out on them by the laws of natural evolution. Yes, it may look like finality, but is *teleonomy* instead of teleology, namely, the more or less blind working of an implemented genetic programme. The function is a consequence of the structure's development, and the structure is constructed according to the “bricolage” as described by the pioneers of contingency, Monod and Jacob, up to more recent authors like Jay Stephen Gould. Teleonomy at Work. Teleonomy is then not the procedure of SB, which, by constructing its alternative forms of life, operates completely on the basis of teleology – at least the bioengineers do so. In this case, the intelligent designer is the synthetic biologist at work. Teleology instead of teleonomy.

Having clarified that, let us now consider another aspect of SB, which is actually different from this engineer methodology.

It is in fact proper to say that SB has a double soul. One corresponds to the bioengineering approach outlined above. The other is instead rooted into basic science.

In this second case, the basic, underlying question is, “why did nature do things in a certain way, and not in another one?” Why 20 amino acids, and not 15 or 55? Why do nucleic acids contain ribose instead of glucose? Must haemoglobin be constituted by four chains? Why not 6 or 12?

From one general, philosophical point of view, this kind of questioning (why this and not that?) links to the dichotomy between *determinism and contingency*: are the things of nature the way they are, simply because there was no other way to make them (“absolute determinism”)? Or are they the way they are, due to contingency – something that some time ago, less properly and less fashionably, we used to call “chance”?

SB possesses the tools that may permit to tackle this kind of philosophical question. The way is conceptually simple: let us synthesize the alternative form, and see whether there are some reasons why this route may have not been chosen by natural selection.

Take the example of the work by Albert Eschenmoser and collaborators at the Swiss Federal Institute of Technology (ETH-Z) on alternative DNA forms (a case of chemical SB *ante litteram*). He and his group synthesized DNA with pyranose instead of ribose in the chain (Eschenmoser, 2005; Bolli et al., 1997), arriving at important considerations about the working procedures of biological chemical evolution. And take the work in Yanagawa’s group (Doi et al., 2005) on proteins with a reduced alphabet of amino acids, showing that in certain instances, enzymes “remade” with only 10–12 amino acids instead of 20 may work rather well. And there is the field of the alternative proteins, with the question “why these proteins and not others?” which leads to the synthesis of proteins which do not exist in nature, the so-called never born proteins (Chiarabelli et al. 2006a, b). Or take the work of S. Benner and collaborators on nucleic acids built with bases different from the four canonical ones (*20*). And: “why are unicellular organisms constituted by thousand of genes, can’t they work with a much lower complexity degree?” – a question which leads the way to the field of the “minimal cell/minimal life”, which is now being pursued by several groups (Pohorille and Deamer, 2002; Ishikawa et al., 2004; Noireaux and Libchaber, 2004; Luisi et al., 2006; Murtas et al., 2007; Stano, 2008; Mansy et al., 2008; Souza et al., 2009).

Several other examples could be given – which, by the way, are examples of "clean" SB, in the sense that they are being carried out without genetic manipulations of the living typical of most engineered SB. In fact, the term "chemical synthetic biology" has been coined to represent this field (Luisi, 2007). In this case, the operation is also teleological, in the sense that we set a priori the construction of the new structure – for example, the DNA with pyranose. However, the function is not set a priori; actually, the functionality corresponding to this novel structure is not known – it is what we want to discover. In this sense, there is a significant difference with the bioengineering approach, where the function is the main prerequisite (e.g. production of hydrogen) set a priori at the very beginning.

One can add at this point that this second approach is the more innovative and begins to be present also in other fields, for example, in robotics and sociology: basically, it is the emergentist and teleonomic point of view, moving away from the mere engineering methodology and mentality. It is the emergentist approach which is more directly related to the most important question: what is life?

However, it is the bioengineering approach that is more popular in SB, also because it is certainly the one which is more interesting from the applicative, and money-making, perspective.

More in general, I feel that it is important to attempt the construction of a philosophical framework for SB, as otherwise there is the danger that this important field of life sciences becomes simply a collection of technicalities.

## 3. Life as Emergence and as a Process of Collective Integration

Since SB deals with the idea of making life in the lab, it is necessary to briefly dwell on the question, "what is life?" limiting the inquiry to the simple cellular constructs that SB is concerned with. For that, consider the simple cartoon of Fig. 1.

This represents the semipermeable membrane, which identifies the compartment in which many reactions and the many corresponding transformations take place. We can learn a lot from this cartoon.

Consider first the question: where is cellular life localized? There is an obvious and very important answer to this question: life is not localized and life is a global property, being given by the collective interactions of all molecular species. This is not true only for the cell but for any other macroscopic form of life. The life of a large mammal is the organized, integrated interaction of heart, kidneys, lungs, brain, arteries and veins. Each of these organs can be seen as the integrated and self-organized ensemble of different tissues and organelles, each tissue or organelle is the integrated ensemble of different cells, and each cell is the organized integration of the molecular species as already discussed from Fig. 1.

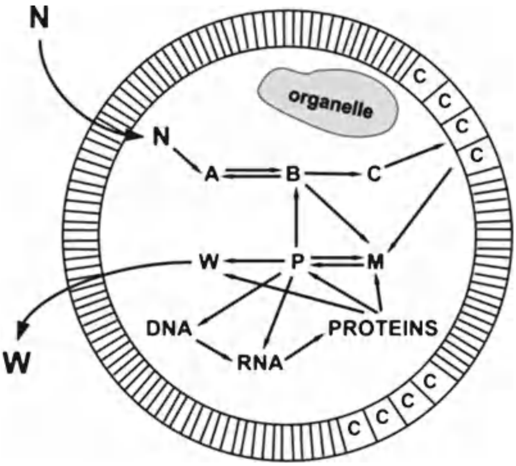

**Figure 1.** A cartoon representing the activity of a cell. Nutrients/energy (*N*) enter the cell and are integrated in the metabolism that produces all its own components (*A, B, M, P, W, DNA, RNA, proteins, organelles*) as well as the membrane component (*C*). Waste material (*W*) is then released in the environment.

The other aspect of cellular life stemming out of the simple cartoon of Fig. 1 is the apparent contradiction between the very many and continuous transformations taking place – and the self-maintenance, the fact namely that the cell maintains its individuality – it remains itself (at least during the homeostasis period). Actually, we could say, with the proponents of the autopoiesis theory (Varela et al., 1974; Maturana and Varela, 1980; Maturana and Varela, 1998), that the cell's main function is to maintain its own individuality despite the myriad of chemical transformation taking place in it. This apparent contradiction is explained by the fact that the cell regenerates from within the components which are consumed away – be it ATP or glycogen, glucose, α-chymotrypsin or t-RNA.

There is another apparent contradiction in cellular life and life in general, which can be germane for our discourse here. This is the fact that a living cell – and by inference all kind of living – must be a *thermodynamically open system*, as it allows the input of energy and nutrients through a semipermeable membrane, and, conversely, the living cell is, from the epistemic point of view, an *operationally closed* system, in the sense that the information for all life activity are contained within the structure's self-organization. The aspect of being thermodynamically open links the living with the interaction with the environment, and we can say that the living is participating in a *cognitive interaction* with the environment. The terminology of cognition is taken again from the Maturana and Varela autopoiesis theory of (1980, 1998) and indicates the specific coupled interaction between the living and the environment with the consequent constitution of a mutual cooperativity, or co-emergence into a mutual unit.

Then, for the time being, let us see life as an integrated system which is capable of self-sustaining due to the activity from within and which is operationally closed and thermodynamically open, capable then to interact with the environment in a specific manner. There is, however, another aspect of life which must be taken into consideration, and which is particularly important for the field of SB.

To say that life is a global property that depends on the interaction of parts is tantamount of saying that *life is an emergent property*.

It is important, for our discourse here, to briefly recall a few aspects of this notion, in particular those which may be important for SB, like, for example, the notion of downward causation.

First of all, emergence and emergent properties are notions that arise upon the formation of a higher hierarchic order starting from smaller parts or components, and indicate the arising of novel properties – novel in the sense that they are not present in the parts or components. Generally, it is accepted that the emergent properties cannot be predicted from or reduced to the properties of the components, and in the literature the notion of "strong emergence" is opposed to the notion of "week emergence". The first term indicates that the prediction or interpretation from the parts is in principle (ontologically) impossible; the second term indicates that such prediction or interpretation is not in principle impossible, but simply technically too difficult. In the case of bioengineering SB, the properties to be expected are set a priori, whereas in the case of basic science SB ("why this and not that"), the emergent properties, as we have already noted, are precisely the matter of investigation. There would be much to say about emergence, about predictability and deducibility, about the relation with reductionism, but we do not need all this here. However, there is another important element we should not miss for our present discussion on SB. This is the notion of *downward causation.*

This has to do with the fact that there is always a mutual interaction between the parts and the whole, in the sense that the formation of the whole affects and modifies the parts. Clearly, the amino acids that form a protein are modified by their mutual covalent and non-covalent bonding with respect to their free state of amino acids; and a tribe, formed by the ensemble of several families, modifies the behaviour and rules of the family, while the family, formed by the ensemble of single people, modifies the properties and behaviour of these constituent persons.

This ties with the notion of bio-bricks discussed previously. To understand better this point, consider that it does not make much sense to consider the heart by itself, as a separate abstract part. We may have it as a frozen organ, but it acquires its real meaning when it becomes an integrated part involved in the interactions with all other organs and parts of the body. It is then generally important to make clear that the "parts" of life cannot be considered as inert pieces as in a Lego game or bricks that can be added mechanically: in reality, the parts, and therefore the bio-bricks also, should be seen as being substantially modified and functionalized by the making of the whole. Actually, and this is the important point, they will acquire a meaning only if they become a functional part of an integrated unity.

All this ties to the question we have raised in the introduction, whether by assembling all the appropriate bio-bricks you can build an organism in the lab. It is proper to answer negatively to this question. Although many bio-bricks are available, the idea of having all possible bio-bricks that constitute, say, the entire *Escherichia coli* or even a simpler prokaryote is untenable. How many would you need for making an entire microorganism? – several hundred to several thousand, depending on how to conceive these parts and how you count them. Let us say, simply 500. But then, how to prepare them experimentally in single vials? And even though there is this practical – but not only practical – impossibility, let us dwell briefly on this question, as it links to the theme of reductionism in SB, and the general idea of making life in the laboratory.

It is then here useful to recall the attempts to the reconstitution of living cells starting from their dismantled components, generally nucleus, cytoplasm and cellular membrane. The first thing to say is that the reassembling is not a simple, spontaneous process – as, for example, the case of TMV (Frankel-Conrat and Williams, 1995) or some ribosomal forms (Cohlberg and Nomura, 1976). In the case of *Amoeba Proteus* (Jeon et al., 1970), *Acetabularia Mediterranea* (Pressman et al., 1973), and some mammalian cells (Veomett et al., 1974), the reassemblage was partially obtained, but always with the help of an operator who with micro-syringes or by other mechanical manipulation has helped the reconstitution by hand.

Why is the case of the cell different from the case of TMV? Basically, this is because the self-organization of TMV is under thermodynamic control, whereas the construction of a cell is not and actually depends on a series of events in a very precise sequential order, with key steps under kinetic control, depending, namely, on the action of enzymes which have to work at a precise time in the general construction order.

Now let us go back to our collection of, say, the 500 bio-bricks which allegedly and rather arbitrarily constitute the *E. coli*. Certainly the idea of dividing up the living microorganism in 500 bio-brick components is classical reductionism, if this operation implies the assumption that there is nothing else to permit the life of the organism but all these parts.

Now, let us mix all these 500 vials together. I assume that a big mess will result. The main point in this thought experiment, and the reason for its failure, lies in the notion of emergence outlined earlier: the various parts must integrate with each other, and this in particular sequential order (as in the ontogeny programme regulated by the homo-boxes).

Perhaps a more intelligent procedure would be to add things one at a time in a certain order, so that things have the time of self-organizing and interact with one another first.

Would it work? Probably not, as we do not know the proper order and the proper timing. Consider also that the bio-bricks idea of SB is based on the assumption that the various genes and DNA strings are simply additive, namely, the actual DNA sequence is not so important, and in thought experiments of this kind, where genes must integrate with each other, this assumption may prove particularly invalid. More in general, the "construction of life" in SB is more aptly carried out within the minimal cell project, as in this case people are content with only a very few components and a very much reduced cellular efficiency and general performance – and also people stay away from the complexity of the real biological membrane.

Let us conclude this point by noting how the reductionism programme of SB, if taken literally, is destined to failure.

Having clarified these general concepts, let us see more in detail how SB operates to reach its goals.

## 4. The Way of Operation of Bioengineering SB

One major operational scheme of SB is based on modularity, which implies "cut and paste" of genetic parts from one organism to another. Some of these parts can be "bio-bricks", originally belonging to a living organism, and then made commercially available, or can be genetic parts synthesized in the laboratory. Let us schematize the major modes of modularity operation with the help of Fig. 2.

Given a starting organism, containing the four genetic elements A, B, C and D, we can have the case in which one element (or more than one) is eliminated, as in the knock-out experiments carried out by Venter's group on *Mycoplasma genitalium* (Fraser et al., 1995) (see Fig. 2a). The result is a genetically simpler novel organism, and the question is, "what is its performance?" The goal of the investigators was to maintain the viability and "life" of the original organism, goal that, according to the authors, was achieved.

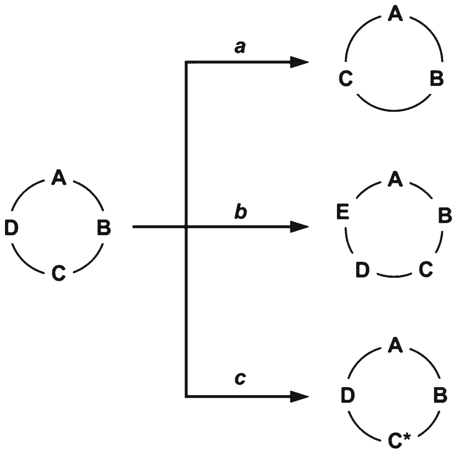

**Figure 2.** Basic operations in synthetic biology.

This procedure also epitomizes one possible way to the “minimal cell”, a cell consisting of the minimal and sufficient number of genes. It is a kind of top-down approach and is conceptually quite different from the other kind of approach, to be discussed later on in this section, which offers a successive addition of genes to an empty scaffold.

In contrast to the mood of operation of Fig. 2a, b illustrates the case in which one gene, or one entire bio-brick, is added to a pre-existing organism. This is a more complex case, as there is a genetic addition: the organism A is now supposed to perform all his previous functions, plus the new ones due to the added B element.

The simplest case of this second manipulation is classic bioengineering: if you want that *E. coli* fabricates insulin, you add to its genome the pig insulin gene, and the *E. coli* genome is thus enriched and does the job of making insulin. However, SB offers more complex and more interesting cases. For example, in the work by Weber and Lienhart (2009), simplifying somehow, the *E. coli* repressor of the biotin biosynthesis operon was fused to the Herpes simplex transactivation domain to generate a biotin-dependent transactivator: biotin-inducible transgene expression was functional in a variety of rodent, monkey and human cell lines.

Let us consider now the case illustrated in Fig. 2c. We have here – indicated with an asterisk – the replacement of a genomic part, in analogy with an organ transplant in humans. The new element added into A can also be synthetic: an example is the replacement of an entire gene of *Mycoplasma genitalium* by the corresponding synthetic gene, synthesis performed in Venter’s group (Gibson et al., 2008). In all these cases, we may obtain a more powerful functionality in the organism, and the integration and the consistency with the whole should be guaranteed by the fact that we have substituted similar or identical parts and, more generally, the demonstration that life – at least at this level – can be seen in terms of cut and paste of parts. A good example of this is the work by Lee and coworkers (2009) who operate on the metabolic engineering for the production of drugs at the whole cell level (a notion germane to system biology) for enforcing or removing the existing metabolic pathways towards enhanced product formation.

Venter’s group experiment deserves a further comment. The original bacterium, once deprived of its own genome, was not alive; the synthetic genome obtained in Venter’s lab was also, obviously, per se, not alive. By putting these two non-alive parts together, a living organism came out. Actually, when this work was published, we all admired the labour endeavour, but nobody was surprised by the fact that life could be regained. Why not, if DNA is just a molecule?

Conceptually, this work reminds one of general cloning, where we have two parts (the enucleated ovocyte and the nucleus), each per se being not living, but once properly put together, the two nonliving things give rise to a living entity. Is this a demonstration then that life is indeed an emergent property, as it can be obtained starting from nonliving parts?

Figure 2c may also illustrate the case in which the new genetic element has been created *in situ* in the A organism by genetic manipulation of the original organism. For example, see the paper by D. Endy and co-workers titled "*Refactoring bacteriophage T7*" (Chan et al., 2005), in which more than one single module has been genetically changed. Also in this case, as in the previous on, we are dealing at the end with a novel organism.

This is also in the example of the *iGEM* work by a young team of Peking University (2007) who has modified bacteria *E. coli* so that it changes in colour when light is switched on/off (see http://2009.igem.org/Main_Page). A novel operational unit is integrated in the original circuit so that the final product (bacterium) is a new form of life.

What is missing in Fig. 2 is the total synthesis from scratch, starting from the synthesis of the genome, as shown by Venter's group, and then making one by one what we have called A, B, C and D moduli. I believe this is well still out of reach.

Let us now turn into epistemology again. Based on the schemes of Fig. 2, life is seen in SB as a series of operational units, which are spatially and logically separated from each other and that can be added and taken away singularly. Under this viewpoint, we can say that there is a strong reductionism attitude. Do the SB schemes of Fig. 2 point out a reductionism scenario?

Yes and no, we have to be careful. In fact, together with the cut-and-paste operation, even if implicitly, there is also the idea that all these operational units must be interconnected with each other to make possible the emergence of life. In other words, insofar as life is reduced to the sum of operational units, we are in reductionism. As soon as we say that life cannot be interpreted nor explained with the sum of operational units, but we need their integration to form a novel emergent unit, then we abandon the narrow limits of reductionism.

In my opinion, this simple discriminating argument is not always clear in the mind of the authors of SB. Actually, the authors can be defined as reductionist, or emergentists, depending upon the stand they take in the above discrimination.

Can these new forms of life, be beautiful or monstrous, be patented as new gadget do? There is an ongoing discussion on that, and fortunately it is an issue which lies outside the scope of this article.

What about the other soul of SB, the basic science soul, that is based on the question, why this and not that?

In this case, there is a structural design, set from the start – for example, the making proteins with a reduced alphabet of amino acids or DNA having pyranose instead of ribose. The synthesis follows then a teleological perspective. However, contrary to the case of engineering SB, the function is not set a priori; namely, one does not know a priori what these novel proteins, or the DNA analogues, will be capable of doing. It is all open ended. The question is rather: which kind of emergent properties are going to arise from such a novel biological structure? The fact that we do not know what the emergent properties are going to be set this kind of science in the realm of basic science, rather than in the bioengineering area.

## 5. Concluding Remarks

The epistemology of SB can be highlighted in terms of a few keyword dichotomies. One is teleology versus teleonomy, and here things are relatively clear. The other is reductionism versus emergentism, and here things are subtler. We have seen that according to a superficial point of view, SB appears as a very reductionist science, as all is based on interchangeable modules which can be assembled together, or dismantled. However, the underlying philosophy, even if is not fully seen or analyzed by most of the workers in the field, is one heavily based on a concept of life which is highly emergentist – as life emerges only from the dynamic integration of parts into a whole – life as an emergent property. In this respect, it would be good if the scientists in the field would acquire some basic notions of philosophy of science and possibly transmit them to the students.

The other thing that should be transmitted more clearly to students of SB and in the life science in general is a first answer to the question, "what is life?" I believe that the few common sense considerations outlined in this chapter – based basically on system biology – may be sufficient to see the SB work in a broader perspective of life sciences, and perhaps dispel the confusing and partly false notion that all there is in life is DNA.

The notion of life as emergence might enjoy with SB its triumph, once that SB succeeds in synthesizing life from scratch from nonliving parts. We have reasoned, however, that this is still far from reach.

Even with the genetic manipulation of the genome of living bacteria, and within the teleological design of engineering SB, emergence may play some unexpected trick, in the sense that a novel combination of modules into a novel configuration may well give rise, in principle, to unexpected properties.

This argument links with the bioethical problems, which is a sore aspect of SB, particularly if we consider the increasing power of mass media. In general, it must be said that that SB has shown from the very beginning a great attention to bioethics, as witnessed by the considerable amount of contributions dealing with ethical problems in the major SB international conferences. It is as if the authors of the field have learned from the older field of genetic engineering and defend themselves a priori from accusations of dealing too light heartedly with potentially socially scary items. Ethical problems are of course less of an issue for the second soul of SB, that dealing with the basic science of chemical SB. Here, too, it would be advisable to see the connection between bioethics and epistemology, reasoning on the notion of emergence.

At the light of the present scientific production, the idea that by bioengineering SB can produce novel and dangerous bacteria is far-fetched. Different might be the case in which somebody wants to produce purposely novel harmful bacteria – a consideration that may link with the suspect that some military research agencies might precisely do that in their biowarfare programmes. I believe SB scientists should be careful not to give a hand to such programmes.

There is another level of the bioethical discourse, which is not dealing with dangerous novel bacteria, but with the more subtle question, whether it is right to "play God", and produce in the lab forms of life which do not exist in nature – particularly when the enterprise may not stop at the level of bacteria, but has the ambition of creating new forms of life by mixing the genome of, say, worms with the genome of butterflies, or by screwing the homo-box during ontogeny so as to obtain monstrous living constructions.

I know that a few (?) colleagues see even this as a challenging enterprise and are not touched by the concern that the construction of biological monsters may be something unethical. Here, too, there is only to hope that the main substrate of all sciences, namely, common sense, may prevail over all other ambitions.

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Biodata of **Josef Svoboda**, author of "***Necessity and Freedom in Designs of Nature***."

**Dr. Josef Svoboda** is a professor emeritus at the Department of Biology, University of Toronto, at Mississauga, Canada. He studied Philosophy and Biology in Czechoslovakia, but in 1949, he was arrested and sentenced by the communistic regime. He spent almost 9 years in prisons and uranium mines' labour camps. After immigrating to Canada in 1968, he graduated at the University of Western Ontario, Canada. In 1974, he obtained his Ph.D. from the University of Alberta, Canada, for a study of productivity processes in polar semi-deserts. For more than 30 years, together with his students, he conducted research in the High Arctic, focusing on plant colonization following deglaciation of polar landscapes and responses of arctic plant communities to global warming. He also published papers on the origin of life and evolution. Honours: Northern Science Award by the Government of Canada and honorary doctorate from the Masaryk University, the Czech Republic.

E-mail: **josef.svoboda@utoronto.ca**

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# NECESSITY AND FREEDOM IN DESIGNS OF NATURE

**JOSEF SVOBODA**
*Department of Biology, University of Toronto at Mississauga,*
*Mississauga, ON, Canada*

Psalm 111

1. Praise the Lord!
2. Great are the works of the Lord, studied by all who delight in them.
3. Full honour and majesty is his work.
7. The works of his hands are faithful and just; all his precepts are trustworthy.
8. They are established forever and ever, to be performed with faithfulness and uprightness.
10. The fear of the Lord is the beginning of wisdom; all those who practice it have a good understanding. His praise endures forever.

## 1. Introduction

Many thinkers would oppose, some vigorously, the idea that the apparent integrity and functionality governing the observable universe might be a manifestation of a pre-existing design (Svoboda, 2009). For them, the universe and its workings appear to be an outcome of random movements in the original chaos. If we pour sand onto the ground, the resulting heap would form a cone. The universe is just such a complex and ever-expanding 'cone'. No design. True, but not a chaos either. There are laws of gravitation, vector forces, etc., involved in these processes directing every grain of sand and making the shape of the cone predictable.

### 1.1. THE DEFINITION

By common understanding, the concept of the *design* refers to an original blueprint or scheme for a *deliberate* purpose, intent or aim…. Design realities are not arbitrary products of random forces, such as a resemblance of a face in a cloud or of physical laws involved in filigree-shaped snowflakes. There are many admirable patterns pleasing the receptive eye, yet these do not qualify for the common notion of a design, although they may be a secondary outcome of an original blueprint.

Design rhymes with divine. The traceable origin and 'behaviour' of the universe point to an intelligent agent, pre-existing and coexisting with its design. Such a hypothesis (Ondok, 1998) is not only logical but inevitable. The author of this chapter clearly sides with those who see a universal design in nature. It is, however, beyond the scope of this chapter to deal with the putative, complementary and causal side of the design itself.

Three approaches could be outlined dealing with the 'Origins of the Design in Nature': the scientific theory, philosophical hypotheses and a theological interpretation of divine revelations. The following reflection is an attempt to analyse and partially clarify this time-honoured enigma based on recent discoveries and contemporary scientific theories.

In this treatise, the concept of nature is synonymous with the concept of the universe. The universe is defined as the totality of everything that naturally (not supernaturally) and objectively exists. In the broadest sense, nature encompasses the same existing totality.

## 1.2. ORIGINS OF THE DESIGN

It must be seen as identical with the origin of the universe. In Plato's sense, the design, if any, would exist apart from the extant physical reality. In Aristotle's sense, however, it would be intrinsically encoded in nature itself (Penrose, 2005). The design has not *developed* over time, yet has unravelled, revealed itself and, in time, was made comprehensible to the intelligent observer. It was present 'in nuce' (Hawking, 2001) at the moment of the universe's conception, narrowed down to 13.7 billion years ago (Lemonick, 2003; Tyson and Goldsmith, 2004).

### *1.2.1. Big Bang with Attitude*

The event of the universe's emergence is known as a Big Bang. The cosmic event was not a simple super explosion of energy. It was a bang with a 'mission' to forge a structured material world, create life, generate intelligence and continue in its creative zeal beyond the all, presently known by us. All started in a zero space, at a zero time, with a zero substance and zero potential: '*out of nothing*' (Fain, 2007). Theoretical physicists are not comfortable with a notion of 'something out of nothing'. Their zero dilemma came from a retro-projection of the universe's expansion and led to an infinitesimally small, nondimensional *singularity. 'All matter inside the past light cone is trapped in a region whose boundary shrinks to a zero in a finite time*' (Hawking, 2001). However, also this sophistic equivalent of Fain's nothingness must have come into being before it exploded at the onset of the Big Bang.

The human zygote (proto-embryo) carries in itself all needed information (DNA) to self-construct into an adult individual. Could we presume that the hypothetic singularity, either pre-existing the Big Bang or emerging into being *Ex nihilo*, carried with it all the 'directives' (called laws, principles, constants) to evolve into the universe we live in and are trying to comprehend? The sceptic would argue that DNA is a tangible apparatus, carrying information and operating by mechanism we have recently deciphered. What is the tangible code and evolutionary mechanism of the singularity? The question is legitimate and the answer not easy. If the pre-existing entity was already 'composed of parts', no matter how sublime, there is a leading edge to grasp and unravel. If, however, it was a non-physical entity, an essence or 'idea' which realized in a void 13.7 billions of our years ago, then we have no edge to grab and face a mystery.

This enigma accompanies us at every step of our mental endeavour: in the microcosm, when we ask about the absolute essence 'of which' everything is made; in the micro- and macrocosm, when we deal with forces and fields; in the biological world, when we deal with the mechanism of evolution, with its directionality, sudden unexpected breakthroughs into higher levels of complexity or functionality; and ultimately when we ask for the meaning of everything and especially the meaning of our existence.

By accepting the notion of laws governing and perhaps directing the process of the universe's unfolding (Penrose, 2005), the notion of a design and a question of a lawmaker becomes inevitable. The answer, as we know, is not unanimous. The God hypothesis is once again rejected. In their new book, Hawking and Mlodinow (2010) argue, yet unconvincingly, that the universe arrived into being out of nothing by *spontaneous creation.* Clearly, what is not possible in mathematics is permissible in a distorted logic.

## 1.3. THE REALIZATION OF THE DESIGN

This is not a closed and accomplished act but a dynamic process, still in progress. In fact, its key feature is 'being in motion' through transitory phases towards the final state. Are there any goals of nature and can we identify them? Based on the present-day science, the inanimate universe is expanding through various intermediary stages into its thermal death (Chaisson, 2001; Seife, 2003; Svoboda, 2006, and others). In contrast, its living component, the biocosmos, presently culminating and represented at this planet by mankind, seeks ever higher emancipation from the external and internal limitations, longing for freedom and happiness (cf. Codex Hammurabi, Magna Charta; the American Declaration of Independence speaks about '*The unalienable rights to Life, Liberty and the pursuit of Happiness*'). These solemn codes are historical expressions of human noble aspirations. They could also be seen as steps and challenges in the realization of the nature's designs. In this non-physical realm, nature is more platonic. The biocosmos *gravitates* towards freedom, higher consciousness and potential immortality, without ever fully achieving it. The exponential character of the bio-evolutionary advancement is not a result of an external 'push' or 'pull' but can be compared to a *free fall*, which is slow at first, yet accelerates with time and distance. Yet, there is a catch, a paradox: aiming at a target and meeting it are two different things. Evolution never hits a bull's eye! In this respect, nature is not perfect. It is imperfect *by design*, as we will argue below. Absolute perfection would spoil the game in sports as well as in evolution.

## 2. Attributes of the Designs of Nature

There is a lot to go on in describing the complexity of nature's design. The entire universe can be seen as emulating the living organism (or the other way around). It started from the seed (embryonic universe), expanded into a rich canopy of galaxies, with living organisms probably dwelling in most of them, and is producing its fruit – the intelligent beings. In the life cycle of a single organism, all information is present in the nuclear DNA. Yet, the individual develops in stages. By following the ontogeny of an unknown organism, the observer would not be able to guess the final image of the emerging form. Likewise, the intelligent observer of the universe in its infancy would not have a clue about its further progression and transformations. Now, at the universe's apparent maturity, the horizons seem to be more open to speculation. Let us now reflect on some of the 'anatomical' features of the nature's designs.

### 2.1. PHYSICAL ATTRIBUTES OF THE NATURE'S DESIGN

#### *2.1.1. Structure*

Real and tangible yet impermanent and transient (emerging and vanishing); sustainable and dissipating (half-life and shelf life of any structure, big or small); terminal or mortal (yet regenerating and reproducing); spatial (separateness, yet interconnectedness and continuousness); chronological; successional; corpuscular and non-material (wave and field); 'stable' and transforming (from a solid state to pure energy); compatible; synergistic and antagonistic (attractive and repulsive); chains, cycles, patterns and fractals (Wolfram, 2002; Mandelbrot, 1999); 'bi-locating' (localized yet 'omnipresent': photons, electrons, protons, even heavier particles); hierarchical (from the hypothetical God's particles, Higgs to galaxies to a person); structured (the minerosphere: molecules and their aggregates), super-structured (the biosphere: organisms), ultra-structured (the homosphere), meta-structured (the noosphere: personal and global consciousness) (Svoboda, 2000).

#### *2.1.2. Function*

Ever in motion as a fundamental expression of existence; self-organization, self-preservation and natural selection (from the birth of the universe to human brain); propensity for change; interacting ('no atom is an island'); progressive (with a policy of no-return); directional (process, succession, spontaneous and self-directed evolution); love and passion; self-centred and altruistic; highly motivating and purposeful, yet for this world terminal, dark and dismal; immanent and transcendent.

#### *2.1.3. Spontaneity and Determinism*

Under right conditions, atoms of oxygen and hydrogen will form a molecule of $H_2O$ (water). There is no exception. Even molecules of higher compounds will be created in the right conditions spontaneously and without exception. However, the right conditions do not always occur. One might reason that for certain potential processes, the right conditions never occur (e.g. for the spontaneous emergence of life). Thus, what in theory should proceed 'without exception' produces often imperfect results in the real world.

### *2.1.4. Imperfection, Corruptibility and Perdition as Essential Features in Nature's Design*

In mineralogy, different compounds form different crystals, shaped after ideal templates, displayed as models in crystallographic cabinets. They are uniquely defined by the structural arrangements of its atoms in crystalline lattices. Yet, no crystal of a kitchen salt, or of any other mineral, is perfect. Gemologists speak about gem defects, departures from crystal symmetry, usually due to impurities and other factors. These diversions from the ideal model or expectation are ingrained in all aspects of nature's existence, be it a form or function.

Curiously, these departures are *essential and necessary* for the physical universe to 'keep going and evolving'. They have extremely narrow tolerances at the microcosmic level, as described by Rees (2000) and Barrow (2001), but increase with the structure's complexity. While peripheral blemishes may allow the systems to function, defects of critical components will reduce the system's efficiency or prevent its functioning completely. To facilitate the progression, the design of nature is equipped with a built-in principle of a 'decommission'. Physical structures break down and decompose. Living beings are affected by anatomical deformities, diseases and pain. Humans suffer also mentally. All creatures are *programmed to die*, to make space for their replacement (Chai et al., 2000). The information is saved and passed forward, and material resources are recycled. With every new generational cohort, there is a minuscule evolutionary progress. '*Praised be the Lord for our Sister death from whom no man alive will escape*' (St Francis of Assisi: Canticle of the Sun).

No complex structure or system is perfect and permanent. Nature operates between perimeters of excessive flaws and perimeters of absolute perfection. At either edge, the physical systems would cease functioning or evolving. Too defective structure would bring a system to a halt or crash. Perfect systems would not need improvements and would stop evolving (cf. eternal heavenly spheres of the ancient world!). One of the strange enigmas of the real world is the element of a *sliding platform*. It has been in operation from the flash of the universe's birth to the functioning of the human society and operates in a barely favourable milieu. What an ingenious strategy nature has embodied in its design! It is nature's balancing act between unreachable perfection and a disastrous failure!

## 2.2. METAPHYSICAL ATTRIBUTES OF NATURE'S DESIGN

In a classical sense, what lies before, above and beyond the physical reality (for the sake of knowledge alone – Aristotle) is not a prime concern of this chapter. Here we use the term in a more specific sense, referring to the *non-tangible* features and dealing with the qualitative rather than quantitative aspects of the physical reality. The metaphysical attributes of the inanimate cosmos, enlivened *biocosmos* and intelligent *noocosmos* are all accessible and comprehensible by empirical means.

### *2.2.1. Indeterminism*

The *inanimate* world is playing by the preset rules (laws) with no exception. This world is utterly deterministic. In the *enlivened* world, we can trace the symptoms of choice in the simplest organisms such as bacteria, and the level of liberty is broadening with increasing complexity of the living carrier. Kauffman (1997, 2000) defines a living organism as an '*autonomous agent acting on its own behalf*', incorporating elements of indeterminism directly into his definition of life. Choice, options and aspirations are the *hallmarks of freedom*.

### *2.2.2. Emancipation and Liberation*

In spiritual beings, there is an inherent conflict between body and mind. Already the most ancient practices of yoga, meditation, prayer and contemplation have centred on altering even conquering the biological limitations in order to enrich inner life and gain higher awareness and fuller consciousness. Many of these techniques are now used worldwide. They are complemented by modern health practices to prolong life and to achieve virtual immortality in the future. Some individuals are trained to conquer space and time via space travel. At a more mundane scale, people are trying to escape from their body through imagination, fiction, drama, films, TV, alcohol and drugs. All these desires and practices are signatures of nature's design, leading (not necessarily always succeeding) to higher peaks and summits.

And then, there is a great mystery of '*good and evil*'. The *moral dilemma* is a supreme expression of freedom of choice, a new phenomenon in the universe and, once again, an integral part of the nature's design (Kropf, 2006).

## **3. The Journey of Evolution**

In peaceful times, under enduring climatic and geological conditions, interspecific cooperation, rather than competition, takes place. The intraspecific competition is more prevalent, fostering microevolution and marking the *stasis* or the 'STOP phase' of evolution. In upheaval times, however, the truce is disturbed and populations of extant species fight for survival or domination. 'The great leap forward' through fierce competition takes place. This marks the 'GO phase' of evolution. Two factors play a decisive role: (a) elimination of weak adaptors allowing the competitive species to advance and to fill the vacant niches and (b) accidental emergence of mutant forms advantageous for the new situation. In both cases (especially if both factors meet in the same species), the evolutionary landscape is open to macroevolution (Svoboda, 2006). Inevitably, when the situation settles again, a new armistice among the species is reached, and cooperation, even mutualism and symbiosis, is more prevalent. In other words, external forces are moving the evolution.

## 3.1. EVOLUTION NEEDS A HELPING HAND

For some of the historical evolutionary occurrences, we have no plausible explanation. One of such unexplained episodes, though there are theories, was the evolutionary 'rapture', the *Biological Big Bang*, ~530 million years ago. Measured by the geological time scale, 'suddenly' 100+ phyla of new animal forms emerged in the world ocean within ~10 million years. What caused such an explosion of new complex forms after almost 3 billion years of 'quiet' evolution of the simple single-cell organisms (bacteria and blue green algae) '*remains an enigma of paleontological enigmas*' (Gould, 1979). Yet the ancient sluggishness may only look superficial. Microbiologists estimate the number of extant bacterial and archaeal species to be 400 million and the number of those that ever lived on Earth to be 4 million millions. This would represent a 1000 new single-cell species for every year of our planet's existence, and that does not include viruses! (Tudge, 2000; Gould, 1989). This microevolution of primitive life forms conforms well to the idea that in less stressful conditions, species diversify *laterally* within the family, while in stressful or catastrophic situations, the surviving species diversify *vertically*, achieving higher complexity. Macroevolution takes place (Wolfram, 2002; Svoboda, 2006).

### *3.1.1. Catastrophic Events*

Bizarrely, the ingrained frailty of the world's ecosystems became the escape hatch for stagnant evolution. When in the past the biosphere became populated with mutually adjusted organisms and functioned in an 'orderly' way, the evolutionary advancement became constrained. Mostly, the *micro*evolution took place. *Macro*evolution has been preconditioned and triggered by catastrophic events, such as the one at the Cretaceous/Tertiary boundary, 67 million years ago. On one side, these events caused the extinction of a great number of species, mainly the great reptiles. On the other side, their massive die-off allowed an echelon of more advanced mammals to replace them. '*We are the end-product of this fast-track post cataclysmic evolution*' (Svoboda, 2006). On our planet, evolution has been marked by a non-linearity. It occurred in relatively short bursts of fast advancement after long periods of sluggishness.

All these events are identifiable features of nature's design strategy. This strategy is dynamic, yet seemingly imperfect, allowing for a certain degree of meandering, but holding the system together. It has been moving ahead slowly, often clumsily, sometimes back-pedalling, as if time were not a factor.

### *3.1.2. Mutations as a Vehicle of Design in Bioevolution*

Mutation is a sudden change in a gene resulting in a new inheritable characteristic. In higher organisms, a mutation can be transferred to a future generation only if it occurs in a germ or sex cell. Their frequency of occurrence is more or less constant but could be influenced by external causes. However, most mutations are a disservice to evolution. Many are deleterious. How is it then that the species are still moving ahead by tiny steps of evolution? How does this movement become directional? Several factors are usually involved, of which a change of the environmental conditions is almost a prerequisite for a major evolutionary shift. Per allegory, Maxwell's demon opens a door in a certain direction, and the population of a species rolls into the 'hollow' spontaneously (Kauffman, 2000). There it may sit indefinitely until the next door opens.

### *3.1.3. Natural Selection*

This is a smart way out of the cul-de-sac of mutually counteracting mutants. The individuals with the most suitable traits for the changed conditions in a specific population will have a better chance to survive and/or produce a more viable offspring. We have to realize that we are talking about an extremely small fraction of new mutants with a favourable survival trait within great numbers of non-mutated or 'wrongly' mutated individuals in an established population. For instance, a new mutant of the annual poppy seed plant with 200 highly germinable seeds in a pod, producing a more attractive dark red colour of its petals, may give rise to a new dark red poppy population a thousand times faster than a population of an insular finch with a differently shaped but more useful beak, producing four chicks per season, of which three will be predated.

In the greater scheme of cosmic evolution, it means that only a tiny fraction of the favourable mutants is available to accelerate and advance evolution. Here the concept of design becomes immensely useful, since it narrows down the alley of potential choices for natural selection.

The strict advocate of random process will indeed protest. What would be the mechanism for the departure from randomness? In our opinion, there is no departure. The random process is not eliminated. *The helping hand of the deleterious mutations obliterating the less fit or defective individuals from the playground would automatically lead to a shift in a desired direction.* Thus, the corroboration of natural selection (since it is a blind force) would be more effective in eliminating the weaker individuals than in fostering the fitter ones.

In an evolutionary landscape, thousands of features, traits and characters are subject to mutational change within a limited time frame. During the macroevolution of birds from reptiles, changes into the bird's skeleton (much lighter), their body shape, surface cover (scales and armour into feather), front legs into wings, plus myriads of physiological and behavioural changes were necessary. At the same time, all the spontaneous and random changes in the genetic apparatus had generated mutants in all directions for every character and function. More often than not, any favourable change could be cancelled by a bad or unfavourable mutation of another character or function. Consequently, the variation and permutation of all needed mutations to result in a '*desired*' new species is staggering, and in terms of diminishing chances, astronomical, even when time, over which such a change had occurred, counted in millions of years. Clearly, streamlining of the process would help.

*Case Study*: Under the present climate warming scenario, a significant movement of the boreal forest tree line, many kilometres in the northern direction, has been observed. The spruce which dominates the boreal forest community produces an overabundance of seed. The open terrain for the northern expansion is also available, yet the forest invasion into the treeless tundra, if left to spontaneous seed transport alone, within a human lifespan would be minimal. Why? The trees disperse their seed only in their close vicinity. Of the large quantity of the dropped seed, only a small fraction will germinate and produce seedlings. After many years, some of these saplings will grow up, and several decades later, a few will mature and produce seeds. In other words, in the marginal situation (Svoboda and Henry, 1987), even under a climate warming scenario, for the seed to produce a seedling, sapling and finally a seed-producing tree takes almost a century. Then, the process must be repeated again and again…. In reality, however, the boundary shifts north much faster due to external help by wind, birds, animals, water and recently humans. With evolutionary progress, it is similar. As the succession also evolution thrives on external help.

No species lives alone. At a time when one species is undergoing a ‘complete makeover’, myriads of neighbouring species are subjected to a similar process of change, although each to a different degree. From the bird’s perspective, the entire community, if not the ecosystem, and on a global scale the totality of the biosphere are continuously transforming and metamorphing in shape, structure and dynamics. The Earth is a macro-polis of ‘busy bees’ at all evolutionary levels, where the dynamism leading to a change is being stimulated to a high degree by processes in the geosphere and by cosmic activity (Lovelock, 1989, 1990).

There is obvious desire of the proponents of a design for a disproportional generation of favourable mutations, and the results of the relevant research seem to support this putative claim. More recently opinions were expressed by some population geneticists and evolutionists that favourable mutations in populations outnumber the unfavourable ones. Some of those ideas sound pretty Lamarckian in condoning that the environment provides a support for the emergence of mutations favourable for a particular environmental situation. Or that nurture depends on genes which in turn need nurture (Ridley, 2003).

### *3.1.4. The Ascent of Man*

Man is a *wanted* child of nature but also an ‘enfant terrible’, a problem child. It is an intelligent and amazingly gifted creature, but as a species, mankind can be considered still adolescent and immature. So far, it has been notoriously harmful and destructive to its surroundings and ultimately to itself. From their early stages, humans began to modify the environment around themselves: first inadvertently, later knowingly, at present intentionally and purposefully (Marsh, 1864).

The study of sustainable systems and their development cannot avoid the history of this atypical member of the biosphere, his colossal achievements but also his atrocious activities and moral faults. In other words, that in accord with other species of this enlivened planet, also humans have behaved utterly ecologically, in Darwinian concepts, as if they were the only species on this world.

Already the hunter and gatherer devastated his surroundings either by overhunting, slash-and-burn practices or resource over-exploitation. When such an area ceased to yield sufficient life support, human bands instinctively moved to another pristine place. Due to their low population density, the affected piece of nature recovered and the previous balance was re-established. Not for too long, however. The distinct edge of their superior intelligence prompted humans to broaden the spectrum of food sustenance, to adapt to various environments and tolerate diverse climates. This way man, rather smart than 'wise' (*H.* '*sapiens*'), expanded quickly throughout the planet without diverging into two or more species. The very fact of remaining a single, genetically compatible species is an evidence of the present mankind's monophyletic and relatively recent origin (Wells, 2002; Wade, 2006).

What has caused the radical change, in fact an explosion of man's intellectual capacity that, in a very short time, separated the human line from other evolutionarily closest creatures? The enigma is a subject of various hypotheses, intense research and heated debates. Yet it remains a mystery.

All evidence indicates that from the very beginning, humans felt unsafe and threatened in their living environment. Before they began building shelters, they sought safe places and protection in caves, as if they felt incompatible, if not aliens in the natural setting in which they found themselves. Subconsciously, they distanced themselves from other animals and took care not to mimic their behaviour. On Earth, humans have been and still remain so incongruous, as to justify a belief by many that they have an extra-planetary origin.

It is also believed that akin to their genetic forbearers, the first humans lived in a harmonic unity with the surrounding nature. This is being characterized as '*Man in Nature*' stage. Gradually, however, with their population on the rise, humans became aggressive and more and more imposing upon their environment. This, '*Man against Nature*' stage, has prevailed until the present. The challenge and goal of the modern, fully emancipated mankind is to make peace with nature again and to reach a conscious balance with nature. This relationship, however, ought to be of a different quality. Not back to '*Nature over Man*', neither '*Man over Nature*' but '*Man with Nature*' entrusted with a new mission. At this 'open scale' of the future evolution, controlled undoubtedly by humans, achieving *sustainability* will be the first qualifying step.

## 4. Sustainable Development

From the very beginning, nature practised the method of *sustainable development* at the following three levels.

## 4.1. IN COSMOGONY

The universe is a *very long-term* sustainable system. Thermodynamically it is a closed yet *dissipating* system which does not exchange energy or matter with its surroundings, since there are no surroundings. It can be considered an immense, highly charged accumulator, a grand pool of stored potential energy, bankrolling all the seemingly chaotic activities within itself.

At the Big Bang, an unimaginable amount of energy was released, inflating and spreading with incredible speed in all directions. Only a minute portion of this energy has condensed in matter, giving birth to subatomic and atomic 'nuclei', the seed of the visible universe. Every atom represents *a bundle of potential energy* to be released in the future and to produce work. All stars, including our Sun, are powerful storehouses of this potential energy at several levels. Release of these energies is gradual, non-synchronized and scattered in time. Nature is an opportunist. If there is space and a supporting milieu, it will act spontaneously without delay until the process is completed and the potential energy spent. We can see it as a *cascading effect* or the energy movement down the potential energy gradient.

Speaking about nature's design, it is programmed to last for billions of years. Even the big stars, however, will burn down eventually, explode in supernovas and collapse into dwarfs. Ultimately, their useful potential energy will approach zero. However, as long as they burn, they function as long-term sustainable sources of energy. These safe and reliable celestial nuclear power plants are warming our planet and provide energy for photosynthesis. Other stars most probably also support life, which is scattered within numerous galactic systems. The origin and evolution of life on this planet have been conditioned by the reliable source of energy from our solar battery.

## 4.2. IN EVOLUTION

The biosphere is an incredibly conservative and *long-term* sustainable system. The biosphere, its host, the planet Earth and the entire solar family are '*open systems*' since they exchange both energy and matter with their surroundings. In time, new species of microbes, plants and animals will emerge and perish in it. However, genetic laws of Gregor Mendel rule over an overwhelming majority of individuals which form the immense number of extant populations. Only an exceedingly tiny fraction of individuals are struck by a 'meaningful' genetic change due to random mutations. Nevertheless in time, this would lead to an onset of genetically altered populations and eventually to a new species. Were it not for the overwhelming constancy and steadiness of extant populations (some over millions of years), expressed in Mendel's laws, evolution would break down. Even a small increase in the mutations' frequency would prevent a build-up of robust and viable populations, incapacitating establishment of a new species. Lower frequency, on the other hand, would bring the evolutionary process to a standstill. The relative constancy of the mutation rate can be compared to the precision of the physical constants governing the self-construction and duration of the universe (Rees, 2000). Even a minute deviation in the *frequency and quality* of mutations would cause chaos in evolutionary advancement. Through the enduring, yet dynamic sustainability, a balance between the lethargic stasis and 'run-away' evolution is secured. Also at this level, nature's design is fine-tuned between desired steadiness (relative permanence) and evolutionary change.

In his significant book *Investigations*, Kauffman (2000) engages in a mental expedition looking for the fundamental character of living systems as attempted by Schrödinger (1944). Schrödinger introduced into the discussion about the origin and essence of living systems the concept of information and negative entropy. Kauffman, a philosophical agnostic, sees the corm of the mystery in the order, spontaneity and self-organization. In a hierarchical order of the universe's attributes, *self-organization* holds a cardinal position, subsequent to *self-preservation*, i.e. maintaining its existence: 'Self-organization mingles with natural selection in barely understood ways, to yield the magnificence of our teaming biosphere…' (Kauffman, 2000).

Fundamentally, self-organization is a primary attribute of the cosmic and biological existence and its evolutionary progress in the broadest sense. Yet without natural selection, the world would become cluttered and would ultimately cease to function. From this aspect, natural selection is not a maker of new species but merely *a mechanism, clearing the way* for its further self-organization.

### 4.3. IN ORGANISMS AND ECOLOGICAL SYSTEM

These are *short-to-medium-term* sustainable biological open systems, such as free living cells or any higher living beings. In a favourable environment, individual organisms are uniquely capable of sustaining themselves to regenerate when not lethally 'damaged' and to reproduce before they die. This is a distinction privy only to living systems and a *new phenomenon* in the known universe.

The general public is inadvertently kept believing that only threatened species had to be protected: the African gorilla from being exterminated by poachers, the polar bear from extinction due to climate warming, even the shark from hunters going merely after the shark fins for gourmet Chinese restaurants. All the above deserve attention; however, the challenge of rescuing individual endangered species, in fact preservation of multiplex assemblages and their complex ecosystems, principally rests in the protection of the entire biosphere.

As is distinct species an outcome of a long evolution, also that species quantitative representation and position or hierarchical arrangement in relatively stable communities is a result of a long adjustment and adaptation. Also here, nature's demand for long-term sustainability is rigorously applied. Every species, embodied by the size of its population and occupying a certain place, is set to function in a narrow, mutually advantageous way (habitat-niche). If the balance is upset (e.g. by fire), the ecosystem will try to repair the damage and to establish a new sustainable state of its functional existence. At the planetary scale, this process involves the geosphere and atmosphere. In other words, the enlivened planet behaves as a living organism (Lovelock, 1990). Individuals of every species, within their own populations, are busy acting first and foremost in their own interest (*intra*specific competition and interaction). At a population level, however, they team to defend their habitat and niche against other species (*inter*specific competition and interaction). Yet, by doing so, they also serve the interests of the entire community. Their sphere of impact as a single species is limited. Were it not so, the natural ecosystem would get rid of them.

*Biomes* are historic, geographically large ecological systems which have evolved under a prevailing climate. The tropical rain forest is the most complex and species-rich ecosystem on this Earth. Its long-term sustainability and development is based on a multidimensional accord of all organisms from the root to the crown level. Below the top of the sun- and air-exposed canopy producing flowers and fruits, there are distinct storeys inhabited by specific species of insects, birds, reptiles and mammals. Everyone is connected with another either directly or communicating in a cryptic cacophony by audible signals, chemical odours and leachates. One might not be able to identify the myriads of connections among the individuals of the same and other species, from the tips of the canopy down to the roots which hold the lofty architecture firmly anchored in the soil. Yet in the underground, there is another, mirror image canopy of ever-branching roots ending with hair-like rootlets. At that level, the distinction between trees and the mineral substrate ceases since the root hairs are entangled in a fine web of fungal hyphae impregnated with bacteria. All these are immersed in the soil solution. One without the other would not persist. The organisms 'know' about each other and 'respect' each other in spite of the essential and inevitable food chain which keeps the living microcosmos in operation. 'We be of one blood, ye and I', greets respectfully panther Bagheera the fearsome python Kaa in the Kipling's Jungle Book. The tropical rain forest is a complex and refined civilization of its own kind.

Biomes are maintained structurally and functionally by a network of 'synapses' and control mechanisms perfected over millions of years. These natural systems are resilient, self-contained and self-sufficient and run on clean solar energy. They recycle nearly completely their own waste, consume vast amounts of $CO_2$ and supply the atmosphere with oxygen. Their evolutionary achievement is not of a lesser significance than is the evolution of a nervous system. There is hardly a better example of a long-term sustainable development. Our contemporary society has much to catch up in emulating Mother Earth in terms of productivity, usefulness, efficiency, economy and organization of its multiple 'societies'.

## 5. Anthropocene

Human impact on the planet began in prehistory (slash and burn), continued through the agricultural revolution (10,000+ years ago), escalated in booms and busts of global civilizations in the Middle East, Asia, South America and Europe and resulted in an uncontrolled grand-scale destruction of natural systems in modern times. The process started about 80,000 years ago with the Neanderthal man, credited with extinction of certain species due to overhunting, yet exploded with the appearance of Cro-Magnons, the modern man, and its culture~30,000 years ago. Some authors feel that the escalating impact of humanity on the biosphere warrants reclassification of the recent time period as a new geological era. Thus, Crutzen and Stoermer (2000) and Crutzen (2002) proposed to rename the new epoch *Anthropocene*. It would have begun with the industrial revolution some 250 years ago, which correlates with the human rise of greenhouse gases. Others include the entire Holocene or the start with the nuclear era.

### 5.1. THE HOMOSPHERE

A *medium- to long-term* sustainable system (von Bertalanffy 1968; Svoboda, 1999). The homosphere can be simply defined as a biosphere permanently modified by man. In the far future, would the Anthropocene be judged as a supernova phenomenon exploding within the biocosmos or as its collapsing phase into a biological dwarfism?

Humans have been unprecedently successful in asserting themselves and enforcing their supreme position on this planet. The Earth has been under stress due to human proliferation, expansion and recklessness. *Homo sapiens* is the only species presently without a macro-predator, though his resilience to micro-predators (microbes) and its exposure to raw environment is weakening. Moreover, man's self-destructive behaviour compensates for the lack of external harmful agents, threatening his very existence.

Gradually, man transformed the biosphere into a badly managed *homosphere*, the spreading domain of its genus *Homo*. Promisingly, however, the burgeoning scientific knowledge and the flare-up of modern global communication have caused the situation to change. We still continue to inflict harm onto the biosphere, but do not maltreat it blindly as before and are mindful of the consequences.

Which way is mankind going to move? Will it start running in many different directions, of which some may lead to a blind alley and others to the edge of an abyss? A condition of any meaningful progress will be putting the house, his homosphere in order, to restore sustainability. That implies a significant reduction of wastage, pollution, poisoning of the environment, prevention of catastrophic events, such as the chemical disaster in Bhopal (1984), the escape of radioactivity in Chernobyl (1986) and the release of crude oil in the Gulf of Mexico (2010), and eliminating the danger of a nuclear war. Alternate sources of energy shall gradually replace the use of fossil fuels. Planting new forests, in compensation for the past and ongoing massive deforestation, would foster the sequestration of $CO_2$ (Paquette and Messier, 2010). Expanding and merging of natural protected areas, as proposed from Yellowstone to the Yukon (Y2Y), would allow free wildlife migration, reduce the pressure on the still functioning ecosystems and reverse the ongoing catastrophic extinction of species. The ultimate goal is to foster biological diversity by 're-wilding' the planet (Donlan et al., 2005). The latter is a plausible objective, were it not in its root disturbingly anti-human (O'Neill, 2010). The list of restoration programmes and inspiring actions could continue. The ultimate goal is an accord between our (human) presence and the surrounding nature. Let us commit the next 100 years to this noble issue: first cessation of hostilities, truce and then the peace accord.

## 5.2. THE MEANING OF EVERYTHING, PARTICULARLY OF OUR HUMAN EXISTENCE

If we uphold the thesis that man is a wanted child of nature, then we shall ask: why did nature bring us to life? Would it be too ambitious to say that after we establish our presence globally and mature as a truly rational species, we are here to facilitate advancement and completion of the cosmic evolution beyond and above the potential of mere biological realm? This intent would not be an antithetical act but nature's intuitive gift of confidence. We are 'different' from the rest of creation, programmed for the supra-natural.

In an effort to penetrate into the outer space, the (human) society is sending its scouts, the modern seafarers – astronauts – into the weightless environment. They shall collect information and gather new, extraordinary experience on our behalf. The rest of humanity is their back-up team providing motivation and logistics, a fitting division of labour! In a broader sense, we all have a mandate to carry on evolution beyond the limits of natural selection into the 'weightless' realm of pure rationality and spirituality.

As a species and as individuals, we are equipped for this task by our intellect and moral imperative. A breakthrough into another level of reality may be the *penultimate objective of nature's design*, entrusted to its prodigal yet prodigious child, as far as it can presently fathom. By fulfilling this specific mandate and mission, the universe is gaining cognizance about itself as a whole, which it, otherwise, would never have.

The ambitious attempts to travel to other places in our solar system, and later, maybe to galaxies (when the space-time paradigm is resolved), are material proof about our exclusive uniqueness in the world we know. Not even the sky is the limit. Biocosmos, spearheaded by man, is an open-ended realm, and its potential is virtually limitless (Calvin, 2004). 'The evolving cosmos acquires the capacity to generate life and even more capable intelligence…. Intelligence is more powerful than Physics' (Kurzweil, 2005).

This cosmic and biocosmic evolution would, indeed, affect also the genus *Homo* as an evolving organism, and this to such a degree that his present and future semblance would be unrecognizable. Are the future 'ultra-humans' with much higher intellectual capacity but less and less rooted in their biology going to replace the present humanity? Extinctions of our prehistoric predecessors are well known, but there is no-one else.

### 5.3. THE NOOSPHERE

This sphere is defined as 'the realm of human minds interconnected and interacting through communication' (Svoboda and Nabert, 1999). Could this subtle sphere eventually liberate itself and emerge as a new entity in the universe, the *noocosmos,* barely connected to its material base? Did it emerge, as also life has emerged, as a realization of the original design of nature, contained *in nuce* from the beginning? After all, what is 'matter' in its true essence? Whatever it is, there is an expiry date attached to it: 'Best if used before….'

As a present representative of nature, man is aching for emancipation from physical and biological constraints, longing for maximum independence and freedom. He is also yearning for being appreciated as a *person*. In the highest form, such an appreciation equals love!

One could predict that as before, the future is going to be marked with successes and failures. No significant expansion into outer space would be possible without first putting our planetary house in order. The idea of an 'escape' from a sinking ship of our planet in order to colonize other celestial bodies is foolish and intrinsically wrong. Quite to the contrary, a thorough yet prudent governance of our earthly heritage and resources is a precondition of a major leap ahead. The goal is not necessarily the liberation from the gravitational forces of our planet but about the future human communion nourished by the well-governed Earth. The exploratory journeys into outer space, whether with people or with mere robots, are deeply symbolic. They represent a challenge to elevate the human race and ultimately *all life* from the restraining gravitational forces of not only our planet but, strangely, of the matter itself. In the words of Teilhard de Chardin: 'We are not human beings having spiritual experience. We are spiritual beings having a human experience'.

If this is so, the universe has been making a *full circle*. From its instant emergence at the point alpha, through all the ages and stages of matter self-organization and energy dissipation, it is aiming back to its immaterial origin to the point omega. On this long-term journey, mankind could be the true and most fortunate seafarer.

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Biodata of **Tom Barbalet**, author of "***Not All Designs Are Created Equal***."

**Tom Barbalet** created the Noble Ape Simulation in 1996 and continues its development to this day. Noble Ape is used by Apple and INTEL as well as a number of universities to teach biodiversity, multimedia education, vector processing, real-time graphical interfaces, and a number of other technologies. He has been the editor of Biota.org (since 2005), a leading community resource for artificial life developers. He is the host of the Biota Live internet radio show where he discusses a variety of topics relating to artificial life, artificial intelligence, and simulation philosophy with a variety of guests. He is also the chair of the International Game Developers' Association's Intellectual Property Rights Special Interest Group.

E-mail: **tom@nobleape.com**

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# NOT ALL DESIGNS ARE CREATED EQUAL

**TOM BARBALET**
*Noble Ape and Biota.org, California, USA*

To explore the origin of design, one must understand that design is not an exact term but rather is a family of terms that cannot reduce to a generalized term due to the internal paradoxes of this family of terms. Some of the design terms are shown in natural systems. An artificial life simulation will be used to describe the many design processes that exist in the simulated world and also hold true in the natural world. An applied proof of the curious absence of "intelligent design" in nature and in human endeavors is offered concluding with an exploration of the origins of these forms of design.

## 1. Flooded by Human Design

It is very difficult to imagine a more corrupted and perturbed form than the definition of design in contemporary discourse. Surrounded by our own creations, saturated in human-designed existence, every level of our being would appear to be manipulated by a human hand and mind. From this basis, let us consider that perhaps design exists in a multiplicity of human-affected and also human-untouched circumstances. This chapter is dedicated to the reclamation of an understanding of design. In most situations, this design is a function of unmediated, haphazard occurrences that result in forms that hold the appearance of design, and arguably are designed, not by a human agent or a makeshift deity but designed by physical properties of the environment or an absence of explicit design.

In order to understand the problem of human design, the limits of this process need to be explored. The barrier of linguistic information transfer offers a vague limit in the capacity of human description where one human describes to another human the properties of a system to the extent the other human can replicate it. Rather than being about information perturbation, this represents the generalized and theoretical limit of such communication where the information remains the same. Intellectually, humans can hold more information than we can visualize and internally manipulate. A complex simulation environment is drastically limited by our own intellectual capacity and the fact that our human brains are not capable of doing the kinds of vastly complex system simulation that are effortless to modern computer processors.

This begs the question whether there can be both an explicit human design (where the created form is engineered in every fashion for the boundaries of possibility) and implicit human design (where the outcomes are not known or even the origins of the human creation can be known). It is clear that explicit human design is motivated by intelligence.

Basic definitions of human-designed solutions offer two dimensions that may initially appear to be identical but result in some interesting fractures to be explored. Having offered a basic definition of explicit and implicit design, let us consider open and closed design principles as a means of further dividing the explicit-implicit design axis.

## 2. The Linguistic Trap of Design

There are many definitions of design. Few of these overlap even in their own terminology with other definitions of design (Ralph and Wand, 2009). In addition to these definitional uses of the term, there are also academic disciplinary uses of the term with their own weightings and subtleties. Rather than exploring these distinct uses of the term design, a basic constraint will be applied. From this constraint, the distinctions in design will be explored through an axial analysis of design in this context. It is intended that the term will not lose its meaning through this constraint and expansion process. The purpose of the process is to avoid various linguistic and disciplinary limitations.

A central theme through many of the definitions of design relates to the planning process. Here, some time is taken and (through many definitions) actual plans or templates are created and studied to produce an overview of both how to create the object and also what the final object will look like. Through these definitions, there is a distinction between design and creation. The problem with the definitions that distinguish planning from creation is that, outside human creations and some small subset of the creations of other animals, little in the natural world can be interrogated finely enough to distinguish between the design and the creation.

For this reason, a definition of design is derived in this chapter through analyzing objects created through the process of information transfer used to create designed objects. Here, design fuses the planning and creation processes. For this reason, the use of the term design in this chapter is not just limited to planning how to create an object but also relates to the mechanisms that create the object. This distinction will be particularly important when studying and understanding properties of design in the natural world away from human hands and minds. In the context of general academic discourse on design through the newly emerging field of design science, the descriptions offered here should be considered action-centric (Ralph, 2010).

### 2.1. CLOSED DESIGN

Closed design describes any process that creates a functional object where all aspects of the object's creation have been explicitly designed.

A trivial example of this is an apprentice artist or simple craftsperson creating an object under the watchful direction of a master. Here, all the knowledge of the master and the master's knowledge of every iteration of the object being created and all its possible uses are embodied in the creation of the student. Direct transfer, not only of the knowledge of the master but also via the object created occurs. Another good example is any artisan builder, who creates an element of a building with full knowledge of the use of the object being created in a much larger structure. An astute observer will note that these are two related examples: the first example offers some knowledge transfer; both are examples fundamentally of creating something that is completely defined and can be created within this focused definition of closed design.

## 2.2. OPEN DESIGN

Open design describes any process that creates a functional object where some aspects of the object's creation have been explicitly designed, but the design strategy offers a number of degrees of freedom in the possible use of the object, as in a computer programming language or a computer processor. Here, although the designer may have some indication of the possible uses of the object, it is created with flexibility that can be exploited by people skilled in the art of the object's use. As in closed design, open design has the benefit of nonprecise delegation. In this circumstance, relationships among participants may not require complete knowledge of the use of the object or, in fact, complete knowledge of the design tasks of other component makers.

## 2.3. IMPLICIT DESIGN

Implicit design describes any process that creates an object where no aspect of the object's creation is explicitly designed. This could both define an object with many degrees of freedom or an object that has no explicit design procedure. This distinction will be explored later in this chapter.

## 2.4. CAUSAL DESIGN

Causal design is a particular subset of implicit design where the object is created by responding to environmental pressures that are not predesigned, as in most instances of design. For example, crystalline structures are created in response to physical properties of the environment, as are most designs in nature. Life counteracts inertia, engaging in a design process within the physical framework of the environment. This definition raises questions about traditional definitions of design, but is offered here in order to understand the continuum of design and some indication of the completeness of this design spectrum. This definition in no way maps onto the human understanding of environmental pressures or the physical framework of the environment. It should be assumed that on a subatomic, atomic, human, and planetary scale, a majority of causal design exists outside human knowledge.

## 3. Hierarchies of Design

In addition to the motivational description of design, there is also a hierarchical component to the design analysis.

### 3.1. MACRO DESIGN

In top-down design processes, a single controlling entity instructs or motivates subordinate entities to create, as in following plans to construct something or in any free flowing process that creates something with a primary point of control and orientation. Within complex construction, there may be a complete hierarchy of control where localized points of control respond to a primary controller. The example of the master and the apprentice provides perhaps the only true example of macro-closed design.

The hierarchical form defines macro design. In large part, macro design is a function of any form of human design as the creation of most things by humans requires a hierarchical chain of command and starts typically with formal planning, including the means of ordering the steps of creating and providing feedback if each step is not followed with the precision required.

### 3.2. MICRO DESIGN

In contrast to macro design, micro design is decentralized. Through either chance or a collective grouping, something is created by independent entities working together. When a number of macro-design elements work together in an apparently decentralized fashion, macro-design components participate in a larger micro-design process.

## 4. Enter the Hobbyist

The artificial life hobbyist as a named group of scientists is a modern phenomena (Barbalet et al., 2005), which describes a kind of software development that has existed in one form or another for at least 20 years, since artificial life was defined as *life as it could be* (Langton, 1997), possibly even 50 years if we include cellular automata experiments conducted by those inspired or motivated by machine models of reproduction (Moore, 1962).

The use of the term hobbyist should not be confused with the model rail hobbyist or the collector of antique dolls or other past-time hobbies. The artificial life hobbyist is named (somewhat tongue in cheek) for someone who does not derive an income from artificial life but who works tirelessly on a particular artificial life project. Artificial life hobbyists come from diverse backgrounds: some from academia (computer science, biology, paleontology, psychology, political science, and many other fields), industry (telecommunications, processor and computer manufacturers, web technologies, and pharmaceuticals, among others), and elsewhere.

Although in the open source developer classification of software engineer hobbyists, artificial life developers tend to be relatively solitary and also to develop projects that exist for tens of years. The artificial life hobbyist's project is distinctly different to normal software development. While there are always exceptions, most of these artificial life environments are rich, multilayer, simulated environments.

The property of emergence may be considered the rewarding intoxicant of artificial life development. It may seem counterintuitive to the uninitiated that someone would design a complex multilayer environment with an eye for detail and maximizing complexity to have something which was (by design) chaotic and evolving in a variety of directions that could not be predicted when it was first created.

The property of emergence in this context simply states that when the simulation creator begins with a set of assumptions and an ever-expanding implementation of this fantastic fictitious universe created in software, there is no way of knowing what will come from this endeavor. More comes from this simulation environment than could have ever been initially imagined. In short, wondrous results emerge from the simulation: this is emergence in the context of artificial life. Simple predictions can be made early on, but as this chapter will explore, the intellectual pursuit of design by humans is limited to our implicit and even time-rigor strengthened explicit knowledge of the design process. Even human experts of particular forms of design (such as the artificial life hobbyist) cannot know or comprehend the full complexity of systems that exist on the barrier of simple language. The artificial life simulation has a property of emergence. This appears through the bridge between open and causal design.

## 5. Enter the Virtual Ape

The author's own particular experience relates to developing the Noble Ape artificial life simulation. Noble Ape simulates a rich biological environment with a randomized landscape (completely new on each run, if required) including weather systems and the apelike creatures that live in the environment. Recently, the simulation had the addition of social graphs to explain the relationship between the simulated apes over time and through many generations. Noble Ape is used by a number of companies and researchers (both academic and independent) in a variety of ways (Barbalet, 2010) including educational research, processor optimization, operating system optimization, and creating simulation/human metrics for analyzing data traffic and disaster prevention.

This approach to extended software development yields many interesting properties and also pushes the boundaries of some of the definitions of design. The artificial life hobbyist, working on a specific project for more than a decade, can design many aspects of the software with methods described in the definitions of design. In fact, an artificial life simulation project may be a very useful example of design for a number of reasons.

It may seem rather grandiose to compare any aspect of creating an artificial life computer simulation with the human-perceived role of physics in the natural world. This would seem to be a two-step-removed problem or a double-interpretation problem, since the creation of an artificial life computer simulation has no direct connection to the natural world or even a meaningful connection between the interplay of physical interpretations of the natural world.

For this reason, the process of creating these simulations will be discussed in the context of design rather than in the linked connections between simulations and what they attempt to simulate. The maturity of the field of artificial life to address the broad scope of these design questions has rarely been surveyed. The account offered here is with a granular level of detail relating to a specific artificial life application. There are shared elements through this and divergent elements with other artificial life simulations. There may be better and more diverse artificial life simulations with which to do this level of analysis. The author is limited in intimacy with Noble Ape specifically. This chapter should be a call to other artificial life simulation authors to explore how their own simulations elucidate the concept of design.

## 6. Simulated Specifics

Noble Ape has many simulations that run independently with shared interfaces. Each of these simulations has completely different internal properties and design properties. The term interface is used to describe either a way to get information from a simulation or a means to change information within a simulation. Each simulation layer can be thought of as an independent or autonomous program. The development of Noble Ape is continuous. Two of the simulations discussed here are in development (one approaching maturity and one in early development):

- Land simulation
- Weather simulation (with interface to Land)
- Biological simulation (with interface to Weather and Land)
- Cognitive simulation (with interface to Being)

- Being simulation (with interface to Cognitive, Land, Weather, and Biological)
- Social simulation (with interface to Being)
- Language simulation (with interface to Being, Social, and Cognitive)

It is possible that there will be more simulations that are either added as layers on top of these first simulations or could absorb them. The modular nature of these simulation components can be underscored by the addition of ApeScript to Noble Ape. ApeScript allows explicit scripting of both the Cognitive and the Being simulations. To clarify the naming convention, the Being simulation governs the agent movement and interaction with the simulation environment. The Cognitive simulation nominally makes the agents in the simulation more intelligent. However, the addition of greater hierarchical simulation layers (such as the Social simulation) adds properties of intelligence that may not require a Cognitive simulation in the future. The idea that society minimizes the meaningful necessity of intelligence is worth noting.

## 6.1. LAND SIMULATION

Land simulation provides both the geographical formations of the Noble Ape landscape and also historically (and curiously) the advancement of time. It could be perfectly feasible for this to be abstracted further, but the description of land includes planetary formations and could easily be redefined as physical properties of the environment. The Noble Ape landscape is generated through fractal maps with 45° rotations to avoid squarish surfaces. The landscape is roughly half water. Most of this water is simulated as salt water, but there is also fresh water. It should be noted that the Land simulation does not require a hard landscape. It also includes tidal information. In the future, the Weather simulation may also be fully embodied in the Land simulation.

The ability for the Noble Apes to deform or shape the land has not yet been fully exploited, though it is intended that later versions of the landscape simulation will also allow Noble Apes to create built-up bays and artificially constructed flatlands. In terms of the design considerations, the Land simulation (aside from the advancement of time) was designed to be visually interesting and to recreate landforms that appeared natural to the user. In terms of design, the Land simulation is a good example of macro-open. It is centralized and not designed to be particularly dynamic, since it forms the metaphorical (and simulated physical) bedrock of the other simulations.

## 6.2. WEATHER SIMULATION

This simulation constructs weather patterns through simulating the movement of pressurized water-laden air over the landscape and waterways of the simulated landscape. The Weather simulation exists as a pure planar equation space that is analogous to classical electrostatics equations. The underlying equations explain natural phenomena that the simulation tries to recreate and describes the traversing of water-laden air currents with a hard ceiling.

The design motivations should be thought of as micro-implicit, rather than micro-causal, due to the hard constants that have been used in creating the slip coefficients and other numerically descriptive components (Barbalet, 2010). This is an interesting boundary between the observations of physical properties in the natural world and the observation of these physical properties through numeric representations (fundamentally the distinction between the natural world and physics).

## 6.3. BIOLOGICAL SIMULATION

This simulation is based on operators in quantum mechanics. The landscape is considered the underlying wave function. Operators are applied to give normalized values for *Height, (Surface-)Area, Water, Moving Sunlight, Total Sunlight, and Salt*. From these operators, the population densities of the plants and animals are calculated. Some examples:

$$\text{Bushes} = -\text{Height} + \text{Water} + \text{TotalSunlight} - \text{Salt} \tag{1}$$

$$\text{Grass} = \text{Water} + \text{TotalSunlight} - \text{Salt} \tag{2}$$

$$\text{Insects} = \text{Water} + \text{MovingSunlight} - \text{Salt} \tag{3}$$

$$\text{Parrots} = \text{Water} + \text{TotalSunlight} + \text{MovingSunlight} - \text{Salt} \tag{4}$$

The operators are added and subtracted produce population densities over the entire surface of the simulation. Moving Sunlight and Salt are time-evolving properties as the sun moves and the tide over time changes the regional salt content of the simulation. Unlike the Weather simulation's basis in spatial mathematics, the Biological simulation was created to model a stable ecosystem that appeared in biological order for the Noble Apes to wonder among and occasionally graze upon. In short, it is a trick of the simulation properties rather than any attempt to model true biological science. In this regard, it pushes the definitional boundaries of macro-open. Other Biological simulations could be used. The UK researcher Bob Mottram has used a cell population growth model to describe the plant and ape-grazing interactions with mixed success (Barbalet, 2010).

## 6.4. COGNITIVE SIMULATION

This was developed from the information-transfer properties observed in a simulated petri dish (Barbalet, 2008). From this initial observation, two competing mathematical effects were observed. They were summarized as two observable, quantifiable attributes of fear (represented by fast reactions in response to unusual stimulus) and desire (representing the long-term planning toward particular goals, maintaining a coherent view of the environment). These two named functional effects were represented through time-evolution response (in the case of fear) and spatial-evolution response (in the case of desire). The Cognitive simulation allows for cognitive activity through both awake and asleep states.

The Cognitive simulation is analogous to the Weather simulation as both simulations use time-evolving multidimensional mathematics and cell grids to calculate the values for each point over time. As an aside, the ability to combine elements of the Weather simulation and the Cognitive simulation, in particular their processing primitives, has been an ongoing aim (Barbalet, 2010). In terms of design, this implementation is intentionally micro-implicit with aspirations to be causal. The only meaningful connection with implicit design is the derivation of distinct numerical representations of the effects of fear and desire through the sleeping and awake ape (Barbalet, 2008), which could be removed in future versions of the simulation or hybridized through the evolutionary components of the Being simulation to remove any tainting of human hand and return these values as evolutionary.

## 6.5. BEING SIMULATION

This is the intelligent agent simulation core of Noble Ape, which currently handles all the biological components of the Noble Apes, including vision, basic social structure, social interaction, genetics, birth, reproduction, and death. With the Social and Language simulations, the Being simulation provides an interface for life events to these simulations. As with most intelligent agent simulations, the Being simulation in Noble Ape is micro-open. Rather than any central control, the Being simulation is effectively a swarm simulation: highly decentralized.

## 6.6. SOCIAL SIMULATION

This simulation is one of the two newest simulation additions to Noble Ape, developed for focused experimentation by Bob Mottram (Barbalet, 2010).

The Social simulation is loosely based on social network graphs popularized by social media websites like Facebook and Twitter. These graphs track the developing relationships between apes and offer a visual account of another level of the simulation: how the apes interact and develop social bonds over time. The social graph of the ape relationships continue on after the apes die. This creates a myth and legend element to the continued oral history of the apes as each new generation is provided with a selective compression of the social graph that has gone before them. The Social simulation is a macro-open designed simulation. The social structure of the Noble Ape society is atomically defined, and the creation of social graphs with the apes placed within the social trees is governed by a central control structure.

### 6.7. LANGUAGE SIMULATION

This newest component to Noble Ape frames the question:

If the apes could convey their inner thoughts, what would they say?

As with the Social simulation, the Language simulation provides another means for the rich interactions in Noble Ape to be tracked and recorded. The current Noble Ape is graphically overloaded, making it difficult to convey even a small fraction of what is going on (Barbalet, 2010). Also as the graphics of Noble Ape evolve in real time, it is difficult to track even what has occurred a few seconds prior. The addition of language and a narrative that can be given to any of the apes means that even minor interactions and incidents for a specific ape can yield some information added to that ape's narrative. The Language simulation provides a substantial account of the day-to-day simulated lives of the Noble Apes.

The Language simulation is by definition a macro-open designed simulation. The language components are atomic, but their joining for complex and understandable language is done through a delegation hierarchy controlled individually by a central organizing structure.

## 7. Metrics of Complexity and Understanding

In software terms, Noble Ape is not particularly complicated. It has been developed since 1996 with a number of iterations adding functionality and also simplifying the underlying code for readability and reusability (Barbalet, 2004). These modifications also tend to distinguish between open source software and closed source software, since open source software requires a certain element of artistic style in the source code as well as the overall design of the software.

In classical software terms, Noble Ape has roughly 10,000 lines of code. This is not a measure of the complexity of the underlying concepts but more the complexity of the implementation. There is no meaningful relationship between the size of a piece of software and the complexity of the software's output.

The purpose of describing the Noble Ape development is in large part to show the multitude of design principles embedded in a relatively simple piece of software. The complexity of Noble Ape versus the construction of a car or a computer or a house is relatively small and trivial, and yet many underlying design principles are used. It would be impossible to create Noble Ape through closed design alone.

## 8. The Paradoxes of Macro-closed Design

This chapter began by defining a variety of different methods of design, including the curious conjunction in macro-closed design where design governed in a top-down fashion, and every aspect of the design process is achieved and planned as if all conditions associated were known. In the context of the modern framing of intelligent design as a Creationist description of the natural world, everything must also be macro-closed designed. This method is unachievable by humans in all but the most basic cases because a single human cannot understand every aspect of the creation of something as a closed object aside from very simple things. Creation through a macro process requires the primary creator to have a full knowledge of every aspect of the design process.

There is a strong argument that such redundancy alone should be a point for concern. The power of both true delegation (which allows for macro-open design) or for micro-open design to produce the same created entity begs the question that an intelligent designer would be intelligent enough to delegate if the end product were identical.

Aside from this, let us consider that there is something other than a human (perhaps a machine) capable of macro-closed design. This highlights an internal paradox. Any machine that delegated through the process would also be part of this process and, so in essence, would be without true delegates and so should more accurately be a case of single micro-closed design.

## 9. Origin of Design

Although it may appear that a logical trajectory has been drawn leading from closed to causal design, in fact the reverse is true. Design in its most natural form starts as causal design, which is obvious from definition alone. As designers come to exist, and the domains they exist in become more complicated, they move from implicit to open and then closed design. Somewhat counterintuitive to the lofty ideals of humanity, the things that are created tend to get less complicated the closer the design is to closed. The benefit of decentralized design is that the created entities can have a complexity vastly greater than centralized design. Nature abounds with micro-causal designed entities and slowly, through the creations of living creatures, approaches toward hierarchical macro design. The pinnacle of this possibility comes through perhaps only a single example of macro-closed design: the master and apprentice working on something relatively simple enough to be truly closed.

Put simply, the origin of design is micro-causal design, and from that definitional point, all other designs evolve.

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Biodata of **Michael D. Miran, Esta Miran**, and **Nicole Chen**, authors of "***Design of Living Systems in the Information Age: Brain, Creativity, and the Environment***."

**Professor Michael D. Miran Ph.D. Psychologist P.C.** is currently an adjunct professor in the Department of Psychology at Rochester Institute of Technology. He obtained his Ph.D. from Rutgers University in Clinical Psychology 1975. Professor Miran's scientific interests are in the areas of models of brain function and dysfunction, information processing at peak functioning in creativity, effective treatment of cognitive dysfunctions in schizophrenia and other mental illness, general clinical services treating anxiety, depression, and problems in everyday living.

E-mail: **mdmgsh@rit.edu; mmiran@mirantherapy.com**

**Dr. Esta Miran** is currently the director of program development for Michael Miran P.C. She obtained her Ed.D. from the Teachers College, Columbia in Art and Education in 1982. Dr. Esta Miran's scientific interests are in the areas of enhancing creativity and higher order thinking and designing manuals to improve cognitive functioning for individuals with a brain deficit.

E-mail: **emiran@mirantherapy.com**

**Nicole Chen** is currently a Masters of Fine Arts candidate in Industrial Design at Rochester Institute of Technology. She obtained her B.A. in Studio Arts from the University of Hawaii, Manoa, in 2008. Nicole's interests are in the areas of design systems and creativity in real world applications.

E-mail: **colilouisa@gmail.com**

**Michael D. Miran**

**Esta Miran**

**Nicole Chen**

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# DESIGN OF LIVING SYSTEMS IN THE INFORMATION AGE: BRAIN, CREATIVITY, AND THE ENVIRONMENT

**MICHAEL D. MIRAN[1], ESTA MIRAN[2],**
**AND NICOLE CHEN[3]**
*[1]Department of Psychology, Rochester Institute of Technology,*
*One Lomb Memorial Drive, Rochester, NY 14623-5603, USA*
*[2] Director of Program Development for Michael D. Miran,*
*272 Sylvan Rd., Rochester, NY 14618, USA*
*[3]Industrial Design Department, Rochester Institute of Technology,*
*One Lomb Memorial Drive, Rochester, NY 14623-5603, USA*

## 1. Introduction

"In the beginning God created Heaven and Earth. The Earth was without form and empty, with darkness on the face of the depths, but God's spirit moved on the water's surface. God said, There shall be light, and light came into existence" (Kaplan, 1981). This biblical description is relevant to this discussion in three significant ways: (1) The state prior to creation is defined in the Hebrew as Tohu, i.e., the primordial unrectified state of creation. This has two meanings, which are a void or emptiness and chaos. Creativity in living systems arises out of nothingness and chaos; (2) we understand the origin of reality and systems in terms of information. The information becomes the operational energy and force leading to creation; and (3) once started, the cycle of information and change becomes self-perpetuating and adaptive.

There are two fundamentally different ways to understand the origin of our universe; the Kabbalist perspective and the perspective of modern science. Relying on meditation, analysis of sacred texts, and their own reasoning and intuition, Kabbalists concluded that the world was a 10–11-dimensional system created during the "big bang." The second understanding is based on scientific method and astrophysical data. Modern physics generated a similar model of the "big bang" and proposed "string theory" based on astrophysical evidence. String theorists proposed a 10- or 11-dimensional universe. Often is the case where significant scientific discovery first emerges from the "mind's eye" and science develops the tools to support the discovery. Both ways of understanding the origin of our universe come to similar conclusions and apply the creative process.

The human creative process facilitates our understanding of the universe and our environments and then transmits our understanding to other communities and future generations. This interaction between man and environment is the evolutionary adaptive process that can be described as the collective knowledge of communities. The salient process is that evolution can be viewed as people progressively mastering their environment and adapting to their ecological niche. This process is associated with creative problem-solving.

Creativity can be considered the preeminent and prototypical evolutionary advantage. Creative thinking, the ability to design systems, and the extension of our abilities through tools and technology have given human beings an amazing evolutionary advantage. Our tools and technology have shaped our adaptation and survival, yet this process is not finished by any means. We are in the midst of a period of extraordinarily rapid evolutionary change. As recently discussed in the NOVA program "Becoming Human", rapid environmental and climate change pushes innovation which coevolves with change in brain size and increased frontal lobe development (White, 2011). The main point is that our enhanced use of language, narrative, toolmaking, bipedalism, opposable thumbs, fire, and cooking all helped us survive and acquire the ability to face challenges and creatively solve problems.

We are beginning to use information technology to track changes in brain function and problem-solving strategies. This chapter sheds light both on the neuroscience of brain function during the creative process and the methods for designing systems that provide solutions to practical problems.

## 2. Ecology of the Brain

### 2.1. HOW NEUROSCIENCE HELPS US UNDERSTAND BRAIN FUNCTION AND CREATIVITY

The brain is a living system in which information processing can be understood in terms of neuroscientific paradigms. The former dominant paradigm of right brain/left brain localized functioning considers that the right hemisphere is specialized for holistic spatial information processing and is the locus of the creative process. This approach to brain function focuses on discrete and measurable localization of brain function associated with specific sites in the brain, such as visual functions and the occipital cortex. Localization tries to make a connection between a distinct event and an associated change in an identified area of the brain. Current evidence shows some basis for localized functioning, but the localized brain function paradigm is not sufficient to account for new evidence in neuroscience that supports plasticity and whole brain functioning.

The emerging paradigm proposes that the whole brain works during the thinking process with some localized areas more active than others. The emerging paradigm is consistent with current theories of brain function, which are actively embracing brain plasticity and the action of multiple areas of the brain in terms of internal information exchanges interacting with environmental events. The brain is constantly changing as the brain is reaching new homeostasis with higher levels of "knowing."

#### *2.1.1. String Theory and Flow of Information in the Brain*

The complex flow of information in multiple areas of the brain in interaction with the environment can best be understood using a new theoretical framework.

The theoretical framework applies a concept from physics of string theory to brain function. This section presents a string theory model of information flow in the brain, which provides a method for describing complex interacting information processing systems.

String theory in physics describes particles as a one-dimensional string of energy, which can interact or be modified by other forces. Our adaptation of string theory to brain function considers that electrical and biochemical strings of information are constantly moving through the brain. These strings interact with and are modified by sensory motor events. The information is transmitted, modified, or maintained, a process which builds algorithms. In terms of brain/behavior relationships, algorithms are nested behavior, which step by step progressively increase in complexity.

A string theory model liberates us from the need to connect a specific stimulus from the environment with the firing of specific neurons in a localized area. Information and realities are constructed as a product of a continuously flowing series of events interacting with multiple neural systems. Hebb (1949) proposes that cell assemblies are activated when a series of neurons form loops and one neuron impacts the next neuron in the loop. We can look at complex phenomena as multiple interacting systems exchanging information and ultimately resulting in a response.

Information can be defined as the exchange of matter or energy from one system across a boundary to another system leading to a response in the second system. Digital definitions of information flow are associated with a computer analysis and tend to think of information as static bits that are either a "1 or 0." Analogue definitions of information flow are associated with slight variance in the composition of information. String theory is a multidimensional model of information flow which allows for simultaneous strings of information to interact in the brain. This processing can be both digital and analogue depending on the systems and networks which are activated or inhibited. Information is a dynamic and fluid phenomenon which permits the multiple constructions of realities. The comparisons of these realities lead to creativity and innovation.

### *2.1.2. Brain Function and Creativity*

This whole brain homeostatic process involves the front, back, cortical, and subcortical areas of the brain. Events in the environment interact with the brain and nervous system using a string of biochemical and electrically transformed symbols. The multiple areas of the brain include large brain systems on a continuum to small brain systems, old brain systems, and new brain systems, as well as nested brain systems. Strings of information travel through the brain, impacting the existing systems and creating an unstable state. The networks in the brain then use inhibition and excitation to create a new homeostasis. The creative subprocesses are made possible by these natural phenomena of generating gradual change in brain function and structures. Brain function proceeds through the chemical and electrical transmitters at the synapses that are either excitatory or inhibitory, and structure is the building of dendritic trees and other neural connection that organize information.

The units of information that the brain operates on are sensory motor events, which are the organizing data for constructing "reality." Reality is constructed in the brain at multiple levels of brain systems such as right and left, frontal, temporal, cerebellum, limbic, and amygdala systems. The information flow of continuous events interacts with multiple neural systems to create new realities. Sensory motor functioning is associated with internal processing of information. Parallel to and overlapping with our perception and representation of the external world, there are internal representations of symbols and events or what is called the "mind's eye." The "mind's eye" is the ability to conceive images, anticipate logical sequences, and generate novel outcomes. These are subprocesses of creativity.

The "Ah Ha" is an emotional experience. It is our ability to evaluate our own ideas and products using subcortical areas of the brain associated with novelty and recognition of emotional stimuli. Our new idea and product becomes connected with a sense of newness, positive arousal, and excitement.

We can systematically examine the processes and subprocesses in the brain. The next step is developing and applying the new technology to explore the creative process.

## 2.2. TECHNOLOGIES FOR STUDYING THE BRAIN AND CREATIVITY

New technology permits observing streams of information moving through the brain. Current technology for identifying neural networks has progressed enormously through fMRI, PET scans, and other advanced technologies. The current technology permits sophisticated imaging of glucose and oxygen metabolism down to the smallest level of a single neuron, or networks of neurons, in multiple areas of the brain.

Previously single neuron activity was measured by recording activity during brain surgery or through implanted electrodes. The crucial issue is that these are invasive procedures with their associated risks. Currently, explorations are using fMRI to measure oxygen metabolism in progressively smaller units of neural structures and activity. New technologies are helping us see deeper and smaller neural structures and functions in finer detail.

These technologies include infrared wavelengths and transcranial magnetic devices during fMRI imaging. EEG mapping of the brain measures relative activity and coherence. FMRI and EEG are limited in the number of data points that can be recorded and analyzed. The limits are how small and deep a structure that can be imaged. The more recording sites increase the accuracy and generate better brain models. What is needed is imaging technologies that permit visualizing deeper and smaller structures in the brain.

What we would recommend as the next step is to develop nanotechnology with multiple wavelengths of energy and a great many contact points. These technologies are in an early stage of development and will be able to focus on specific areas of the brain, as well as whole brain functioning. These methods are being developed to be able to record events, transform these events mathematically, and create an image of the full complexity of multiple systems and networks as they function simultaneously. Another use of these imaging technologies could be to treat brain dysfunctions by measuring brain activity during cognitive tasks. These measurements over time can track improvement in brain functioning.

There are similarities and differences in processing information between people. Many broad categories of people such as men and women seem to have somewhat different patterns of brain function and neural organization. However, these differences need to be qualified by two important limitations. First, all human beings have the same general layout of the brain and its neuroanatomy. This fundamental plan provides for the same general distribution of functions and organization for all people. In contrast, every human brain is unique and has a unique genetic and developmental composition. This means that no two living brains, even those of identical twins, are the same. Hence, the path to creativity and higher-order thinking varies from individual to individual. The similarities are the broad template of neuroanatomy, and the differences are subtle biochemical and electrical processing of information.

Our new technologies are shaping how our brains work; our brains are extending our technologies on an extremely rapid basis to create new environments that influence our creative thinking. Information is shared between researchers almost immediately. Researchers and theoreticians can communicate what they are thinking today. Previously, the field of study would have to wait until information could be disseminated. Currently, anyone can post on a blog. Research is published in books and on the Internet simultaneously. Keywords are searched and the relevant and significant information appears on the computer screen. This body of facts, speculations, and theorizing provides the basis for selecting relevant information to hypothesize. Current methods of communicating information advance vast and indefinite areas of study. Concepts and theories can become viral and move fast and furious throughout the world.

Our ability to create is exponentially increasing. The products of our creativity grow at a constantly multiplying rate that is being shared worldwide through the Internet.

## 3. Ecology of Creativity

### 3.1. QUEST FOR CREATIVITY AND HIGH-ORDER THINKING

What do the following people have in common: Einstein, a criminal, the international businessman, the housecleaner, a college student, and a scientific research team? As well as many others, these people want to be able to achieve their goals, which require solving problems and gaining the best advantage in the situation.

People use ingenuity to generate original solutions to problems. They have the capacity to imagine and dream in the abstract mode. The previous section discussed the brain and how individuals process information to generate innovation. This section of the chapter will aid readers in achieving a deeper understanding of the creative process and guide the reader on their own journey toward enhancing brain functioning. The quest is to have the brain work at its most efficient.

Creativity is associated with intense attention to external stimuli and internal representation of symbols. The process of creating is using extreme concentration from multiple areas of the brain and information from external events in the environment. During a period of incubation, symbols are recalled and reconstructed, leading to innovative outcomes. There is a connection between free association, memory, emotion, and the creative process.

Each person collects as much information as possible and then applies logical reasoning to solve their problem. There is a great sense of accomplishment from achieving a realistically challenging goal. During the logical reasoning process, the person is imagining possible outcomes and then uses strategic trial and error. Parallel to the logical reasoning process, there is an emotional processing of the information. This involves a more intuitive experiential and feeling approach to solving the problem. The journey through the problem to the solution can be associated with the journey through life. This journey is a creative process.

Papanek (1971) provides a design philosophy and practical guidance for solutions to current design problems. A critical issue in design in living systems is to be able to identify patterns. Andrew Herbert's (2008) work on visual pattern identification is an example of creative problem-solving and brain functioning, such as attention and logical reasoning.

In terms of creativity, there is the internal brain processing in conjunction with feedback from events in the external environment. This is an interaction which is ultimately a feedback loop. Individuals assimilate available information from the environment, transform the information, and produce something to a degree that is new. The product of this process is measured against the goal of achieving what is needed.

During the transformation process, many things are happening that can interfere with the productive work leading to a solution to the problem. At times, it is a struggle for creative people to go forward, and they may need a longer time to incubate the creative solution. Other times, there is a fear of failure that infers with solving the problem (McClelland, 1961).

The intent to create is a strongly human quality and provides a biological advantage. It includes insight and commitment, then culminating in satisfaction. It is a reciprocal interchange and interaction. It is a homeostatic process with feedback loops. The introduction of new information impacts the homeostatic process and creates a state of imbalance. The state of imbalance is resolved by creating a new homeostasis. This new homeostasis or balance brings the level of "knowing" and "awareness" to a higher level and improved problem-solving. It is a powerful and accurate metaphor to see the whole evolutionary process from the beginning of human evolution as an increase in knowledge and information structures, leading to creative transformations and problem-solving.

People create and access their higher-order thinking because it expands their grasp of reality, which leads to better control over their environment. It is adaptable and it feels good, as well as getting the person's needs and wishes met. In terms of personal fulfillment, creative experiences and higher-order thinking are gratifying.

Creativity and higher-order thinking are the processes by which new patterns of design emerge to solve problems and improve the world. Human beings have been able to propel creativity and higher-order thinking to new levels and have changed or transformed the world into a better place. This can be seen in things ranging from developments in food distribution networks that can increase world food supply to small improvements such as farming better salad greens or walking through a maze.

## 3.2. EVALUATING CREATIVITY, HIGHER-ORDER THINKING, AND CULTURAL SYMBOLS

### *3.2.1. Measuring Creativity*

Traditionally creativity has been measured on linear scales with statistics. Previous studies of creativity have examined intellectual abilities, creative output, and personality traits. Core to this method of measuring is the concept that there was an innate fundamental human process identified as "creativity," that it progressed in increments which could be measured on a linear scale, and that creativity could be produced on demand. Unfortunately, this is not the case. Creativity testing has failed to produce both validity and reliability which are fundamental to statistical measurement. Tests and measurements are not good ways to predict creativity.

Frank Barron's study of creativity sheds light on the whole field of tests and measurements. One of the most prominent creativity researchers, Frank Barron, is highly respected in the field and sums up the problems with tests and measurements. He did the definitive study on creativity in architects. In the 1970s, he went back to his original data, which was collected in the 1940s and 1950s. At the American Psychological Conference (1970), Barron reported that the major predictor of creativity, i.e., success as an architect, was inherited wealth. Architects who produced the most innovative work were those who could support their projects independently until they became famous. Other less-fortunate architects had to earn a living and spent their time designing less grand projects.

Test and measurement of creativity is being succeeded by and replaced with the study of the transformation of symbols which is the flow of electrical and biochemical strings as transmitted and/or maintained information in the brain. The salient characteristics of how symbols are transformed delineate the creative process. Thinking is the reciprocal action between events in the community in interaction with the flow of transformed symbols in the brain.

### *3.2.2. The Transformation of Symbols*

Communities function as collectors, categorizers, and keepers of human symbol systems. Humans have unique brain systems that interact with the symbolic design systems creating variations of those symbolic design systems. Individuals transform symbols and evolve symbolic design systems to express innovations and solutions to problems.

Creativity is an evolving process between the individual and the culture symbols. Individuals assemble categories of symbols, transform these symbols, and produce innovation. Here we are looking for the unusual. There are some people who will take the same information and combine the facts in such a way as to arrive at an innovative solution to a problem. The individual's brain in interaction with events in the environment produces feedback loops that can generate new configurations of ideas and symbols. The process of thought and the product of thought are constantly in interaction, leading to a progression of the creative products over time.

Anthropologist Margaret Mead (1976) discussed her work with people in "Stone Age" cultures in the early 1900s. She went on to describe that the grandchildren of these "Stone Age" cultures were attending Cornell University, one of the most prominent universities in the country. She discussed the question of intelligence and capability of "Stone Age people." "Stone Age people" in two generations were able to achieve at a high level of current intellectual and creative abilities in the modern world. These people were supplied new information systems and encouraged to apply creative and higher-order thinking. Here lies the key to the question of can you or anyone improve their cognitive and creative abilities. The answer is a resounding yes!

In this chapter, the study of creativity and higher-order thinking moves the field away from the idea that there are some individuals who are more creative and that these creative individuals can be identified through tests. Rather some people immerse themselves into complicated interactive information systems and challenge the construct of these information design systems, accessing their higher-order thinking. These individuals are driven with an obsession to solve an identified problem. Each individual has their own unique multilevel information storage base, skill, and mental proficiency to recall symbolic code and use that information. Developing innovative conceptual schema and, eventually, new realities can be understood in terms of transforming symbols both as identic and metamorphic.

### *3.2.3. Identic Transformation*

Identic transformation is taking information in its isomorphic form to develop conceptual schema. Individuals and communities develop algorithms to create consensual knowledge, such as the spelling of a word. Identic transformations are the building of sequential hierarchies of information, generating a progression of shared knowledge.

The purpose of identic transformation is to gather information and to store it as discrete events in multiple areas of the brain. Information is golden. You are looking for gold, and you must look long, deep, and hard because the easy gold has been taken. You want the nugget of information that will shine and enrich the creative product. Acquiring the most current information is a necessary subprocess in creativity and higher-order thinking.

### *3.2.4. Metamorphic Transformation*

Metamorphic transformation combines elements from multiple data bases with new information to construct innovative conceptual schema, new realities, and better solutions to problems. New structural systems replace old information structures with a "higher degree of knowing." Metamorphic transformation uses existing data bases to generate creative solutions.

There is a feedback loop while transforming symbols. New information clashes with existing information, leading to a new understanding of the problem. With a new and clearer understanding of the problem, more information can be gathered and the cycle continues. The process of gathering information and innovating is an interaction between free association and cold logic. These theoretical paradigms provide a deeper understanding of design and the creative process. Using the theoretical paradigms, this chapter suggests concrete strategies for enhancing subprocesses in creativity and higher-order thinking.

## 3.3. HOW TO TEACH PEOPLE TO BE CREATIVE

The creative process involves restructuring patterns of behavior, content images, logic, and value judgments. The compelling objective is how to become more creative and how to stimulate the brain, thereby achieving higher-order thinking. Where do we begin on this quest of pushing the edge of the envelope? Where is the "magic wand" that will make people be better problem solvers?

It is part of the human condition to want a quick easy fix. There are books on the market, Web sites, and computer software that offer the development of creativity in the equivalent of "five easy steps." Some of these products are games that are fun and engaging and may activate specific areas of the brain.

Unfortunately, the problem is that these products do not generalize to necessary changes in the brain that lead to logical and abstract thinking. There is no core "creativity" to measure, and these products have not produced data that they enhance thinking. Some products claim certain brain areas are activated, but the actual stimuli presented are simply auditory and visual discrimination tasks, which have not been directly validated by research showing that they change the functioning of specific brain areas. What is validated is that there is a large market and these products are often very profitable.

The stakes are high for being creativity. People become economic powerhouses of the current millennia when they generate creative concepts and translate them effectively into competitive products. "Winning" in the global markets demands a high rate of idea generation, the ability to overcome obstacles, and the skill set to translate those ideas into marketable products that solve real-world problems.

There are as many strategies to gathering information and solving problems as there are people on this earth. While there is a broad template as to how the brain works, each individual brain is unique to some degree. In the near future, we will have a better understanding of the exact track that information takes through the brain as this information is transformed and translated into a product. For now, we must be satisfied with each person developing a behavioral understanding of how they are most productive. Each person has a style of creativity using tools and strategies. If you want to increase your creative output and enhance your higher-order thinking, then you might want to map out how you have done this in the past. This should give you some strategies that you can become consciously aware of so that you can use them in the future.

Arasteh and Arasteh (1976) states, "While writing Schiller kept his feet on ice in order to diminish the circulation of blood and thereby increase it in his head." Blood flow, as well as electrical and chemical activity in the brain, is the new method of tracking areas of the brain that are activated and inhibited during the creative process. Blood flow increases oxygen and glucose to the brain.

Let us look at strategies to confront problems and improve creativity and higher-order thinking, hence solve problems:

- You might try immersing your feet in cold water. The pros are that it has been tried by a very successful writer. The cons are that it is not so appealing or comfortable to have freezing feet. In fact, it does not seem very appealing at all. An alternative method for enhancing blood flow to the brain is exercise. Exercise offers another advantage. While you are exercising, you are thinking. This can be a time when new ideas come together to solve problems. Some people prefer to think about the problem while they are exercising. Others prefer to let their brains solve the problem on "autopilot," and these people exercise and keep their minds blank. What is best is to try the two different exercising strategies, and then select the strategy that works for you; or alternate thinking about the problem or keeping your mind blank. Exercise your body. Get the blood flowing and the endorphins vitalizing your mind and energizing your body. Enjoy the feeling.
- Rest is a great help and healing for your body and mind. Sleep, take a walk in the woods, watch TV, play a video game, read a book, meditate, or do whatever facilitates rest and relaxation. Total relaxation and vigorous exercising might be alternated but kept in balance. Your personal balance between resting and exercising promotes creative thinking leading to solutions to problems. During both resting and exercising, your mind is working. Your mind is making new connections to solve real-world problems.
- Attach yourself to amazing people. These people should be from varying fields. They should know things that you do not know. You will be getting the best information from the best brain power. You can feed off their understanding

of the complexity of the problem, or for that matter, the simplicity of the problem. Sometimes others become tangential and muddy the waters, confuse you. There may be too much stimulation. There is the possibility that you might get confused and distracted from your goal. You might feel more comfortable and think more clearly when you are working alone. The best solution is to reach out to others and gain the benefit of what they have to offer and then work independently. When you get stuck, go back to these amazing people for further stimulation and new ideas. Only you know how to balance engaging with brilliant people, with reducing the stimulation from others by turning to your own internal processes.

- Some people are able to rapidly scan and retrain facts but have limited abilities to recombine the facts into novel ideas. Other people are slow at learning facts but are able to recombine facts to generate creative solutions. The best approach is to know your strengths and find others to work with who compliment your strengths. If you are a fact cruncher, then find a creative thinker to partner with. If you think creatively, find someone who can help you focus and avoid getting lost in tangential thinking.
- Immerse yourself in the information. At this point, do not try to judge. Use the most current information as possible. Put your full attention into the task. Take a break, relax, or exercise. During the break, let your mind work out the problems. Alternate between working intently and resting the brain. This strategy facilitates the brain working at it most effectiveness to produce creative solutions to problems. Let your brain incubate.
- Exercise your "mind's eye." Brain imaging has demonstrated that during Tai Qui, the person can be either doing the movements or simply imagining doing the movements and the same areas of the brain are being activated (Miran and Miran, 2000, 2011). Imagining is a powerful tool for higher-order thinking. Imagining can include meditating. While meditating, you are resting your brain. A practical method for creative problem-solving is to train yourself to meditate or visualize.
- If you become anxious and fearful that you will not succeed, then just do the above behaviors. You should immerse yourself in the information, detach from the information and let your brain incubate, exercise and get physically exhausted, rest and relax, and most importantly repeat the behaviors until you achieve your goals.

## 4. Ecology of Design in Living Systems: Macro, Meso, Micro

### 4.1. MACRO, MESO, AND MICRO LEVEL OF PROBLEM-SOLVING

Creative solutions emerge out of ecological dynamic interactions. Systems theory and analysis uses a hierarchical organization from macro- to meso- to micro-systems. A problem can be examined on a macro level, meso level, and micro level using systems analysis.

#### *4.1.1. Macrosystems Are the Big Picture, the World*

Macrosystems are interconnected systems which can be nested that ultimately are the overarching grouping of the largest of systems. The goal is to track the whole large system by collecting as much information as possible. This large systems analysis involves multiple interacting forces. When dealing with a complex system, changes in any one of many forces acting on the system will affect many components of the system. In any macroanalysis, the purpose is to understand how the whole system works. This will be the platform for initiating one change. The change can then be examined throughout the system. A successful strategy is to generate the initial definition of the problem and proposed small intervention with clearly delineated benchmarks. A benchmark for the intervention will provide information as to how the intervention is affecting the system either helping move toward the goal or impeding the goal. A benchmark can provide you with data that indicates if you are on the right track or if you should consider other options.

#### *4.1.2. Mesosystems Are the Settings that Are Both Interconnected and Directly Linked to the Individual*

There are multiple systems that are in some way joined on a broad scale and can be directly impacted by the individual and their community. Decisions and creative problem-solving are the tools for change. The creative individual's first strategy is to state goals and then propose solutions. In stating the goals, the individual should identify benchmarks for determining the progress toward achieving the goals. This is a medium scope problem searching for a creative solution.

#### *4.1.3. The Microsystems Are the Designed System that Is Directly Linked to the Individual*

Individuals will have a direct impact on defining the problem and proposing solutions. This is an extension of the individual's behavior as the individual interacts with the one event.

### 4.2. EXAMPLES OF PROBLEM-SOLVING

In daily life, people are always encountering problems; something is not working as well as possible, not working to maximized gain. There will then be a clash between what is and what needs to be. This clash defines the problem, the need for inquiry, and the search for a solution. Any change at any level of a system has ramifications. There are many obstacles to overcome in an effort to solve problems at all levels. If you make a small change, then other elements of the system change. A useful approach is to define the problem in as much detail as you can. Then consider how you might impact the system. Consider the benchmarks that indicate that you are on the right track to a solution.

This section of the chapter provides examples of the problem-solving process. The first example is a larger-scale problem that teams of researchers may face, which is designing a food chain for Hawaii. The second example is a gardener's efforts to produce salad greens. The final example is a person walking through a maze.

### *4.2.1. Food Distribution in Hawaii Macrosystem*

Hawaii's food system is in turn an ecosystem that has found itself in a challenging and precarious position. Once a self-sufficient island has now become dependent on imported food. There is a lack of accessible and equitable distribution of fresh produce. People living in Hawaii lack awareness about where food comes from. Hawaii is an example of a complex living system that needs to be redesigned to bridge the gap between what people have and what people need in terms of food.

Hawaii's food distribution can be systematically analyzed. On a macrosystem, food can be examined in terms of national and international distribution, analyzed in terms of local food production, and discussed in terms of individual and families access to food.

Hawaii once had about a million residents and a food system that could support the local people. While the population today is at about the same number of people, people no longer work the fields and fish the seas. The interdependency between the island, sea, and people no longer exists.

Previously, the island was broken up into sections called an ahupua`a. This meant each division of land was self-sufficient in terms supplying food to its people. Hawaii once consisted of diverse groups of fishermen, farmers, hunters, and gatherers. Some of the foods that Hawaii is still able to produce are (1) meat such as grass-fed natural beef, lamb, and pork; (2) fruits such as papayas, bananas, strawberries, oranges, lemons, limes, mangoes, avocados, and tropical fruits; (3) vegetables such as lettuces and salad mixes, sprouts, tomatoes, won bok, bok choy, cabbages, eggplants, cucumbers, celery, zucchinis, pumpkins, squashes, green beans, green peppers, green onions, ginger, soy beans, beets, taro, breadfruit, and sweet potatoes; and (4) other foods such as fish, eggs, milk honey, chocolate, goat cheese, coffee, and macadamia nuts.

While not everyone in Hawaii today has the land to farm their own food, there are people who do support local foods and farmers in a limited way. The important problem with Hawaii's food system is that it has become integrated into the United States and global food distribution systems. If Hawaii were unable to import food, the islands would have only a week's worth food to sustain the island's people.

Problems with Hawaii's food distribution are as follows:

- Hawaii is dependent on the international food distribution systems for their basic survival.
- The food is not fresh foods because it is imported, and people are forced to pay higher food costs.

- Owning land and growing food in Hawaii are not cost-effective, and agriculture needs to be subsidized
- Imported foods are recalled as a result of contamination in the current model for food systems.
- Imported produce hurts the structure and competition for the distribution of locally grown foods and the improvement of sustainable practices.
- The food distribution system consists of grocery stores as well as local farmers' markets. These markets are located in areas that a customer must drive to and stand in long lines.
- The fear of having only a week's supply of food on the island is a daunting threat.

Possible solutions:

- The government in Hawaii is trying to solve the limited food supply threat. There are currently 46 farmer's markets that take place on Oahu throughout the week at different times of the day. There is only one cooperative market on Oahu that carries produce from local farmers.
- The government and farmers try to implement a more diversified agriculture, as well as increasing the numbers of farmers.
- The emphasis is being placed on locally grown foods. There are attempts to educate residents as to the benefits of buying local produce. Food would be from the field to the table. Getting fresh local produce is more tasty and healthy.
- Imported food has hidden costs that need to be published so that the residents can understand the cost-effective benefits of local food produce.
- Accessibility to these produce areas can be improved by encouraging more mobile vendors. Mobile food carts have proven to be convenient, efficient, inexpensive, and on-demand.
- Residents could have flexible marketing, so they could choose online or vote what produce they wanted and the farmers would distribute more of that particular fruit or vegetable.
- A farmer's market-on-wheels would be an ideal way to help distribute produce to many urban areas. There could be a system setup, such as an online schedule, so that people could track where the mobile vendor would be throughout the day.

Obstacles:

- Hawaii residents still buy imported foods because it is cheaper than locally grown foods.
- Food would be limited to what farmers could produce at any time. Some residents would find this limiting in terms of their choices.
- Large corporate interests and international agriculture businesses have political and financial influence. These businesses benefit from importing food.

### *4.2.2. Designing a Living System – A Garden – Mesosystem*

A garden is a complex series of interacting living systems that are linked to an individual's plan. A garden can be examined in terms of a mesosystem, with a variety of interconnected systems. When planning the garden, the individual sets goals and defines problems that may occur. The goals are to produce a large and healthy crop of vegetables. The individual can learn from others and experience how to accomplish the goals and deal with the obstacles.

Every year in the eternally joyous expectations of fresh salad greens, zucchini and basil, I plant an organic garden. As I feed the soil, plant seeds, and harvest the vegetables, I am engaged in a process of designing and interacting with living systems. I have benchmarks that provide me with information as to how the garden is producing. I used this information as well as information from experts to overcome obstacles and produce new designs, including the garden plan.

For example, I put down compost and put a layer of potting soil over it. Then I planted rows of lettuce, radicchio, arugula, and radish seeds. In accordance with a biblical law that forbids mixing different types of seeds in the same row as the French do in mesclun (salad mix) planting, I planted each row separately. I had a design plan and visualized the end garden design. I wanted to create rows of harvestable salad greens.

The living system responds and creates a new system. This is the unexpected and must be included in any evaluation of the garden. A strip of radishes and arugula came up. In front of the patch, a small area of lettuce grew (not in the area I had planted). Nothing seemed to grow there. I tried to rake the soil and turn over more seeds to allow them to grow according to my design.

After several weeks, I returned to look at the patch. It was filled with flowering and fruiting tomato plants. My salad green patch was now a tomato patch. I did not plant tomato seeds. The living systems operating on their own genetics, epigenetics, and environmental options had transformed my salad greens patch into a different system with a different design. The tomatoes also had help from heavy rains and squirrels burying walnuts. This example highlights two processes. The first process is the human design process, which we will discuss as creativity. The second process is the discovery of design in nature (Alexenberg, 2008).

I can take my iPhone and via the internet and satellite GPS get a simultaneous online vision of my house and garden. In the information age, my tomato garden can have a Web presence and interconnect with the wider world beyond my garden. The design of a living system can become interactive, widely distributed, and contribute to the experience of people worldwide.

### *4.2.3. Mazes: Microsystem*

Is it possible to design a living system that has as its purpose challenging human creativity and higher-order thinking? People have created mazes, i.e., plantings of walks, hedges, and grasses to create a puzzle for more than 2,000 years. Mazes can be discussed in terms of microsystems. There is a one to one connection with the individual and that individual's creative ability to solve the maze. The use of "state-of-the-art" fMRI techniques now permits us to see that the solution of mazes involves the activation and inhibition of right parietal areas as we think our way through this maze (Gourtzelidis et al., 2005).

The first element is that creating such mazes is an example of design in nature and living systems. The second aspect of mazes is that another person who does not know the solution to the maze walks through the maze. The individual has to figure out the pattern and then find the exit which is the goal. This is a challenge and requires creative thinking on the part of the person trying to solve the maze. It takes the ability to imagine possible outcomes and then through trial and error find the solution.

## 5. Conclusion

Three different perspectives and content areas merge to provide models that can be used to develop designs including living systems. These models are suited to the new environment of the information age. The goal of this chapter is to inform the field regarding the most current findings from neuroscience concerning brain information process and design methods to solving problems in the real world.

Emerging paradigms incorporate new data to present a comprehensive and current understanding of how the brain processes information. New data provides a fuller understanding of the creative process and higher-order thinking. This section will conclude by pointing the direction for future work in this field including new technologies.

What is the vision for the future?

- Scientist, artists, and educators want to be more creative. Previous, quick fixes have not worked. What is the future of training people to be creative?
- It is very demanding and difficult to generate creative solutions to problems. New data from imaging information flow in the brain provides a deeper understanding of how the brain acquires and uses new and old information. How can this new data provide shortcuts to creative problem-solving?
- There is debate and discussion as to whether computers can be creative. If they can, then how do we make computers creative?
- Children are spending more time in front of the computer playing video games and social networking. Are we preparing our children to be successful in the new millennium, or are we rotting their brains?
- Brain/computer interfaces are emerging as the next area of human/technology interaction. How can we have computers read thoughts and perform behaviors based on the direction from a person's brain?
- Can a computer play G-d? How can a computer design a living system?

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Biodata of **Massimo Negrotti**, author of "***Technological Design of Natural Exemplars***."

**Massimo Negrotti** has taught at the Universities of Parma and Genoa and is now full professor of methodology of human sciences at the University of Urbino "Carlo Bo," Italy. His main areas of interest are methodology, cybernetics, and the culture of the artificial. Since 1980, he has carried out theoretical studies on the relationship between culture and information technologies and has conducted surveys on AI specialists in Europe and in the USA. In 1990, he edited the book *Understanding the Artificial. On the future shape of Artificial Intelligence* (Springer), in which he introduced the basis of what was to become the Theory of Naturoids (See *The Theory of the Artificial*, Intellect Books, Exeter, 2002 and *The Reality of the Artificial. Nature Technology and Naturoids*, Springer-Verlag, Heidelberg, 2012 in press). He has given several lectures on this subject in European, American, and Japanese universities.

E-mail: **massimo.negrotti@uniurb.it**

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# TECHNOLOGICAL DESIGN OF NATURAL EXEMPLARS

**MASSIMO NEGROTTI**
*DISC-LCA The Lab for the Culture of the Artificial, University of Urbino "Carlo Bo", Via Saffi, 15 61029 Urbino (PU), Italy*

## 1. Nature and Naturoids[1]

The fundamental presupposition for a theory of naturoids is that it is reasonable to think of technology, and of its underlying theory, as a set comprising two basic classes: conventional technology and naturoid technology. The first of these proposes to design objects, machines, or processes with no intended similarity to anything existing in the natural world. The second, which is perhaps even older than the first, involves the design of technological objects or processes explicitly intended to imitate, or even reproduce, objects or processes observed in nature.

What follows is a brief summary of the main conceptual steps that characterize the design and construction of naturoids, including some simple methodological stages that appear to be inevitable in the ideation process, and which make inevitable, in turn, the final transfiguration of the naturoid with respect to its natural counterpart – a conclusion that will provide new elements for a reflection on what human design implies with respect to the status of things generated in nature.

The reasoning involves the selection of an *observation level*, an *exemplar*, and an *essential performance*, and the theory, which involves nonformalized methodological steps that need to be followed by anybody who intends to design a reproduction of a natural object or event by means of some technology, proceeds roughly as follows.

## 2. The Observation Level

The observation level is to be considered as a profile of a given object or process. The term *observation level* recalls, to some degree, T. Kuhn's thesis concerning the ability of paradigms, during the phase of "normality" of a science, to orient the observer mainly toward that which is consistent with the dominant paradigm. It also has something in common with Husserl's *Abschattung*, and even with Max

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[1] For a more detailed introduction to the theory of naturoids, see (Negrotti, 1999, 2002, 2004, 2005, 2008a, b, 2009, 2012).

Weber's assertion that social science researchers always bring to the foreground those aspects that are worthy of consideration, while simultaneously letting all other aspects drift into the background. Finally, it recalls the concept of the *perspectives* introduced by Charles Morris, or the *reality levels* of Paul Oppenheim e Hilary Putnam (Oppenheim and Putnam, 1958).

If we prefer the term *observation level*, it is because of the selective, and sometimes constructive, character of the observation which characterizes not only scientific exploration but also any sensible interaction we may have with the empirical world, and, subsequently, any description of the observed object. We may describe an object at more than one observation level, but humans are able to adopt only one such level per unit of time. Simultaneity, indeed, would imply an inexpressible holistic synthesis, because every descriptive choice inevitably brings with itself a type of "qualification," revealing, as a consequence, the priority assigned by us to some particular observation level. In this context, the sciences constitute a sort of institutionalization of the observation levels thus far discovered or constructed by scientific research.

The notion of an observation level reminds us, in turn, of the fact that when *homo faber* attempts to design a naturoid, he does not, as a rule, assume any philosophical premise regarding what an observation process is. Rather, he simply resorts to his natural senses and his previously acquired scientific and technological knowledge, in order to decide whether he will be able to reproduce the observed natural exemplar on the basis of a model that reduces its complexity.

On the other hand, whatever sensorial, technological, or cultural background a designer brings with himself, it will tend to condition his observation to privilege a profile, of the selected exemplar, that is consistent with that background. This is, after all, a quite universal constraint for human beings. For instance, in defining a tree as our exemplar, we assign boundaries to it, so that it can be described at a mechanical, chemical, electrical, physiological, or anatomical level, or, more simply, at an aesthetic or sensorial level. According to the chosen boundaries, certain parts or properties of the exemplar will either be included in, or excluded from, the final model we set up.

The complexity-reducing role of observation levels in our interaction with real things is easy to understand by resorting to a simple experiment: ask some people to speak at will about, say, the Sun. Unavoidably, right after the word *Sun* is introduced, the nouns, verbs, and adjectives that accompany it will clearly reveal what sort of observation level our interlocutor has chosen (be it astronomical, physical, chemical, aesthetic, religious, or whatever). As is easily understandable, nobody may properly claim to have a complete and conclusive definition of the Sun – its "ontology" – and this is true for any other empirical object, whose description always feels the effect of the dominating observation level at which is being observed and described.

The same is true of a finished naturoid, be it a painting or sculptural reproduction, a technological reproduction with little or no visual similarity to the natural object (such as an industrial robot or artificial kidneys), or an object characterized by the attempt to mix functionality and aesthetic resemblance (such as the famous fourteenth-century rooster on the clock of Strasbourg Cathedral or the many forms of artificial limb created over the ages). It is important to consider that when both functionality and appearance are pursued, the connection between them is always achieved by means of expedients, or tricks, that have little or no correspondence to the ways nature realizes its instances and the interactions between the various internal parts of such instances.

We could perhaps name this the "Daedalus's glue syndrome." Daedalus and his son, Icarus, so the legend has it, were imprisoned on an island. Daedalus, a skillful craftsman fascinated by the flight of birds, fashioned some birdlike wings with which they could both escape, but having no way to examine and reproduce the fine biological structures of the wings as integrated parts of the body, he recreated them "as he saw them." As a result, he chose a bad way of gluing together his artificial wings – namely, with wax – with the well-known consequence that Icarus (admittedly failing to heed his father's warning) "flew too near to the sun," thus melting the wax and falling to his doom. So, while wax proved suitable as an expedient, it did not possess all of the qualities necessary to match nature's glue, as it were.

## 3. The Exemplar

The *exemplar* is to be understood as the natural object, system, or process that one aims to reproduce (e.g., heart, muscles, intelligence, snow, flavors, and so on). In order to design something meaningful, one must start from some shared, or "objective," *definition* and description of the exemplar. The human propensity to separate things induces us to see the world as a collection of distinct exemplars, but, as a matter of fact, a major constraint consists in the arbitrariness of any given "definition" (in the early Latin sense of "fixing the boundaries"). Therefore, fixing the boundaries of an exemplar – conceptually and, so to speak, anatomically – is a very crucial point. For instance, if an animal lives symbiotically with another, we cannot easily "define" it, just as intelligence cannot easily be separated from other mental faculties, nor an organ from its organism, nor even a pond from its surrounding ground. Activities, too, have boundaries and may thus be defined in this sense. The sciences, for example, are very carefully defined, and the boundary of each scientific discipline, though not formal, is usually strongly defended against intruders from other disciplines and from the generic common-sense environment.

To sum up, exemplars are static or dynamic portions of the empirical reality, more or less accurately conceptualized, which we isolate from their context, giving them a name, and attributing to them some set of features. Even here the designers of naturoids have to make serious decisions that largely depend upon the selected observation level. Furthermore, at a given observation level, every definition of an exemplar – be it topological, anatomical, functional, systemic, or whatever – may cut off structures or relations whose exclusion from the model will not only reduce the power of the naturoid in emulating the exemplar, but very probably, and perhaps more importantly, introduce qualities or behavior in the naturoid that are simply not present in the exemplar itself.

## 4. The Essential Performance

The design of a naturoid always requires that, when passing from a general description to the actual design, one has to indicate concretely what is to be reproduced – it being excluded, as we shall see, that one could reproduce the entire exemplar, even as described at just one observation level. For instance, if a designer says "in this lab we are trying to reproduce a rose," the statement will be too generic to be understood clearly. Actually, what he will try to reproduce will be that performance – i.e., that quality, function, behavior, or appearance – which, at a selected observation level, and on the basis of a clear definition of the exemplar, will appear as *essential* in order to have a "rose." Although here we adopt the adjective "essential" from a pragmatic perspective, we should not forget that the problem of *essentiality* of things, both natural and artificial, has long been, and still is, the subject of much philosophical debate (Elder, 2007). The importance of identifying a performance as *the* essential one is therefore quite apparent in the design of naturoids.

The most open-minded designers have always been explicitly aware of this design constraint. For example, J. de Vaucanson, in the eighteenth century, speaking of the digestion of his artificial duck, defined the essential performance he wanted to reproduce approximately as follows: "I do not claim that this should be perfect digestion, able to generate bloody and nutritional particles in order to allow the survival of the animal. I claim only to imitate the mechanics of this action in three points: in the swallowing of the wheat; in soaking, cooking or dissolving it; in allowing its going out, forcing it to visibly change its stuff" (de Vaucanson, in Losano, 1990).

Even today, this selection process is unavoidable in every project. Thus, for example, we find affirmations such as "In building a silicon retina, our purpose was not to reproduce the human retina to the last detail, but to get a simplified version of it which contains the minimum necessary structure required to accomplish the biological function" (Mahowald and Mead, 1991).

What is essential in an exemplar is always "decided" on the basis of several, often competing, criteria, such as scientific paradigms, cultural models, available technology, practical needs, and even just personal preferences. For instance, an artificial rose might be needed merely for embellishing a house, for teaching botanic anatomy, or as a means for completing some artificial landscape. To the different aims will correspond different selections, and therefore different reproductions, of the performances of the natural rose. The conceptual and real boundaries of the rose and its performances assumed to be essential will, in turn, be described and modeled according to the personal or culturally shared scientific, technical, or aesthetical observation levels to which the designer orients himself.

The history of biology and of medicine has shown continuously changing attributions to the various exemplars drawn from the human body. Humors and organs were once associated with different aspects of human character, mood, and state of health. Only later were organs, along with glands, nerves, blood, and so on, viewed as functionally distinct parts of the body. The discovery of cells changed the picture once more, as did the discoveries of chemical elements and compounds, salts, hormones, vitamins, etc. The shifts in establishing an essential performance depend on several circumstances, and will often be the result of previously unsatisfying attempts. Thus, for example, in the field of thyroid medicine, the problem of identifying the boundary of the exemplar led to initial misunderstandings and a failure to establish the exact functions of the thyroid gland, owing to the inadvertent removal, when performing experimental thyroidectomies, of not only the thyroid but also the parathyroid gland (Hamdy, 2002). Something similar could be said for the functions of the heart and of the blood, from Galen to Harvey, or for the functions of other parts of the body, such as skin or the nervous system, before and after the access to new observation levels rendered possible by such inventions as the microscope and x-ray photography.

## 5. The Inheritance Principle

Reality does not, so to speak, make discounts. By a sort of inexorable “inheritance principle,” the multilevel interactions among the adopted materials, and between the adopted materials and the context in which the naturoid will be placed, will give rise to unplanned performances. The performances and other features of the naturoid are not necessarily less numerous and powerful than those exhibited by the natural exemplar in its own context, but the two sets are not superimposable. In other words, the complexity of a naturoid is not necessarily lower than that of its natural exemplar: it is only different. This inevitable difference should not automatically be regarded as a failure, although unintended interactions may sometimes undermine the intended goal. The reduction of complexity to be found in the model that drives the design consists of a skeleton, as it were, to be filled out by the complexity of the materials and of the interactions which, by inheritance, will come into play.

In fact, something always emerges in any field of interactions, but, even in the area of naturoids, the probability that undesigned “natural” performances will emerge from the complexity of the device appears to be quite negligible.

This is also, as all designers in bioengineering know with regard to side effects and sudden events, a fact that concerns all naturoids: from robotic sensors, actuators, and supervising software, to artificial sweeteners and flavors; from artificial skin, limbs, joints, discs, or kidneys, to artificial grass, snow, flowers, nests, or landscapes; from artificial intelligence programs for translating, summarizing, learning, or recognizing (Teiling, 1988), to artificial hydration, nutrition, and ventilation processes; and from artificial vision, smell, or taste, to artificial climate manipulation or irrigation. A separate chapter might usefully be devoted to the various side effects of artificial pharmacological products. Anyway, the inheritance of materials is a very complex problem that explains why the so-called materials science has become one of the most strategic issues in current research.

## 6. Transfiguration

A naturoid is always ready to present some novelty with respect to its corresponding natural exemplar. That is to say, an unavoidable *transfiguration* occurs when a given essential performance is transferred to the naturoid. In brief, the transfiguration comes from the combined effects of (a) the subsequent selections of an observation level, a definition of the exemplar, and an essential performance; (b) the undesigned and unexpected interactions among the adopted materials, and between the materials and the host environment; and (c) the possible rearrangement of the naturoid's behavior under the pressure of external phenomena. All this can give rise to good or bad novelties but, as a general rule, something unexpected will always occur.

The transfiguration can, in some cases, irreversibly modify the context in which the naturoid operates. If, for example, the joints of an artificial limb induce some physical deformation in the natural physiological parts of the organism to which it is attached, the whole project may be definitively compromised. Much the same thing can happen when the context is simply the natural environment, with which the naturoid may strike up unforeseen interactions – be they mechanical, chemical, biological, ecological, or whatever – which might make further adjustments impossible. In brief, the transfiguration may trigger irrecoverable recursive interaction phenomena.

## 7. Three Agents of Design

With regard to design, we may distinguish three principal agents which, through their autonomous capacity of elaboration, give rise to designs and realizations. These agents are Nature (NA), conventional designers (CDs), and naturoid designers (NDs). By *Nature* we mean the set of microscopic or macroscopic phenomena which together characterize sensible reality, including the human species regarded under a strictly biological profile. Conventional designers, for their part, are to be regarded as human beings observed in the activity of conceiving and designing artifacts or machines, based on available knowledge of the natural world, but not intended to imitate natural objects or phenomena. The aim, rather, is to *produce* things which, while being subject to the natural laws, generate some effects not found in nature.

Naturoid designers, by contrast, are designers who, as we have seen above, attempt to *reproduce* natural objects and phenomena. NDs, in their work, must obviously take account of available scientific knowledge regarding the given natural object or phenomenon in question, but, in trying to reproduce a part of nature – imitating, at various levels, its structure or dynamics, or perhaps both – they seek, in a sense, to enter into a more intimate relationship with nature.

## 8. Natural Design

It should not be forgotten that nature, too, produces and reproduces, although we still have much to learn about its underlying mechanisms. We cannot even be certain whether NA's "designs" are somehow pre-established, or whether, instead, they are essentially the result of random processes. That which is certain, however, is that NA follows precise rules, both at the level of fundamental physical laws and at that of large-scale systemic phenomena. Any natural event, such as a rock falling down the side of a hill, unfolds inexorably, respecting physical norms and constraints as if the whole event were planned by somebody. In fact, gaining an understanding of an event such as this consists in the attempt to perform what Daniel Dennett has called "reverse engineering" (Dennett, 1998), on the supposition that a given phenomenon is decipherable by examining a succession of appropriately describable states correlated according to precise behavioral rules.

Within this framework, intellectual discussions regarding the nature of Nature, as it were, have perhaps not taken sufficient account of the principle of least action proposed in the eighteenth century by Pierre-Louis Moreau de Maupertuis, who, having meticulously calculated the action associated with many types of movement, concluded that NA always chooses the movement that minimizes the total action (Israel, 1997). Whether or not NA is governed by an omnipresent finalism, it invariably demonstrates a high level of efficiency in its dynamics, just as if events were based on optimization calculations, and not just on the physical laws applicable to the circumstances.

The physical laws, which it is science's task to reveal, seem to reflect an intrinsic natural rationality whose universality and persistence suggest, in turn, the potential for complete predictability. It is certain, at least, that a highly accurate knowledge of initial states can often give rise to similarly accurate predictions – as demonstrated in astronomy, for example, which enables predictions of periodic events over hundreds or even thousands of years. At other levels, however, such as the submicroscopic world of quantum physics, descriptions and predictions come face to face with an uncertain foundation of reality, dominated by an apparent randomness intrinsic to matter. Yet even here, beginning with the work of Werner Heisenberg and Erwin Schrödinger, the introduction of probability calculations has allowed scientists to make highly accurate and reliable predictions of submicroscopic events, by incorporating the uncertainty, and its calculation, into a congruent rational vision.

## 9. Conventional or Creative Design

The work of a CD is often called "applied science," precisely because it involves the creation of an artifact through the application (always subject to a greater or lesser degree of error) of scientifically discovered natural laws. CDs hope to create objects or events that nature has not (as yet) produced, but which it can nevertheless tolerate. We might say that man seeks to unite his rationality with the intrinsic rationality, if it may be so called, of Nature. However, a notable discontinuity exists between these two types of rationality because, while NA includes, in a given state, all that can potentially be done in accordance with that state, the rationality of a CD is not limited to the fixed set of materials, knowledge, and procedures available in the given moment of history in which he finds himself. The biologist Steven Vogel, interested in biomechanics, outlines this distinction succinctly when he writes "Nature is certainly marvelous, but let us not forget what we do that she doesn't" (Vogel, 2001) taking a position already taken by Aristotle when he refers to technology as completing Nature. Indeed, even if it may seem a silly question, perhaps we should ask ourselves why evolution applies to biological species but not to structures that we call "inanimate." We know that the universe has undergone various physicochemical evolutions since its origin, but, at a macroscopic level, we observe nothing akin to Darwinism as it applies to living beings – that is to say, without any growing and goal-oriented complexity.

Why, we may ask, has NA not generated machines, or wheels, or even regular plane and solid geometric forms, instead leaving such tasks, at various levels of sophistication, to the higher animals, and particularly to man? The extinction of countless animal and vegetable species has often been due to unfavorable climatic or environmental conditions that NA, notwithstanding the time and materials at her disposal, has never planned for specifically. Yet all the materials were already available, just waiting for somebody (or perhaps chance, so active in the biological sphere) to establish the right interactions among them – in accordance, of course, with the same universal laws that have always applied.

Thus, for example, while many species of bird certainly know how to construct, with care and patience, nests that are sufficiently elastic, resistant, and long-lasting for their purpose, they will nevertheless often willingly make use of man-made structures, from houses to barns to specially constructed nest boxes, seemingly appreciating the improvement proposed by man. A similar sort of cooperation could not reasonably be expected in "inanimate" nature. NA, in essence, has always provided a complex and dynamic background scenery with which the living species must cope, seemingly as irrelevant guests, substantially detached from the configuration and dynamics of the material world. Life as we know it on Earth arises from interactions within a rather limited region of matter: all the rest is extraneous and often hostile.

Yet nature provides us with many technological starting points. The primitive CD who invented the wheel, for example, presumably arrived at the idea through observing, by chance, natural phenomena that involved rolling. Likewise, the first person to construct a lever may well have done so only after having witnessed some natural phenomenon that suggested the underlying mechanism. We could imagine, for instance, a rock falling from a hillside onto one end of a fallen tree trunk resting by chance across another, thus lifting a second rock resting (again by chance) upon the other end of the trunk. Similarly, improvised shade from harsh, dehydrating sunlight must surely have saved various species which, grasping the advantage to be gained, constructed devices to protect themselves from the worst of its effects.

But no case is known in which NA has ever generated, by means of its own evolution, "ready-to-use" technological devices. The higher animals have had to provide these through simple stereotyped and repetitive constructions whose designs often seem to be transmitted genetically. Primitive man would presumably have developed early technology through direct imitation of natural phenomena, while the CDs of the last 2,000 or 3,000 years, above all since the advent of the natural sciences, have founded their projects on ever-more-reliable models and observations of Nature's properties and regularities.

Finally, all this seems to lead us to the conclusion that conventional technology, including its likely imitative prehistoric beginnings, arises precisely for the purpose of filling a sort of gap in NA – namely, its substantial lack of finalism, or at least its ineptitude in placing itself at the service of living beings, toward which, to use a rather anthropomorphic expression, it seems to show no interest. This, after all, is the true significance of the statement that life and survival constitute a highly improbable fact.

A modern-day CD, as we said at the beginning, generates projects that are highly creative, or at least innovative with respect to those found in nature, even if, at times, they seem to be inspired by already existing structures or processes, such as naturally evolved endowments of other species. Thus, for example, the form of a tuna, or perhaps of a shark, is a first step in the design of submarine or boat intended to be as fast as possible in the water. Both radar and sonar adopt the same basic functional principle as that observed in the naturally evolved echolocation of bats. Mechanical diggers are based, at least in part, on the specially adapted limbs of animals that are able to dig efficiently through wood or earth.

Yet in each of these cases, and in any number of others that we could mention, the CD applies radical modifications to nature's designs, including many improvements. Aquadynamic calculations can lead to drag coefficients well below those found in fish; modern-day radar systems, unlike a bat's ultrasonic echolocation, can scan beyond the horizon; mechanical diggers often rotate continuously rather than moving back and forth as animal limbs must do; and so on. In principle, therefore, most of the products created by modern-day CDs correspond minimally, if at all, to natural objects or phenomena. In nature, there is nothing akin to electronic microscopes, cathode-ray tubes, spectrographs, electric motors, computers, typewriters, screws, nuts and bolts, or pulleys.

## 10. Imitative Design

Reviving an age-old tradition and, as we have seen, presumably the very origin of primitive design, NDs today constitute a sort of link between NA and conventional, creative technology. In reality, we are faced with an inversion of the teleology, based on the difference in the kind of problem to resolve: if CDs seem to ask themselves "with which technology can we exploit the sunlight?," NDs seem to ask "with which technology can we generate light similar to sunlight?"

A technology inspired by Nature should be, according to J. Benyus, the best way of designing devices and machines because, in this way, a greater amount of integration between humans and Nature may be reached (Benyus, 1997). Nevertheless, this can be revealed to be a new utopia since, as we said in the previous sections, all naturoids are destined, thanks to their unavoidable transfiguration of the exemplars, to enhance the heterogeneity – and, in some cases, variety – of the world rather than act as a miraculous link between technology and Nature. In fact, the limitless number of observation levels, interacting each other, at which we could design a device able to mimic a natural object or system, prevent us from discovering the "right" level at which the things have to be done. Not even a radical bottom-up strategy, as the one introduced, ideally, by the nanotechnologies, could take us away from various degrees of uncertainty (Bensaude-Vincent, 2004). In other words, technology always opens the door toward something which always contains something unexpected.

As we would expect, there are many classes of ND, but they can be grouped, on the basis of practical effects, into two main types: on the one hand, there are the radical NDs, who aim progressively toward the reproduction of a natural exemplar in every structural and dynamic detail; and on the other, there are the pragmatic NDs, who prefer, instead, to reproduce a certain functional aspect of the exemplar, ignoring any questions regarding the resemblance between the naturoid and its natural counterpart.

A typical example of a naturoid of the first type is an anthropomorphic robot, designed explicitly with the ambition of approximating, ever more closely with each generation, human appearance and behavior. By contrast, a typical example of a naturoid of the second type is an industrial robot, which in no way resembles a human being, but is eminently capable of matching a skilled factory worker's essential performance – namely, the precise manipulation of tools and other objects in order to achieve certain predefined tasks. Both these types of robot have sensors, actuators, and computerized control systems, but their purposes are obviously very different. Nevertheless, in both these cases, efforts are directed toward the most faithful reproduction possible of some or all of the properties of an exemplar, and, moreover, they are often intended to improve upon the functional performance of the exemplar.

Thus, above and beyond the limited objectives of Vaucanson, which amounted to the construction of physical models of his exemplars, we find the more radical, bold, and at times rather utopian, predictions of A.I. designers such as Hans Moravec, who sees a future in which the capacities of robots will easily surpass those of human beings (Moravec, 1998). From a more pragmatic point of view, we should not forget the approach taken by advanced modern-day researchers in the field of artificial organs, who seem to be guided by the principle that the most realistic and practical objective is not the faithful reproduction of one or other human organ, but rather the rendering of such an organ both compatible with the natural organism with which it must interact, and able to carry out the same basic function as that which is lacking in the patient. Not by chance, the late Willem Kolff, one of the pioneers in the development of artificial organs, once said that "the objective of an artificial heart is fundamentally to 'cheat the body,' because the body has to be persuaded that blood comes from a natural heart" (Negrotti, 2009).

The strong inclination toward the production of naturoids that improve upon natural essential performances is demonstrated, for example, by the development of a rotating, rather than pulsating, artificial heart; by the various types of artificial skin now available; by the numerous solutions offered in the field of artificial limbs (among which is an artificial hand that can rotate through 360°); by the different types of sensors proposed, for various tasks, as substitutes for the natural senses; and, more generally, by the wide range of different products, sometimes mere gadgets, used in alimentation, or in sport, or even in interior or urban design to imitate natural structures and processes. These replacements for natural objects and substances are characterized, almost without exception, by the claim to offer, at preestablished observation levels, improvements, with respect to their natural counterparts, in hygiene, digestibility, weather resistance, durability, aesthetic effect, costs, and so on.

## 11. The Future: An Interactions Dilemma

Clearly, improvements arise through the design and production of systems or subsystems capable of enhancing the properties observed in the exemplar. That seems to contradict the view of many thinkers, beginning with Aristotle, who, with his concept of *mīmēsis*, maintained that the artificial, precisely because it is inspired by Nature, shares Nature's goals. However, as we noted above, it is rather difficult to establish just what goals Nature might have, and we should not forget that a naturoid – a generalized version of the reproductive artificial – always ends up transfiguring the properties and dynamics of its exemplar, for reasons related not only to the logic of its very design and construction but also to the intentions of the designers.

Nowadays, the technological sector in which all this is perhaps more evident than ever is that of Artificial Intelligence, whose algorithms and software are able to provide highly useful, if still strictly circumscribed, design features, often more powerful than those exhibited in man.

The constraint of the "circumscribed features," moreover, regards all naturoids. Thus, for example, artificial grass produced for sports fields is designed to reproduce just those properties or performances of the natural exemplar retained essential for a given activity and certainly not, for instance, to provide grazing for animals. In general, biomaterials and all other naturoids are planned with similarly circumscribed objectives. In this way, technology, by inserting various types of naturoid into the natural environment, is increasing, when biological matter is concerned, a sort of pseudo-variety of the world considerably – a fact which, in turn, can often provoke random interactions well beyond those of Darwinian evolution, and certainly less predictable than the set of interactions derived from conventional technology, which generates heterogeneity but not pseudo-natural variety.

To return to the case of birds, we can, with a shotgun – a product of conventional technology – kill enough of them to modify significantly the quantitative distribution of one or other species. Alternatively, with an artificial bird-call device – a product of naturoid technology – we can interfere with the behavior and communications of a given species, thus (less directly) generating quantitative variations, some of which may well be unpredictable. In a more human-centered context, psychosociological studies of the interactions and relations between people and robots – and especially anthropomorphic robots – are becoming ever more common. Such studies are intended to discover what cultural variations might arise with the proliferation of such robots (Kim et al., 2009).

Moving into the barely-begun age of nanotechnology – a discipline that seems highly likely to embrace, more and more, the design of micro- or nano-naturoids – we can already envisage the creation of tiny objects specially designed to intervene in, and collaborate with, the finest of Nature's process, including those inside the human body. Even here, however, we can foresee the possibility – indeed, the likelihood – of transfiguration effects, as yet unfathomable in their subtlety, giving rise to interactions, both positive and negative. Some researchers assume drastic and rather pessimistic positions in this regard, suggesting that Nature's best-kept secrets will forever remain her own: "…implantable materials with very fine mechanical and structural properties for host-cell migration and proliferation in order to create new hybrid artificial organs or tissue-engineered systems cannot be produced from synthetic materials. Biological materials have an extremely fine structure and unique properties that cannot be imitated with synthetic polymer materials" (Noishiki and Miyata, 2008). For a collection of various other examples in this field, see (Negrotti, 2010).

Whatever the case, the strategy summed up in the idea of "cheating the body," or, more generally, "cheating Nature," is sure to bring forth some big surprises.

In conclusion, it is evident that the reuniting of a part of technological design with NA through the activities of NDs is in no way a sort of resigned recognition that Nature's wonders are superior to the designs of conventional technology. On the contrary, the tacit but unremitting general objective of NDs is the perfecting of Nature's exemplars, sometimes for pragmatic reasons and sometimes for deeper, psychological, and anthropological reasons, perhaps connected to a deep-seated desire for omnipotence, through the reproduction and gradual surmounting of Nature. Such activity is perceived not only as cognitive dominion over Nature but also as the power to recreate Nature at will. Seen from one point of view, the design of naturoids seems to recall the ultimate folly of the alchemist's dream, but from another, it resembles more the positive side of what I called Daedalus's Glue Syndrome, which, notwithstanding all its potential dangers, may lead to considerable cognitive and practical advantages, tinged with the flavor of a complement to Nature, at times through imitation and at times through modification and even supersession – a combination whose virtues were amply extolled by Edgar Allan Poe in his short sketch *The Landscape Garden*. It is an inexorable process of redesign, and nobody knows where it will lead.

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Biodata of **Arthur Ward**, author of "***Trouble for Natural Design***."

**Arthur Ward** hopes to be awarded his Ph.D. in philosophy in 2011 from Bowling Green State University, where he earned his M.A. in philosophy in 2007. His areas of specialization are in normative ethics, metaethics, and philosophy of biology. His current work looks skeptically upon natural teleology and natural design, focusing on the implications for ethical theory once these scientific theses prove to be untenable. He is also the author of the article "Free Will and Foreknowledge: Does Jon Know What Laurie Will Do Next and Can She Do Otherwise?" published in the volume *Watchmen and Philosophy* (Wiley, 2009).

E-mail: **award@bgsu.edu**

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# TROUBLE FOR NATURAL DESIGN

**ARTHUR WARD**
*Department of Philosophy, Bowling Green State University,*
*Bowling Green, OH 43403, USA*

## 1. Introduction

It is increasingly popular among philosophers and biologists to frame questions of biological adaptation in terms of *natural design*. The benefits of the design approach are apparent. Thinking of organisms as akin to artifacts ignites the imagination of scientists and places one in a position to discover the processes that led to the wondrous complexity of traits. Some philosophers, notably Daniel Dennett (1995) and Michael Ruse (2003), have argued that the design paradigm is an essential, ineliminable part of biological investigation. Thinking of organisms as the product of design of course is not new. For centuries the assumption of learned scientists had been that God the creator had designed all life – an argument most famously detailed in William Paley's *Natural Theology* (1803). But until fairly recently, committed naturalists would have opposed the design argument, conceding to Paley that design conceptually implied a designer, all the while rejecting a designer. Breaking with this assumption, some new natural design enthusiasts including Dennett and Ruse, as well as others such as Allen and Bekoff (1995) and Phillip Kitcher (1993), have attributed design to biological organisms while denying the necessity of a designer. Dennett writes, "The key to understanding Darwin's contribution is *granting* the premise of the argument from design… watches and other designed objects don't happen; they have to be the product of what modern industry calls 'R and D'-research and development…what Darwin saw was that in principle the same work could be done by a different sort of [natural] process" (Dennett 1995, 68).

Although it is common ground among all naturalists including myself that natural selection is a blind process capable of generating wondrously complex and sophisticated biological traits and processes, I aim to show that equating this natural process with design is untenable. This is more than a mere terminological dispute. A world with natural design would be a metaphysically different place than a world without. Most notably, the concept of "design" is interconnected with the concept of "defect," an incorrect deviation from a design. Obviously, something is able to be "not according to plan" *only if* there is a plan in the first place. In this chapter, I argue that contrary to recent motions to embrace design in nature, there is trouble for this approach. In fact, I believe a commitment to naturalism precludes the very possibility of natural design. I will first explain the stakes for attributing design to nature and then argue that although design may not *conceptually* imply a designer as some naturalists have previously thought, the mental activity of a designer proves to be a necessary condition for the presence of true design. With this conclusion, I seek to rebut the new design enthusiasts and provide a substantive rather than semantic argument for the link between design and designer. My own commitments to naturalism lead me to abandon design in nature, although it would be an open move to retain design by abandoning naturalism instead. With this conclusion, I form an uncomfortable alliance with intelligent design proponents in that I believe some mental activity is required for design to exist. Since I see no evidence for God or any other designer of nature, however, I propose abandoning natural design altogether.

This chapter steers away from the body of literature on natural teleology and biological function, though anyone familiar with that literature will notice the obvious parallels. Function and design are interrelated concepts, after all. Although I delve into the literature on functions elsewhere, I have found that approaching the puzzle of natural teleology from the direction of natural design allows for a more streamlined argument with a minimum of technical jargon. I would add, however, that my conclusion in this chapter has implications for some theories of biological function. In particular, I take my argument against natural design and defect to work equally well against natural proper function and malfunction (see Millikan, 1984; Buller, 1999). It is not the objective of this chapter to make that case nor is there adequate space to do so; however, theories of proper function have the very same vulnerability I will point out in the case of design. I will return to this point briefly at the end of this chapter.

The denial of design in nature may seem quite radical to some, for design allows for the kind of evaluations regarding natural "goodness and defect" we engage in regularly. Thus, as well as rebutting some popular views in the philosophy of biology, my thesis asks us to revise some of our intuitions about biology. If there is no design, and no standards for normal or defective traits, all phenotypic outcomes are normatively on a par. Strictly speaking, there could be no such thing as *defective* hearing or eyesight, no *malformed* limbs, or no *abnormal* psychologies because there would not exist a correct, normal, or natural "way for these traits to be" in the first place. As counterintuitive as this implication may sound, I want to emphasize that we can of course *make sense* of all of these attributions of normativity. This is because we can capture nearly all of the content of attributions of "goodness and defect" in nature through a combination of understanding what is statistically common and what kinds of traits lead to human happiness. Without the concept of design, there is no "correct" standard for human eyesight given by nature – yet we can still decide which eyes see with greater clarity and distance, and by and large, we all desire accurate eyesight because it helps us get around. Therefore, we *can* have a standard of "good" eyesight, but it comes either from our own observations of statistical commonality or from our preference to see accurately. The relevant standard of eyesight, given my interests, is that of clarity and accuracy, but this is a standard that I have set – not one that I have objectively discovered in nature. Were I to face a great reward for being blind, I might well prefer to be blind instead of sighted, and my standard would change. If the majority of us preferred to be blind, would our notion of what counts as "good eyesight" change to reflect this? Perhaps it would, perhaps not, but one point I must insist on: there simply is no fact of the matter about what eyes are "supposed" to do, and therefore no way for them to be defective according to any standard *but* one we set ourselves. There does not exist an objective standard laid down in anything like natural design.

A combination of these alternative standards can grant us near-extensional equivalence with typical attributions of design and defect, but I admit that some intuitive attributions of natural design and defect will not find their corollary with either statistical frequency or human welfare. Take the clever example from Anscombe (1958) that "humans have 32 teeth." The statement seems intuitively correct, despite the fact that *hardly any* humans in fact have 32 teeth, nor should we necessarily want to, given the limits of space in our mouths and our ability to chew just fine with fewer. So if the claim rather implies that humans *naturally or properly* have 32 teeth, my analysis treats this claim as false. Therefore, the denial of design is revisionist regarding some of our biological intuitions but, as Davies (2001, 2009) and Cummins (2002) have aptly pointed out, not in a way that interferes with scientific inquiry. In what follows, I try to carefully describe the trouble I see for natural design and provide an argument for its illegitimacy.

To make my case, I do not need to work with a complete definition of design. I take for granted that design is a process, and it may have necessary features such as the structural modification (Allen and Bekoff, 1995). However, I am less interested in the verb "to design" than the noun "design." I take it that any item that is the product of design *has* a design, and my argument focuses on just one necessary feature of the latter. A design has the following necessary criterion:

> Authoritative Standard of Correctness (ASC) criterion: an item has a design only if there is some Authoritative Standard of Correctness for phenotypic form and/or development.

That is, a design represents a standard for phenotypic outcome such that some possible phenotypes count as correct and others incorrect. I do not mean to imply that only one narrowly defined phenotypic outcome can be correct – there could be two or more equally legitimate ways for an item to meet the standard. However, it must be the case that *some* possible outcomes are contrary to the design and are ruled out as not conforming to the correct standard. This is what we refer to as a *defect*: the failure of an item to meet the authoritative standard of its design. Note that it is insufficient that an object just have *some* standard of correctness. Standards of some kind or another come cheaply (e.g., knives make for good cutting tools, adequate trowels, but terrible baby rattles). The standard that emerges from a design, however, has a privileged status for it alone dictates the way the designed item is "supposed" to be. As I explain later, this privileged status of the ASC is rather weak. Nevertheless, it is a distinctive feature of design, and one reason for attributing design to nature is to show that one standard above others is authoritative. In an artifact, the authoritative standard of correct form is a product of the mental activity of a designer, having to do with what the designer *intends* the artifact to be like. The challenge for natural design proponents is to demonstrate exactly how nature can produce a similar standard for organisms.

## 2. Why This Criterion?

I posit the ASC as a necessary rather than sufficient criterion. The "authority" of the ASC criterion is of utmost importance because if there is no privileged standard that an item is "supposed to" meet, then it cannot truly be defective. I can go about setting all sorts of standards: items that best balance on my head, items that are between 3 and 6 miles from the British museum, etc. But no one much cares, nor should they, about this kind of promiscuous standard-setting. There is no sense in which any item "ought" to balance on my head or be a certain distance from the British museum. There is no proprietary relation present. If an item is designed, however, there is some weak sense in which it "ought" to be a certain way. I must be careful, however, to disambiguate between two meanings of "ought." That some item can be held to the standards of its design is a soft kind of "ought" that concerns "the way the world ought to be." This is to be contrasted with the normativity that plays a part in ethical matters of right and wrong, or questions of "the way agents ought to act." The latter we could call agent-normativity (though ethicists usually stipulate that this is just what they mean when they use the word "normativity"), and it comprises what reasons we have as agents to act in certain ways. The former I sometimes call non-agent-normativity or "protonormativity" because it seems somehow more basic and elemental yet nevertheless wholly less important than full-blown agent-normativity. Even if it were true that sharks are "supposed to be" ruthless killers and humans are "naturally" omnivores (both protonormative claims that apply standards of correctness to nature), nothing about normative ethics, our reasons to act, follows directly from these facts. Protonormative premises do not entail ethical or practical reasoning conclusions without some other normative premise to do the heavy lifting. For instance, even if it is true that humans are *naturally* omnivores, it does not follow that I necessarily have a *reason* to be an omnivore. To support that further conclusion, we would need an extra premise that contained agent-normativity, such as "humans ought (or have reason) to do what is natural for our species," but this premise would be quite controversial and strikes me as just plain false. Facts about the way the world ought to be do not necessarily generate reasons for any agent to act in accordance with those standards. This is what I mean when I say that the "authority" in the ASC is rather weak. It sets up a proprietary relation between an item and some standard, but it lacks the kind of full normative force that would necessarily require action on anyone's part.

My criterion asserts that designs imply an authoritative standard of correctness. I hope now that this taken on its own will be uncontroversial. Mundane examples illustrate the point. A bicycle is designed to carry a passenger over land on two wheels. If a wheel is bent or the chain falls off, these outcomes are contrary to the correct form the bicycle was designed to instantiate. There need not be a single platonic "form of the bicycle," for a diverse variety of bicycle phenotypes will meet the standards set by the design. However, that a bicycle is designed implies that some possible phenotypes will count as defective. Not all phenotypes are on a par. Try to imagine designing some artifact such that any possible resulting form is commensurate with all others. The idea is nonsensical. Even the most abstract and silly designs specify some purpose or function, even if the item is "to be whimsical," and thus there is some possible outcome that is contrary to what was designated. I hold in this chapter that contrary to the intuitions, even convictions, of a great many biologists and philosophers, the notion of defect in nature is untenable and should be rejected. The implications of this are indeed revisionist. Strictly speaking, I deny that hearts are "supposed to" pump blood, that humans "naturally" have ten fingers, and that tulips "ought to" flower in the springtime. I not only deny the moralistic tone these terms might take (what I called agent-normativity), I deny that any (protonormative) standards of correctness exist in these cases. Science can inform us about what is statistically common, but I claim it cannot inform us about what *ought* to have been the case when an item develops in a statistically uncommon way. In the sections that follow, I explain how the ASC criterion is met in the case of artifacts and why it fails to be met in the case of nature.

## 3. How Artifacts Meet the ASC Criterion

The answer to how artifacts are able to meet or deviate from an authoritative standard in one sense is perfectly obvious. Artifacts have designers with intentions, purposes, plans, etc., that act as standard setters. In other words, the origins of design in artifacts lie with the mental states of a designer. The standard of correctness is literally what the designer "intended" or "had in mind." Yet more must be said because the proponents of natural design argue that mental activity is just *one way* of establishing the standards that come with the design process. Natural selection, they will argue, is an alternative design process that occurs without any mental activity. Dennett argues that all design, whether natural or artificial, is unified by a common process of "research and development" in what he calls "design space" (Dennett, 1995, 135). So, before I lay out my argument against this latter claim in the next section, it behooves me to give a more robust description of mental design such that it has critical properties that natural selection lacks.

The crucial claim in my argument is that a design represents the correct phenotype (and in some cases, also the correct path of development) of an item, whether artificial or natural. That is to say, a design dictates what an item is to be like in the end. It may not dictate every detail, which is why typically a range of phenotypic outcomes will be consistent with the ASC. In the bicycle I design, I may be indifferent to details such as paint color and leave out color information in any physical design manifestation (such as a blueprint or schematic). But designers sometimes omit important details from a blueprint or model as well, usually because they are taken for granted or believed to be obvious. In particular, intended environmental conditions are frequently omitted. Sometimes cake recipes specify different temperatures or cooking times based on altitude because of the effect this environmental detail can have on the finished product. Yet these recipes do not bother specifying that baking is to be done on dry land rather than underwater or with earth gravity rather than Martian gravity. Such details are taken for granted, though their importance to the resulting cake is obvious. Am I wrong, then that designs represent phenotypes? After all, a phenotype is the product of genotype *and* the environment. To have a norm for phenotypic outcome, one must privilege an environment as well as a genotype. My answer to this puzzle is that designs *do* implicitly represent norms for environmental factors even when their physical manifestations leave out such information. Designs themselves are not necessarily physical. Blueprints, recipes, schematics, and models are all physical manifestations of design, but a design itself is *information* and it may contain data that its physical cousins lack.

Returning to the cake example, obviously it will turn out considerably worse if baked underwater or with Martian gravity. These phenotypic outcomes would count as defective cakes. Are we to conclude that there is something wrong with the recipe if our underwater cake is mushy and disintegrates? Is it the result of a bad recipe or design flaw? Of course not, and for the very reason that all these relevant environmental constraints must have been part of the design *even if not specified in the recipe*. Take another, more dramatic example: if the great pyramids of Giza had a blueprint at all, it would not have bothered to specify that gravitational pull was to come from beneath the pyramids rather than from the side. Of course, Egyptians had no knowledge of gravity, let alone that it *could* possibly come from a different direction. As good evidence that the designer did not even entertain the possibility, note that no adhesive was used between the giant blocks: the structural integrity *depended* on gravity coming from beneath. Now imagine some science fiction scenario in which a huge source of gravitational pull is placed beside the pyramids, causing the blocks to fly helplessly sideways, thereby destroying the structure. I pose the question again: would anyone call this development the result of a design flaw? On the contrary, we would all want to say that rather than a design flaw, this is a result of an *unintended environment*. If this is true, and supposing that the pyramid designers did not even *consider* this eventuality, we are forced to conclude that the pyramid design carried implicit information about the intended environment in which the pyramids were meant to sit. Only by attributing this implicit environmental data do we avoid blaming the design for artifacts caught in bizarre environments. Where recipes and blueprints fail to include enough environmental specificity, we know that because the designer had some phenotype or range of phenotypes in mind, and only certain environments will be consistent with those phenotypes, those environments count as being implicitly represented by the design itself.

## 4. Why Nature Cannot Meet the ASC Criterion

A conscious agent can have "something in mind" when designing an artifact, and nature, lacking a mind, cannot. This is the basic reason why nature lacks the ASC criterion, crude though it may seem. This might appear to be a straw man. After all, none of the mainstream advocates of natural design ever said nature *did* have a mind. Rather, they have sought to ground the conditions of design in natural selection – a mindless and random process that can generate amazing complexity and sophistication. To avoid erecting a straw man, this section will seek to demonstrate *why* the presence of mental activity explains why the ASC criterion is met in artifacts and not in nature.

As detailed in the last section, a design represents the phenotype of an item. It bears information about the substance and structure of the item (its genotype, if you will) and also information about the proper environment the item is to inhabit. Where critical environmental information is lacking in some physical design manifestation such as a blueprint or recipe, the correct assumption is that this information was implicitly a part of the original design. If we did *not* make this assumption, we would be forced to conclude that objects in bizarre environments that do not perform as intended are the result of flawed design. While a bicycle on land rolls, when placed underwater it rusts, and when placed on the surface of the sun it vaporizes. Assume that the bicycle designer never dreamed that anyone would put the bike in these peculiar environments and thus never stated explicitly in any plans, schematics, or blueprints that these environments were improper. Nevertheless, it is obvious that the problem in these cases is not the design but the environments. They are contrary to what the designer *had in mind*, even if the designer never specifically thought about these possibilities. The designer had in mind a phenotype of the bicycle, and only environments that are capable of supporting the conditions for this phenotype are consistent with what the designer *intended*. This psychologistic language of "had in mind" and "intended" are essential elements of this analysis. As I will argue, nothing in natural selection can properly replace them such that non-mental nature can meet the ASC criterion.

There are broadly two kinds of possible sources of an ASC for an organism. The standard could be set externally, akin to artificial design where an agent foists a purpose upon it. Or the standard could be internal to the object itself, somehow self-determining. The latter account is a deeply Aristotelian idea, detailed in book II of his *Physics* (Irwin and Fine, 1995). For Aristotle, living things were internally purposive: their own source of form and function. The Aristotelian notion of internal purposiveness has had a number of modern-day advocates. Notably, the biologist Ernst Mayr has suggested that the discovery of DNA vindicated this Aristotelian concept of "eidos," an ancient parallel to our concept of "design." Mayr championed the idea of *teleonomy*, which he describes thusly: "A teleonomic process or behavior is one which owes its goal-directedness to the operation of a program…it depends on the existence of some endpoint, goal, or terminus which is foreseen in the program that regulates the behavior" (Mayr, 1988, 45). A program is defined by Mayr as "coded or prearranged information that controls a process (or behavior) leading it toward a given end" (Mayr, 1988, 49). Mayr intends the above definitions to cover purposive behavior in both natural and artificial entities. A program might be a computer program, a DNA program, or anything else fitting the above description.

He writes that it is "legitimate to employ modern terms like *genetic program* for *eidos*," continuing, "just as the blueprint used by the builder determines the form of a house, so does the *eidos* … give the form to the developing organism, and this *eidos* reflects the terminal *telos* of the full-grown individual" (Mayr, 1988, 56, 1992). The story is a familiar one: DNA is an *information* molecule, guiding the development of an organism. If Mayr's story is correct, it appears we would have the natural standard that design enthusiasts are looking for. The genetic program lays out the form of the organism, and we can compare actual results against what the program has called for. Deviations from the program, from the standard of correctness, are errors or defects. We can play as foremen touring a construction site, blueprint in hand, pointing to the windows that *ought* to be 6 in. lower and the roof that *should* have been pitched 3° steeper.

Dennett and Dawkins eschew the blueprint analogy in favor of a recipe. A blueprint is the wrong metaphor, they say, because it suggests a one-to-one mapping of genes to traits as well as a "reversibility" of design; just as one can construct an accurate product by examining a blueprint, one can construct an accurate blueprint by examining a product (Dawkins, 2003, 89, 105; Dennett, 1995, 116). On the contrary, they point out, one cannot examine a cake and necessarily reproduce its recipe – it may be opaque. The same is true, of course, for organisms and their DNA. Furthermore, as Dawkins writes, a recipe is not just a description of a finished cake, but rather "a set of instructions, which, if obeyed in the right order, will result in a cake."(Dawkins, 1996, 419) This too seems like a better description of DNA than a blueprint, which is typically just a representation of the final product. But a recipe is still a physical remnant of design, just one with more specificity. One can follow it incorrectly and end up with a defective product.

DNA may be like a recipe or blueprint in significant ways, but we have already seen that these are incomplete manifestations of design. They lack critical environmental information that would be required in order to have a standard for correct phenotypic outcome. Two organisms with the same genotype, when placed in two radically different environments, may result in two radically different phenotypes. Mayr claimed above that DNA reflected the telos of the mature individual, but since DNA itself contains no environmental data, this cannot be true. Unless DNA bears some information about natural/normal/proper environmental conditions, it cannot truly dictate any standards of correctness for phenotypes. And as we all know, DNA is but a genotype and lacks the environmental specificity required to represent a phenotype.

Am I being unfair to DNA, uncharitably denying it the capability of carrying the very same implicit environmental information that I postulated in artificial design? Is not DNA a replication molecule, whose ASC can be judged objectively according to the accuracy of replication? This is a tempting thought, but it is ultimately question-begging. To see why, examine the following speculative story in Dawkins' *The Selfish Gene* about the origins of life:

> At some point a particularly remarkable molecule was formed by accident. We will call it the *Replicator*. It may not necessarily have been the biggest or the most complex molecule around, but it had the extraordinary property of being able to create copies of itself… So [eventually] we arrive at a large population of identical replicas. But now we must mention an important property of any copying process; it is not perfect. Mistakes will happen… We do not know how accurately the original replicator molecules made their copies. Their modern descendants, the DNA molecules, are astonishingly faithful compared with the most high-fidelity human copying process, but even they occasionally make mistakes, and it is ultimately these mistakes that make evolution possible. (Dawkins, 2006, 15)

This seems like a reasonable account of the DNA molecule's ancestry but a skeptic might wonder how the word "mistake" enters the story. A mistake or error occurs when a task is done incorrectly or when some standard fails to be met. A thing can only err in reference to an end. In Dawkins' story, the end is replication, which we know because the molecules in question are called *replicators*. But if Dawkins were around observing these early molecules, what would he notice? He would notice that these fancy molecules sometimes replicate perfect copies, sometimes replicate imperfect copies, and sometimes do not replicate at all. From this observation, it seems the honest description for them would be *sometimes-replicators*. And if sometimes-replicators do not replicate a perfect copy, they have not made a mistake at all – in fact, it is to be expected! One only arrives at an ASC for DNA molecules if one assumed it from the start. There is no reason we need to call mutations errors as long as we all agree that a mutation is the result of "dissimilar" genetic replication. DNA bears some similarity to blueprints, recipes, and models; however, these are but physical manifestations of design – not designs in themselves. Artificial designs are able to contain information not included in their physical counterparts precisely because their origin is mental. There is a fact of the matter about what a designer *intended* or *had in mind*, such that we may credit the design with containing some information omitted in the recipe. The same cannot be said for DNA. Any attempt made to find this implicit environmental specificity would have to look outside the DNA molecule, to, say, natural selection. In doing so, one would abandon the position of internal design in favor of an external source.

If one pivots from an internal to an external standard of correctness for phenotypic outcomes, we find more symmetry between artifacts and organisms. What the natural design theorist needs is an explanation for how a nonmental process is able to dictate the proper/normal/natural environment for an organism. This task is critical because only with the addition of this environmental specificity in the equation can we arrive at a standard for correct or incorrect phenotypic outcome. I will consider several leading candidates for generating a nonmental ASC and describe the ways in which they fall short of achieving their goal.

Without someone to have an environment in mind or otherwise mentally represent the intended outcome, how could such specificity occur? The most obvious candidates for what environment counts as normal/natural/proper for any particular organism are (a) the environment of statistical frequency, (b) the environment of greatest fitness, and (c) the environment of evolutionary adaptedness. All of these have some intuitive pull, yet none will suit our needs. Remember that what we seek is a sense of "proper environment" that matches the force of what a designer would represent as the environment an artifact is *supposed* to be in or the one she *intended* it to be in. Without this force, any standard lacks the authoritativeness of the ASC criterion and would seem arbitrary and insufficient for attributing design.

The environments of statistical frequency and of greatest fitness are the most obviously problematic, so I will address them first. The environment of statistical frequency is the one in which token organisms are most commonly found. Though "normal" is sometimes *colloquially* taken to mean "statistically common" in some circumstances, it clearly will not suffice here. One could poison or otherwise interfere with a population of organisms, effectively altering their environment of statistical frequency, but no one would be inclined to see this as normal or proper. If increased pollution somehow led to mass blindness or sterility in humans, would anyone conclude that this was the normal environment such that resulting phenotypes met the ASC criterion? On the contrary, the likely reaction would be that humans had *deviated* from their natural state because of this highly *unnatural* environment. So much for the environment of statistical frequency. What about the environment of greatest fitness? All that it takes to realize that this will not meet the normal/natural/proper description is to realize that for any given organism, its environment of greatest fitness is almost certainly in the lab of some mad scientist who keeps it alive cryogenically, cloning copies from its DNA *ad infinitum*. This would ensure long life and optimal reproduction, but this is as absurd a candidate for a natural environment as the polluted world was. It is about as *unnatural* as an environment can be. It is a standard, to be sure, but we might as well choose "the area within two miles of the British museum" as a proper environment if our standards are going to be so disconnected from the authority the ASC criterion requires.

A far more reasonable environment to consider as normal/natural/proper is the one of evolutionary adaptedness. Indeed, it is this environment that most people would cite in their attribution of something like a "natural habitat." Cacti belong in the desert and whales in the ocean rather than vice versa because these are the conditions to which their species have adapted, or so the story goes. Notice that this solution captures much of the appeal of the two solutions rejected above. The environment of evolutionary adaptedness, for example, is going to be one in which an organism has a high degree of fitness, and it rules out bizarre "mad scientist" thought experiments. However, Elliot Sober cautions against this temptation in his influential article "Evolution, Population Thinking and Essentialism":

> When one looks to genetic theory for a conception of the relation between genotype and phenotype, one finds no such distinction between natural state and states which are the results of interference. One finds, instead the *norm of reaction*, which graphs the different phenotypic results that a genotype can have in different environments…[according to the] norm of reaction: all environments are on a par, and all phenotypes are on a par. (Sober, 1980, 374)

In his book *Adapting Minds*, David Buller picks up the fight where Sober leaves off. Against the notion of the environment of evolutionary adaptedness (EEA) counting as "normal," Buller protests:

> The EEA of a genotype is simply the environment in which that genotype had *higher fitness than available alternative genotypes* in the population. In a different environment, the genotype may have had an even greater fitness advantage over those alternatives. So why not identify the "natural environment" of a genotype with the environment in which the genotypes has its highest fitness? (Buller, 2006, 435)

His point illustrates the sense of arbitrariness that pervades any attempt to pick out a particular environment as a proper one. The contingent accidents of evolutionary history seem no more promising for generating any kind of normative standards than pure statistical frequency did. The environment of evolutionary adaptedness has both intuitive appeal and widespread agreement on its side, but neither of these is sufficient to ground a normative standard. Compare attempting the same feat in artifact design. No amount of intuition or popular agreement could make it the case that an artifact is supposed to be a certain way if it is contrary to the designers intentions. We might decide that we have reason to use it in a manner contrary to its design, but this is to make a claim about "agent-normativity," and does not alter any fact about the underlying "protonormative" standard set down by its designer. There may be epistemic difficulties in deducing the intentions of a designer, but it is transparent that a fact of the matter exists about what the designer had in mind.

Learning about the environment of evolutionary adaptedness can be useful in explaining the traits and behaviors of organisms. The history of causal interactions between genotype and environment can explain the origins of marvelous adaptations such as the human eye, for example. However, all this can be done without attributing any norms for phenotypic outcome. There is no design in nature, though fear not, for as Davies says (contra Dennett), "Darwin did not show us how to understand the world in terms of design despite the absence of a designer; he showed us instead that we ought to stop thinking of the world in terms of design" (Davies, 2001, 14).

## 5. Conclusion

A design generates a norm for a phenotypic outcome, representing what form an item is to take. It entails the existence of some standard of correctness for phenotypes such that some count as normal/natural/proper while others count as defective. Such a distinction among artifacts is easily set by a designer, whose mental activity is responsible for such standard-setting. A designer can dictate both proper structure (a genotype) and proper environment to arrive at an intended phenotype for an item. The ability of a designer to form a representation of the finished product enables us to attribute *implicit* environmental specificity even when the designer does not *explicitly* express it. It is this critical feat that the nonmental natural world lacks. There is not an objective scientific way to designate normal/natural/proper environments for organisms. Without a designer to specify proper environmental conditions, no standard for phenotypic outcome is possible. Since this is a necessary criterion for the attribution of design, we must therefore abandon the notion of natural design.

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# PART VI:
# DESIGN IN THE PHYSICAL SCIENCES

**Kak**
**Dickson**
**Issar**
**Pollak**
**Winters**
**Beloussov**
**Grand**

Fan palm in Utuado, Puerto Rico, taken by Liz Swan.

Biodata of **Stephen P. Cook**, author of "***Imagining a Theory of Everything for Adaptive Systems***."

**Stephen P. Cook** is currently managing director of Project Worldview and a research specialist in the Department of Astronomy at New Mexico State University. He received an M.S. in physics from the University of California (Los Angeles) in 1976. Given his interest in global, environmental, and science education, he has authored four books. Given his interest in astronomy, he served as director of Arkansas Tech University Observatory from 1994 to 1997 and discovered a bright new eclipsing binary star in 2008.

E-mail: **scook@projectworldview.org**

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# IMAGINING A THEORY OF EVERYTHING FOR ADAPTIVE SYSTEMS

**STEPHEN P. COOK**[1,2]
*[1]Project Worldview, 332 Weed Road, Weed, NM 88354, USA*
*[2]Department of Astronomy, New Mexico State University,*
*Las Cruces, NM 88003, USA*

## 1. Introduction: Worldviews, Reality, and a Theory of Everything

By worldview, I mean the conceptual framework, beliefs, and values used to make sense of reality. Well-developed worldviews incorporate a cosmology that answers questions like "How did I get here?" or a more teleological "Why am I here?" To aid analysis and guide worldview development, I have formulated 80 worldview themes (Cook, 2009). To illustrate their use, I interpret something physicist Leonard Susskind wrote, "Modern cosmology really began with Darwin and Wallace…they provided explanations of our existence that completely rejected supernatural agents" (Susskind, 2006). My interpretation from a "secular humanism" and "scientific materialism" perspective: these men used the "scientific method" in developing their "global vision." In telling a story, they did so without building it around God, the Creator, and Father, that is, without "monotheism" and "belief in a personal God." They shunned use of "vitalism," "mysticism," "magic," and "religious fundamentalism."

Many scientists define objective reality as independent of mind or worldview by limiting it to events and phenomena that can be recorded by devices. Reality is different from how we describe it, like the difference between physical terrain and the map of that terrain. Biblical passages hint at this difference: in *Genesis*, "In the beginning God created the heavens and the earth," and in *John*, "In the beginning was the Word, and the Word was with God, and the Word was God."

Some feel that scientific accounts of "In the beginning…" are about to change. Recently, Erik Verlinde has advanced efforts to unify the four fundamental forces as part of a "grand unified theory" (Verlinde, 2010). He claims one of the forces, gravitation, can be understood as something else: "an entropic force caused by changes in the information associated with the positions of material bodies." Verlinde deduced this using some new physics: the holographic principle. Perhaps difficulties reconciling the theory of gravity (general relativity) with the successful, but difficult to understand, theory of quantum mechanics are over.

We mustn't get our hopes up! I don't think a "theory of everything" (TOE) is right around the corner. I don't think we'll ever have a map of reality that perfectly represents the terrain or a model that gives perfect predictions for everything of interest. A worthy goal is making them increasingly useful.

Physicist James Hartle, who in 1983 collaborated with Stephen Hawking in a paper entitled "Wave Function of the Universe," tells a story about Murray Gell-Mann (Hartle, 2003). Murray used to ask Hartle, "If you know the wave function of the universe, why aren't you rich?"

Certainly, seeking fundamental understanding is important, and there is more to life than economic gain. But environmental concerns point to problems scientists might work on that seem especially urgent. In this chapter, I imagine what might inspire the construction of a useful TOE and consider how it might be formulated. I begin by identifying what questions such a theory should attempt to answer. At the top of my list I'd put a problem, "How can humans adapt and learn to live as part of nature?" Solving that might require exploring "Who are we?" and "How'd we get here?"

Daniel Dennett describes *Darwin's Dangerous Idea* as the notion that design can emerge in the natural world from mere order via an algorithmic process rather than requiring an intelligent creator (Dennett, 1995). Skeptics see it as highly improbable that blind, mindless, random processes could have produced seemingly purposefully designed complex structures. Richard Dawkins answers them in *Climbing Mount Improbable* with an analogy emphasizing the power of accumulation (Dawkins, 1996). "On the summit sits a complex device such as an eye or a bacterial flagellar motor. The absurd notion that such complexity could spontaneously self-assemble is symbolized by leaping from the foot of the cliff to the top in one bound. Evolution, by contrast, goes around the back of the mountain and creeps up the gentle slope to the summit – easy!"

While biologists overwhelmingly accept Darwin's idea, other scientists including physicists and cosmologists are not so sure. As Susskind describes it, "The bitterness and rancor of the controversy have crystallized around a single phrase – the Anthropic Principle – a hypothetical principle that says that the world is fine-tuned so that we can be here to observe it!" In *The Cosmic Landscape*, he describes "the illusion of intelligent design" and provides a "scientific explanation of the apparent benevolence of the universe," one he calls "the physicist's Darwinism." An eternal inflation mechanism has created a "bubble bath universe" in his conception. Space cloning itself in nucleating bubbles has conceivably produced $10^{500}$ possible separate universes. While not all of these actually exist, enough do to make our part of this megaverse look like nothing special. While it's obviously compatible with the intelligent life we represent, most other pocket universes are not. Susskind thinks maybe we're just lucky after all!

Clearly, any TOE needs to, once and for all, answer the question, "How, why (if there is a reason), and when was the universe created?" For those still clinging to an Intelligent Designer, if a TOE posits one, it must address questions like, "How did the Intelligent Designer come into being?" and "What maintenance (if any) on this design does the Intelligent Designer do?"

Surviving in nature requires building and continually refining an internal model of it – something which requires constant "dialogue with nature," to use Ilya Prigogine's phrase (Prigogine, 1997). "What makes this dialogue possible?"

he asks. In arguing time is real and connected with irreversible processes, he responds, “A time reversible world would also be an unknowable world. There is an interaction between the knower and the known, and this interaction creates a difference between past and future.” Those who believe time is an illusion would disagree. We’ll want to ask, “What is time?”

Poet and mystic William Blake imagined it might be possible “to see a world in a grain of sand.” Given renewed interest in hologram-like universes, it seems we’d want our TOE to tackle “Does the universe somehow contain its whole essence in every part?” Some mystics equate the universe with God; others believe a living consciousness pervades the universe, something they equate with the Cosmic Mind, or God. We’ll need to ask, but we’re getting ahead of ourselves! Certainly before we make that inquiry, we’ll want a full explanation of consciousness and its relationship to life.

Speaking of life, a TOE should describe what forms it exists in throughout the universe and explain its origin. We’d like detailed instructions on how to make it from nonliving building blocks. Speaking of building blocks, we’d like to know, “Of what fundamental stuff is the universe made?” Are matter and energy more fundamental than space? Perhaps information or consciousness or vital spirit is more important still? And what exactly will happen to that inner essence I think of as myself after my body dies? It seems our expectations of a TOE are so great there is no end to the questions!

## 2. Building Information Concepts and Optimizing Principles into a TOE

I could call the fundamental mechanism by which information is exchanged, how “it” becomes “bit,” “handshaking,” or “pinging.” Instead I’ll relate it to action and Newton’s Third Law: forces come in pairs: action forces and reaction forces. Action forces and action, though related, are different. Action refers to an amount of energy transferred in a process multiplied by the time elapsed $\Delta t$. Optimizing principles are laws in which some physical quantity must be a maximum or minimum under certain conditions. Action is such a quantity; entropy, a measure of disorder, is one; free energy is another.

The second law of thermodynamics says the entropy of an isolated system can only remain constant or increase, the latter occurring where irreversible processes are involved. Life’s processes, in tending toward increasing organization and decreased entropy, seemingly violate this law, but that’s only because they are open systems. For a larger system made up of living creature and surrounding environment, the decrease in entropy in the living subsystem is offset by increased entropy in the environment.

While the second law can be seen as a principle of maximum entropy, it can also be connected to energy transfer and gradients. In this form, it prohibits a spontaneous transfer of heat from lower to higher temperature regions. By itself, heat doesn’t move up the “temperature hill.” In general, one can view nature’s inexorably driving matter toward equilibrium as pushing it downhill toward stability and attempting to level any gradients that exist in the process. As biologist Eric Schneider puts it, "Nature abhors gradients" (Schneider, 2004).

In creating order and existing far from equilibrium, life seemingly resists nature's leveling tendencies, but only if one focuses on living system *S*. Schneider believes detailed energy accounting for both *S* and surrounding environment *E* shows that life represents a particularly efficient way of carrying out nature's overall mandate of increasing entropy, leveling gradients, and seeking equilibrium. For inanimate matter, Verlinde's connecting forces with entropy gradients wonderfully illustrates this. He traces the origin of gravity and inertia to nature's seeking to maximize entropy. Appreciating his argument requires understanding entropy from an information theory perspective.

Inspired by Boltzmann's 1877 characterization of entropy in terms of the number of possible microstates which are available for a macroscopic system to occupy, in 1948, Claude Shannon conceived of measuring information content in terms of the binary digits (bits) needed to describe it. While convention specifies thermodynamic entropy and Shannon's information-related entropy in different units, when calculated for the same number of possible microstates or degrees of freedom, they are equivalent.

Information is not just an abstraction. It has a real representation, being encoded in atomic or molecular energy levels, spin states, sequences of nucleotide bases, neural synaptic connection patterns, etc. Rather than information quantity, information transfer deserves attention. As Bateson pointed out, "All receipt of information is necessarily the receipt of news of difference" (Bateson, 1979).

Physicists connect information transfer with energy and entropy changes. If an electron's spin changes from up to down, not only is there an energy transfer associated with that event, but communicating knowledge of such an event requires energy to successfully transmit it through a background of noise.

Entropy changes as information is transferred. Whereas a system in thermal equilibrium with the environment has maximum entropy, its randomness suggests maximum uncertainty and algorithmic incompressibility. There is no discernible message for an observer trying to extract a signal carrying information from such a source. Generally speaking, the entropy of a system has decreased if its state after the event (measurement, information transfer, etc.) is more sharply defined (less uncertain) than before, and the entropy of the surrounding environment has increased. Where life is concerned, living systems have been described as "sucking information out of the environment," and their fitness determined by "the most fit is the best informed." Such systems pull energy from the environment and occupy low entropy, minimum uncertainty states.

Whereas entropy is often associated with unorganized or useless energy, free energy is connected with energy capable of doing useful work. Like entropy, free energy has been interpreted in an information theory context. Karl Friston, a neuroscientist, has examined theories about how the brain works (Friston, 2010). He writes, "If we look closely at what is being optimized, the same quantity keeps emerging namely value (expected reward, expected utility) or its complement, surprise (prediction error, expected cost). This is the quantity that is optimized under the free energy principle."

Friston's free energy gauges some difference of interest between living system and environment. Grandpierre has used extropic energy in making a similar assessment (Grandpierre, 2007). Verlinde's conception of gravity is based on equating an energy difference, between a configuration of matter and an equilibrium configuration, with both work done by a restoring force and the product of temperature and change in entropy.

Depending on the interpretation, free energy, extropic energy, entropic energy, traditional Lagrangian, or combinations of these are appropriate as "energy difference" input to action principles. Such principles can be generalized and made more applicable. In this regard, consider a *generalized optimal action principle* (*GOAP*) that maximizes stability:

$$\delta\left(\text{generalized action}\right) = \delta\left(\int\left(\text{energy difference}\right)dt\right) = 0 \tag{1}$$

Here variation $\delta$ requires generalized action be optimized, minimized, or maximized, over some path in some unspecified (real, phase, or conceptional) space.

Applying the GOAP requires computing generalized action. Imagine system *S* changes state, moving along some path from point 1 at time $t_1$ to point 2 at time $t_2$. Computing the generalized action involves breaking the path up into tiny time intervals, multiplying the energy difference for each one by the tiny time duration, and summing (integrating) these products over the path. If *S* is nonliving, the energy difference can be the total energy (the Hamiltonian) minus the potential energy that exists between system and environment stored in the conservative force field. For living system *S*, the energy difference can be interpreted in different ways. Whether generalized action is minimized or maximized depends on the system being considered.

If boundaries are drawn to solely include a living system, summing up the products of energy transferred from the environment by time over a path representing the lifetime of the system will maximize generalized action. If system boundaries are drawn to include the surrounding environment, generalized action is minimized. Entropy is maximized, but in attaining equilibrium, the associated energy difference between the matter part of the system and the environment fluctuates around 0. Many will argue that for living systems in a steady state (homeostasis), generalized action will be only locally minimized since the path will not include the death of the organism (where it arrives at a true minimum). Schneider disagrees. He believes life represents the most efficient way to degrade energy. His models suggest life's processes maximize entropy faster than a system that did not include living creatures would (Schneider and Kay, 1994).

Complex adaptive systems (CAS) that learn from their environment can be considered as minimizing generalized action. This view is facilitated by a system that represents an internal model the CAS has of itself and of the environment.

Ideally, the fit between system and environment is an increasingly good one over time. I see Friston's free energy principle, based on his modeling of the brain, as calculating generalized action based on (what he calls) surprise or a quantity gauging system minus environment prediction error expressed in information theory terms. Then minimal generalized action represents minimal uncertainty, meaning the most probable, most stable state.

In concentrating on the interaction or fit between system and environment, the GOAP recognizes "physics is simple only when analyzed locally" (Misner et al., 1973). Information transfer requires the handshaking of action/reaction forces. Accordingly, Newton's Third Law can mean, "If the system pushes on the environment, the environment unavoidably pushes back on the system."

## 3. Building Adaptive Mechanisms into a TOE

The GOAP applied to living systems can quantitatively assess life adapting to its environment. What specific adaptive mechanisms are employed? Classically, we think of genes experiencing mutations (changing genotype) and expressing themselves (changed phenotype) in the structure or behavior of the organism. Mutations that enhance survivability and lead to more copies eventually establish themselves within the population. Such changes are called adaptations. In this way, the fit between an organism and its environment improves. This fit can vary due to environmental changes, forcing whole populations to respond by adapting or dying out. Mutations and resulting adaptations are usually thought of as part of a slow process, like a drunk setting off from a street corner in random walk fashion. As we shall see, quantum random walks may speed up this process.

Complex adaptive systems (CAS) can speed up the learning about the environment process. Where such a system is positioned in a 3D fitness landscape helps determine what adaptations it can make. Before considering such a plot, note where life is found in a simpler diagram (Fig. 1): at a medium distance from equilibrium where structures experience a range of fluctuations, where maximum capacity for adaptability lies (Macklem, 2008). To further distinguish living CAS from nonliving systems, consider Fig. 2, where stability (the inverse of biologists' fitness function) is plotted vertically down from a 2D horizontal plane. There, potential niches are identified using two variables (expressed in energy units): a system's distance EX from thermodynamic equilibrium and the amount of information IX it exchanges with the environment.

In this plot, the deeper the valley, the greater the stability, and the steeper the slope, the greater the selection pressure. It pictures the stability the GOAP could conceivably specify mathematically for complex systems. For a CAS, the worst place to be is at the origin, where $EX = 0$ and $IX = 0$, representing equilibrium (death). The randomness there represents maximum uncertainty in terms of trying to extract a message, meaning information transfer between system

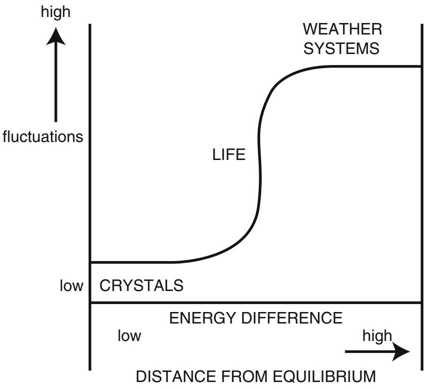

**Figure 1.** Life at the edge of chaos.

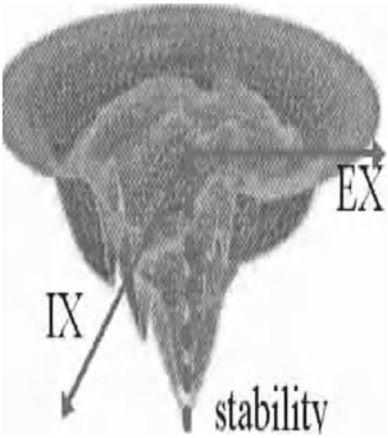

**Figure 2.** Fitness stability landscape.

and environment is impossible. The best place is in one of the not so deep valleys a medium energy distance away from the origin and "on the edge of chaos." Chris Langton says this is where "information gets its foot in the door in the physical world, where it gets the upper hand over energy" (Lewin, 1992).

A diversity of living systems – ecosystems, immune systems, neural networks, and genetic landscapes – have been successfully modeled using both simple binary networks and more advanced networks known as cellular automata. One such model is the Game of Life, invented in 1970 but recently in the news with a discovery that prompted this headline: "The Life Simulator – a self replicating creature that might tell us something about our own beginnings" (Aron, 2010).

Before life's origin can be definitively described, we need to agree on a definition of it. By 1950, von Neumann decided living things differ from machines in that, unlike machines, they not only reproduce themselves, but also do self-repair. Biologists' definitions typically included homeostasis, meaning systems work together to maintain the internal temperature, pressure, nutrient levels, waste products, etc., within normal ranges. The new field of cybernetics helped to broaden the conception of life. Norbert Wiener was fascinated by systems where "causes produce effects that are necessary for their own causation" (Wiener, 1948). With understanding of DNA and messenger RNA, it soon became apparent that a nice closure existed in the genetic code and its operation: "nucleotides code for proteins which in turn code for nucleotides" (Prigogine, 1997).

By the mid-1970s, Varela and Maturna had described the organization typical of most adaptive systems (Varela et al., 1974). Using the term autopoietic system, they characterized it in similar circular fashion, noting "the product of its operation is its own organization." Besides this conceptual closure, they recognized the importance of a boundary (cell membrane, etc.) that provided physical closure. To them, living things are built around three interwoven things: an autopoietic pattern of organization, embodied in a so-called dissipative structure, and involved in a structural coupling life process they call cognition. Acts of cognition, they say, produce structural changes in the system, which itself specifies which perturbations from the environment trigger such changes. Just as Prigogine, whose dissipative structures concept they borrowed, liked to stress the dynamic, spontaneous aspect of life by emphasizing its "becoming" rather than its "being," Maturna and Varela felt "to live is to know."

Stuart Kauffman has investigated $NK$ genetic fitness landscapes. Learning from complex binary network models with $N$ nodes and $K$ inputs to each node, he located the boundary between order and chaos in the $K=2$ region. Below that, periodic attractors became, as $K$ decreased, more stable point attractors. As $K$ steadily increased above 2, strange attractors and totally chaotic behavior resulted. Using a more sophisticated model and random adaptive walks, Kauffman let the genes of different organisms interact and found the evolving genes of one organism altering the fitness landscape of other organisms. He eventually concluded, in the words of science writer Roger Lewin, "coevolving systems working as CAS tune themselves to the point of maximum computational ability, maximum fitness, maximum evolvability" (Lewin, 1992).

In an effort to improve their fit with the environment, some CAS have a mechanism for anticipation, based on pattern seeking and internal models of the environment. According to John Holland, these take two forms, tacit and overt (Holland, 1995). The first "simply prescribes a current action, under an implicit prediction of some desired future state." He cites "a bacterium [moving] in the direction of a chemical gradient, implicitly predicting that food lies in that direction." In contrast, more advanced CAS use both tacit and overt models. The latter "is used as a basis for explicit, but internal, explorations of alternatives, a process often called look ahead." The internal model physically realized in neural network connections in our brains is often employed for this purpose.

Some CAS maintain a dialogue with nature in which feedback continually informs internal models by testing the predictions they make with real experience outcomes. According to Friston, the human brain employs Bayesian probability to continually update probabilities of certain outcomes based on new information (Friston, 2010). Unlike most complex systems, human internal models include not only system and effect of the environment on the system but also effect of the system on the environment. It seems that neither top down nor bottom up one-way processes are typically found in nature's mechanisms; instead, circular feedback loops are everywhere.

Dennett has characterized evolution over geological time in terms of matter steadily relying less on random dumb luck and more on skill (Dennett, 1995). This skill, in the form of pattern recognition programs sorting and winnowing to gather information, storing it in structures that grow in complexity over time, learning about the environment through feedback, has been slowly acquired. Systems able to take advantage of a fortunate position in a fitness landscape learn faster and adapt better than others. Natural selection weeds out those that don't. In the long run, not just individual organisms but whole ecosystems evolve in a way that maximizes fitness and stability.

## 4. Building Understanding of Mysterious Information Transfer into a TOE

Consider mysteries involving living creatures. By some accounts, green plants convert sunlight into chemical energy with nearly 100% efficiency; birds find their way back to preferred sites after journeys of thousands of miles; after intercourse, humans are naturally drugged and their lethargic inactivity gives sperm a better chance of fertilizing an ovum.

To physicists used to thinking about forces causing certain effects, these are troubling examples of life directing its future behavior, of processes where goals seemingly initiated at higher levels in a system's organizational hierarchy dictate what happens at lower levels. They seemingly involve teleology and downward causation mechanisms. They are difficult to explain. Perhaps the ultimate mystery for evolution to explain is consciousness, described as an emergent phenomenon in a multileveled system in our brain where "the top level reaches back down toward the bottom level and influences it" (Hofstadter et al., 1979).

The mysteries aren't confined to the living world – the quantum world is full of them. Consider something as simple as the famous double slit experiment of physics, in which light shines on a screen containing two narrow slits. Which slit do individual photons go through in producing the interference pattern seen on a second screen? It seems like they go through both of them simultaneously and they are both particles and waves! Many feel understanding this is the key to making sense of quantum mechanics and explaining many of life's mysteries.

Before applying the GOAP to quantum systems, consider a statistical physics approach to handling systems involving large numbers of interacting particles. This can involve isolating each particle $S_i$ of the system and studying its Brownian motion. In the resulting random walk, each step, due to a collision with a particle $E_j$ in the environment, would be expected to cover distance $d_{12}$ = the square root of $N$, where $N$ = # of collisions or steps between times $t_1$ and $t_2$ (Feynman, 1963).

An optimal action principle is used in quantum mechanics, with the action appearing in the phase of wave functions. Feynman's path integral formulation (Feynman and Hibbs, 1965) supposedly removes teleological concerns about how the particle knows the "right" path to take. It involves calculating the probability of the particle taking a particular path and doing this for *all* possible paths. The process can be connected to quantum random walks, which have significant advantages over classical random walks. They are more efficient at moving particles: particle $S_i$ taking $N$ steps between times $t_1$ and $t_2$ would be expected to travel distance $d_{12} = N$ – quadratically faster (Kempe, 2003)!

Quantum random walks seemingly allow systems to do something analogous to what a good chess player does: analyze all possible moves and pick out the best one *before it is made*. Perhaps this can explain what puzzled physicist Roger Penrose back in 1989, when he said, "There seems to be something about the way the laws of physics work which allows natural selection to be a much more effective process than it would be with just arbitrary laws" (Penrose, 1989). How do the laws of physics explain this and other mysteries of the quantum world?

In the last three decades, physicists in the tradition of Bohr and Wheeler have made progress in understanding how particles like photons choose a particular path and how classical trajectories emerge from the randomness of the quantum world. One of their leading theories is Quantum Darwinism (Zurek, 2003). It uses an environment-induced selection rule, based on minimizing uncertainty, to explain which of a multitude of possible quantum system states are physically realized. These quantum states, which actually survive to have more than an imagined, virtual existence, are called pointer states. The extent to which these disseminate and are redundant measures their fitness. Using GOAP, and thinking of a ball naturally rolling to a stable, lowest energy position of equilibrium in a gravitational field, I see pointer states as follows. Of many possible systems operating between fixed points between times $t_1$ and $t_2$, they represent those in which the generalized action, based on the energy difference between them and the surrounding environment, is minimal – meaning they are the most stable states.

Why is this called Quantum Darwinism? I think of a Darwinian process as follows. Copies, some slightly different, are made of the original initial system $S$; these copies' fit with their environment varies; as time passes, and natural selection does its work, the population of copies of $S$ will reflect the fitness (i.e., the most fit copies will survive and produce more copies). Respecting a (no-cloning) theorem that forbids making copies of pure quantum states, in Quantum Darwinism, the most robust, most stable pointer states replicate the most in the classical realm. These interact with the environment, leading to slight variations of them, and the testing by natural selection you would expect.

In general, the quantum state of the system is a superposition of many individual states. The coupling or coherence that exists between two of these individual states can be likened to the interference effects seen between light waves emanating from the two slits in the double slit experiment. Just as forcing a photon through one slit by measuring its position destroys the interference effects (and makes wave functions collapse), measurements or interaction with the environment destroys coherence in quantum systems. While Quantum Darwinism details how information about decohering systems is coded in the environment, quantum computing involves working with (initially) coherent quantum systems to encode information and avoiding decoherence. So each step of a quantum random walk is made without an intermediate measurement, which would destroy information and its advantage over its classical counterpart. A quantum walk can be seen as a process in which a system learns about its environment without provoking it.

Nature apparently employs quantum random walks, most notably in its design of a key photosynthetic mechanism as the following news item highlights. “Photosynthetic proteins are ‘wired’ together by quantum coherence for more efficient light harvesting in cryptophyte marine algae” says a report in *Nature* (Collini et al., 2010). It’s referred to as nature’s “quantum design for a light trap.” Seemingly, the photons involved explore all possible paths and pick the best one. The previous week, another group reported finding unexpected long-lived quantum coherence at room temperature in photosynthetic bacteria (Engel et al., 2010). They cite protection provided by a “protein matrix encapsulating the chromophores” and assert “the protein shapes the energy landscape and mediates an efficient energy transfer despite thermal fluctuations.”

How photons know the best path to take is one mystery physicists seek to explain using quantum theory; another involves how the 100 or more amino acids in proteins so quickly fold into the correct shape to become biologically active. After a stunning breakthrough in modeling why such folding depends on temperature in such an unexpected way (Luo and Lu, 2011), it seems clear that a quantum approach is needed to understand this mystery. A third mystery involves resolving the incompatibility between quantum field theories, one being quantum electrodynamics in which the photon serves as field particle, and the holographic principle. Basically, field theories allow an infinite number of degrees of freedom, whereas holography restricts these to a finite number. According to the latter, our universe has two alternate, but equivalent descriptions (Bousso, 2002). One is provided by information that fills the 3D (or ND) volume of space, the other by information stored on a 2D ([N-1] D) surface bounding the volume. The descriptions are equivalent, so the maximum amount of information that can be stored in a region, or equivalently its entropy, depends on its surface area, not volume. Could it be the universe acts like a giant hologram with information transfer being the fundamental process?

Like holography, certain quantum phenomena suggest the possibility of nonlocal information transfer. From experimental tests of Bell's theorem, physicists conclude that for two coherent, entangled particles, what happens at one place to one of them can instantaneously affect the other, no matter what distance separates them (Kuttner and Rosenblum, 2010). Could it be in this virtual world of entangled photons time does not exist? A TOE could clear up many mysteries involving information transfer, whether they arise from seeming downward causation, quantum weirdness, etc. A final one that deserves mention: how random matrix theory, developed to model quantum fluctuations but increasingly applied to diverse phenomena, hints at a "deeper law of nature" (Buchanan, 2010).

## 5. Building Mechanisms for Improving Conceptual Models into a TOE

The conceptualization process involves observing, abstracting, recalling memories, discriminating, categorizing, etc. As you grow, you steadily organize these concepts into conceptual schemes and put those schemes into a framework. Gabora and Aerts seek to explain this worldview development process using a model and a theory of concepts, known as SCOP for State COntext Property (Gabora and Aerts, 2009). They consider "how concepts undergo a change of state when acted upon by a context and how they combine." After building a formalism that begins with a set of states the concept can assume, and another set of relevant contexts, they identify a theoretically possible (but in practice difficult to observe) "ground state" of a concept as "the state of being not disturbed at all by the context." A context "may consist of a perceived stimulus or component(s) of the environment…or entirely of elements of the associative memory."

They add concept states together like a linear superposition of quantum states, identify a "potentiality state…subject to change under the influence of a particular context," and liken the change of state associated with this to quantum state collapse. I see their concept states as system states, and context states as the environment. They go on to define a cognitive state in an individual's mind as "a state of the composition of all of [the] concepts and combinations of concepts of the worldview of this individual," discuss how they employ SCOP to study how "more elaborate conceptual integration" can be achieved, and proclaim the worldview is "the basic unit of evolution in culture."

I like the thought of competing worldviews. Seems the competition will be decided on the basis of which model best represents reality, as measured by the ability to make useful predictions over the time frame of interest, and how well the conceptional system representation $S$ fits the real environment representation $E$. The winner will be the worldview that minimizes the $S$-$E$ difference over the relevant path in conceptual space. Perhaps a next step is translating that difference into energy, or prediction error information counterpart, and applying the GOAP!

## 6. Putting It All Together

Here's a recipe for using my imagined TOE to attack certain problems of interest.

1. Define the problem, gather data, and define the system and hierarchy. Quantify the system <===> environment relationship and build an initial model. Identify and attempt to quantify uncertainties and approximations. If modeling a system that learns from the environment like a CAS, provide an internal model and provide for Bayesian updating. Build in and quantify adaptive mechanisms, feedback loops, and autopoietic organization.
2. This model uses the GOAP to optimize fit between system and environment.
3. Refine the model by testing, using related problems with known solutions.
4. Construct initial candidate (imagined optimum system) to use as input. Create more by making slight alterations, combinations. Test using Darwinian selection.
5. Let output dictate what steps need repeating, perhaps for another part of the system.
6. After many iterations, after runs for various subsystems if need be, the model's output should converge on an optimum solution, specifying how well the selected system adapts to the environment, gauged by reproductive, perpetuative, or predictive success over time.
7. How fast steps 4–6 above are carried out may depend on how (or if) the model and the TOE use quantum computing and apply holographic principles.

At its core is optimization based on the Generalized Optimal Action Principle (GOAP) and use of Darwinian natural selection. Given the amazing range over which these techniques are potentially applicable, we might refer to the latter as Universal Darwinism! Conceivably, it might be applied to quantum states (Quantum Darwinism), genes (biological evolution), neural networks (brain), conceptual frameworks (worldviews), or universes. For the latter, Susskind cautions the cosmological natural selection he describes doesn't involve competition among pocket universes for resources. Clearly, there are limitations. For social problems, this recipe may not help – see "Dancing With Systems" (Cook, 2009)!

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Biodata of **Subhash Kak**, author of "***Hidden Order and the Origin of Complex Structures***."

**Subhash Kak** is Regents Professor and Head of Computer Science Department at Oklahoma State University in Stillwater. Born in Srinagar, Kashmir, he completed his Ph.D. in Electrical Engineering from Indian Institute of Technology, Delhi, in 1971 and then joined it as a professor. During 1979–2007, he was with Louisiana State University, Baton Rouge, where he served as Donald C. and Elaine T. Delaune Distinguished Professor of Electrical and Computer Engineering. His technical research is in the fields of information theory, neural networks, and quantum information. He has also written on the history of Indian science and on art. This work, as well as a resolution of the twin paradox of relativity theory, has received considerable attention in the popular press. His work has been showcased in the popular media including Discovery and History channels, PBS, Dutch Public TV OHM, and most recently in a documentary on music (www.ragaunveiled.com). He has written on philosophy of mind and showed how recursion plays a fundamental role in art, music, and aesthetics. He is the author of 20 books of which the most recent is "The Prajna Sutra." He has also authored six books of verse. These books have been translated into French, German, Italian, Spanish, Korean, and Serbian. The distinguished Indian scholar Govind Chandra Pande has compared his poetry to that of William Wordsworth. Among his awards include British Council Fellow (1976), Science Academy Medal of the Indian National Science Academy (1977), Kothari Prize (1977), UNESCO Tokten Award (1986), Goyal Prize (1998), National Fellow of the Indian Institute of Advanced Study (2001), and Distinguished Alumnus of IIT Delhi (2002).

E-mail: **subhashk@cs.okstate.edu**

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# HIDDEN ORDER AND THE ORIGIN OF COMPLEX STRUCTURES

**SUBHASH KAK**
*Department of Computer Science, Oklahoma State University,
Stillwater, OK 74074, USA*

## 1. Introduction

Consider the limitations of logic and language for our understanding of physical reality. It is known that formal systems are incomplete and inconsistent, which means that our knowledge of the physical reality as a formal system can never be complete, even in principle. Here we look at the problem of incompleteness from a different perspective, seeing it as a consequence of a deeper order. This order is opposite to that of explicit order of classical scientific theory in which an isolated system is taken to be localized and separate from the rest of the world. Hidden order implies strong correlations across space and time as are true for quantum theory, and there is evidence that correlations exist in the domain of human affairs (Kak, 2009; Bem, 2011). We propose that similar correlations are present across structure and the origins of design lie in this hidden order.

We begin with the relationship between incompleteness of knowledge and its communication by means of paradoxical statements. The word "paradox," from Latin *paradoxum* or Greek *paradoxon* (para-, *beyond*; doxa, *opinion*), literally means "conflicting with expectation." Another form of paradox is a statement that truly is contradictory and yet follows logically from other statements that are not open to objection. A paradox is a consequence of the application of an incomplete theory or a consequence of the use of a nonapplicable logic. The existence of paradox implies that hidden order underlies the behavior of the system.

If we step back and consider what we mean by a system, we realize that its mathematical conception creates interesting problems. At the philosophical level, objects of study may either be seen to be *real* or only *phenomenal* contents of our mind. At a more practical level, when it is posited that agreement on the phenomenal contents of many minds implies real existence, the question of the nature of the qualities of the objects arises. Do these attributes or concepts have a real existence or do they arise from the intuition of the observers? This question cannot be resolved using logic.

The scientist's intuition is central to a personal understanding of reality. Certain concepts must be left undefined in any theoretical framework because otherwise the framework would involve circular reasoning. These undefined

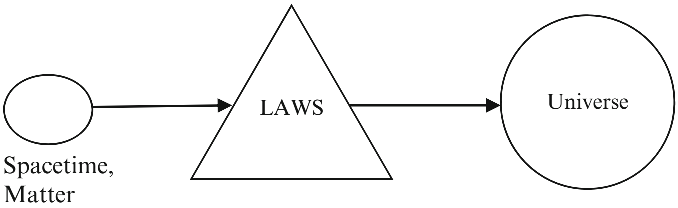

**Figure 1.** Universe unfolding out of the prism of laws.

concepts are understood intuitively. Time and space are left undefined in physical theory, and our intuitions about these arise from our personal experience of change and extension. Objects that go directly into physical theory are defined in operational terms and related to well-defined protocols of measurement.

Figure 1 represents the standard scientific view of the evolution of the universe by the flow of space-time and matter through the prism of laws. As these laws are linear, it is possible to study local regions (Kak, 2009). Although this picture has served science well in determining the large-scale structure of the universe, it does not work as well in the investigation of teleological systems.

Philosophers are aware of the limitations of "scientific explanations." The skeptics in Greece spoke of the impossibility of "complete explanations" when they said that demonstration depends either on things that demonstrate themselves or on principles which are indemonstrable.

In India, the Vedic view takes reality to be unitary at the deepest level for otherwise there would be chaos. This reality is called *Brahman* (neuter gender). Brahman engenders and, paradoxically, transcends the mind/matter split. It may be seen as consciousness at the cosmic scale that informs individual minds. Turning focus to the very nature of the mind provides insight on consciousness. Since language is linear, whereas the unfolding of the universe takes place in a multitude of dimensions, language is limited in its ability to describe reality. Because of this limitation, reality can only be experienced and never described fully. All descriptions of the universe lead to logical paradox, and Brahman is the category transcending all oppositions (Kak, 2004).

The Vedic view classifies knowledge into two categories: the higher or unified and the lower or dual. Higher knowledge concerns the perceiving subject (consciousness), whereas the lower knowledge concerns objects. Higher knowledge can be arrived at indirectly through intuition and contemplation on the paradoxes of the outer world. Lower knowledge is analytical, and it represents standard science with its many branches. There is a complementarity between the higher and the lower, each being necessary to define the other. This complementarity mirrors the one between mind and matter. According to the Vedic view, it is impossible to develop a language-based "theory of consciousness" (Kak, 2010).

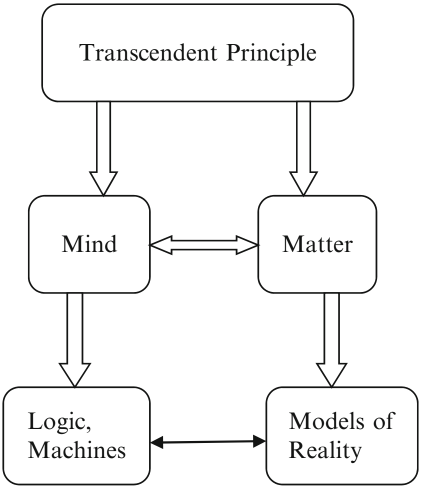

**Figure 2.** Universe as projection of a transcendent principle (*broad arrow* is projection; *narrow arrow* is full representation).

Those aspects of reality that are well described by theories of physics are mathematical. Currently, there is no single overarching theory of reality, and the theories that we have are valid only over specified domains, leaving other conditions where the outcome of experiments is far from certain. Even if one were to accept that reality at the deepest level is mathematical, the question of the relationship between paradoxes of mathematics and physics remains (Fig. 2).

A scientific theory expresses relationships between concepts that are abstractions of observational processes. Equivalently, a theory is a linguistic description of natural processes that highlights causal relationship between variables. Logic and mathematics are the languages of science, and as the capacity of instruments to observe phenomena increases, it becomes possible to examine relationships between new objects or concepts and thus new theories are born. Linguistic descriptions of reality are, by definition, rational. Although science assumes that reality is rational, it is not clear that it is indeed so.

A scientific theory is a formal or logical system; therefore, there is a connection between limits of formal systems and limits of science. But it is well known that given *any* consistent set of axioms, there are true mathematical statements that cannot be derived from the set. The idea behind it is similar to the analysis of the Liar Paradox: *This sentence is false*. This sentence cannot be a true statement because if it were, it is false. Similarly, it cannot be a false statement because if it were so, it would be true. If a formal system is consistent and complete within itself, then it is inconsistent (Davis, 1965).

Since a scientific theory is a formal system, it follows that such a theory must be incomplete, and it must have paradoxical aspects. Conversely, one can think of simple formal systems (such as those that are applied to the social world), which are consistent, but which do not have any predictive power. Going from theory to physical systems, one may assert that physical systems will show paradoxical behavior, and if a system's behavior is entirely consistent, that is only because it has not been explored for the entire range of possibilities.

Paradoxical aspects of quantum description, and, by extension, of quantum reality are well recognized. Quantum mechanics may be viewed as an information theory related to observations associated with measurements. In the standard Copenhagen interpretation, it is assumed that one cannot speak of a reality outside of one's observations (Penrose, 2004). Quantum reality may also be seen to imply an implicate order (Bohm, 1982).

In this paper we show that hidden order not only characterizes quantum systems but also classical systems and that it should be seen as manifesting itself in correlations across time, space, and structure. These correlations explain why complex organic structures, which should be improbable based on frequency considerations, are commonly encountered in asteroids and meteors. The next sections of this paper consider mathematical and logical paradoxes, singular systems, evolution and genetics, and explicit and hidden orders.

## 2. Mathematical and Logical Paradoxes

Contradictions and paradoxes are a consequence of conflation of different intuitions or self-referral. M*athematical objects must have proper predicative definition* in which their properties are fully defined, but not all mathematical objects correspond completely to physical objects.

A finite mathematical system can be completely defined, at least in principle, in terms of all possible relationships that are associated with its elements. But a finite system is fundamentally incomplete since more elements can be added to it. Finiteness may be seen with respect to the number of elements as well as rules that govern the relationships among the elements.

Complete enumeration cannot be done for an infinite system. Furthermore, if the infinity is uncountable, as is true for our conceptions of time and space, then mathematical and logical representation may fall short.

Mathematical paradoxes make it clear that problems arise when intuitions from a finite set are applied to a reality associated with infinity. Consider, for instance, the Liar paradox in the following form: *A man says that he is lying; is what he says true or false?* Although a finite set of individuals may be taken to be truthful or liars, the sentences produced by them are potentially infinite in number, and these sentences may be true, false, or meaningless. The sentence of the Liar paradox belongs to the third category.

Zeno's arrow paradox shows that use of logical categories leads to the conclusion that motion is impossible. If we were to take the snapshot of an arrow at a point in its flight, the arrow is motionless. To move, the arrow must get from one point to another, and at each point considered individually, the arrow is still. If at every point and at every moment in its flight the arrow is still, then how is it

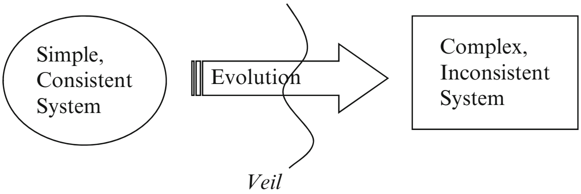

**Figure 3.** The paradox of estimating the finite basis of the complex system.

possible for it to move from the bow to its target? Similar reasoning applies to any other case of motion, and therefore, the assumption that the arrow is stationary at any point in time or space is wrong. It negates the view that space and time can be considered discrete.

Diogenes Laërtius in *Lives and Opinions of Eminent Philosophers* put Zeno's views in context by listing him as one of the skeptics who believed that complete knowledge could not be obtained:

> Zeno endeavors to put an end to the doctrine of motion by saying: "The object moved does not move either in the place in which it is, or in that in which it is not." (Laërtius, 1853)

Zeno clarifies his view of the impossibility of reality being many in this summary by Socrates in Plato's *Parmenides*: "If being is many, it must be both like and unlike, and this is impossible, for neither can the like be unlike, nor the unlike like."

The Achilles and the Tortoise paradox points to the impossibility of the runner overtaking the tortoise if motion is ordered by a mind that counts in discrete steps. Zeno explains in Plato's *Parmenides* that his objective is to show that the "hypothesis of the being of many, if carried out, appears to be still more ridiculous than the hypothesis of the being of one" (Plato, 2006).

"Being is one" is the idea that reality must be seen as a unity and not as a collection of parts that are *separate* from each other. Conversely, while analysis may work at some levels of discourse, it will not at other levels.

Figure 3 represents the paradox of deriving the complex from the simple. Since the inconsistent complex cannot be directly derived from the simple and consistent basis, a veil obscures a look back at the origins. In physical cosmology, the theory of cosmological inflation in the early universe is a device that acts as the veil. The other option is to discount a specific origin of the universe and assume that it was always infinite.

## 3. Singular Systems

Broadly, a singularity is a subsystem that is isolated from its environment, and it is able to interact independent of its neighborhood. A singularity is defined by much fewer parameters compared to the characterization of the larger system.

It cannot be put in a contextual relationship with other systems and may only be referred with respect to itself. The biological organism is singular, and it is also a hierarchical ecological system. Some paradoxes of the previous section arise out of the reconciliation of the action of the singular individual with the dynamics of the whole system.

In physics, black holes are an example of matter singularity. The entire cosmos is also a singularity. Under certain conditions, the black hole is a simple and consistent formal system. Conversely, the physical world of nonsingularities is a complex and inconsistent formal system (Fig. 3).

Since a consistent formal system cannot evolve into an inconsistent one, we can conceive of three possibilities:

1. Singularities do not exist.
2. If singularities exist they are veiled, implying that we cannot view them directly, as they are observationally absent.
3. A singularity cannot be viewed as a formal system.

The question of singularity may also be viewed from the perspective of information. A singularity, being apart from its neighborhood, cannot be part of a continuum physical theory.

The existence of black holes that are completely isolated violates the second law of thermodynamics. If black holes have entropy, then black holes get reintegrated in the larger physical system, and any decrease in the entropy of the particles entering the black hole is compensated by a corresponding increase in the black hole's entropy. This entropy can be related to temperature and, therefore, black holes emit radiation.

But the entropy measure for a black hole has a very high value. This leads to the paradox that the measure of entropy for material objects under the influence of gravity is different from that of gas particles. "For gas in a box, initially all tucked in one corner, entropy increases as the gas starts to spread itself throughout the box, finally reaching the uniform state of thermal equilibrium. For gravity, things tend to be the other way about. An initial uniformly spread system of gravitating bodies represents relatively low entropy, and clumping tends to occur as the entropy increases. Finally, there is a vast increase in entropy as a black hole forms, swallowing most of the material" (Penrose, 2004, p. 707).

In one proposal, elementary particles are mini black holes at different energy levels. But why shouldn't the entropy of uniformly distributed black holes be greater than that of a single black hole?

The selfhood of humans leads to paradoxes related to autonomy and freedom. Humans reject the idea that they are mere machines, yet they often equate their "self" with the machinery of the body. On the other hand, the human's self-image is that of the body, together with transient thoughts, which is overseen by an observing "I" within.

The human makes a distinction between the "autobiographical self," which is based on one's memories and relationships, and the "core self," which is rooted in the momentary present. The “autobiographical self” is *nāmarūpa* (Sanskrit for name and form), which is partly a result of one’s imagination since it is an interpretation of the past and it includes hopes for the future. The “core self” is elusive; it is the light that shines on things around and associates with them in time and space.

## 4. Genetics and Evolution

New evidence challenges the orthodox version of evolution according to which adaptation occurs only through natural selection of chance DNA variations. It is now known that organisms have evolved mechanisms to influence the timing or genomic location of heritable variability and, therefore, selection and variability are not independent.

Epigenetic inheritance is brought about by chemicals that change the way enzymes and proteins have access to DNA. One of the best understood mechanisms of epigenetic change is nucleotide methylation that can alter gene expression. It was found that DNA methylation is crucial step in memory formation (Miller and Sweatt, 2007).

Rando and Verstrepen (2007) provide the following summary of the influence of epigenetic inheritance:

> Microbes often find themselves subject to rapid environmental change (and thus variable selection) without any means of escape. They experience rapid changes in nutrient levels, osmolarity, concentration of (toxic) chemicals, and, in the case of pathogens, the continuous dynamic battle against host immune defense. Hence, it is perhaps not surprising to find that at least some microorganisms have developed mechanisms to maximize variability when and where it is most needed. Most of the described variability is in the cell surface, which is the cell’s most direct interface with the environment. Notably, the best known example of regulated variability in higher eukaryotes is that of increased variability in the immune system (which interacts with highly variable pathogens).

The extreme environmental change experienced by microbes mentioned above is paralleled by the extreme changes in the inner environment experienced by humans.

Jablonka and Lamb (2005) speak of four inheritance systems that play a role in evolution: genetic, epigenetic, behavioral, and symbolic, and that these systems interact among each other. The system of the interactions between the different inheritance systems may be viewed as the hidden order underlying evolution. Beyond this, if basic molecules that carry genetic information are formed at rates higher from those estimated on frequency considerations, this is an explanation for origin of life different from panspermia, which provides a resolution to the problem by assuming that it exists all over the universe (Wickaramasinghe, 2009). Panspermia does not address the problem of origin of consciousness (Kak, 2000), which may be seen as a consequence of hidden order.

## 5. Explicit and Hidden Orders

In classical physics, the time evolution of a system is completely given by initial conditions and differential equations that characterize the system. Such characterization is valid only for a certain range of applicability. The characterization considers ideal behavior, and departures from it are due to the limits of precision in modeling the system and its conditions and also the random perturbations affecting the system. At a broader level, such characterization is further circumscribed by the limitations of formal systems.

Photons or electrons sent one at a time through a double-slit experiment strike the screen at random locations individually, but collectively they form dark and light bands. Although this is viewed as individual particles going through both slits and interacting with themselves, this is impossible in a discrete conception of the photon or electron. An alternative explanation is in terms of hidden order in collectives.

The reductionist conception of simultaneous passage through two slits indicates the inadequacy of language and logic to explain the phenomenon, the conception of hidden order provides a clearer picture that throws light on paradoxes of physics and cosmology. Quantum theory uses the language of superposition of mutually exclusive properties and collapse upon observation. This is a dual description: the system is deterministic as long as it is left alone to evolve by itself, but upon interaction with the environment (which could be the observer), it reduces into one of its components. This is equivalent to saying that a web of interactions that are not just local determines the unfolding of the system. In quantum theory, particles that are far removed from each other can be strongly correlated as is true for entangled particles. The conception of hidden order helps us to consider this problem as well as the problem of consciousness from a new perspective.

Hidden order may be viewed in terms of correlations or coincidences. Thus, in the double-slit experiment, one might speak of correlations that create dark and light bands. It is easy enough to test these correlations in an experiment at the atomic scale. The correlations on a larger scale are correspondingly harder to measure.

It is common to speak of chemistry arising out of physics, biology out of chemistry and consciousness out of biology. This means that just the physical laws do not fully describe the universe. Since chemistry, biology, and consciousness are latent in physics, it must be accepted that order and structure is latent.

Lothar Schäfer stressed that in addition to matter one must also consider potentiality and virtual states. Potentiality states are quantum states that are described in terms of probabilities. Virtual states are empty states that are a part of the system. In the words of Schäfer (2009):

> When a given atom or molecule is in its ground state, the higher states also exist, but not as empirical entities, because they are empty: there is nothing there to see. They exist in the sense that their mathematical order is part of the constitution of the system, contains its empirical possibilities, and is a priori predictable. Virtual states are mathematical forms, patterns of information, but they are more than mere formulae, because they have the potential to manifest themselves in the empirical world.

With the recognition of virtual states, it is clear that the evolution of the system is predicated on an order that is not apparent from the filled matter states alone. Likewise evolution cannot be viewed as a consequence of random events and flourishing of the forms that are best able to survive in the environment.

Hidden order may be mapped into the geometry of the attraction basins of the complex dynamics of the system (e.g., Kak, 1993). Stable structures are these attraction basins that are latent in the framework of laws together with the environmental conditions.

## 6. Concluding Remarks

The idea that observed laws are a consequence of the large-scale structure of the universe implies that in the conception of the localized early universe, descriptive theory will be characterized by further paradoxes. For example, we have the paradox that if entropy was a maximum at big bang, how can it still increase?

One way to circumvent these paradoxes is to acknowledge a veil over the earliest period so that one need not worry about the system being consistent. Consistency is problematic because if the universe is completely predictable and consistent in the early phase, it should be so at later phases, which is contradicted by the Incompleteness Theorem (Davis, 1965).

Conversely, one must postulate new mechanisms such as inflation or to live with big gaps in the descriptive framework as is done by dark matter and dark energy as far as the physical universe is concerned and by ignoring the problem of the origins of consciousness.

Hidden order may be behind the rise of complex systems. It is due to this order that the probability of these structures is much higher than what may be estimated from chance. The concept of hidden order is not a matter of change of terminology since it should be possible to design experiments to confirm or refute it at the macroscopic level.

The idea of hidden order has some convergence with the anthropic principle according to which laws of nature and the physical constants have the values they have because they make life and, consequently, observers possible. But unlike anthropic principle, where evolution is viewed as a random path, hidden order perceives complex structures as latent stable states implicit in the system of laws. One may go as far as to say that since hidden order can be comprehended by consciousness, consciousness is an expression of hidden order.

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Biodata of **Michael Dickson**, author of "***What the Fine-Tuning Argument Shows (and Doesn't Show)***."

**Michael Dickson** is currently professor in the Department of Philosophy and director of the Consortium for Science, Technology, Environment, and Medicine in Society at the University of South Carolina. He obtained his Ph.D. in philosophy from the University of Notre Dame in 1995. Professor Dickson's research interests are in the philosophy of physics, game theory, decision theory, and ancient philosophy.

E-mail: **dickson@sc.edu**

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# WHAT THE FINE-TUNING ARGUMENT SHOWS (AND DOESN'T SHOW)

**MICHAEL DICKSON**
*Department of Philosophy and Center for Humanistic Study*
*of Science, University of South Carolina, Columbia,*
*SC 29208, USA*

## 1. Introduction

### 1.1. THE FINE-TUNING ARGUMENT

Current physical theory contains a number of parameters, and if current physical theory is true, we can determine what the universe would be like (broadly), were those parameters to have different values. It appears that in order for the universe to be more or less the way it is in certain very general respects (e.g., in order for there to be atoms as heavy as carbon), the allowable range of their values is "very small" in comparison with the total range of mathematically possible values.[1]

Some physicists, philosophers, and theologians see in these facts evidence that the universe has been "fine-tuned" to be more or less the way it is (e.g., Leslie, 1989; Collins, 1999; Davies, 2007; McGrath, 2009). They argue that the extreme unlikelihood that things would turn out this way cries out for explanation and that the only decent explanation is that some intelligent designer, with the aim of generating a universe more or less like ours—a universe, in particular, in which intelligent life is at least possible—chose the values of various physical constants to be such as to generate such a universe.

This argument is in the tradition of "design arguments" for the existence of God. Perhaps the most famous example is the argument from analogy made by Paley (1802), who pointed out that a watch found on the heath would be supposed by any reasonable person to have come to be through the work of some intelligent designer rather than by chance. The cosmos (as the name implies!) is analogous to the watch—it is complex, appears to be delicately balanced to function in certain ways, and so on. Hence, a reasonable person will suppose that it, too, came to be through the work of some intelligent designer.

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[1] No attempt is made, here, at bibliographic completeness. The literature is too large. The interested reader will get a good start by following the references in the works cited throughout this chapter. A classic work examining some of the physical theory mentioned here is Barrow and Tipler (1986). Cf. Barrow (2003).

For present purposes, design arguments are interesting because they apparently do not appeal to anything but empirical evidence, and they reason from it in ways that are not at all uncommon. If you found a watch on the heath, I presume that you *would* conclude that it was designed and produced by some intelligent agent, and I know nothing about your theological views. The fine-tuning argument is thus often intended to appeal to a very general audience, unlike, for example, Anselm's (1965) ontological argument, which Anselm himself characterized as "faith seeking understanding" ("fides quaerens intellectum") rather than as a knock-down, drag-out argument for the existence of God that must convince all reasonable people. In this chapter, I argue that the fine-tuning argument is, however, an example of "faith seeking understanding." (The point here is not to condemn the argument but to characterize it.)

First, it will be helpful to have a slightly more explicit statement of the argument:

FT1 If some physical parameters were slightly different, then the universe would lack some properties apparently required for life as we know it.
FT2 The probability that these parameters would take this value "on their own" is very low.
FT3 Hence, they demand an explanation.
FT4 The explanation that they were chosen by a designer of some sort is better than the explanation that they arose by chance.
FT4′ That they were chosen by a designer of some sort has higher likelihood than that they arose "by chance."
FT5 Therefore, they were (probably) chosen by a designer of some sort.

## 1.2. SOME PRELIMINARY WORRIES

This argument has been questioned at every step. Here is a sampling of the problems that some have seen with it.[2] The point here is not to investigate these objections (and replies and replies to replies) comprehensively but only to give the reader some sense of how the dialectic often goes:

1. FT1 is misleading. While slight deviations of values could result in a loss of important features, significant deviations could give rise again to the features in question, or others that are sufficiently similar.

   Reply: We still need an explanation of why the values are 'here rather than nearby'.

   But: Only the absolute probability is important. What was originally surprising was the mere fact that our universe has certain features, not that those features are present in precisely this particular way.

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[2] What follows is by no means complete. To explore both these and other issues more closely, one might start with Manson (2000, 2003); Colyvan et al. (2005); Monton (2006). For the issue of multiuniverses, not explored here, see, for example, White (2000) and Manson and Thrush (2003).

2. A Grand Unified Theory (GUT) might determine values for the parameters, in which case FT2 is false.

   Reply (a) Restrict attention to phenomenological theories, not GUTs.

   But: The probabilities then depend unacceptably on ignoring the GUT. For example, given my total background knowledge, there is no mystery why I have a green car in my garage, but take away certain crucial elements of my knowledge, and suddenly the fact that I have a green car in my garage (or a garage at all) becomes surprising.

   Reply (b) Changing parameters in a phenomenological theory is just like changing the laws of the GUT.

   But: There is no guarantee even that there *is* a law corresponding to the altered value, much less that one could, e.g., 'continuously vary' the laws in the same meaningful way.

   Reply (c) But we don't *have* a GUT.

   But: True, so we just stay humble (fallibilist) about our conclusion.

3. What makes something a 'best explanation' (in FT4) is a notoriously slippery concept.[3]

   Reply: We have no general account of 'best explanation', but we make assertions about which explanations are best quite frequently, and our intuitive understanding of best explanation, guided in part by theory, is good enough for us day to day, so why not here?

   But: Because we are talking about the explanation of an event that is radically different from the sorts of event about which we normally assert that some explanation is best. Nor do we have theory to guide us here.

4. On what grounds is it claimed that 'design' has a higher likelihood than 'chance' (in FT4′)? One must have some way to determine what the features, capacities, aims, intentions, of a designer are before one could say how likely it is that the designer would make things one way rather than another.

   Reply: We know exactly what the features, capacities, etc., of the designer are by examining the product of the design.

   But: This is circular reasoning. If one antecedently believes in the designer, then this is a fair way to determine the designer's features, etc., but one cannot then conclude that the probability that a designer would do things this particular way is 'high', at least not in a way that would confer any more likelihood on a designer than on chance. For advocates

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[3] It is somewhat surprising that skeptical doubts about inference to the best explanation do not arise more explicitly than they do in this debate. For generic discussions of this issue (not in the context of fine-tuning), see, e.g., van Fraassen (1980) and Lipton (1991).

of chance could say the analogous thing, namely: *given* that things happened by chance, and given this particular result, the probability that chance produces this particular result is high (unity!). The argument is equally bad in both cases.

5. If FT5 is derived from FT4, then concerns about the validity of inference to the best explanation (IBE) come into play (see note 3).

   Reply: If admit skepticism about commonly accepted modes of reasoning, then all bets are off. IBE is widely used in science and elsewhere.

   But: The context here is quite different from the usual contexts in which IBE is applied. In the usual contexts, we have independent knowledge of the sort of thing proposed as an explanation (though admittedly the degree of independence is higher in some cases than in others—e.g., very high for 'a mouse is in my house', somewhat lower for 'a free electron is present in the outer shell', and quite low for 'the top quark mass is such-and-such'). In the cosmological context, we have very little independent understanding of 'that which gives rise to universes' (as opposed to 'that which gives rise to mouse droppings and scratchy noises', and so on)—the *only* evidence we have to go on, in fact, is this single product of that purported 'generator of universes'.

6. If FT5 is derived from FT4′, there is the additional problem that higher likelihood does not imply higher probability. For example, approaching things in a roughly Bayesian manner, likelihoods are related to posterior probabilities by $\Pr(H|E) = [\Pr(E|H)\Pr(H)]/\Pr(E)$, where $\Pr(E|H)$ is the 'likelihood' of $H$.[4] If $\Pr(H)$ is very low, then even when likelihood is high, the posterior probability $\Pr(H|E)$ may still be very low.

   Reply: One should (by the Principle of Indifference—see Sect. 2) assume equal prior probabilities for the two hypotheses 'design' and 'no design'.

   But: The principle of indifference is problematic (see Sect. 2). Indeed, the problem is very clear in this case, because we just don't know 'how many' hypotheses are 'contained in' 'design' and 'no design'. Neither by itself is specific enough to *be* an hypothesis, so both contain many hypotheses disjunctively. But how many?

None of the above considerations are, to my mind, conclusive. I turn, now, to a more careful consideration of FT2 and the inference to FT3. I begin with some observations about the nature of probability (Sect. 2), moving on to the

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[4] $\Pr(E \mid H)$ is the usual meaning of 'likelihood' in this context, and must be what is meant in FT4′, as opposed to $\Pr(H \mid E)$, because claiming that $\Pr(H \mid E)$ is higher for $H$ = design than for $H$ = chance would beg the question. For a discussion of likelihood in the context of design arguments, see Sober (2005).

question "What is *low* probability?" (Sect. 3) and finally to the question "Why (or when) does low probability demand an explanation?" (Sect. 4). I then return (in Sect. 5) to the fine-tuning argument.

## 2. The Nature of "Probability"

The interpretation of probability is a contentious area of inquiry, and here I set aside traditional debates about subjective versus objective interpretations and so on (though they are not irrelevant to the argument). Instead, I consider the issue (also controversial) of the extent to which probabilities depend on our mode of description of the possibilities. I will argue that in fact probabilities depend very strongly on how we describe the space of possibilities, in some trivial and some nontrivial ways.

### 2.1. THE ROLE OF THE SAMPLE SPACE IN FIXING PROBABILITIES

What is the probability of getting "heads" when we flip a fair coin? The usual answer is, of course, "1/2" and, of course, the same for "tails." But isn't there *some* chance that the coin will come to rest on an edge, or get caught up indefinitely in a cyclone, or be caught by a person before landing? If so, then the probability of getting heads and tails *cannot* be 1/2 each, on pain of violating the axiom of total probability. Hence, the correct probability to assign to "heads" depends, in part, on which other events one is countenancing as possible outcomes of the flip, i.e., on how one specifies the "sample space." Without a sample space, the probability of "heads" should be left undefined.

There does not appear to be, in general, a *unique* way of resolving the ambiguity that arises when we do not specify a sample space. In other words, events can be embedded in several sample spaces, and there does not appear to be any uniquely rational way to choose which is the "best" for any given event.

In the case where the sample space contains just "heads" and "tails," and we are given no other information, the Principle of Indifference ("In the absence of any information to the contrary, assign equal probability to all possible outcomes") says to assign probability 1/2 to both "heads" and "tails." Suppose, then, that we expand the space to include "edge." How do we assign the new probabilities? Of course, we are free to proceed as we wish, but presumably the reasonable answer is to assign nearly 1/2 to both "heads" and to "tails" and a low probability (to make up the difference) to "edge." What grounds such an assignment?

My view is that such an assignment, if carefully justified, will ultimately again rely on the Principle of Indifference. Here's how the justification would (or at any rate, in my view, should) go. One would observe that there are many orientations that the coin might have as it strikes the surface of the table and that only a small number of these orientations lead, physically, to the outcome "edge," while the others are equally split between "heads" and "tails." Of course, a lot of physics (or possibly geometry) lies behind a statement like that, but let's grant that a careful physical investigation of the dynamics of the process leads to that conclusion.

We are still left with the question: Why does the fact that only a small range of orientations leads to the outcome "edge" imply that "edge" has low probability? Here, the Principle of Indifference again comes into play. In the absence of any additional information bearing on the orientation at the moment of landing (e.g., about applied forces of the initial orientation of the coin), we should appeal to the Principle of Indifference to conclude that all orientations are equally likely.[5]

At this stage, then, the point is just that the probability of any given event will change, depending on one's choice of a sample space, together with a reasonable method for assigning probabilities to the elements of the sample space. Moreover, there is, in general, no uniquely compelling choice for the sample space. My further claim (merely illustrated here, not argued) is that this "reasonable method" for assigning probabilities once a sample space is chosen necessarily involves an application of the Principle of Indifference. However, appeal to that principle leads to yet another sense in which probabilities depend on choices made by us.

## 2.2. THE ROLE OF MODE OF DESCRIPTION IN FIXING PROBABILITIES

It is well known that the Principle of Indifference is problematic. Consider the following simple example (Keynes, 1921, ch. 4). You are to assign probabilities to the possible birthplaces of some unknown individual known to hail from one of France, England, Wales, Scotland, or Northern Ireland. You know *nothing else* about the situation (e.g., about the birth rates in these countries). Then, so the story goes, you should appeal to the Principle of Indifference and assign equal probabilities to each, making your probability for birth in France 1/5. What if, instead, we had described the possibilities as "France or the United Kingdom"? Now, merely as a result of changing our description of the sample space, the probability of France is 1/2.

There are a number of analyses of what has gone wrong in such cases.[6] A quick way to state the problem with these examples is that the two sample spaces are intrinsically different—we switched, in this example, from a five-membered space to a two-membered space.

One might suppose that the resulting shift in probabilities reflects *only* this intrinsic difference in the spaces and, thus, is just another example of the sort of sample-space dependence that we've already seen. But there are much stronger cases, as Norton (2008) has recently emphasized, cases that violate what Norton

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[5] For an account, the details of which I largely agree but whose conclusion I would characterize quite differently, see North (2010). Cf. Van Fraassen (1989).

[6] See, for example, Mikkelson (2004) and Bangu (2010).

calls the "Principle of the Invariance of Ignorance" (PII): An epistemic state of ignorance is invariant under a transformation that relates symmetric descriptions.

A famous example is von Mises' (1957) case of the ratio of water to wine in a glass. We are told that the ratio, *W*/*w*, of water, *W*, to wine, *w,* in a glass lies in the (real) interval [1/2, 2]. You are to assign probabilities to the possible values of *W*/*w* based only on this information. The point of von Mises' example was to show that the Principle of Indifference leads to nonintuitive results. But there is a more serious problem, as Norton points out, namely, the failure of the Principle of Invariance of Ignorance.

Suppose that you assign a flat probability distribution to the range of *W*/*w*. Having done so, you will have assigned probability 1/3 to the ratio's being in the interval [3/2,2]. There is another way to describe this ratio, namely, as the ratio of wine to water, *w*/*W*. This description is just as good as the first, in the sense that it describes exactly the same set of possibilities, and any description of the contents of the glass in terms of *W*/*w* has a corresponding description in terms of *w*/*W*. Indeed, there is a 1–1 and onto map from the first set of descriptions to the second, and this map is self-inverting. Hence, probabilities assigned by the Principle of Indifference (whatever they are) ought, by PII, to remain unchanged under this map. But this map takes the interval [3/2,2] to the interval [1/2,2/3], and the latter is not 1/3 the total range but 1/9.

Such examples can be multiplied indefinitely once one sees how they are generated. Norton shows that they are not even dependent on the fact that the cardinality of the sample space is that of the reals (an observation that is sometimes invoked to argue that the Principle of Indifference is unproblematic for discrete sample spaces). What lesson should we draw? Norton draws the lesson that total ignorance should not be represented by probabilities. But if you take the view—as I suggested above—that *all* ascriptions of probability are ultimately justified by an appeal to the Principle of Indifference, then Norton's view entails the (unacceptable) wholesale rejection of probability. My preferred conclusion is to admit that probability is *always* relative not only to a choice of sample space but also to a mode of description.[7]

## 3. What Is "Low Probability"?

There are thus two senses in which an event's being "low probability" may be relative: it may be relative to a choice of sample space and to our mode of description of that space. In this section, I investigate two more senses in which "low" may be relative.

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[7] The resulting position is not entirely relativist. Given a sample space and a mode of description, there is (or at any rate, may be) a correct answer to the question "What is the probability of *E*?". However, it *is* relativist in the sense that there is no absolute answer to the question "What is the probability of *E*?"; or rather, I prefer to say that this question is incomplete, as it fails to specify a sample space and mode of description.

## 3.1. HOW LOW CAN YOU GO?

Some [Refs] have argued that there is some number below which any probability must be supposed “low.” The number is typically based on various physical considerations, such as the number of particles in the universe, the number of quanta of energy in the universe, the age of the universe, and so on.[8]

Typically, such enterprises are accompanied by an attempt to overwhelm with incredibly low numbers. Such inconceivably low numbers such as $10^{-60}$ or even $10^{-40,000}$ are sometimes bandied about, [Refs] along with analogies such as hitting 1 part in $10^{60}$ is like hitting a 1-in. target from across the universe. But don’t be misled by these analogies. If you suffer from being too easily bowled over by such low probabilities, there is a cure. Every day in Las Vegas, dealers at the blackjack tables deal out a sequence of cards, the probability of which is (by a back-of-the-envelope calculation), to within a few dozen orders of magnitude, around $10^{-900,000}$.

There are no grounds for thinking that there is an *objective fact* about the universe that makes the sorts of numbers sometimes mentioned ($10^{-60}$, $10^{-40,000}$) “low” in a way that qualitatively differentiates them from “run-of-the-mill low.” What counts as “low” is what we *decide* counts as “low.”

## 3.2. LOW-PROBABILITY CLASSES

FT3 says that some particular “low-probability” outcome *demands* an explanation. Apart from the issues that may be raised by the considerations above, the claim faces the additional problem that *all* outcomes chosen from a sufficiently large sample space have the same low probability—do they *all* require an explanation (if they occur)? Presumably not—there is, presumably, no explanation to be offered for the sequence of blackjack cards dealt yesterday apart from “that’s just what happened.”

There is a standard solution to this problem, namely, to partition the class of all possible outcomes into the “random” ones and the “nonrandom” ones, or the “complex” and the “simple, or patterned” ones. There are various proposals for how to do so [Refs], but it is enough here to consider an example. Which sequences of cards drawn from a deck (let’s make it a single deck to keep things simple) should we consider “random”? A common answer to this question is that the nonrandom sequences are the ones that can be generated by some algorithm whose length is appreciably shorter than the sequence itself. An algorithm

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[8] It is far from clear what these physical facts have to do with the notion that a “low”-probability event needs explanation, but I will set that point aside.

that is the same length as the sequence can just be a list of the elements of the sequence itself.

In virtue of what could an algorithm do better, there are *relations* among the cards in virtue of which a sequence could be said to form a "pattern." For example, the sequence

$$\text{Ad, Ah, Ac, As, 2d, 2h, 2c, 2s,} \ldots \text{Kd, Kh, Kc, Ks} \tag{1}$$

can be reproduced by the algorithm "put the cards in order by rank and, within rank, by suit." This algorithm relies on the fact that the cards are taken to be ordered in a certain way. On the other hand, the sequence

$$\text{2d, 4h, Kd, Js, 8h,} \ldots \tag{2}$$

can (if I've chosen well) be reproduced only by the algorithm "put the cards in the following order: 2d, 4h, Kd, Js, 8h, …" (or algorithms approximately as complex as that—one is to imagine, of course, that (2) continues "in similarly random fashion").

As it turns out, the nonrandom sequences form a vastly smaller class of sequences than the random sequences. Hence, the random sequences, as a class, have high probability, while the nonrandom sequences have low probability.

Now we can say why it makes sense to say that sequence (1) has low probability, while sequence (2) has high probability. This talk is shorthand for the following: (1) is a member of the low-probability class of "nonrandom" sequences (i.e., sequences containing some pattern that can be exploited by an algorithm), while the latter is a member of the high-probability class of "random" sequences.

Note, finally, that if we ordered cards in some other way, the members of these classes would change. More generally, what *counts* as a pattern would change. You can impose any order you like among the cards. By convention, we order them in the way that my discussion has presupposed thus far, but there's nothing stopping you from declaring that the cards are to be ordered as they appear in (2). You'll be a miserable poker player if you order the cards in this way, but as far as "being an order" goes, it meets all the criteria.[9]

Hence, there is an element of relativity in the notion of "low probability"—a sequence's (or in general, an event's) being "low probability" means that it is a member of the class of nonrandom sequences (or events), and this latter notion depends on a choice that we make about what constitutes a "pattern" or an "order" (more generally, on relations that we impose on the sample space). Here, then, we have yet another sense in which probabilities are relative to choices made by us.

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[9] That is, it can be expressed as a relation on the set of cards with the proper mathematical properties (one that is reflexive, antisymmetric, transitive, and total).

## 4. When Do Events Demand an Explanation?

The topic of explanation is vexed in the philosophy of science [Ref]. While some sort of progress has been made on it in the twentieth century, I don't think that philosophers are anywhere close to having definitive things to say about it. Without a reasonable account of explanation, we will have to address the question "when do events demand an explanation?" very cautiously. My strategy is to suppose a minimal account of explanation, one that probably encompasses many of the more specific accounts on the market. I then propose a minimal account of what it means to "permit" an explanation and then consider what it means to "demand" an explanation.

### 4.1. A MINIMAL ACCOUNT OF EXPLANATION

The minimal account is just that explanations are answers to why-questions [Refs] and that a why-question, $Q = \langle T, C, R, K\rangle$, is characterized by four things. The "topic" ($T$) of the question is the thing to be explained by an answer to the question. The "contrast class" ($C$) is a set of things that one has in mind as "the things that could have happened instead of $T$, but did not"—the answer to the question will then account for why $T$ rather than any of $C$. The "relevance relation" ($R$) is the relation that any successful answer to the question must bear to $T$—for example, we might be interested in the *mechanical cause* of $T$ or, perhaps, the intentions of the agent who brought about $T$. Finally, the "background knowledge" ($K$) is what the inquirer already knows, which helps to determine what the answer doesn't need to mention ("You don't need to mention that chocolate has a pleasant bittersweetness; I already know what it tastes like"), as well as which answers that are unacceptable because they merely repeat what the inquirer already knows ("Yes, I assumed that you chose the chocolate because you like chocolate—I was really asking *why* you prefer chocolate to strawberry").

(The minimal account does *not* suppose that explanations are to be *characterized* as answers to why-questions, which would be a much stronger claim, but only that they in fact are such. So long as explanations, whatever they may be, can also answer a why-question, the minimal account stands.)

Given this minimal account, let us say that a topic, $T$, in contrast to $C$, *permits* an explanation of type $R$ for an agent with background knowledge $K$ just in case there is some legitimate why-question $\langle T, C, R, K\rangle$. This account is quite liberal but it is not vacuous: not every proposed why-question is a legitimate question. Some why-questions should be rejected rather than answered. There are at least four (and probably more) reasons to reject a why-question:

1. $T$ implies a falsehood. (Why is the moon made of cheese rather than wood?)
2. The members of $C$ do not truly contrast with $T$. (Why is the moon made of rock, rather than the Earth being made of rock?)

3. Nothing in fact bears the relation *R* to *T*. (Why, causally or mechanically, are there correlations in the EPR-Bohm experiment?[10])
4. Nothing that bears *R* to *T* accounts for the occurrence of *T* rather than any of *C*. (Why did the electron come out spin-up rather than spin-down?[11])

If *K* implies one of these problems, then the asker should, or at least could in principle, know better, and the question is itself illegitimate. If *K* does not imply any of these problems (nor any others that might render the question unanswerable), then the question itself is legitimate, though, of course, it might still be unanswerable (if one of the problems above does in fact obtain, just not in a way that follows from *K*).

## 4.2. THE (MINIMAL) ROLE OF LOW PROBABILITY

What, now, of *demanding* an explanation? One might be tempted to say that a topic *T* in contrast to *C* *demands* an explanation of type *R* for an agent with background knowledge *K* just in case it permits such an explanation, and the probability of *T* given *K* is much lower than each element of *C*; *T* is "surprising," relative to the alternatives. I claim that this approach is wrong and that low probability has almost nothing to do with "demanding" an explanation. I will not pursue that general claim here, however, but instead focus on explanations where *R* is "intentionally brings about"—let's call them "i-explanations." I consider two examples, focusing, at first, on permission.

John chooses a jelly bean from a jar containing 98 blacks and 2 reds. He chooses a red. Does the result ("red rather than black") permit an i-explanation? We need to know more about this situation (i.e., more about *K*) before we can answer. So consider the following two ways of filling out the details of *K*.

John is blind. The beans are well mixed. John has no stake in the outcome. In this case, probably no i-explanation exists, and it would be reasonable, given this knowledge, to reject the question. "Red" just happened. Sometimes things just happen.

Alternatively, suppose that John can see the beans as he chooses. He strongly prefers the taste of red to black beans. He will be asked to eat the bean that he chooses. In this case, an i-explanation is permitted—given what we know, the question cannot be rejected. (Of course, the answer is obvious—he intentionally chose a red bean because he prefers reds to blacks—but the point is that we are naturally, and correctly, driven to that explanation in this case, and not in the previous case.)

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[10] Assume, for the discussion, that there is no causal-mechanical explanation of the EPR-Bohm correlations.

[11] See the previous footnote.

Note, moreover, that this situation would not change much if the beans were distributed instead as 98 reds and 2 blacks. If John knows that he is going to have to eat the bean, he will still, one can easily imagine, act intentionally to get a red; the main difference is that it would be much easier for him to do so. Of course, there is some fuzzy territory; perhaps John is a gambling man, and he loves the thrill of risk taking enough that he will risk the 2% chance of a black for the fun of gambling. (He values the thrill of gambling sufficiently more than he dislikes black beans to take the risk.) But notice that even in this case, it is not the low probability of black per se that closes the door on the i-explanation; rather, that explanation is foreclosed (or its plausibility is diminished) because of our additional information about John's love of risk taking.

Now consider a second example. I deal out a deck of cards, about which nothing of its history is known (to you), and it comes up as in sequence (1) above. In this case, unless *K* is atypical (involving, e.g., no information whatsoever about decks of cards), an i-explanation is permitted. In particular, you know (I shall suppose) that there are people in the world who take decks to be "ordered" when the cards are as in (2) and that such people sometimes handle decks of cards. So you have reason to believe, because of what you know about agents in this world, that there may be some agent who intentionally brought about (1).

Note, indeed, that given your knowledge about agents in this world and their proclivities towards cards, *K* would need to include *very* strong assurance that the deck was thoroughly shuffled, that nobody touched this deck in the meantime, etc., before we would be willing to give up the obvious explanation ("somebody ordered the deck") and attribute the result to chance. Why? And why might it be the case (as I think it is) that the standards of assurance are much higher in this case than they would be in the jelly bean case, where we should be (I claim) more inclined to accept that the result was chance or good luck from John's point of view? One answer is that the probability of the chance result in the jelly bean case is much higher (of order $10^{-2}$) than it is in the card case (of order $10^{-67}$). This answer is, I suggest, very incomplete.

The problem with this answer as it stands is that mere low probability, as we have seen, is not enough to demand an explanation because (even setting aside the relativities of Sect. 3) all outcomes of any sufficiently complex process that is indifferent to its possible outcomes have low probability. In resolving this difficulty, we said that "low probability" *really* means "in the nonrandom class of results," meaning, roughly, "in the class of results that has a pattern." So who says whether there is a pattern?

Answer: Not you! (Nor me.) The fact that *you* see (or do not see) a pattern in the result, *E*, is irrelevant to whether an i-explanation of *E* is permitted. For example, I happen to place special significance on the poker hand (6d, 4d). Until now, nobody knew this about me. If I were to receive this hand, say, three times in a row, and assuming I were absolutely confident that the secret was mine, I would find being dealt the hand three times in a row amusing, perhaps, but I would not suppose that it needs some explanation apart from chance, despite the incredibly low probability. But if I were to receive the hand (A, A) (no matter the suits) three times in a row, I might begin to doubt the honesty of the dealer, and others might too, and not without reason.

What matters, in other words, is not what *you or I* believe, but what the agent who has some control over whether *E* occurs believes. If that agent's understanding of what counts as "nonrandom" puts *E* in the nonrandom class of outcomes, then appeal to the agent's control over whether *E* occurs becomes the basis of a potential explanation.

Now, as we saw in the jelly bean case, low probability can still come into play, but only in conjunction with some further knowledge about the agent. One might even wish to parlay this observation into a general claim about the relevance of low probability, in the form of a principle, the truth of which is an empirical matter, and one on which surely more work is needed. The principle is that agents are more likely to be compelled to bring about a desired outcome *E* the less likely *they think* that *E* will occur by other means (without their intervention) and the more strongly they desire *E*. For example, we don't tend to set up irrigation systems in places where rain is frequent and regular, despite the small probability of drought. On the other hand, despite the small risk of my house burning down, I have smoke detectors installed.[12]

To sum up, given some background knowledge, *K*, *T* in contrast to *C* permits an i-explanation to the extent that *K* permits the existence of agents that *could* intentionally bring about *T* in contrast to *C*, desire *T* in contrast to *C*, and take the probability of *T* rather than *C* to be sufficiently low that they are not willing to let chance "decide."

What, now, of *demanding* an explanation? I take an i-explanation to be *demanded* just in case denying that the corresponding question $\langle T, C, R, K \rangle$ has a plausible answer is contrary to *K*. Such might be the case, for example, if *K* included the knowledge that there exist agents who *could* intentionally bring about *T* in contrast to *C* (rather than merely not ruling out their existence), who believe that *T* in contrast to *C* is unlikely without their intervention, and who desire *T* in contrast to *C*.

## 5. Putting It All Together: What the Fine-Tuning Argument Shows

Does the fact that the values of the physical parameters are in their life-permitting ranges rather than any life-forbidding ranges *demand* an i-explanation? If what I've said is correct, then a positive answer requires that our background knowledge include that there exists some agent who is capable of being at least partially responsible for the values of the physical parameters, who believes that the values will not (or are unlikely to) take values in those ranges by some other means, and

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[12] There is, of course, the additional consideration of the cost of bringing *E* about.

who has as a desired end (whether instrumentally or categorically) that the values be in this range.

As we saw earlier, the existence and strength of the alleged demand may depend on how unlikely the agent believes that the values will be in those ranges by chance (and how important it is to the agent that they be in those ranges), which in turn depends on what *this agent* takes the sample space to be, how *this agent* chooses to describe that space, and how *this agent* distinguishes random from nonrandom elements of the sample space, i.e., what *this agent* takes to be a "pattern" in an outcome.

If what I've said is correct, then one *cannot* use the fine-tuning argument to conclude that such an agent exists because FT3 requires that we already believe that such an agent exists. What anybody does or does not know about the existence or nonexistence of such an agent is (far!) beyond the scope of this chapter.

I conclude, admittedly dangerously, with a bit of theology. I am not a theologian, so what I say here should be taken with a bucket of salt. It strikes me that the fine-tuning argument, at least if we are ultimately to conclude that the designer in question is anything like the traditional monotheistic God, faces a formidable theological hurdle, which results from a mixing of perspectives that I hope my preceding analysis brings into the open. The point is this: God (let us suppose) is omniscient. In that case, God knew, at the "moment" of creation and "before,"[13] that there would be life, that the parameters of the true physical theories would be such as to support life, and so on. For God, probabilities just don't enter the picture. They enter the picture only for us. Moreover, as I argued above, whether an explanation is permitted or demanded does not depend on what *we* estimate the probabilities to be; it matters what we believe the intending agent believes. And even if we set aside the special problem stemming from God's omniscience, we face the formidable problem of saying how God defines and describes the sample space of values for the parameters, how God distinguishes the "special" class of values (in present terms, what God *counts* as a universe that satisfies His "intentions" or "desires"), in order to say what God "believes" about the probability of this "special" class. Reading the mind of God on these points is tricky at best.[14]

I leave it to the theologians to clean up the fine-tuning argument in order to take such considerations into account, to whatever extent—if any—they constitute legitimate concerns, and I conclude by saying that *if* one antecedently believes in, or knows of the existence of, an agent of the sort that could bear the "intentionally brought about" relation to the universe, then, while the argument should not be the *cause* of belief, it is not pointless either. I take it that, having

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[13] The use of temporal terminology to describe a God who is, by traditional accounts, "outside" of time (whatever we mean by that locution) is inherently problematic, of course, and raises additional serious obstacles to the application of normal reasoning about i-explanations to this context.

[14] The amount of hedging in this paragraph should make it clear that I am skeptical that many of the notions invoked here even make sense.

taken into account, or otherwise dismissed, the theological concerns above (and no doubt others), the argument becomes, in the tradition of Augustine, an example not of generating faith by means of naturalistic reasoning alone, but of faith seeking understanding by means of natural reason.

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Biodata of **Arie S. Issar**, author of "***The Continuous Increase in the Complexity of the Designed Structures of the Universe Is Described as Movement Against Maximum Entropy***."

**Arie S. Issar** is a professor emeritus at the J. Blaustein Institutes for desert research, and the Geological Department of Ben Gurion University of the Negev. He founded, and was the head of, the Water Resources Center of the Institute for Desert Research since 1975 until his retirement in 1998. It was partly his inspiration, which saw the founding of the Institute for Water Sciences and Technologies.

He received his Ph.D. at the Hebrew University of Jerusalem in 1961. From 1980 to 1998, he was the holder of the Alain Poher Chair in Hydrogeology of Arid Zones. In 1985, he was awarded the Ernest D. Bergmann Prize for Special Scientific Contributions to the Development of the Negev Desert. In 2003, he received the Prize of the President of the International Association of Hydrogeologists for Outstanding International Contributions toward the Advancement of Hydrogeology. In 2005, he was awarded Honorary Member of the Israeli Association for Water Resources.

Prof. Issar's current research focuses on the impact of climate change on the hydrological cycle and socioeconomic systems, and developing conceptual models in order to mitigate the negative impact of global change on the water resources of the Middle East, including long-term policies of sustainable development of the fossil aquifers of the region. He has published about 100 papers, coedited 5 books, and wrote 5 books in the fields of geology and hydrogeology.

In addition to his research in the above-mentioned fields, he is investigating the evolution of intelligence in the bio-world and has published a book with Late Professor Robert G. Colodny of Pittsburgh University (1995), *From Primeval Chaos to Infinite Intelligence – Information as a Dimension and Entropy as a field of Force*. Ashgate-Avebury, UK. He also published a few papers in the field of philosophy of science in Hebrew and English.

E-mail: **issar@bgu.ac.il**

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# THE CONTINUOUS INCREASE IN THE COMPLEXITY OF THE DESIGNED STRUCTURES OF THE UNIVERSE IS DESCRIBED AS MOVEMENT AGAINST MAXIMUM ENTROPY

**ARIE S. ISSAR**
*Geological Department, Ben Gurion University of the Negev,*
*Be'er Sheva, Israel*

## 1. Introduction

A designed configuration is a spatial (static) or spatial-temporal (changing) configuration expressing a certain idea, which can be described also by a series of mathematical sentences. The opposite is any disordered configuration, the infinite state of which is absolute entropy. The apprehension by the human being that the forms and events in nature observed by him have a certain design led him for millennia to look for a supreme designer. At a certain stage, it was found that any designed configuration can be described by logical sentences. These sentences expressed directions, either static-spatial, like geometric forms, or spatial-temporal, namely, changing place or form, like the movement of the celestial bodies. Once the logical steps forming the sentences were codified into mathematical symbols, then also the thought or idea utilized to create a certain designed configurations was also described by mathematical symbols. This trend of mathematical expression soared up as a result of the "scientific revolution" kindled by Isaac Newton. This revolution led to the understanding that the movement of the celestial bodies, which until then were believed to have been created in order to give light and "*to be for signs*, *and for seasons*, *and for days, and years*" (Genesis 1:14), really move according to physical–mathematical laws. The same laws also govern the fall of apples from the tree in the back garden.

The erosion of the role of a supreme designer during the 6 days of creation continued with the "evolutionary revolution" kindled by Charles Darwin. This revolution was responsible for the understanding that man was not formed of the dust of the Earth, and in his creator's image, but in the image of his ancestor, i.e., an ape. Later the primary ancestor of all living organisms was claimed to be a primitive cell.

To date, the merging together of space-time and the understanding of the universe as a feature of expansion in a continuum of space-time, following the Big Bang, has reduced the need for a primordial creator and at the same time contributed to the appreciation of the role of exact and natural sciences in explaining the interaction between the enormous number of facets of nature.

With all the tremendous past achievement of the human creative mind, a holistic theory is still not avwwailable which will include an explanation for the random dance of quantum particles and the ordered predictable movement of the celestial bodies. At the same time, the number of dimensions required for the construction of such a holistic model is constantly increasing, although remaining in the framework of the physical dimensions of space-time.

In the following chapter, it will be argued that these dimensions are not sufficient to describe creativity in nature in general and not of the human mind in particular. For this purpose, a new nonphysical dimension, namely, the dimension of information, is suggested. “Nonphysical” means that it has no weight, and it is not measurable by a meter nor by a clock. It will also be argued that the basic questions of why and what is life have not been answered. Viewing entropy as a field of force pulling toward infinite disorder and life as a movement against this pull, feeding on negative entropy (negentropy) offers an answer to these questions as well an understanding of the role of creativity in the process of evolution of form and intelligence on Earth.

## 2. Why Life? Why Survival? and What Is Life?

For the author, a geologist, the form of a certain fossil is sufficient for locating its position on the evolutionary scale and thus its geological age. This information and the nature of the rocks in which the fossil was found enable one to depict the paleoenvironment. The biologist, according to the form of the fossil, will be able to reconstruct its soft tissues and tell how it functioned in that special environment. Based on observations from the area where the fossil was found and the correlation with other regions around the world, the interdisciplinary team will be able to describe the other life-forms, which lived simultaneously in the same surroundings. According to Darwin’s theory, these organisms competed to exploit the limited local resources, in the various levels of Earth, marine, terrestrial, surface, and subsurface and that which did it more efficiently survived. Thus, it is agreed today by most scientists that this competition between the various life-forms and between the members of each form was the driving force for the evolution of new varieties. At the basis of this process was, in the first place, the process of appearance of heritable differences which appeared randomly due to mutations, i.e., “The principle of divergence.” In the second place came the competition for limited natural resources, between the various living organisms, which stimulated the process of “natural selection” and led to the survival of “the most suitable” as phrased by Charles Darwin or the “The survival of the fittest,” as phrased by Herbert Spencer.

The assault on these principles was stirred up in the first place by the clergy, who opposed the elimination of God from the general picture of creation and the disregard of the biblical story as narrated in the book of Genesis. The other opponents were scientists who argued that Darwin’s suggestion regarding natural selection between species, which were gradually altered due to mutations causing tiny variations, was in contrast with the Mendelian principles of Particulate Inheritance. These principles claimed that the determinants of inherited traits are discrete units that are passed between generations unaltered, and not blended together. Accordingly in order to jump from one form to another, even if it is from a smooth pea to a wrinkled one, evolution must make giant jumps and not minor ones, in the case of peas, only gradual appearance of wrinkles. Such minor wrinkles would be in accord with Darwin's theory of tiny changes. This opposition disappeared once the understanding of the role of genes in heredity developed and it became clear that any given form was the product of many genes rather than a single one. Thus, a series of small mutations of the genes could create small and thus gradual changes to the forms. These changes, once giving even a slight advantage, will let the form spread rapidly through a group of living forms and cause other forms less fitted to the environment, whether new or old, to disappear.

Yet in all these theories of survival through change and adaptation, starting from the grandfathers of this theory including Erasmus Darwin, grandfather of Charles, and Jean-Baptiste Lamarck who first touched upon the problems of evolution of the variety of forms from ancestral primitive forms, continuing with Charles Darwin, Alfred Wallace, Aldous Huxely, and the following generations of biologists, no one has raised the question: Why survival at all? Not to speak about the question: Why life at all?

Recently this question is being approached in connection with the problem of the emergence of life, namely, how life emerged from inert chemical compounds. This includes questions regarding the successive stages of self-organization of chemical compounds into organic self-replicating molecules (Fry, 2000; Pross, 2003). It is beyond the scope of this chapter to present the various theories suggested during recent decades, yet, as already stated, the basic questions "why life in the first place?" and once it was formed, then "why survival?" were seldom brought up and discussed.

If the questions of "why life?" and thus "why survival?" were not treated appropriately, the question "what is life?" was even less explored. The classical study was carried out by Erwin Schrödinger, who approached this question from a physicist's point of view (Schrödinger, 1944). Accordingly, his answer was that life is a system, which is able to generate order out of disorder as well as order from order. As the first faculty may appear to contradict the second law of thermodynamics (SLT), according to which entropy only increases, Schrödinger suggested that the living organism is feeding on negative entropy, i.e., "negentropy." This physical process enabled the living organism to avoid decay into the "inert state of equilibrium," as dictated by the SLT. Thus, negative entropy, i.e., negentropy, enables the living system, not only to become disorganized, i.e., disordered as dictated by the SLT, but to do just the opposite, to increase organization or order. Yet it is quite surprising to find out that Schrödinger in his book *What is Life* did not define "order" per se, but discussed the physical aspects of orderliness only as contrary to disorder in connection with entropy. The author suggests the following definition: “a system will be recognized as ordered, if one can observe a principle which allows forecasting the distribution of its components” (Issar and Colodny, 1995). On the dimension of space, it involves foretelling the position of each component after the principle is known according to which the spatial structure was planned. On the dimension of time, it involves the possibility of timing of future events according to the past. The forecasting of cosmological events defines order along space-time dimensions. Yet, there is also order in numbers with no relation to space and time. The simplest order is the arithmetic one of 1,2,3,4. More complex sets will form series of numbers which may be very complicated. Yet if one studies a series of numbers once he gets to know the principle or the key for their arrangement, and will be able to predict what should be the next number, he will admit that there is order in the set of numbers. Since ancient times, the human being learned that he can express order in space and time by abstract symbols, which developed from scratches on a piece of wood or wet clay tablet to mathematical symbols (Marshack, 1972).

The fact that the laws expressing order in a series of numbers are applicable to daily experience in the real world, from the counting of sheep to the timing of celestial events, and the deciphering of the language of mathematics intrigued the human mind for millennia. This question became even more intriguing once it was understood that mathematics, grasped by the human mind, helps to decipher the code of nature. It started with Pythagoras, who claimed that numbers rule the universe, to Plato to Kepler and the physicist and mathematician James Jeans who asserted that the Great Architect of the universe is a pure mathematician. Another among the scientists who considered the wonder of mathematics was Albert Einstein, who expressed it in the following words, “How can it be that mathematics, being after all a product of human thought which is independent of experience, is so admirably appropriate to the objects of reality?” (Einstein, 1921). His answer to this enigma was by accepting as a fact that mathematics is intrinsic both in nature and in the human mind. Yet while the human mind can build wonderful logical structures with the aid of this mysterious tool, these structures are not factual if not cross-checked by empirical observations. In Einstein’s words: “In my opinion the answer to this question is, briefly, this: as far as the propositions of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality” (Einstein, 1921, p. 233). In 1933, in his Herbert Spencer lecture at Oxford, Einstein manifested his faith in mathematics as the skeleton of the edifice of nature, and thus the power of abstract mathematical thought to reveal the secrets of the laws interconnecting our observation of natural phenomena. He stresses the role of mathematics as a bridge between mind and nature. In his words: “Our experience hitherto justifies us in believing that nature is the realization of the simplest conceivable mathematical ideas” (Einstein, 1933). Yet to his question, how comes that etc.? his only answer is “One may say that the eternal mystery of the world is its comprehensibility.

From the philosophical point of view, this question was approached by Einstein by viewing nature in the framework of the philosophy of Baruch Spinoza, who equated nature with the supreme holistic entity ("God"), being also a supreme mathematician. On April 24, Rabbi Herbert Goldstein of the Institutional Synagogue, New York, cabled Einstein: "Do you believe in God?" Einstein answered: "I believe in Spinoza's God who reveals himself in the orderly harmony of what exists, not in a God who concerns himself with fates and actions of human beings."

## 3. The Dimension of Information: A Suggestion to Answer Einstein's Question

Related to the subject of this chapter, namely, the phenomena of "Creation" and of "Creativity," is the fact that the mode of creation, namely, the Big Bang event, was derived by developing the equations of Einstein's General Theory of Relativity by Alexander Friedman. It showed that these equations demand either a contracting or an expanding universe along space-time dimensions. Hubble's observations proved the latter, namely, that the universe is expanding, and by running back, the "motion picture" on space-time dimensions reaches the conclusion that at the beginning, there was a primordial "body" of enormous density and temperature, which exploded.

All the theoretical physical-mathematical models of contracting the universe to reach the Big Bang and expanding it to its present state, and beyond, were run along the space-time coordinate system, according to mathematical procedures, demanding various assumptions at various stages. The basic assumption, following Einstein's basic conceptual model, is that our universe is four-dimensional, measurable by observers using meters and clocks. The contracting and expanding of the universe along space-time dimensions was done by applying mathematical-logical steps along which the physicists ran their models. Yet, it never occurred to the physicists traveling forward and backward, along the mathematical-logical structures they constructed and were running on their computers, to ask themselves the question: On what dimension do our brains run as well as the computer in front of us, whose screen gives us these wonderful sights of space along time sections, since the Big Bang? Not to speak of the question: "Should we not consider mathematics, i.e., logic, as an additional dimension intrinsic in our space-time universe?"

One will not be surprised, however, that any physicist adherent to the mandate of his profession, i.e., investigating the physical world by physical meters, clocks, and thermometers, will revoke this question, claiming that it smells of metaphysics and endangers the objective approach to science. In other words, once the subjective anthropoid physicist sitting in front of his computer becomes involved in the program being run on this objective machine, the results cannot be trusted. This approach makes redundant further questions like but who programmed the computer? Or on what dimension is the program running?

This question bothered the present author in connection with his study of the evolution of the flint tools of the hominids, the "fossils" of Quaternary age (the last 2.5 million years) which he used in order to construct the geological structure of the Coastal Plain of Israel and of the Plain of Zin in the Negev Desert of Israel (Issar, 1968; Issar et al., 1984). The flint tools showed an evolutionary process of form from the most primitive tools of the Paleolithic hominids, dating more than half a million years, which were pieces of flint edged at one end to become sharp and pointed, to the evolved flint arrowheads, used by the Neolithic hunters, about 10,000 years ago. It was obvious that the evolution of the form of the tools could be illustrated on space-time dimensions, the question which arose was:

On what dimension or coordinate can the evolution of the increasing knowledge of the tool manufacturers be shown?

In his book *From Primeval Chaos to Infinite Intelligence – Information as a Dimension and Entropy as a Field of Force* (Issar and Colodny, 1995), the author suggests that an additional dimension must be added to space-time to be called "dimension of information." This dimension is defined as all that is measured by the brain or a computer. Space is all that is measured by the foot or meter, while time is all that is measured by the pulse or clock. Space has six degrees of freedom, namely $x,y,z$, in two directions, i.e., forward and backward, and time just one degree of freedom from present to future. The dimension of information has four degrees of freedom, which are addition and reduction (i.e., "+" and "−") and induction and deduction (i.e., "if-then" and "when-then"). Altogether, the world is observable along a three-dimensional continuum of space-time-information, having 11 degrees of freedom. In a recent chapter (Issar and Sorek, 2010), it is suggested that space refers to gaps in distance, measured by a meter. Time refers to change in instances measured by a clock. Information is measurable by a computer, which counts the number of steps made (or bytes used) in order to perform (describe or solve) a certain logical sentence or a sequence of logical sentences. In the attempt to quantifiably formulate the incorporation of information into physical laws, Issar and Sorek (2010) refer to Hamiltonian extended stationary principle in terms of space, time, and an additional degree of freedom, suggested as an information state. The obtained Euler equation is demonstrated for the case of a thin rod under longitudinal vibrations, investigated by dimensional analysis. It is shown that depending on the value of information and its rate, one may obtain dominant forms conforming to Poisson's equation in space vs. information, wave equation in time vs. information, and the expected wave equation in time vs. space.

The dimension of information enables the description of the evolution of the production of the flint tools in particular, and of tools in general, can thus be written as an algorithm or flowchart of the instructions to produce a certain tool. These instructions can be given in the form of words, or illustrations, or mathematical symbols. Comparing the algorithms for the construction of a primitive flint tool to that of an advanced tool, to that written for the production of an earthenware pot, and to that of metal and even electronic tools will show an increase in the number of instructions. These are built as logical steps starting from the first instruction and followed by more: "if…then…" steps. It should be remembered that before writing was invented, these algorithms were kept in the memory of the manufacturers and transmitted verbally from one generation to the next. On what dimension were these algorithms written and preserved? In the opinion of the author, the most simple yet comprehensive, albeit not conventional, answer to this question is the dimension of information!

In order to facilitate the reader's orientation in a space-time-information world, it is suggested that he ask himself on what dimensions did he progress from infancy to the present. In the first place, since some years passed, he progressed along the dimension of time, and most probably, he changed also along the dimension of space (and weight, namely, mass, which is an issue beyond the scope of this chapter), but being able to read this chapter and agree, hopefully, with its content, he must have expanded his knowledge, which is based on more and more information. On what dimension can this expansion be measured, if not on the dimension of information? Yet it is important to add that knowledge involves construction of units of information by the mind based on former knowledge. This construction follows the laws of movement along the dimension of information, i.e., arithmetic and logical steps. In comparison with the dimension of space, it can be said that accumulation of information is just a pile of bricks, while knowledge is equivalent to the construction of a structure from these bricks. Thus, knowledge means organizing by mathematical/logical steps of information-about-information, according to information.

## 4. Life an Event Along Space-Time-Information Dimensions Feeding on Negentropy

Accepting the conceptual model of a space-time-information, the question "what is life?" can be answered by describing it as an event occurring in this continuum. This event involves also the observation and transformation of sequences of events from the surrounding environment into structures of knowledge on the dimension of information. This is accomplished by the transformation of mechanical and electrochemical stimuli into ordered complex structures of notions, namely, knowledge. Such an accomplishment is equivalent to arranging points on the dimension of space and instants on the dimension of time. The rise in complexity of the structures of notions on the dimension of information enables the promotion of concepts into ideas and into theories. The rise in the organized complexity of arranged points on the dimension of space will form ordered structures, while on the dimension of time, will form sequences and histories.

This building of structures of ordered events of information is a movement opposing the slope of universal entropy, namely, the pull toward maximum disorder = entropy. This process of movement against the universal pull toward disorder, intrinsic in the surrounding environment, can be described as movement against the pull of a field of force acting along the dimensions of space-time-information, which has 11 degrees of freedom. With analogy to the free fall in the field of gravity described as movement down the slope of the cone formed by any mass in the space-time continuum, it is suggested to view entropy as a cone in the multidimensional coordinate system of space-time-information, pulling every ordered structure down this cone toward maximum disorder, i.e., maximum entropy. In order to overcome this pull, investment of energy is needed, namely, "feeding on negative entropy, i.e., negentropy," which enables "creation of order from disorder" (Schrödinger, 1944).

Physicists will undoubtedly oppose the suggestion to regard entropic processes, as analogical to gravity or electromagnetic field forces, arguing that, by definition, a field of force has to be reversible in time, namely, every movement can be reversed to get back to the initial point, and the movement, forward and backward, can be precisely measured. On the other hand, thermodynamic systems are, by definition, irreversible in time; this is connected with the conjecture of the "arrow of time" which is intrinsic in the theory of thermodynamics. Thus, according to the SLT, there is a perpetual loss of order in the universe, and thus each moment, on the dimension of time, differs from its neighbors. Moreover, thermodynamical phenomena obey statistical laws and cannot be precisely measured. The answer to this opposition is, in the first place, concerning the fact that the classical physical fields are limited to space-time coordinates and do not take the observer (the information-meter) into consideration. It is claimed that once the observer, and his world view, is introduced into physics, reversibility and precision disappear, as shown by quantum physics. Another argument relates to the introduction of life and consciousness into the universal balance of order in the universe. Thus, while the SLT is limited to space-time dimensions, the addition of the dimension of information, which dictates order, arithmetic, as well as logical-mathematical, introduces also the arrow of evolution of cosmological order. This arrow points toward higher levels of ordered complex systems, from the Big Bang, to the formation of galaxies to the formation and evolution of life, which involves the evolution of consciousness.

Needless to say that for a physicist, the understanding of "consciousness" in the framework of a space-time continuum is rather difficult if not impossible. Thus, it is interesting to note that in the Epilogue of the book *What Is Life?*, Schrödinger (1944) tries to elucidate questions emerging from the fact that the human mind can control the body, which according to him "functions as a pure mechanism according to the Laws of Nature." This brings him to speculate on "determinism and free will" as well as the questions related to the personal self and the awareness of the existence of an entity, which comprises the conscious existence of the other selves, namely, "the pluralization of consciousness or minds." The next step is the pondering about body and soul, mortality, etc. It is beyond the scope of this chapter to deal with these issues; the reader interested in their examination in a space-time-information continuum is invited to read the chapter "The information dimension in retrospect" (Issar and Colodny, 1996).

## 5. From the Big Bang to Albert Einstein

On the basis of the discussion in the preceding sections, it is suggested to view the universe as an expanding system along space-time-information dimensions (with 11 degrees of freedom). This expansion started with the Big Bang as the primal form of creation and continued in the ensuing stages of the evolution from the quark-gluon plasma to galaxies to the primordial soup on Earth, to the first DNA molecule (a space-time-information complex), to the hominids, to the *Homo sapiens sapiens*. The expansion against the pull of entropy and along the dimension of information leads to a higher complexity of design, which on the dimension of information is expressed in a higher level of intelligence. It also explains the fact that the principles of survival did not bring to dominance the most basic forms of life like microbes or even crickets, which are found all over the globe, adapting to most extreme and various environments. In other words, the scaling of the ladder of complexity of life-forms, which started with primitive creatures and arrived at the most intelligent creature, namely, *Homo sapiens sapiens*, cannot be explained as just a result of random mutations and selection by better adaptations but only as a result of the above-mentioned expansion along space-time-information dimensions against the pull of the field of entropy.

The same conceptual model renders redundant the other explanations for the trend of ascent in the level of complexity observed in the evolution of the tree of life, namely, that of spontaneous dynamic self-organization or that of the involvement of a watchmaker, namely, an intelligent designer and performer, whether blind or able to see, who has or has not a blueprint before his eyes (Kauffman, 1995). This expansion causing advancing complexity of the design forms of life describable on space-time dimensions explains also the evolution of intelligence in the bio-world, defined either as "the power of perceiving, learning understanding and knowing" (Oxford Dictionary, 1982) or "the ability to develop a new way of reaction when an entirely new situation comes up" (Bitterman, 1965). This definition was in the framework of a research on the evolution of intelligent behavior of a variety of animals, which showed that the level of intelligence of the animal was a function of the level of that animal species on the tree of evolution.

The spontaneous ascent of the level of intelligence of the *Homo sapiens sapiens* along the dimension of information, in the framework of the universal movement along the arrow of negentropy, explains not only the technological achievement of humanity starting from the first pebble tools but also the evolution of science. It started with the first queries about the nature of the world and its creation and first answers found in the ancient mythologies as well in the story of Genesis. Science began with the Pre-Socrates philosophies, continued to the classical Greek philosophers, to the Copernican-Newtonian theories which prompted the "scientific revolution." This step can be viewed as a jump in the evolutionary process of ascending complexity, mounting to the space-time universe of Einstein, from which the theory of the Big Bang was just a logical-mathematical further step.

Thus, nature can be viewed as a continuous process of creativity, in the first place of the continuous creation of new forms of more complex design when described on space-time coordinates, and at the same time the creation of higher levels of intelligence and the invention of new ideas when described on information-time coordinates (Issar, 2008). This movement is in the framework of a general field of force having two poles, one pulling toward maximum entropy, namely, reducing the ordered complexity of any structure (physical and mental) to zero, while the other pole is of maximum ordered complexity of design. The movement toward this pole needs feeding on negentropy, resulting in a continuous process of creativity of ordered complex structures of tools and ideas.

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Biodata of **Professor Moshe Pollak**, author of "***Law, Order, and Probability***."

**Professor Moshe Pollak** is the Marcy Bogen Professor of Statistics at the Department of Statistics of the Hebrew University of Jerusalem, from which he received a Ph.D. in Statistics in 1974. He has spent a number of years of teaching and research in various institutions in North America and in Europe. He is a Fellow of the Institute of Mathematical Statistics, a Fellow of the American Statistical Association, a Senior Member of the American Society for Quality, and a member of the International Statistical Institute, the Israel Statistical Association and the Israel Association for Quality. His main research interests are in sequential statistical analysis, with an emphasis on SPC (statistical process control).

E-mail: **msmp@mscc.huji.ac.il**

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# LAW, ORDER, AND PROBABILITY

**MOSHE POLLAK**
*Department of Statistics, The Hebrew University of Jerusalem,*
*Jerusalem 91905, Israel*

## 1. Introduction

What is a law and order? Both law and order have two meanings: command and generalization. Human law is order in the sense of command: a set of statutes to be obeyed, such as "Thou shall honor thy father and thy mother." Natural law is order in the sense of generalization: phenomena that have things in common are organized in a statement that embodies what they share jointly, such as the Law of Gravity ("all objects fall down at the same rate of acceleration, regardless of their weight"). At a first glance, randomness is the antithesis of law and order, being at times synonymous with anarchy and chaos.

As a general rule, in order to survive, living creatures have a need for understanding their environment and keeping it manageable. To realize this, human beings resort to law and order, in both senses of the terms. Randomness is often regarded as an impediment, obstructing comprehension and preventing planning for the future. The modern method of approaching randomness is by attempting to quantify it: hence the mathematical theory of probability.

## 2. Randomness

But what is randomness? Is it real? Is it a figment of the imagination? The ancients didn't really believe in it: fate reigned, governing everything; life was regarded as deterministic. In modern times, things are regarded differently, but a definition of randomness is elusive: philosophy hasn't yet been able to provide a satisfactory definition (cf. Eagle, 2010), sometimes regarding randomness in axiomatic terms. Nonetheless, we all (even the ancients) have a heuristic sense of it, reminiscent of the US Supreme Court Justice Potter Stuart, who wrote (*Jacobellis v. Ohio,* 1964) that he can't define pornography, "but I know it when I see it."

Perhaps one way of trying to get a stronger grasp of a concept is to see where it is applied. When do we regard something as random? When something takes place unexpectedly. When we cannot explain why something happened even in the aftermath of its occurrence. When there are so many factors affecting a phenomenon that even if all were known, the complication caused by their vastness or by our inability to measure them all is beyond our powers of comprehension.

(For example, once a coin is flipped onto a table, the outcome of the toss is deterministic, depending on the speed or angle when leaving the tosser's hand, its height above the table, the friction coefficient between the coin and the table's face, etc. Nonetheless, the outcome is considered to be as random as it was before the coin was tossed.) A main ingredient of regarding phenomena as random is ignorance (Taleb, 2007). Since precise mathematical measurement of everything is impossible (cf. Heisenberg's principle of uncertainty; Heisenberg, 1927), randomness will always be part of our conceptualization of things.

## 3. Law and Order

To consider randomness as chaos is fallacious. There is law and order to randomness: although one cannot predict the outcome of a flip of a fair coin, one has strong expectations in a long run. (If the coin were to be tossed 1,000,000 times, it is expected that approximately 500,000 of the outcomes will be heads, and a sharp deviation would raise doubts regarding the assumption that the coin is fair. Similarly, for reasons of symmetry, when tossing a fair die many times, one expects the average per toss to be approximately 3.5.)

To get an inkling why the "law of large numbers" is valid, consider an experiment that consists of tossing a fair die twice. Every one of the six possible outcomes of the first toss is equally likely, and the same goes for the second toss, so that each of the $6 \times 6 = 6^2 = 36$ possible outcomes of the experiment (as illustrated in Fig. 1) is equally likely to occur.

What will be the average dots per toss in the experiment? That, of course, would justifiably considered to be random: if the first toss were to be 4 and the second 5, the average would be 4.5; if the first were to be 2 and the second 4, the average would be 3; etc. The range of possible averages is (in jumps of 0.5) from 1 (when both tosses are 1) to 6 (when both tosses are 6). But these (11) possible values of the average are not equally likely: realizing an average = 1 can take place only if both tosses are 1 – only 1 of the 36 equally likely outcomes of the experiment – whereas 6 of the 36 equally likely outcomes yield an average = 3.5. The likelihood of realizing a value $X$ (as the average of the two tosses in a given realization of the experiment) decreases the more $X$ deviates from 3.5, as illustrated in Fig. 2 (Pollak, 2011).

What is an intuitive explanation for this? To obtain an extreme value of the average – say, 5.5 – both tosses have to be relatively extreme. There is more leeway to obtaining a "typical" value – such as 3.5 – both tosses can be "middling," and both tosses can be extreme (with the extremity of one canceling that of the other). Since each of the 36 possible outcomes is equally likely, in the long run, each is observed roughly the same number of times – and since most yield an average close to 3.5, it is not surprising that we usually expect to see an average $\approx 3.5$ in the long run. This effect increases as the number of tosses becomes large: of the

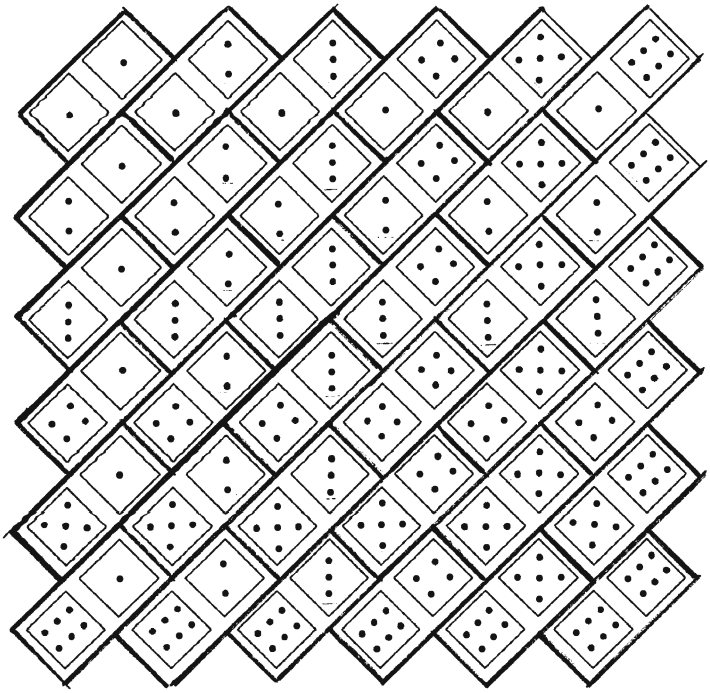

**Figure 1.** The 36 possible outcomes of an experiment where a die is tossed twice.

$6^n$ possible outcomes of tossing a fair die n times, the averages in most of these cluster close to 3.5. (This does not mean that it is impossible to obtain an average markedly different from 3.5, but it does imply that that would be very unlikely.)

What type of "law" is the "law of large numbers"? Definitely, the generalization type. If a coin is really fair, even if 20 tosses in a row turned out "heads," there is no less (nor more) probability of observing "heads" on the 21st toss than it was all along. (After all, the coin has no memory.) This is frequently misunderstood: often a sportscaster would say after a stretch of misses of a star basketball player that "by the law of averages, a basket is overdue."

## 4. Probability

The empirical evidence of the law of large numbers is the reason why probabilities are defined as numbers between 0 and 1. Since the proportion of observations of an event $A$ settles down in the long run, it is natural to let this proportion represent the likelihood of the occurrence of $A$. Proportions being between 0 and 1 imply the same for probabilities.

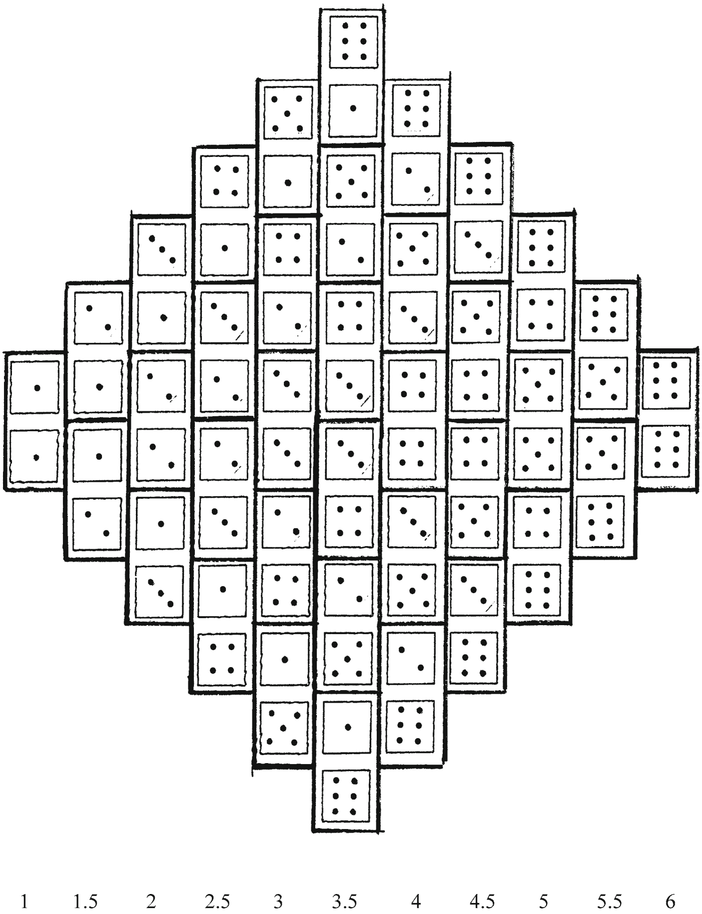

**Figure 2.** Average dots per toss in an experiment where a die is tossed twice.

Human intuition in the application of probability theory is fragile, very often leading to the most erroneous conclusions. The aforementioned misuse of the law of large numbers is only one example. Other examples are more serious. People play the lottery, praying to win, being oblivious to the fact that the probability of winning may be much less than being killed on a given day in a traffic accident. In a similar vein, people refrain from visiting Israel for fear of terrorist attacks, not giving a thought to death by accident, not realizing that the probability of death by terror is markedly less. People don't understand that when there is a race between many similarly qualified contestants, someone must come out the winner, so being a winner is nonnegligibly a matter of luck. (Thus, if a mutual fund was "best" in a given year, the likelihood that it will repeat being "best" in the following year is low. Daniel Kahneman won a Nobel Prize, among other things for his work exposing the irrationality of people when confronted with situations having a probabilistic ingredient; cf. The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, 2002.)

## 5. Events That Have Zero Probability

A frequently misunderstood concept is an event whose probability is zero. Although an event that cannot occur has probability zero, the converse is not true. What is the probability that the height (measured in meters) of the next person that you, the reader, will meet is $\sqrt{2}$ ? If not 0, then all numbers very close to $\sqrt{2}$ should have approximately the same probability, and since the sum of these will quickly exceed 1, there is no way that the probability is not 0. (How can this be? It is similar to the following analogy: the area of a $1 \times 1$ square is 1. But the square is made up of a union of straight lines, each of which has area = 0.)

But wasn't your height, the reader, once equal to $\sqrt{2}$ ? As a matter of fact, events whose probability is 0 happen all the time: what is your precise height at this instance in time? But the probability is 0 that the height of a person you'll meet next is exactly the same! (Or, the next person that you will meet will be observing an event of zero probability!) So, one component of randomness may be timing. (Interestingly, Onkalos' second century translation of the Bible into Aramaic renders the Hebrew root "KRH" (meaning "happen") as "ZMN" in Aramaic (a root having to do with "time"); c.f. Genesis 12:24. Most translations shy away from using "chance.")

## 6. Uses of Randomness

Although the use of probability theory described above is passive, randomness can be applied actively. The ancients used lotteries to determine guilt (cf. the sailors who settled on Jonah's culpability by casting lots; see Jonah 1:7), to apportion land, to decide on an auspicious time, etc. – as if giving the powers that be an opportunity to involve themselves in human affairs. Apportionment by lottery was considered a fair procedure, leveling the ground for all. ("The lot causeth contentions to cease" (Proverbs ch. 18 v. 18).) In modern times, too, randomness is used actively. Many allocations of which team plays the other are decided by lottery. It is recognized that creating nebulousness can have benefits, especially in adversarial situations. (A soccer player planning a penalty kick (where the decision has to be made whether to aim to the right side of the goal or the left) would be well advised to let a toss of a fair coin decide, thus keeping the goalie in the greatest possible state of ignorance.) Much of game theory involves randomization as part of an optimal strategy. Statistics sometimes employs randomization to test hypotheses and create confidence intervals (bootstrapping, permutation, cross-validation). Clinical trials allocate prospective patients to test and control groups by randomizing. So, all things considered, randomness has its benefits.

## 7. Randomization

Randomization requires a mechanism that produces randomness. Typically, this involves the creation of random numbers. Since humans have a hard time producing a sequence of events that stands up to a specified measure of randomness, standard procedures call for producing these by a computerized random number generator. At first glance, this appears to be an oxymoron; after all, a computer program is one of the most precise things on the planet, where repeating the same program on the same data will always produce the same result. So, how can a computer generate something that is random?

Consider the sequence

1592653589793238462643383279502884197169399375105820974 9….

Does it look like a sequence of random digits? Can you guess the next digit, or would you ascribe a probability $1/10$ to each digit?

Would you react differently if 3.14 were placed at the start of the sequence so that it would be

3.14159265358979323846264338327950288419716939937510582097 49…. ?

Perhaps you recognize this as (the beginning of) the decimal representation of $\pi$. Of course, this means that nothing is random in the sequence. (Subsequent digits are necessarily 44592307….) Nonetheless, the sequence does look random. That is how computers churn out random numbers. Actually, they are pseudorandom numbers, and the generator is a pseudorandom number generator. For practical purposes, this does not make a difference. But this example highlights the problem of randomness: is it real? After all, the sequence didn't change. It is the knowledge that the sequence represents $\pi$ that changed its perception from random to deterministic.

## 8. Probability: Subjective or Objective?

As proposed above, the concept of randomness involves ignorance. This in turn means that likelihood – hence probability – is subjective. The probability that the Yankees will beat the Red Sox depends upon one's knowledge. If you know that the Yankees' star pitcher has been injured and I don't, the probabilities that each of us may ascribe to the Yankees' winning will not be the same. Things get even worse: the probability of an event depends on one's frame of reference. "Doctor, what are the statistics – what is the probability – of a successful solution of my herniated disc problem by the operation that you propose?" The answer depends on whom are you being compared to: People of your age? Of your age and gender? Of your age and gender who have the same smoking habits? What about taking into consideration other medical conditions that you have? Socioeconomic status?, etc. – there's no end to considerations. But there is a limit to statistics – if too many contingencies are being considered, you may find that no one has the same specifications as you; i.e., there is not enough statistical experience to estimate a probability relevant for you. This means that the doctor's answer will necessarily be subjective, depending on which categorization is chosen for classifying you. So, in a major sense, probability is in the eyes of the beholder.

## 9. A Point to Ponder

Having said all of this, how are we to regard an event that has a low probability ascribed to it, but has nevertheless occurred? What are we to make of a statement that claims that the probability of a recently constructed atomic power plants exploding within the next 1,000 years is $10^{-22}$? Leaving aside the question of how such a figure was arrived at, what should be said after the unlikely event took place (e.g., Chernobyl)? Of course, maybe the original assessment of the probability was erroneous. But it is not necessarily so – after all, even events having zero probability take place, and (in a paraphrase of Murphy's apocryphal formulation of the law of large numbers) what can happen will. Once one becomes aware that an event has taken place, despite its low prior probability, one cannot argue with the fact that it occurred.

## 10. Probability and Intelligent Design

With the above as background, we address the attempt to apply probability theory as evidence of intelligent design. One of the arguments runs as follows: the probability that the force coefficient of gravity, the basic electric charge, the size of the earth and its distance from the sun, etc., would be exactly what they are (without which we would not have been around to discuss the issue), if they were all to be generated "spontaneously" by "chance," is so low as to make the idea of the universe having been created without a creator untenable (cf. Gonzalez, 2004). This train of thought is standard in statistical analyses: if an observed event has a relative likelihood too low under a given hypothesis, then it gives credence to the assumption that the hypothesis is wrong. Thus, a driver that was clocked at 85 mph on a highway with a 65-mph speed limit who consequently got a ticket for speeding will lose the case if brought to court, due to the low likelihood that the police radar makes a measurement error of 20 mph or more; the judge will accept 85 as proving "beyond a reasonable doubt" that the ticket was well earned (although it is not impossible that an error had been made). For acceptance of DNA evidence in a parenthood suit, and of course in a capital case, the requirements defining "beyond a reasonable doubt" are much more stringent. There is no formal definition of what the threshold should be. What is the level for believing in intelligent design?

The counterargument could go as follows: so you think that the probability of spontaneous generation is (say) $10^{-167458}$? So what? Don't forget that you are regarding the observation (i.e., our universe) after it happened. So, maybe your original assessment of the probability was wrong. Alternatively, maybe your prior assessment is correct, but you can't alter the fact that the universe is there. After all, even events that have zero probability occur. In what sense is the situation different from the explosion of the atomic reactor in Chernobyl? Furthermore, if you assess the probability of spontaneous generation as $10^{-167458}$, an equally cogent inference would be that there are approximately $10^{167458}$ universes that imploded upon generation.

## 11. Conclusion

In this chapter, we have tried to present a heuristic description of basic elements of randomness and the intuition behind the laws governing probability. Although probability theory is an exact subject, as in any mathematical application, its application is subjective. Hence, probability cannot settle an extrinsic philosophical argument in terms of objective proof. Whether the universe was generated spontaneously or made by a creator remains a matter of faith (either way), where the decision to conclude one way or another beyond a reasonable doubt is personal, subjective. "וצדיק באמונתו יחיה – and the righteous shall live by his faith" (Habakkuk Chap. 2 v. 4).

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Biodata of **Andrew M. Winters**, author of "***Design and Self-Organization***."

**Andrew M. Winters** is a university graduate fellow at the University of South Florida where he is currently working on a Ph.D. in Philosophy. He holds an M.A. in Philosophy from the University of Colorado, Boulder, and an M.A. in Philosophy and Religion (with an emphasis in philosophy, cosmology, and consciousness) from the California Institute of Integral Studies in San Francisco, CA. He has written and presented on topics within the areas of metaphysics, history and philosophy of science, epistemology, religion, and (even) serial killers. He has taught courses at the University of Colorado, Denver, in philosophy, logic, ethics, and horror. His current research focuses on the intersection of metaphysics and philosophy of science and laws of nature.

E-mail: **wintersandrewm@gmail.com**

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# DESIGN AND SELF-ORGANIZATION

**ANDREW M. WINTERS**
*Department of Philosophy, University of South Florida,*
*4202 E. Fowler Avenue, FAO 236, Tampa, FL 33620, USA*

## 1. Introduction

This chapter will explore how recent developments in systems theory impact, what I will call, the *design thesis*. The design thesis claims that a designer in some form exists. This thesis has been contemporarily supported in the Intelligent Design (ID) movement by appealing to results in the natural sciences. If we are to understand the design thesis in a contemporary light, we should understand the implications that recent developments in the sciences have for the design thesis. Since the natural sciences, notably biology, appeal to self-organizing systems to understand natural phenomenon, it will be of interest to understand what implications self-organizing systems have for the design thesis.

In what follows, I claim that self-organizing systems pose a problem for the design thesis. In developing this claim, I focus on a particular argument for the design thesis—the *teleological argument*. I briefly discuss traditional accounts of the design argument leading up to its current formulation in the ID movement. In doing so, I suggest that the ID thesis is not easily susceptible to classical rejections of the design argument. I then describe contemporary formulations of self-organizing systems. From this, I argue that self-organizing systems do not independently provide evidence for a designer since they are capable of explaining natural phenomenon without appealing to any external causal agent. My hope is that this discussion will provide grounds for moving the design argument and philosophy to a contemporary scientific light.

## 2. The Design Thesis

In this section, I will briefly sketch some of the highlights of the debate surrounding the design argument leading up to its current formulation in the ID movement. This section follows in form Blackburn's (2005) definition of "design." I recommend Ratzsch (2005) for a discussion of the various underlying structures of design arguments.

## 2.1. BACKGROUND AND SCOPE

The discussion of design is not a new one. Although the idea of what a designer is has shifted throughout historical discussions, the concept of what is designed seems to remain consistent insofar as what is allegedly designed is the natural world and the complex organisms found within. Plato appeals to the demiurge in the *Timaeus* as being responsible for imbuing the world with a soul. In Plato's dialogue, the character Timaeus states,

> For which reason, when he was framing the universe, he put intelligence in soul, and soul in body, that he might be the creator of a work which was by nature fairest and best. On this wise, using the language of probability, we may say that the world came into being—a living creature truly endowed with soul and intelligence by the providence of God. (Plato, 1989)

Aristotle follows suit by claiming that God exists. For Aristotle, however, God is "neither the creator of that order, nor its continuing efficient cause" (Hankinson, 1995). Instead, we see nature, not God, as having the role in Aristotle's work that the demiurge has in Plato's *Timaeus*. These different accounts of God lead Aristotle and Plato to also have different teleological accounts. Plato's account can be described as an *intentional teleology* because it is the intentions of the demiurge that provides the world with an aim. Aristotle's account, on the other hand, can be understood as a *nonintentional teleology* (Hankinson, 1995). On this view, nature provides organisms with their attributes, which by virtue of these attributes, allows the organism to function in the way that allows it to survive even though nature may not consciously intend for organisms to survive. In other words, even though Aristotle does not believe that nature is conscious, he still believes that nature has a purpose. He writes,

> It is absurd to suppose that purpose is not present because we do not observe the agent deliberating. Art does not deliberate. If the ship-building art were in the wood, it would produce the same results by nature. If, therefore, purpose is present in art, it is present also in nature. The best illustration is a doctor doctoring himself: nature is like that. It is plain then that nature is a cause, a cause that operates for a purpose. (Aristotle, 1984a, see also Aristotle, 1984b)

The prevailing formulation of the design argument is found in Paley's *Natural Theology*. Paley suggests that if a person saw a watch on a trail, the person could, on the basis of the intricacies found within the watch, justifiably infer that some intelligent artisan created the watch. Paley goes on to describe how the universe, too, has observable intricacies. For this reason, Paley claims that we are justified in believing that the universe is the product of an intelligent artisan's handiwork (Paley, 1802).

The classical formulations of the arguments from, or to, design have been met with much contention in both the classic and modern eras. Hume, for example, provides what can be construed as a direct response to Paley's analogy. In his *Dialogues Concerning Natural Religion*, Hume's interlocutor Philo provides two main objections: there are not similarities between the objects of the universe and human artifacts, and even if there are similarities between the objects of the universe and human artifacts, there are other potential candidates aside from an intelligent designer for producing the objects of the universe (Hume, 1993).

Kant follows Hume's tenuous commitment to causal relations to criticize the argument from design. Kant claims that the only way we can infer causal relations is by observing the things in the world. Since the cause of the universe is something outside of the world, we cannot observe this cause, and, therefore, cannot infer the nature of the cause of the universe as such. He writes,

> For in the case of God I have to omit all those conditions under which alone I am familiar with an understanding; and hence this predicate, which serves to determine only man, cannot at all be applied to a supersensible object, and therefore through a causality determined in this way we cannot at all cognize what God is. (Kant, 1987)

Contemporarily, Dawkins claims that the design argument leads to an unpalatable regress (Dawkins, 2008). He suggests that if the universe is something that requires a designer on the basis of its complexities, then it seems that the designer must also be complex. For this reason, it would seem that the designer also has a designer, and, thus, the regress begins.

According to Groothius (2009), Dawkins' regress argument relies upon a faulty assumption that proponents of ID also believe that anything that is complex necessarily has a cause external to itself. He suggests that it is possible that the designer of the universe, an arguably complex entity, does not require a designer. In other words, it is possible for the designer to exist simply on its own.

An issue to be pressed is that if the designer is able to exist on its own, then there is little reason to believe that the universe is incapable of existing on its own. Some philosophers attempt to reply that the designer is not complex, but is mereologically simple. This would mean that the designer has no parts (Swinburne, 2004). It's difficult to understand, though, how a mereologically simple entity could go on to design the universe, but this is a digression from the design argument to a discussion of the attributes of the designer.

In looking at contemporary arguments for the design thesis, we see that there are similarities between these arguments and Paley's watchmaker argument. Specifically, contemporary design arguments start with the observations of the natural world and the perceived complexities and design-like attributes that lie within. The proponents of these arguments go on to infer that these complexities and design-like attributes provide evidence for the existence of an intelligent designer. We find this type of argument for the design thesis in both the ID and fine-tuning camps. Because ID is more closely aligned with the genealogy of the design argument, whereas the fine-tuning argument is one that is dependent upon appeals to probability distributions, I will focus on the design argument as defended by proponents of the ID theory.

Advocates of ID can be further divided into two groups: those who appeal to observed phenomena in the natural sciences and those who are motivated by religious beliefs. This chapter, however, is not an attempt to reconcile or grapple with the details of religious texts or the personal beliefs of ID advocates, but is an attempt to understand what implications recent developments in systems theory have for the design thesis. Furthermore, as Monton points out, "It is true that almost all proponents of intelligent design believe in a supernatural creator, but it doesn't follow that the thesis that there is a supernatural creator is part of the intelligent design doctrine itself" (Monton, 2009). For these reasons, the following section will be a summary of the formulation of the design thesis as presented by proponents of ID who appeal to evidence from the natural sciences.

## 2.2. INTELLIGENT DESIGN

In *Intelligent Design Uncensored*, Dembski and Witt provide a science fiction story to illustrate the key issues of the intelligent/evolution debate. The first chapter ends with a statement by the captain of a microscopic space ship,

> We know from experience that intelligent agents build intricate machines that need all of their parts to function, things like mousetraps and motors. And we know how they do it—by looking to a future goal and then purposefully assembling a set of parts until they're a working whole. Intelligent agents, in fact, are the one and only type of thing we have ever seen doing this sort of thing from scratch. In other words, our common experience provides positive evidence of only one kind of cause able to assemble such machines. It's not electricity. It's not magnetism. It's not natural selection working on random variations. It's not any purely mindless cause. It's intelligence—the one and only! (Dembski and Witt, 2010, 20–21)

By an analogy similar to the one that Paley provides, through observations of intricacies found within natural organisms we infer that such organisms exist as the product of design because the objects that we observe in the everyday world that exhibit such design-like attributes are products of an intelligent designer's handiwork.

At first gloss, it would appear that the ID argument would suffer similar objections that the classic argument from design has faced. We can imagine Hume's ghost shaking its chains as it howls "The universe is not like a machine!" The design thesis as developed in the ID movement is more complex than Hume's ghost would have it. Firstly, there is no unanimous agreement as to what "intelligent design" means, so we cannot simply dismiss the ID argument by presuming that what design theorists have in mind is the same sort of intelligent design that Paley endorsed. Because of this varied usage, it would be difficult to grasp what "intelligent design" means using conceptual analysis alone. We'll have to look at some of the real-world examples that are used as evidence for ID.

Secondly, Paley's argument is an analogy developed between the observation of a watch and the universe as a whole. The design argument as presented by ID is an analogy between the inherent complexities found within organisms of the world and human artifacts. So, whereas Paley's argument seems to be a weaker argument insofar as we are incapable of observing the overall complexities of the universe, the ID movement is able to gather direct evidence for the claim that individual organisms exhibit design-like properties. It's this appeal to individual organisms that distinguishes the ID argument from Paley's analogy.

The formulation of the ID theory that I will adopt in this essay is the one developed by Monton, an atheist. He writes,

> *The theory of intelligent design holds that certain global features of the universe* provide evidence for the existence of *an intelligent cause, or that certain biologically innate features of living things* provide evidence for the doctrine that the features are the result of *the intentional actions of an intelligent cause which is not biologically related to the living things,* and provide evidence against the doctrine that the features are the result of *an undirected process such as natural selection.* (Monton, 2009, emphasis in original)

Although many proponents of the ID argument only appeal to the complexity of individual organisms (Behe, Dembski, Meyer), some ID theorists also appeal to the global properties of the universe (CSC-Top Questions 2010). Much of what I say can be applied to those who maintain the global properties of the universe as being design-like. My focus, though, will be on the arguments given by proponents of the ID argument who appeal to the "biologically innate nature of living things."

Before looking at the arguments given by ID theorists, it may be useful to first clarify what is meant by "design." As used by proponents of the ID theory, "design" seems to mean "has an organized structure that exhibits the intentions of an external causal agent." For something to be designed requires that there be a designer. This is consistent with the claims of the pilot of the microscopic spaceship and is in line with the claims of the proponents cited below.

Many advocates of ID appeal to biochemistry as a source of support for their arguments. Behe (2006) famously maintains that there are "irreducibly complex" systems that are "composed of several well-matched, interacting parts that contribute to the basic function, wherein the removal of any one of the parts causes the system to effectively to cease functioning" (Behe, 2006). Rana (2008) uses the idea of irreducibly complex systems as evidence for the design thesis when he writes,

> If the protosystem doesn't have function, then natural selection can't operate on it to produce an improved form. Without function, natural selection has nothing to select. Irreducibly complex systems, and hence biochemical systems, must be produced all at once. Therefore, it's completely within the bounds of rational thought to conclude that irreducibly complex biochemical systems came into existence through intelligent agency. (Rana, 2008)

He continues, "As we look at the systems that constitute life at its most fundamental level, it is my hope that the weight of the evidence will convince you that biochemical design results from a Creator's hand, a Divine Artist" (Rana, 2008). Rana, however, does not clearly explain why biochemical phenomenon should be taken as design-like other than their inherent complexity and why this complexity is evidence for a “Divine Artist.” We could take such complexity to be epistemic complexity—that is, the complexities we observe are an indication of our limited ability to understand nature, but nothing more.

In reference to Dembski’s account, Meyer states, “[Dembski] concludes that the information content of DNA—like the information in a computer program or an ancient scroll—had an intelligent source” (Behe et al., 2000). This is because of the way that DNA functions to encode organisms for a specific task. ID theorists take DNA to be a complicated record left by an intelligent source. The analogy that Dembski develops for the complex nature of DNA is that of archaeological evidence. In reference to archaeological evidence, Dembski describes the way that archaeologists are able to make discoveries that other humans were present in an area when he writes, “good reasoning often leads people to infer the activity of intelligent agents from the effects that they leave behind” (Behe et al., 2000).

The above quotes suggest that by observing objects with design-like attributes, we can infer that there is a designer. For example, archaeologists often use this kind of reasoning to maintain that a person was present in an area by observing the remains of fire rings, pottery, or hunting grounds. What’s different, though, between the archaeologist and the evidence that Behe, Rana, and Meyer appeal to is that we *have* observed humans making fire rings, pottery, and weapons. We have not observed a human making bacterial flagellar motors.

There are arguably enough similarities, though, between the archaeological artifacts and the biological “artifacts” that the biological evidence is evidence for an intelligent causal agent in the same way that archaeological evidence is evidence for an intelligent causal agent. The idea is that it is extremely improbable that something like a decorated piece of pottery will come into existence and become decorated, given the history of the universe, without the aid of an intelligent agent. By analogy, the complexity of the inherent structure of biological organisms is also extremely unlikely to have arranged itself *just so* such that the biological organism can exist without the aid of an intelligent agent.

Beyond these analogies, though, it seems that Dembski, as well as the other ID theorists, is making use of *abductive reasoning* (also sometimes known as *inference to the best explanation*). This type of reasoning allows a person to formulate the best account of how things have come to be as they currently are. We see such reasoning used in legal situations in which a detective attempts to piece together the cause of a crime, or in cosmological situations in which astrophysicists attempt to provide an explanation for the origin of the universe. In the case of the ID discussion, the burden is to demonstrate that an intelligent designer is the best explanation for currently existing phenomenon when compared to naturalistic explanations.

In an attempt to corroborate evidence for the existence of an intelligent designer, it is unclear to what extent biochemical systems should be appealed to for such purposes. At this juncture, it seems that we have come down to a burden of proof issue, as Rana states, “Of course, the burden of proof should be on evolutionary biologists to explain in detail how biochemical systems originated on their own” (Rana, 2008). What if the apparent intricacies of natural organisms were not the products of design? What if the elements of nature come together in such a way as to exhibit design-like attributes without being created exogenously? If we are capable of providing natural evidence that serves as an explanation for how things came to be, and this body of evidence serves the same explanatory role that an intelligent designer does, then the complexities found within nature do not necessarily provide evidence for the design thesis in the way that ID advocates claim. The appeals to self-organizing systems in the other sciences may provide some insight to this discussion. It's with these issues that we now turn to systems theory.

## 3. Systems

This section provides a basis for understanding some of the key components of self-organizing systems. Although many of the details are of contention among systems theorists, what I say does not tread into these debated issues. Furthermore, much of the developments in systems theory are found in mathematics. I will only focus on the mathematical concepts that I believe will illuminate this discussion.

### 3.1. SYSTEMATIC DETAILS

Although peripheral to contemporary physics, biology, chemistry, philosophy, and theology, systems are not a new concept. We can describe a system as being a set of independent yet interacting parts. It's useful to think of systems in terms of a function. A function is a mathematical expression that takes an input and applies some rule to produce an output. Like a function, a system has independent elements that serve as inputs, and given the nature of the system, the system generates outputs.

We can classify systems in two ways: *noncomplex* and *complex*. A noncomplex system is one that generates predictable outputs. Although noncomplex systems are the less interesting of the two, an understanding of how noncomplex systems work will provide insight to the underpinnings of complex systems. When given relevant data, we can model a noncomplex system using a simple input–output function table. Another identifiable trait of noncomplex systems is that they exemplify *superposition*.

A system exemplifies superposition if the system is *homogeneous* and *additive*. A system maintains homogeneity when the doubling of any input of the system will uniformly double the output. For example, for a system that is modeled using the function $f(x) = 2x$ and given an input $i$ where $x = 2$, we then obtain the output $o$ of 4. By doubling the input $2i$, where $x$ would then equal 4, we then have an output $2o$ of 8.

A system is additive if the sum of the inputs $i$ and $j$ generates the sum of their respective outputs $o$ and $p$. A folk example will help illustrate. Take a system in which the input is the slamming of a door and the output is the sound produced. Using the function $f(x) = 2x$, given a slam input $i$ of 2 we generate a sound output $o$ of 4. Given a slam input $j$ of 3 we generate a sound output $p$ of 6. If additivity maintains, the sum of $i$ and $j$, when taken as slam input $k$, will generate a sound output $q$ that is equivalent to the sum of $o$ and $p$.

Complex systems, on the other hand, do not satisfy the superposition principle. Whereas the outputs of a system that maintains superposition are directly proportional to their inputs, as described by a function $f(x)$, the outputs of complex systems are not directly proportional to their inputs. For this reason, complex systems are not easily modeled using input–output function tables. Instead, nonlinear equations are often used to represent complex systems. These equations are difficult to solve but illustrate how the interactions of the members of a complex system usually bring about unpredictable outputs. These systems are commonly described as being *chaotic*, insofar as they seem to lack any inherent order. This, however, is a misnomer (Lorenz, 1993). Rather than thinking of complex systems as being entirely directionless and unpredictable, these systems are epistemically surprising because they exude variation through the passing of time.

We see these variations in complex systems occurring over time in both the formation of a new system and the modification of a preexisting one. The weather is an example of the latter. Given slight variations in the temperature, wind, humidity, or any combination thereof, we observe diverse changes throughout the system. Lorenz argues that we have reason for believing that the overall atmosphere is a "chaotic" system. He writes,

> Almost without exception, the [mathematical] models have indicated that small initial differences will amplify until they are no longer small…Unless we wish to maintain that the state-of-the-art model at the European Centre and competitive models at the National Meteorological Center in Washington and other centers, do not really behave like the atmosphere, in spite of the rather good forecasts that they produce at short range, we are more or less forced to conclude that the atmosphere itself is chaotic. (Lorenz, 1993)

The formation of an ant colony, on the other hand, is an example of a complex system whose output is the formation of an organized system. Given the genetic encoding of an individual ant, an ant is then capable of performing a task: tending to a queen, searching for food, or setting out to establish a new colony. An individual ant, however, does not organize the efforts of other ants to then obtain the overall sustainment of a colony, and it is not simply by virtue of having a group of ants that a colony comes into existence. It is a particular combination of ants that then allows a colony to exist. Of course, a colony must have a queen, but the queen does not dictate what each ant will do. Instead, the queen is necessary for the survival of the colony, but in a sense so is every other ant. A colony arguably comes into existence through the execution of a series of performative actions that each ant completes. But it is not because each ant completes each action $x$ amount of times; it is because each ant performs the right kind of action in the right way for an extended duration that then allows the colony to exist (Johnson, 2001).

Because systems are used to model many natural phenomenon, it seems that ID theorists should also incorporate the findings of systems theory to account for the biological complexities that they observe. I am not aware, however, of any proponent of ID who takes into account the findings provided by systems theory. Although Behe (2000) responds to some objections of ID that systems theorists have made, he dismisses the self-organization account as an untenable explanation for the irreducible complexities that he appeals to as evidence for an intelligent designer. ID theorists, furthermore, maintain that the inner intricacies of biological organisms are unpredictable given the background assumptions of the system in which the organisms arise. This unpredictability is motivation for the idea that there is some creative artisan behind the intricate components that biological organisms depend upon. The intricacies of biological organisms, however, are complex. For this reason, I believe that complex systems of a particular type, self-organizing systems, will provide some insight to the development of the complexity found within biological organisms.

## 3.2. SELF-ORGANIZING SYSTEMS

A system is self-organizing if a pattern or structure arises within a system without the aid of an external causal agent. Put another way, a system is self-organizing if the system constructs its own order in the process of organizing itself. Whereas a complex system typically has unpredictable outputs as a result of how the system is organized, a self-organized system is arguably complex because it is the organization itself that is the unpredictable output. An ant colony is an example of this.

There is also evidence in the other sciences for the existence of self-organizing systems. For example, self-organizing systems are used to model the formation of planets, stars, and crystals. Most relevant to this discussion is the recent debates in evolutionary biology regarding the application of self-organizing systems to evolutionary theory (Van de Vijver et al., 1998). The outcome of these debates seems to have the most bearing on the design thesis seeing how they aim at providing an account for the very thing that ID theorists use as evidence for the existence of an intelligent designer—the internal complexities of biological organisms.

The debates are sparked by the two complementary processes that Darwin maintains are responsible for evolution: "on the one hand, an evolution of species by some random mutations and, on the other, a natural selection of the species which fit best with their environment" (Dubois and Daniel, 1998). Whereby, for Darwin, the process of preserving favorable mutations and rejecting unfavorable ones is natural selection (Darwin, 2004), it is unclear what is being selected for and what the aim of selection is—that is, it is unclear what the *telos* of selection is, if there is any. Kaufmann states, "Selection achieves and maintains complex systems poised on the boundary, or edge, between order and chaos" (Kauffman, 1993). Even if this is what selection does, it doesn't provide an account of the aim of selection. If selection is only the maintenance of complex systems, then it seems that self-organizing systems do not provide any challenge to the ID theorist since complex systems can be understood as the products of design.

Kaufmann goes on to suggest that self-organizing systems are the fundamental components that natural selection has to work with. So the self-organizing systems that are observed in nature are what is being selected for, whereas nature allows the self-organizing systems that are favorable to an organism to persist and those that do not contribute to the survival of the overall system that the self-organizing systems are the basic constituents of to desist.

It is tempting to think that a self-organizing system, when left unattended, will become inherently more chaotic given the complex nature of a self-organizing system. This thought may in part be motivated by a particular reading of Boltzmann's formulation of the second law of thermodynamics, which states *the entropy of a closed system cannot decrease*. It would seem that the system requires an external source to maintain the order that we observe in the world. This, however, is a mistaken understanding of the second law. It is true that the entropy of a closed system cannot decrease, but it is not the case that entropy must always increase. A system that is at maximum entropy is one that is in a state of equilibrium. For example, a cup of ice will reach maximum entropy when all the ice has melted in the cup and the remaining liquid is at the same temperature as the air that surrounds the cup. So, there are cases in which some external agent is arguably not needed to prevent the onset of continuous entropy. For this reason, I believe that the formation of complex patterns that have self-organized systems as their bases provides insight as to how biological intricacies begin to exist and sustain themselves without the aid of an external causal agent. In other words, by looking at self-organizing systems, I believe that we can provide an account of how the intricacies of biological organisms come to exist and are sustained without appealing to a designer. This is a similar point made by Dong (2010).

## 4. Self-Organizing Systems and Design

So far, this discussion has been an exegesis of the design thesis and its contemporary formulation in the ID movement. As this very volume shows, there is much contention as to whether or not the design thesis in any form is a tenable one. What I set out to do in this section is to discuss whether or not self-organizing systems provide evidence for a designer and what implications self-organizing systems have for the design thesis as formulated by the ID movement.

### 4.1. DO SELF-ORGANIZING SYSTEMS REQUIRE DESIGN?

This is the question that needs to be asked if we are to understand what impact self-organizing systems have on design arguments. Another way of framing this question is as follows: Is it possible for a self-organizing system to come into existence without the aid of an external causal agent? Since a system is self-organizing, by definition, if a pattern or structure arises within a system without the aid of an external causal agent, it seems that we have already answered our question without needing to go further. But this definition can be formulated by mere stipulation and does not provide much insight as to whether a self-organizing system requires a designer or not. Furthermore, it is unclear how a self-organizing system will exude design-like attributes, as in the cases of the intricacies found within biological systems, without appealing to the aid of a designer. The question now is what is the cause of self-organizing systems? The intelligent designer will be tempted to say a designer designs self-organizing systems. Someone like Hawking would say something along the lines of "Spontaneous creation is the reason there is something rather than nothing, why the universe exists, why we exist. It is not necessary to invoke God to light the blue touch paper and set the universe going" (Hawking and Mlodinow, 2010). I maintain that something similar to Hawking's statement can be said for the formation of self-organizing systems and the biological complexities that these systems are the constituents of.

It is useful to first consider why someone might believe that self-organizing systems do require design. Self-organizing systems seem to arise from nowhere—that is, we seem to lack epistemic access to the causes of such systems. Because these systems appear to come together in just the right way, it is difficult to conceive how random chance can lead to the formation of such intricate systems. Even if we were to entertain the idea that random chance and natural selection were the sources of self-organizing systems, evolution has not had enough time for these systems to be selected for. The *only* rational alternative is to posit an intelligent designer as the source of these self-organizing systems. Let's table this view for the moment.

Perhaps a look at how self-organizing systems come to exist will offer a solution as to whether or not they require a designer. I believe that Csányi's (1998) account of *autogenesis* in *zero systems* will provide some insight to this issue. A zero system is a set of components that lacks organization. Given the definition above, a system is a set of independent but interacting parts. From this, a zero system is arguably a system because each of its components interacts with one another, just not in an organized way. A way to think about these components is that these components are a set of inputs for a function, and the function has not been applied to the inputs to generate the outputs. A zero system is similar in that it has all the components present that the function will be applied to. For the function to be applied to the components of the zero system, there must be a minimally sufficient set which is capable of replication or copying. Furthermore, the set "contains at least one cycle of component-producing processes, [and] at least one of the components participating in this cycle can be excited by the energy flux flowing through the system" (Csányi, 1998). The informational content of a zero system will increase with time once it has become excited. During this time, the functional information of the system will begin to regenerate itself, thereby creating structure. As information is produced, more complex inputs are developed which then allow for changes in the overall system to occur. At this point, the system is said to have self-organized since it is by virtue of its own components that it generates a pattern which can lead to other complex self-sustaining structures.

Returning to the idea of a function, if we take the zero system components as the input and then, after applying energy to any one component to begin exciting the other components, the system organizes in such a way that it generates a function that then determines how future perturbations of the system will behave. The overall system can be said to *iterate*—that is, the system will take as input the output of the last perturbation. After many repetitions, the system then obtains additional components to the initial set, this then allows for the system to become more complex. Through this overall process, a more complex system emerges that would not have been predictable given the initial conditions of the system.

We can apply this model of self-organizing systems to the way in which biological organisms form. A self-organizing system is one that is capable of replicating itself, and it is through the process of replication that the system develops new information. With this new information available as inputs for the next perturbation cycle, the system is able to generate more complex patterns. Turing further develops this idea of self-organizing systems to provide an account of the formation of biological organisms when he states, "Most of an organism, most of the time, is developing from one pattern into another, rather than from homogeneity into a pattern" (Turing, 1952). Using a model of self-organizing systems, given the initial genetic material of an organism, complex structures arise through the chemical interactions of the genetic material. It is on the basis of these complex structures that an organism is able to develop and sustain itself once it reaches a sophisticated level of development. The specific case that Turing considers is the formation of an embryo, which by chemical reactions is able to form although the tissue that makes up the embryo is not itself growing. From this we see a caricature in which "simple" components (tissue) interact to generate a more complex organism.

The idea that complex organisms can emerge from interactions of simple components has further paved the way for sophisticated models of other complex phenomena (e.g., life). Conway's *Game of Life*, for example, attempts to simulate how complicated structures can arise in a two-dimensional array given a set of initial conditions and basic rules or laws (Hawking and Mlodinow, 2010). This simple two-dimensional model is a powerful example of how a particular set of initially unarranged components, which are constrained by a set of laws, are capable of generating complex self-replicating systems analogous to the ones that we find in the empirical world. (For a demonstration of Conway's model, see Martin (2010)) These models have direct correlations to our own empirical discoveries. As Hawking writes, "One estimate, based on the earlier work of mathematician Jon von Neumann, places the minimum size of a self-replicating pattern in the Game of Life at ten trillion squares—roughly the numbers of molecules in a single human cell" (Hawking and Mlodinow, 2010). Not only do these models help us understand how large complex systems can emerge from simple parts, but they help us understand individual organisms as well. This is in line with what Hawking suggests when he writes, "One can define living beings as complex systems of limited size that are stable and that reproduce themselves" (Hawking and Mlodinow, 2010).

Given the initial formation of self-organizing systems from zero systems through autogenesis, we do not have reason for positing a designer as the cause of self-organizing systems. Furthermore, we see both empirical and theoretical models that make use of self-organizing systems without appealing to a designer. As in the case of Turing's account of morphogenesis, we have an account of how organisms are capable of developing complex structures. Conway's *Game of Life* provides a theoretical model for understanding how complex structures can arise from an initially unorganized set of component parts. Each of which suggests that self-organizing systems do not require design, and, therefore do not require a designer.

Let's now bring back the idea that self-organizing systems do require a designer. To review, this claim is based on the inference that since it is very unlikely for the complex structures found within self-organizing systems to arise without the aid of an external causal agent, and since these complex structures do occur, we have reason for believing that they exist as the outcome of an external causal agent—namely, a designer.

We have two competing views on the table: self-organizing systems do not require a designer and self-organizing systems do require a designer. Given that the first view is supported by both empirical and theoretical data, whereas the second view appears to be a claim based on human epistemic limitations, it seems that we ought to adopt the first claim. At this point, someone could argue that I've simply left the designer out of the picture, that it is a designer who has set in place the initial conditions and rules or is the energy flux that allows the zero systems to begin perturbation cycles. Perhaps, but there doesn't seem to be any substantive evidence to corroborate this claim. It's unclear, though, what exactly would count as evidence for this claim. Until we've resolved these issues of what counts as evidence and such evidence is available, I'll have to leave a designer out of the picture. These burden of proof issues will be further discussed in the following section. For the meantime, because self-organizing systems do not require design, I maintain they do not independently provide evidence for a designer. The next section will discuss some of the implications of this inference.

## 4.2. IMPLICATIONS

As the above discussion suggests, self-organizing systems do not require design. This has implications for the design thesis as formulated by proponents of ID. To review, the formulation of ID I have been concerned with is the one that suggests

> *that certain biologically innate features of living things* provide evidence for the doctrine that the features are the result of *the intentional actions of an intelligent cause which is not biologically related to the living things,* and provide evidence against the doctrine that the features are the result of *an undirected process such as natural selection.* (Monton, 2009, emphasis in original)

I will divide this formulation into two parts: *evidence for* and *evidence against*.

The bacterial flagellum motor is often used as evidence in favor of ID. Miller attempts to reject Behe's argument by suggesting that the flagellum motor is the end product of nature collecting components from other systems, thereby suggesting that the flagellum motor is not irreducibly complex. Dembski and Witt respond to Miller's charge that it is nature that is doing the arranging, and this arrangement is done by an intelligent agent (Dembski and Witt, 2010). Perhaps self-organizing systems will offer another alternative to these views.

We can take what follows as a rough sketch of what a biochemical account of the formation of the bacterial flagellum motor might look like on the self-organizing system picture. It appears that the bacterial flagellum motor can be the product of a self-organizing system. The components that make up the bacterial flagellum can arguably only exist in specific environments. If we attempt to isolate a bacterial flagellum from any of these environments, then it will surely not survive. From this, it seems that the environment plays some causal role in the survival of the bacterial flagellum, so why not also suggest that the environment plays a causal role in bringing the bacterial flagellum about? This is similar to the development of an embryo, which is much more complex than a bacterial flagellum. By having the embryo in a particular chemical environment, the tissue that makes up the embryo is capable of reacting to generate the appropriate complexities that form a biological organism. We can agree that the biological organism is a complex myriad of biochemical elements that would unlikely develop in the appropriate way had its elementary components not been in the right environment to begin with. By analogy, it seems that a bacterial flagellum can only develop if its component parts happen to be in the appropriate environment that allows for the parts to react to one another, thereby developing into the complex structure that is the bacterial flagellum motor. This appeal to self-organizing systems appears to strip the bacterial flagellum motor of its evidential support for the intentions of an intelligent designer.

This account is consistent with Behe's claim that "the removal of any one of the parts causes the system to cease functioning" (Behe, 2006). By removing any one of the initial component parts that make up the bacterial flagellum motor, the motor will not function. Adopting the above account, we can take Behe's suggestion one step further to suggest that without the components being present within the appropriate environment, the component parts are incapable of organizing themselves. We can also run a similar argument for the inner workings of a cell that Rana (2008) appeals to for evidence of an intelligent designer. The main thrust of this approach is that self-organizing systems appear capable of accounting for design-like complexity without appealing to a designer since the inherent complexity can be accounted for by the interactions of the component parts of the system within an appropriate environment.

If it turns out that something like the above account of how the bacterial flagellum motor comes to exist is true, then it seems that ID theorists lose the bacterial flagellum motor as evidence against the doctrine of natural selection.

Someone might argue that self-organizing systems themselves are not the product of an unguided process, but there doesn't appear to be ready available evidence for this claim—whereas, there does appear to be evidence that in at least some cases, self-organizing systems arise by natural selection. This is also consistent with Kaufmann's claim that self-organizing systems provide the foundation for what nature selects (Kauffman, 1993).

A further, and perhaps more positive, implication of the above discussion is also available. The claim that self-organizing systems do not require design does not entail that *no* self-organizing system requires design. This suggests that there are some self-organizing systems that do not require design, but this is also compatible with the claim that there may be some self-organizing systems that do require design. Perhaps the self-organizing system that serves as the basis for bacterial flagellum motors happens to be one of these systems that does require design. For this reason, the claim that self-organizing systems do not require design is compatible with ID. This upshot is dependent upon the ID claim that not every observed complexity is the product of a designer (Behe et al., 2000). The challenge of this reconciliation is that non-ID theorists may be content without the positing of a designer, so it will be up to the ID theorist to delineate the conditions under which a designer is the artificer of inherent biological complexities and when such complexities arise simply as the outcome of natural processes.

## 4.3. BURDENS OF PROOF AND GOING FORWARD

With these lingering alternative explanations for the prominent evidence used in support of ID, it appears that the burden of proof has been moved to the ID theorists to show how these potential natural nondesign explanations are implausible, provide evidence for an intelligent designer, or are consistent with the design thesis. I can imagine that a potential response would be an appeal to the inherent complexities of the self-organizing systems themselves and that such complexities are evidence for an intelligent designer. At this point, though, the disagreement between naturalists (those who endorse the thesis that there is nothing beyond the natural world) and ID theorists will not make any progress.

I can imagine the overall scenario as follows: naturalists attempt to provide an explanation for some previously unexplained phenomenon that is dependent upon complexity. The complexity itself, however, is not explained in terms of the natural account and leaves an explanatory gap of a sort. ID theorists use this complexity as evidence for an intelligent causal agent to fill in this explanatory gap. With advances in science and technology, the previously unexplained complexity may become explainable in natural terms, thereby leaving some other complexity without a natural explanation. The cycle repeats.

In the board game GO, *ko* is a sequence in which each player returns the game to the previous state by repeating the same moves. There are different interpretations as to how many times this is permissible, but the general consensus is that ko is frowned upon. I believe something similar can be said for the debate between ID and non-ID theorists.

Overall, I do not believe that direct investigations into nature will provide the evidence needed to determine conclusively that nature itself is the product of an intelligent designer. Any effort made in this direction is likely to be met with an equally competitive natural explanation, and because the competing explanation does not require appeals beyond the natural realm will be the stronger of the two because of parsimony. But is this really the right approach?

A more fully developed account of explanations will provide insight to this issue. Specifically, we require an account of what will count as an adequate explanation for design or a designer. As the situation stands, any inference to a designer from observed design-like attributes can be met with a critique of human faculties along the lines of it being the way that the human brain interprets the world that leads us to believe that we are observing design-like patterns, when in fact there are none. Most importantly, though, whatever account is developed, we must be careful to distinguish what we want to be true from what we have reason for believing is true.

With these comments in mind and the above discussion, future theories that endorse the design thesis would do well to develop an argument for the design thesis that does not make use of analogies. There will always be complaints that the analogy does not hold between the observations and an intelligent designer, and there will always be naturalists who are willing to hold out for a natural explanation. There is, however, always the option that we can provide a van Fraassen-type response and suggest "that there doesn't have to be an explanation for everything" (van Fraassen, 1989). I'm sure that this solution, though, will leave many of us, naturalists and design theorists alike, unsatisfied.

## 5. Conclusion

To sum up, this essay has been an attempt to understand what implications self-organizing systems have for the design thesis as defended by ID. The process has been to first discuss how ID is not susceptible to the same critiques as historical formulations of the teleological argument. By providing a summary of how self-organizing systems offer insight as to how complex structures can arise from simple parts, I suggest that self-organizing systems provide a potential problem for ID's formulation of the design thesis. The principal problem that self-organizing systems put forward is that we can offer an account of the formation of self-organizing systems without appealing to an external causal agent. Furthermore, these systems can account for the inherent complexities found within biological organisms—thereby offering a causal explanation for these biological organisms themselves. In an attempt to reconcile this problem, it seems that the ID theorist would do well to avoid attempts at formulating an argument from analogy to support the design thesis. Otherwise, it seems that the discussion will reach a standstill, leaving both naturalists and design theorists to develop their theories without interaction. If our aim is an understanding of how the world really is, then it seems we should avoid a route that would lead to such an outcome. Lastly, I hope that this chapter will assist religion in avoiding critiques similar to the one that Hawking offers of philosophy when he writes "philosophy is dead. Philosophy has not kept up with modern developments in science" (Hawking and Mlodinow, 2010).

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Biodata of **Lev V. Beloussov**, author of "***Development of Organisms as Self-Organization of Mechanically Stressed Macroscopic Designs***."

**Lev V. Beloussov** was born in St. Petersburg in 1935. He graduated from Moscow State University (MSU) at 1957. He is a professor of embryology (since 1980) and a professor emeritus, MSU. His main interests include physical factors of embryonic development, mechanics, and self-organization of morphogenesis. He is the author of more than 200 papers, including books: *Biological Morphogenesis* (1987) Moscow University Press (in Russian) and *The Dynamic Architecture of a Developing Organism* (1998), Kluwer Acad. Publ. For his works on mechanics of development, he was awarded with Carlo Bondi Prize (1990, University of Perugia, Italy) and Alexander Kowalevsky Prize (2009, Russian Acad. Sci.).

E-mail: **morphogenesis@yandex.ru**

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# DEVELOPMENT OF ORGANISMS AS SELF-ORGANIZATION OF MECHANICALLY STRESSED MACROSCOPIC DESIGNS

**LEV V. BELOUSSOV**
*Laboratory of Developmental Biophysics, Faculty of Biology,*
*Moscow State University, Moscow 199991, Russia*

## 1. Introduction

According to a primitive but nevertheless still vivid view, any substantial progress in biology is directly linked with the increase of technically achieved limits of the optical resolution: in order to "explain" anatomical structures, one should go down to the level of a tissue, then to the cells, and finally to the molecules. Meanwhile, such a primitive version of reductionism has been recently undermined by the ideas forwarded by a self-organization theory and its affiliations (chaos theory, etc.: see, e.g., Capra, 1995). As a result, it became obvious that the upper level events are far from being enslaved by the lower levels machinery but are instead at least equal, if not the leading participants of the causal chains, moving forward a given multilevel process.

A focus on the "design," taken in this book, gives an opportunity to discuss, whether such a macroscopic approach may be relevant for the development of organisms. The classical embryology was indeed mostly a macroscopic science, dealing with designs seen by a naked eye or under low optical magnifications. Enormous progress achieved recently in revealing genetic and molecular machinery underlying macromorphological events led to a conclusion that the latter can be completely "explained" by the lower level processes. It is meanwhile not the case. The main problem of embryonic development – why the given embryonic structures are arisen at the given times and locations – cannot be even properly formulated, not to say solved if ignoring an important role of the upper level(s) processes in regulating developmental events.

In this chapter, we develop an idea that a regulation coming from the upper level is associated with a system of nonlinear feedbacks based upon self-generated mechanical stresses, intimately connected with successively arisen shapes (morphological designs).

## 2. Embryonic Designs Are Self-Organized and Mechanically Stressed

The immediate association born by a word "design" is a voluntary, man-made image or a tapestry, painted over an indifferent blank background. Such an anthropocentric view profoundly affected conventional scientific interpretations of morphological designs, observed in developing embryos. As a rule, they were believed to be determined, or “programmed” by certain agents (genes, embryonic inductors, factors of PI, and so on) external to embryonic material itself, while the latter was treated as a “tabula rasa,” able to passively accept any imposed blueprint.

We would like to show that such an idea is incorrect and should be replaced by the opposite one, emphasizing the *self*-organizing properties of the living matter. Our first arguments will be based upon the analysis of mechanical properties of embryonic tissues.

Let us ask ourselves: what should be the most favorable mechanical properties of a material used by a sculptor for performing a voluntary creation? Obviously, (1) a preferable material should be mechanically isotropic, and (2) artificially imposed deformations should not generate any resistance forces, tending to restore the initial shape – in other words, the deformed sample should not have any “memory” about its past. Or, what is almost the same, the elasticity of such a material should be close to zero.

Meanwhile, the mechanical properties of embryonic tissues are just the opposite. By performing a series of strictly localized incisions of frog’s embryonic tissues, we have observed that some of them, quite specifically located, were followed by very rapid (practically instantaneous) deformations (bendings) of incised parts (Beloussov et al., 1975).

We considered these “mechanical jumps” (as defined by Hutson et al., 2003) as relaxations of preexisted quasi-elastic stresses.

Most important, the sites of mechanical jumps created quite precise patterns, which remained invariable during several hours long developmental periods (perfectly fitting to those defined in classical embryology as blastulation, gastrulation, neurulation, and tail-bud formation) while drastically changing in between. Each of these developmental periods was characterized by a specific “stress design,” or a tension field, whose main elements were the stretched embryonic surfaces, prolonged files of stretched cells crossing embryonic tissues (so-called cross-lines) which encircled compressed compartments, and the tension nodules (meeting points of two or several cross-lines and/or cross-lines – embryonic surfaces. Close to the nodules, the tensile lines were maximally concentrated. Thus, the tension gradients have been emerged (Fig. 1).

Quasi-elastic tensions were detected by “mechanical jumps” and related techniques in the embryos of all the studied species, from Cnidarians to Amniotes (Kraus, 2006; Kiehart et al., 2000; Brouzes and Farge, 2004; Cherdantzeva and Cherdantzev, 1985, 2006; Kucera and Monnet-Tschudi, 1987; Bellairs et al., 1967; Taber, 2006). At the earlier stages of development, the main tension-producing force was the turgor pressure within a blastocoel and/or subgerminal cavity (Stern, 1984). Meanwhile, since the beginning of gastrulation, new stress patterns were generated by collective morphogenetic movements, mostly based upon a complicated actomyosin and endocytotic machinery (e.g., Krieg et al., 2008; Pouille et al., 2009; our data, in preparation). In any case, embryonic tissues are quite far from

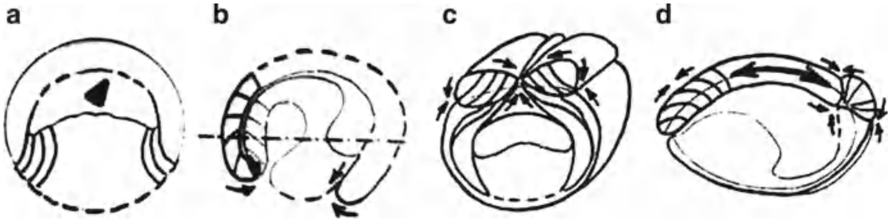

**Figure 1.** Sketches of mechanical tension fields during successive periods of amphibian development. (**a**) Blastula, (**b**) gastrula, (**c**) neurula, and (**d**) tail-bud stage. Outlined are the main tension lines. *Converged arrows* point to tension nodules. They are directed uphill the tension gradients. *Black oblique triangle* in (**a**) displays turgor pressure in blastocoel. *Double-head arrow* in (**d**) indicates a longitudinal pressure stress within the rudiment of the notochord. (Modified from Beloussov et al., 1975.)

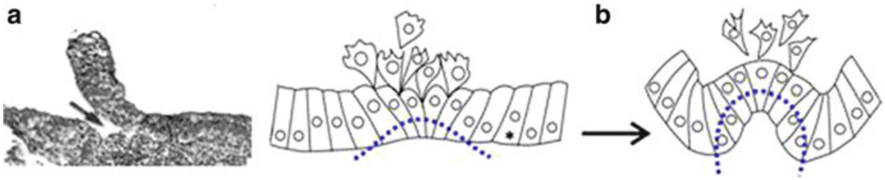

**Figure 2.** Rapid relaxations and "quasi-relaxation strategies" in morphogenesis. (**a**) Immediate bending of a separated (*arrow*) part of a neural plate of amphibian embryo precisely imitates the position of the same layer to be taken in about an hour of normal neurulation. (**b**) Two successive contours of invaginating archenteron during sea-urchin gastrulation. In each case, the next stage contour (*dotted*) is perpendicular to the lateral walls of the earlier stage oblique cells and is hence achieved by their approaching to rectangular (more symmetric) shapes. (**b** is from Cherdantzeva and Cherdantzev, 2006, with the authors' permission.)

being plastic, what would be expected if regarding morphogenesis as a kind of molding, performed by any outside forces. At the same time, their elasticity turned out to be quite useful for a mechanically based self-organization.

## 3. Stress-Relaxation Strategies

Interestingly, tissue deformations under mechanical jumps reproduced with a great precision just those morphogenetic movements which should be performed by the same tissue regions, if left intact, during next few dozens of minutes (Fig. 2a). This does not mean, however, that the normal morphogenetic events can be treated as pure relaxations, while moving along the relaxatory pathways, they, nevertheless, waste energy (similar to sledges moving downhill along a viscous snow). We define these movements as "quasi-relaxational" ones. Importantly, their directions are predetermined just by those mechanical stresses which are relaxed.

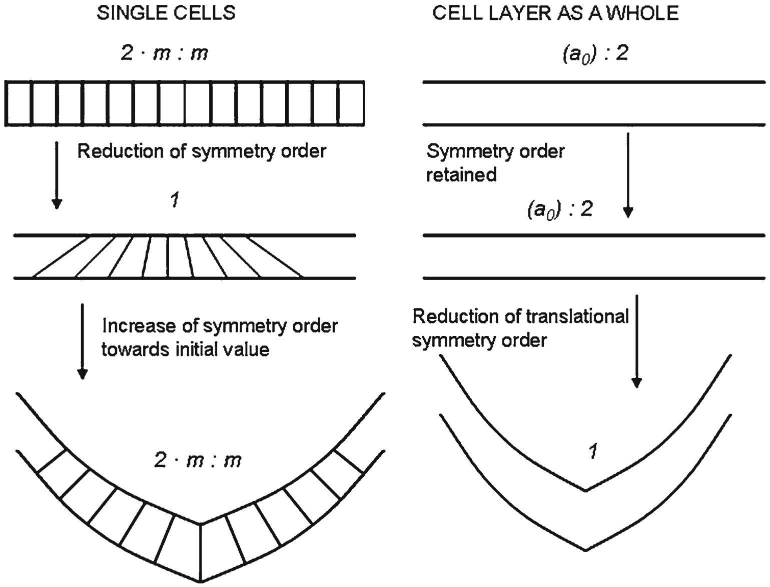

**Figure 3.** Symmetry changes on the levels of single cells and of an entire cell sheet during "quasi-relaxational" morphogenetic processes. Numbers over the frames are the orders of a rotational symmetry; letter $m$ displays mirror symmetry and letter $a$ translational symmetry; $a_0$ means a translational symmetry of indefinite order.

Quasi-relaxational movements are widely spread in morphogenesis. Most of them are based upon a phenomenologically simple process of a minimization of cell surface/volume ratio, which is realized in different taxonomic groups by different mechanisms. For example, gastrulation, neurulation, formation of sensory organs, etc., are achieved due to relatively slow (taking no less than several dozens of minutes) shifts of the coherent rows of elongated and oblique cells toward isodiametric shapes, associated with generalized contractions of cell surfaces under constant volumes (Fig. 2b). On the other hand, in the growing tips of thecate hydroids, similar cell transformations are owed to the cells swelling-deswelling, proceeding in a strictly periodic fashion each few minutes (Beloussov et al., 1993). In all the cases, however, the quasi-relaxational movements are associated with a heterochrony of symmetry breaks of the individual cells and of an entire cell layer: a first step, associated with generation of stresses, is in reduction of symmetry order at the individual cell level, while a symmetry of an entire sheet remains unchanged. Meanwhile, the next step (a visible deformation of a cell sheet, i.e., the shaping process itself) is linked with the restoration of the initial symmetry order (and hence relaxation of tensions) at the individual cell level and the break of translational symmetry at the entire sheet level (Fig. 3).

Two important properties of these "quasi-relaxational" strategies should be emphasized. First, due to a complicated mechanical structure even of an early embryo (the abundance of hardly deformed sites), the tensions never relax up to zero values. Moreover, the location of nondeformed (fixed) surfaces largely affects the macroscopic results of the partial cells relaxation. For example, during vertebrate neurulation, it is a firm fixation of the dorsal embryo midline, which provides the bending of a neural tube. On the other hand, in hydroid polyps during the main part of their growth cycle fixed are the basal cell walls, providing thus a straight elongation of a stem. The second point is that in developing embryos, the relaxation of one part is followed as a rule by the active increase of tensions in another one. We comment this point in the next section.

## 4. Stress-Based Developmental Feedbacks

In most of not so numerous studies which apply a self-organization approach to developmental events, the feedbacks are formulated in purely chemokinetic terms, such as auto- or heterocatalysis and/or inhibition of certain chemical reactions and diffusion of their products (e.g., De Robertis, 2009). Meanwhile, already three decades ago, several independent groups came to the idea that the role of feedbacks can be effectively played by mechanical stresses which, contrary to chemical factors, are closely linked to the shape (geometry and topology) of an entire embryo or its part. One of the first models of morphomechanical feedbacks (Odell et al., 1981) suggested that the stretching of a given part of a cell layer triggers its active contraction, which in its turn stretches the next adjacent part of a layer, and so on. In other words, a positive stretch–contraction feedback is postulated. Almost at the same time, Harris et al. (1984) experimentally demonstrated the existence of more complicated, "+, −" feedback between cells aggregation and cell-generated tensions. Quite similar feedbacks acting now within an epithelial sheet have been employed in the Belintzev et al. (1987) model. As a result, a segregation of a homogeneous epithelial sheet into coherent domains of tangentially contracted (radially elongated) and tangentially stretched cells could be reproduced.

Although each of these models properly described some important developmental events, none of them were able to imitate more or less prolonged chains of processes, proceeding in normal development one after another. For example, the formation of cell domains, reproduced by Belintzev et al. model, is usually succeeded by the changes in the layer's geometry, or by generation of pressure stresses, or by the both events together, which are, meanwhile, out of the model scope. Is it possible to embrace them, at least qualitatively, by a more general morphomechanical feedback? Following is the formulation of such an attempt:

"Whenever a change is produced in the amount of local stress applied to a cell or local region of tissue, the cells or tissue will respond by actively generating forces directed toward the restoration of the initial stress value, but as a rule

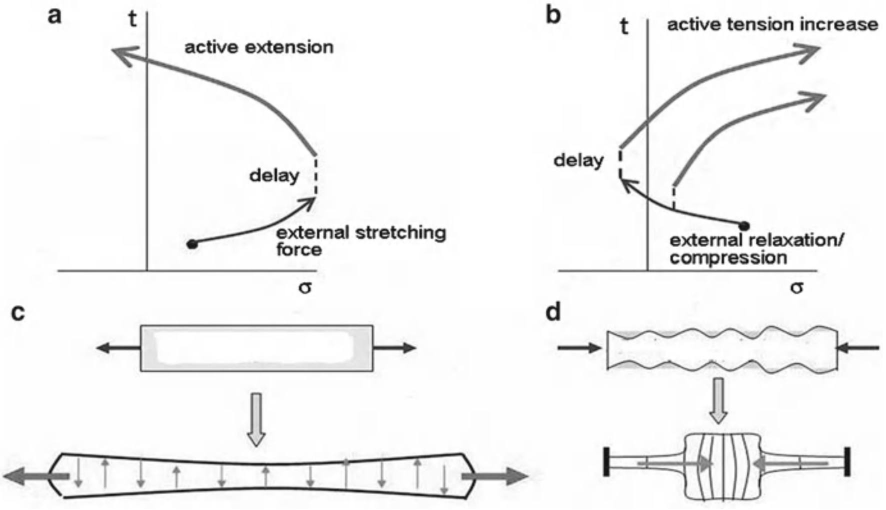

**Figure 4.** Model of hyperrestoration of mechanical stresses. (**a**, **b**) Schemes of the responses to stretching and to relaxation/compression, correspondingly. *Horizontal axis*: mechanical stress (compression to the left, tension to the right). *Vertical axis*: time. (**c**) A typical way for a response to stretching (cell intercalation). (**d**) Response to relaxation by tangential contraction (columnarization) of some neighboring cells. *Vertical bars*: firmly fixed edges.

overshooting it. Whenever such changes in stress are unevenly distributed, or anisotropic then the responses will be directed towards reducing (with an overshoot) whichever deviations are greatest" (Beloussov, 1998, 2008).

Figure 4a, b sketches two main HR responses. Noteworthy, the active response is in most cases slower than the deformation caused by an external force, and a certain lag period (dashes) should take place in between. Changes in the amplitudes of HR responses and in the lag period duration were shown to be of a primary morphogenetic importance.

Next, one should emphasize that the model's predictions largely depend upon boundary conditions, namely, upon whether the edges of a sample (let it be a cell, or a tissue piece) are free, mobile, or firmly fixed. If some sites of a stretched sample are firmly fixed while others let free, expected HR response will be its contractile relaxation associated by a shift of free sites (surfaces). This is just what was postulated by Odell et al. (1981). On the other hand, same response is expected according to the above described "quasi-relaxation strategies." Meanwhile, more typical for embryonic tissues is firm fixation of a sample edges during application of an external force, or tension release. Under these conditions, an expected HR response to a stretching would be the generation of internal pressure acting in the stretch direction. This is usually associated with redistribution of a cell material within a sample (so-called cell intercalation), as shown by vertical arrows in Fig. 4c. Just this was observed under the artificial stretching of explants taken from early gastrula *Xenopus* embryos (Beloussov et al., 2000; Troshina and Beloussov, 2009). In these experiments, cell intercalation started immediately after stretching, and in few hours, some of explants took a dumb-bell shape, visualizing the emergence of internal pressure, acting just in the stretch direction.

Correspondingly, after mechanical relaxation of a sample with fixed edges, one should expect a tangential contraction of at least some of its cells and/or cells emigration outside a sample: under these conditions, the tangential tensions should inevitably increase. This was indeed confirmed by measuring percent of tangentially contracted cells in the relaxed double blastocoel roof explants: within 2 h after relaxation, a percent of extensively contracted cells increased from 1 to 20, giving more than 70% tension increase, which considerably exceeded an initial stress relaxation (Evstifeeva et al., 2010). A real tension increase was even greater due to emigration of some epithelial cells from a cell layer.

Most important, these primary HR responses are coupled with each other into the *second-order morphomechanical feedback loops*, which we now come to describe.

## 4.1. CONTRACTION–EXTENSION (CE) FEEDBACK

We start from a slightly relaxed state of a cell layer with firmly fixed ends and suggest that some part of it (up to several cells) is actively contracted (Fig. 5a, α). As a result, the resting part (β) will be passively stretched and hence is expected to respond by the active (cell intercalation mediated) extension. This will shrink α part, inducing its subsequent active contraction (Fig. 5b), and so on. In this way, it is established what we call the contraction–extension (CE) feedback. As one of its consequences, an extensively compressed part due to its cell incompressibility can be extended (firstly passively and then actively) in perpendicular direction (Fig. 5b, α, c).

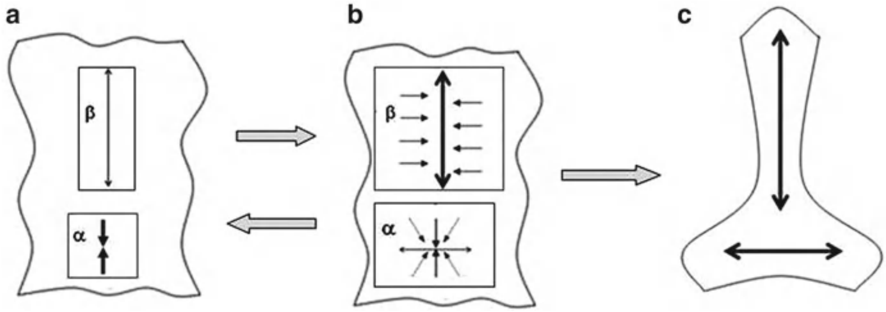

**Figure 5.** (**a**–**c**) Contraction–extension (CE) feedback. For explanations, see text. (From Beloussov and Grabovsky, 2007.)

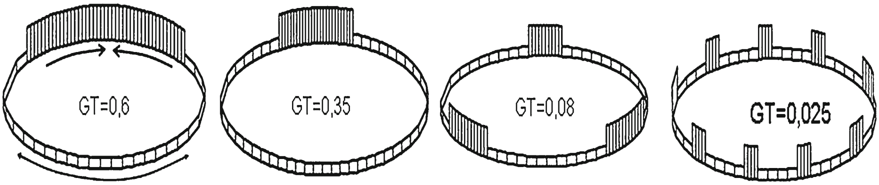

**Figure 6.** Formation of increased number of tangentially contracted (columnar) cell domains out of a homogeneous cell layer under diminished values of GT parameter. (From Beloussov and Grabovsky, 2007.)

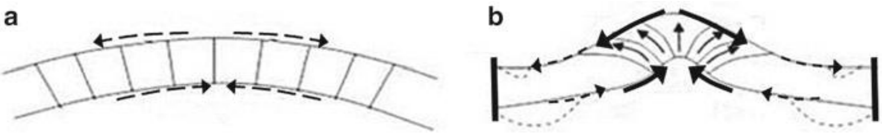

**Figure 7.** Curvature-increase (CI) feedback. (**a**, **b**) are passive and active phases of the curvature increase. For explanations, see text.

Even more important is that if the minimal value of a stretching stress triggering the active extension (so-called global threshold, or GT: Beloussov and Grabovsky, 2007) is not large enough, the number of compressed and extended domains will be greater than 1 and increase with GT diminishment (Fig. 6). In such a way, we come to the multidomain segregation of an initially homogeneous cell sheet which reduces its translational symmetry and imitates a widely spread process of segmentation. CE feedback looks as one of the most powerful tools of morphogenesis!

## 4.2. CURVATURE-INCREASE (CI) FEEDBACK

Suggest that a cell layer is slightly bent by an external force. As a result, its concave surface will be compressed while the convex one stretched (Fig. 7a, dashed arrows). If, as usual, the layer's edges are firmly fixed (Fig. 7b, vertical bars), the expected HR reaction would be the *active* extension of the stretched (convex) side and the *active* contraction of the compressed concave one (Fig. 7b, solid arrows along the layer's surfaces), associated probably with cells migration toward the convex side (Fig. 7b, radial arrows). In this way, a curvature just initiated by an external force will be actively increased. The active curvature increase of an artificially bent cell layer (taking place within several hours after fixing in a bent position) has been directly observed (Kornikova et al., 2010). Importantly, the active reactions should automatically generate onto their flanks the passive stresses (Fig. 7b, dashed arrows) which, in the case of the firm edge fixation, will trigger the formation of the opposite curvature folds on the flanks of the primary one (Fig. 7b, dotted contours). That means, that within HR model framework, a cell layer of a zero or uniform curvature should be unstable and tends to make folds (to break its initial infinite order translational or rotational symmetry). This opens wide possibilities for modeling various shapes, characterized by specific curvatures. For doing this, however, the following sets of morphomechanical parameters, able to take different values, should be specified:

1. Numbers ($N$) of kinematically independent units within a cell layer ($N \leq n$, where $n$ is a number of cells within a sample). If $N = n$, all the cells are kinematically independent from each other and may be shifted in the opposite radial directions. If $N < n$, several neighboring cells are bound together and respond to the lateral pressure by creating a common arch. $N$ is mostly associated with mechanical properties of lateral cell–cell contacts. It is reverse to what is called the bending rigidity and also to the wave length of so-called generic undulations of closed laterally pressurized contours (Green et al., 1996).
2. Temporal patterns of the lateral cell–cell pressure impulses. In many epithelial rudiments, especially in those belonging to lower invertebrates, the forces which increase the curvature consist of a series of quite regular growth pulsations (GP) (Beloussov et al., 1993). Different species-specific shapes created by these animals are closely correlated with GP time-amplitude patterns. We imitated different kinds of GP patterns by introducing five termed repeated successions of positive and negative pressure impulses, for example (1; 0,5; –0,2; 0,1; 0,7) (Beloussov and Grabovsky, 2007).
3. A constant elastic-like resistance $W$ to the local curvature increase ($0 < W < 1$). This parameter is assumed to keep a constant value throughout the entire GP series.

The main results of the modeling were the following:

(a) Periodicity of the pressure impulses turned out to be crucial for generating a large enough set of *long range ordered* realistic shapes (e.g., Fig. 8d, i), that is the shapes in which the distance between the neighboring curvature extremes exceeded that taking place between the neighboring kinematically independent elements. On the contrary, under constant pressure regime, the model rudiments were uniformly indented without any signs of long range order (Fig. 8b, g).

(b) Under periodic regimes and constant $N$ values, the arisen shapes were the functions of both $W$ and GP. For each GP pattern, a finite range of $W$ values compatible with generation of realistic shapes is taking place. Outside this range, under increased $W$ values, the arches were unfolded toward semicircles (Fig. 8e), while under smaller $W$ values, they became transformed into dense tangles (Fig. 8c, h).

(c) Circular shapes were able to produce, as depending upon the *ratio* of $W/N$ parameters (rather than their absolute values, taken separately), several discrete domains of stable lobular shapes of a definitely symmetry order, divided by spaces, populated by unstable asymmetric shapes, that is, rotating during each next iteration (Fig. 9).

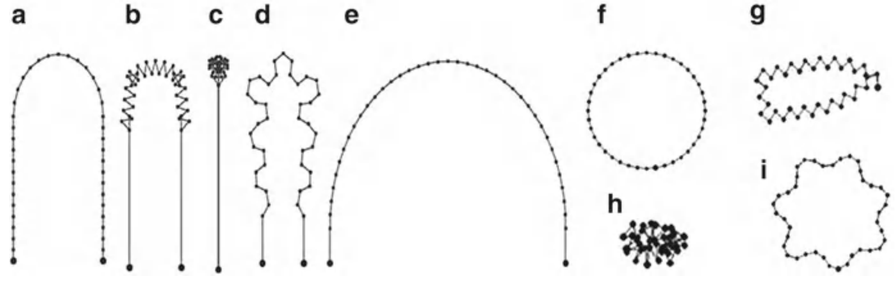

**Figure 8.** Shapes arisen from an arch (**a**) or from a circle (**f**) under constant pressure regime (**b**, **g**) or under periodic pressure impulses, obeying the same temporal pattern, but having different $W$ values (**c**–**e**, **h**, **i**). (**b**, **d**) $W = 0.38$. (**C**) $W = 0.15$. (**e**) $W = 0.7$. (**h**) $W = 0.3$. (**i**) $W = 0.5$. Only (**d**) and (**i**) shapes are long range correlated and biomorphic. (From Beloussov and Grabovsky, 2007.)

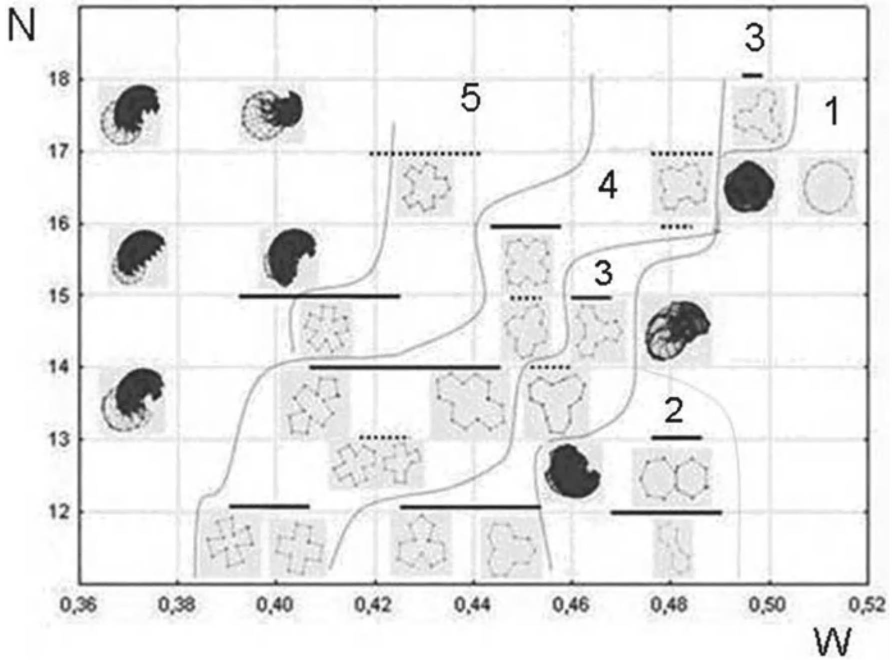

**Figure 9.** Diagram of shapes generated under different $W$ (*horizontal axis*) and $N$ (*vertical axis*) parameter values. Each frame is a superposition of several last iterations. *Solid lines* roof the ranges of $W$ values producing symmetric and absolutely stable shapes. *Dotted lines* roof the shapes which are only temporarily symmetric and metastable. *Black images* display unstable asymmetric shapes. *Figures* within the *graph* indicate the numbers of lobes within a given $W/N$ domains separated from each other by *wavy lines*. For all the cases, GP pattern is the same (1;1;–0,2;1;1). (Modified from Beloussov and Grabovsky, 2007.)

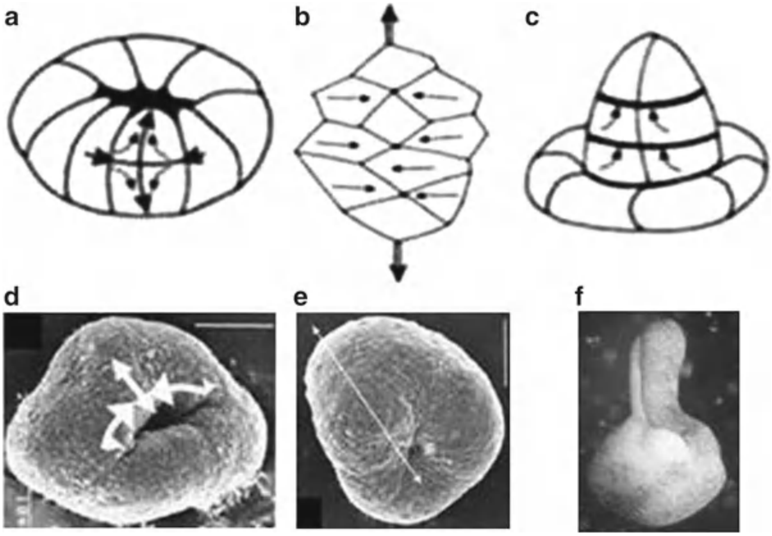

**Figure 10.** HR reactions in toroidal structures. (**a**–**c**) Transformations of toruses (**a**) to elongated bodies (**c**) due to convergent cell intercalation toward meridians (**b**). (**d**, **e**) Elongation of a *Dynamena pumila* embryo starting from a toroidal shape. (From Kraus, 2006, with the author's permission.) (**f**) A real structure similar to (**c**) arisen from toroidal explants of *Xenopus* blastopore circumference. (From Beloussov, 2008.)

## 4.3. HR FEEDBACKS IN TOROIDAL SHAPES

Although only in one case (embryos of a hydroid polyp, *Dynamena pumila*: Kraus, 2006) an entire embryo consists of real tori, a very important and widespread class of dynamic embryonic structures can be regarded as semitoroidal. First of all, to these belong so-called lips, that is compact folds including still noninvaginated and already invaginated cell material and ranging from circular to arch-like (mostly known among them are so-called blastoporal lips). Taking into consideration that toroidal or semitoroidal structures are pressurized from interior, the meridional tensions on their surfaces should be, by mechanical laws (Landau and Livshitz, 1976), twice as great as equatorial ones. Therefore, according to HR model, there are meridian tensions to be firstly relaxed and then transformed to meridian pressure stresses, most probably due to convergent cell movements toward meridians (Fig. 10a–c). Consequently, semitorus is expected to elongate along its meridians. This is indeed the case (Fig. 10d–f). From this point of view, the universal process of the blastopore closure and archenteron elongation (gastrulation) can be derived from the properties of stressed toroids, without requiring any additional specifically located causes. Meanwhile, precisely circular (of infinite rotational symmetry) blastopores should be also unstable: due to

CE feedback, established around the blastopore circumference, one or several of its meridian(s) will dominate as cell convergence sites, reducing thus a symmetry $\infty \cdot m$ up to $n \cdot m$ ($n$ order radial symmetry) or in the most robust case to $1 \cdot m$ (bilateral symmetry). The latter is closely associated with the establishment of dorsoventrality in vertebrate embryos, where the meridian of a dominating convergence becomes a dorsal midline.

### 4.4. "GENERALIZED GASTRULATION," REGARDED AS A CHAIN OF HR-BASED MORPHOMECHANICAL FEEDBACKS

Now we attempt to reproduce in broad outlines a prolonged chain of morphogenetic events, which may be defined as "generalized gastrulation" because it embraces the main properties of gastrulation, which are similar even in taxonomically diverse groups of animals. We start from an idealized blastula stage which we take as a spherically symmetric body with the walls of equal thickness surrounding a concentric blastocoel and stretched by the turgor pressure within the latter. According to HR model, a spherical symmetry of such a body is unstable: under even small variations in the regional thickness, the thinner part of the wall will become under the greater tensile stress and should be hence actively extended, compressing thus the resting part of the wall. (These events are easily reproduced in small fragments of blastocoel roof, developing into highly eccentric miniature blastulae: Beloussov and Grabovsky, 2006.) That means the establishment of a CE feedback throughout the entire blastula circumference. The next step will be the active contraction of the compressed part which fits the start of gastrulation. Meanwhile, the contraction can be achieved by different ways. The first of them, the emigration of some cells from the compressed part inside the blastocoel is typical for lower invertebrates (Cnidaria). Another one, the folding corresponds to more elaborated type of gastrulation, namely, to invagination. The folding may produce, however, two designs with quite different topogeometry: either a flat, two-dimensional slit-like fold (Fig. 11a) or a circular three-dimensional fold (Fig. 11e). Obviously, the latter one demands a refined balance between the fold's deepening and the removal (emigration) of excessive cells from the folded area. In principle, CE feedback can provide such a mechanism, but it should be well tuned. On the contrary, a slit-like folding does not demand any of such requirements.

A living nature employed the both ways: the first one is dominating throughout Protostomia while the second one in Deuterostomia (remarkably, some Cnidarians take quite a variable intermediate way: Fig. 11b). Each one of these designs affects profoundly a subsequent embryonic development. The slit-like Protostomia blastopores together with their immediate surroundings should elongate actively along the slit axis and compress the polar regions (which later on transform to stomo- and proctodeum), while the rest of embryo acquires very simple and uniform tensile field (Fig. 11c, d ). On the contrary, a circular blastopore of Deuterostomia embryos, due to its semitoroidal shape, becomes a center of a

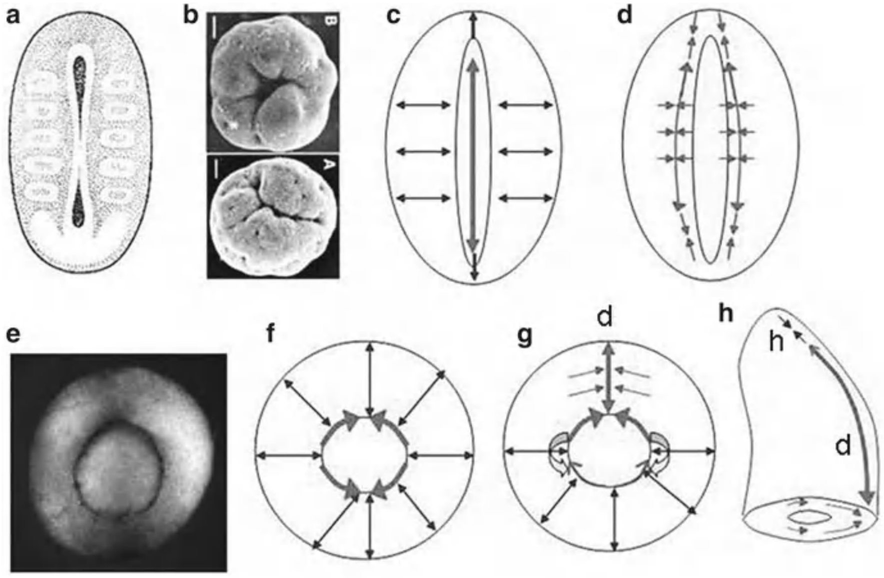

**Figure 11.** Formation and mechanical role of slit-like and circular blastopores. (**a**) A typical blastopore of Protostomia (Onychopora). (**b**) Irregular blastopores of Cnidarian embryos (courtesy of J. Kraus). (**c**, **d**) Tensile fields in the vicinity of slit-like blastopores. (**e**) A circular blastopore of amphibian embryo. (**f**–**h**) Transformation of a radially symmetric tensile field around a circular blastopore (**f**) into $1 \cdot m$ symmetry field with a dominating dorsal axis (**g**, **h**). (**h**) is a view from the left. *d* dorsal side, *h* head region.

*converging* tensile field extending over the entire embryonic surface (Fig. 11f). At the next step, as commented above, one of the converging meridians dominates and becomes a middorsal line (Fig. 11g, h). This is the line of the maximal active extension of embryonic body. To the anterior it creates a zone of longitudinal compression/transversal extension which becomes a head region (Fig. 11h, h). In such a way, contrary to Protostomia, the entire embryonic territory becomes involved into an effective and largely nonuniform tensile field, providing the formation of regular morphogenetic patterns quite far from the blastopore.

## 5. Simple Morphomechanical Shifts Can Trigger Extensive and Discrete Switches of Embryonic Architecture and Cell Differentiation Patterns

Among the basic properties of self-organizing systems is their ability to perform discrete switches from one stable state to another. Here we expose briefly the results of two recent experiments from our group, demonstrating that such events are taking place in developing embryos as a consequence of some simple morphomechanical interventions.

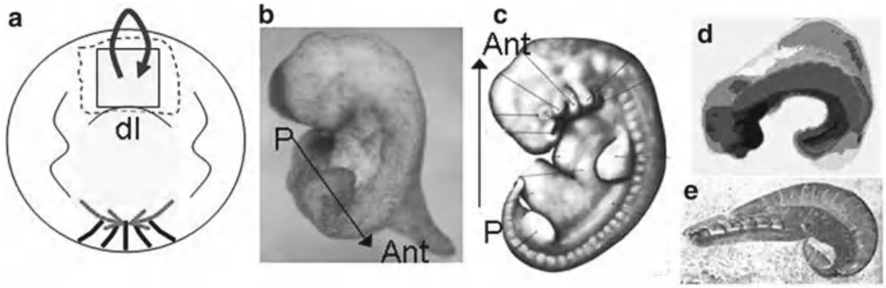

**Figure 12.** Producing discrete architectonic switches by mechanical interventions. (**a**) A scheme of experiment on the extirpation–retransplantation (*loop-like arrow, top*) of SBA piece. *Solid rectangular contour*: extirpated piece; *dashed contour*: wound edges immediately after operation; *wavy lines*: relaxation of tensions along the blastopore lips; *converged arrows* and *solid bars* (*bottom*) indicate the formation of a new tension nodule at the ventral blastoporal lip. *dl* dorsal blastoporal lip. (**b**) A typical result of operation, as compared with a textbook pharyngula embryo (**c**). Note almost opposite orientations of posterior–anterior (P-Ant) axes in (**b**) and (**c**). (**d**) Typical arrangement of neural (*dense black*) and mesodermal (*heavy gray*) rudiments in the artificially bent double SBA explants. (**e**) *Haikouella lanceolata*, a Cambrian vertebrate ancestor with a similar arrangement of neural and mesodermal tissues. (Modified from Kornikova et al., 2009, 2010.)

The first experiment (Kornikova et al., 2009) consisted in the extirpation of a small piece of SBA, returned in few seconds back to the same place (Fig. 12a). This time period was enough for the wound edges to be pulled apart and the entire blastopore circumference relaxed. As predicted by HR model, in few dozens of minutes, the circumferential tensions have been restored, even with some overshoot, owing to the active contraction of the ventral blastoporal lip area (Fig. 12a, converged arrows). This phenomenologically simple change in morphomechanics led to a tremendous reorganization of an entire embryonic architecture, surprisingly approaching now to that of a well-known “pharyngula,” a “bottle-neck” developmental stage of higher vertebrates but lacking just in amphibians (Fig. 12, cf. b and c). Interesting, in spite of close shape resemblance, the orientations of anteroposterior (Fig. 12b, c, Ant-P) and dorsoventral axes in experimental embryos were almost opposite to those in conventional pharyngulae. Hence, shapes can be decoupled from embryonic axiality.

In the second set of experiments (Kornikova et al., 2010), double SBA explants were bent to about 110° either parallel or perpendicular to their anteroposterior axis. In about a day after the experiment, a mutual arrangement of the neural and mesodermal tissues, obeying in the control (nonbent) explants a precise polar symmetry, became extensively asymmetric: a neural tissue was biased toward a concave side, while mesodermal to the convex one (Fig. 12d). Noteworthy, such an abnormal arrangement also resembled the architecture of an evolutionary archaic form (Fig. 12e).

Common in both experiments was that simple mechanical interventions, rapidly leading to the expected redistribution of stress patterns, resulted in a sharp discrete switching of an entire sample's architecture (including cell differentiation) toward remote but nevertheless existed species. That argues once again for the important role of morphomechanics in self-organization of embryonic architecture.

## 6. Concluding Remarks: Regulation of Development from the Upper Levels

A main message of this chapter is that a self-organization of embryonic designs can be driven by the interplay of passive and active mechanical stresses, located at the upper structural levels. In particular, we associate shape formation with a partial relaxation of the beforehand established stresses. A usual question addressed to this concept is what role it assigns to nonmechanical (chemical) factors of development. The response consists of two parts. (1) At the molecular–supramolecular levels, mechanics and "chemistry" are inseparable and should be treated as a common entity. (2) At the macroscopic (cellular–supracellular) levels, they play indeed different roles; that one played by diffusible chemical substances can be qualified as the establishment of initial conditions and mainly of the *parameters* for morphomechanical feedbacks. Such a role may be quite powerful, because a simple change in the feedback rates (not to say their complete inhibition) should profoundly affect the course of development (Beloussov and Grabovsky, 2007). A principal point is, however, that out of the feedback context, the parameters per se do not contain any definite developmental "meaning." This is shown, for example, by a far going degeneration in the genes–development relations: same or homologous genes can "control" quite different, nonhomologous embryonic structures, and vice versa. Similarly, embryonic inductors are acting, by the modern views (De Robertis, 2009), as mere inhibitors, rather than bearers of any definite "developmental information." In any case, what is attributed to the category of developmental factors acquires a definite meaning only within the context of the upper level events, which we associate with indivisible combinations of mechanics and geometry. Such a view can be traced back to Gurwistch's cell field theory (posthumous edition: 1991). Recently the primacy of macroscopic organization has been convincingly argued by Kupiec (2009), although we cannot agree with the author in his denying the explanatory role of self-organization theory. One should also emphasize that HR feedbacks, considered to be the main driving forces of morphogenesis, can take place only in far from thermodynamic equilibrium conditions (see for more details Beloussov, 2008).

## 7. Acknowledgments

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Biodata of **Stephen Grand**, author of "***Playing God: The Historical Motivations of Artificial Life***."

**Stephen Grand** is an independent researcher, software developer, and writer, specializing in biologically inspired artificial intelligence, computational neuroscience, and robotics. He received an honorary doctorate (D.Univ.) from the Open University (UK) in 2008 and was made an Officer of the Order of the British Empire for his A-life work in 2000. He is author of two books on artificial intelligence and a commercial artificial life computer game called *Creatures*.

Email: **steve@cyberlife-research.com**

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# PLAYING GOD: THE HISTORICAL MOTIVATIONS OF ARTIFICIAL LIFE

**STEPHEN GRAND**
*London, UK*

## 1. Introduction

Artificial life is, one might reluctantly say, a form of "intelligent design" and therein lies an interesting tension. Why should the desire to understand something which so conspicuously and definitively designs *itself* be at all well served by actually attempting to design it? Is it simply a prosaic desire to test specific theories or is it about playing God? Is it sheer hubris or merely a gross underestimate of the complexity of biology? What motivates research in artificial life research, both today and in the distant past? What is its philosophical status and how have its practitioners dealt with the tension between the need to design and control, and the desire for emergence and autonomy?

As a recognized and named discipline, artificial life has only existed since 1986 (Langton, 1989), although its roots stretch back hundreds of years. At each stage in its history, somewhat different motivations and paradigms have held sway, from the prosaic to the mystical. Almost invariably, however, the objective has been to understand the essence of life by attempting to create it or at least by simulating aspects of it in a computer.

This process of "understanding by doing" currently has a poor standing among the sciences and is more often associated (almost by definition) with the arts. In fact, just like cybernetics before it, artists have contributed a good deal to A-life. Making things is often not considered "real" science: Where are the laws? Where are the equations? Where is the solid theory? Of course, there *are* equations (or, more accurately and not insignificantly, functions) inside any computer simulation, and artificial life is no different in that respect. Nevertheless, in A-life, it is not really the equations themselves that matter.

"Understanding by doing" has a very different flavor from "understanding by theorizing," but it hardly deserves to be derided and sometimes it is our only reasonable option. Consider the simple word "as," for example. Can you define it? Dictionary.com lists 4 meanings as an adverb, 8 as a conjunction, 3 as a pronoun, and 1 as a preposition, not to mention 15 idiomatic uses. It is extremely hard to define what "as" means, and yet most of us can use the word fluently and effortlessly, so it would be absurd to say we do not understand it. We understand its meaning *operationally*, and this is perhaps the best we can be expected to do.

As a more relevant example, if someone can build a working internal combustion engine from scratch, without slavishly copying an original, who is to say that this person does not understand its principles of operation, even if they are quite unable to articulate or codify them?

The same perhaps applies to life. Life may, in fact, turn out to be irreducible in a philosophically quite satisfying way. Thus far, there is not even a universally accepted definition of the term, and perhaps for good reason: "Life" is not necessarily a distinct category in nature; merely a line that we choose to draw around certain objects and phenomena because it is useful for us to do so and because, despite its ambiguity, it still seems to capture an important truth. But even a satisfactory definition of life would barely get us anywhere in theoretical terms. It is not *what* life is but *how* and *why* that really matter. The purpose of biology is not to define but to understand, and understanding an organism is ultimately a systems-level problem.

Systems are more than the sum of their parts because it is not only the parts themselves but their interrelationships that matter. Just as a radio receiver and a radio transmitter are very different objects, with very different behaviors, that can be created from precisely the same set of parts arranged in slightly different ways, some arrangements of molecules are alive while others (even almost identical ones—consider how little changes at the moment of an organism's death) are not. Because of this unavoidable holism, life is not necessarily reducible to a neat theory.

Perhaps life may still be understood operationally, but like the construction of the internal combustion engine above, slavishly copying an original is not sufficient either. Current attempts to build real artificial cells, molecule by molecule, tell us a great deal about the details of life, but they may fail to get at the *essence*. A true operational understanding lies somewhere between the extremes of a perhaps impossible reductionistic theory and a detailed blueprint. It lies in recognizing the *principles* of biology: the ubiquitous cybernetic tricks and techniques that chemistry has discovered, which make self-designing, self-perfecting, and self-replicating networks of reactions possible. Finding this essence is what artificial life is about and perhaps always has been.

## 2. History

Being alive and being consciously aware of one's existence are such notable things that it is hardly surprising to find the pursuit of their understanding, including understanding by attempting to recreate them, stretching back through the ages. Perhaps the only things that have varied over time are the means and the model. As early as 1651, Thomas Hobbes was able to speculate:

> why can't we say that all automata (engines that move themselves by springs and wheels as a watch does) have an artificial life? For what is the heart but a spring? What are the nerves but so many strings? What are the joints but so many wheels enabling the whole body to move in the way its designer intended? (Hobbes, 1651)

This mechanistic hypothesis has existed in some form for centuries, and a number of times have been acted upon. Around 1730, Jacques de Vaucanson took the "if it quacks like a duck and defecates like a duck then it is a duck" philosophy seriously, by building a mechanical duck that did all of these things and more. Whether Vaucanson or others of the period really believed this duck to be alive or on the way to being alive, I cannot say. Nevertheless, the seeds of a mechanistic explanation of life were clearly present, well before the industrial revolution.

Earlier attempts at creating artificial life (stretching back to the Greeks and Egyptians) were understandably much more vitalistic than mechanistic, involving clay figures or cunning automata that needed to have the essence of life magically "breathed into them." Both the vitalistic and the mechanistic views have coexisted and sometimes been blurred together. Even as recently as Mary Shelley's day there was a good deal of ambiguity about whether life involved some kind of "vital spark." In *Frankenstein* (Shelley, 1818), she describes an artificial being made from ordinary raw materials (contrary to popular belief, the monster does not appear to have been made from body parts, and cadavers are only mentioned in regard to Dr. Frankenstein's research). This monster was then animated, or so the story implies, almost literally by a vital spark. Only 20 years before Shelley was born, Luigi Galvani had showed that a frog's leg could be "vitalized" by the use of electricity, and it is not surprising that this miraculous fluid should be a strong contender for the *elan vital* at such a time.

And yet, when Mary Shelley was busy dreaming up Frankenstein's monster, she was sharing a house with Lord Byron, who was the father of Ada, Countess Lovelace. Lovelace, in her turn, was the patron and supporter of Charles Babbage, the inventor of two of the first machines to emulate an aspect of human intelligence. By Shelley's time, it is clear that vitalism was being eroded and the essence of life was degrading into some kind of substance, while a mechanistic standpoint was in the ascendant. Before the end of that century, Samuel Butler felt able to echo Hobbes and say:

> I first asked myself whether life might not, after all, resolve itself into the complexity of arrangement of an inconceivably intricate mechanism. If, then, men were not really alive after all, but were only machines of so complicated a make that it was less trouble to us to cut the difficulty and say that that kind of mechanism was 'being alive,' why should not machines ultimately become as complicated as we are, or at any rate complicated enough to be called living, and to be indeed as living as it was in the nature of anything at all to be? If it was only a case of their becoming more complicated, we were certainly doing our best to make them so. (Butler, 1880)

Until the middle of the twentieth century, "intelligent design" was the order of the day. These machines and fantastical creatures were unequivocally designed and constructed objects. If their behavior or structure was emergent at all, it was only to a very limited degree. However, with the beginnings of the cybernetics movement in the late 1940s, complex feedback loops and electronics made more lifelike and autonomous behavior possible. Perhaps the most lifelike and elegant of these at the time were the "tortoise" robots made by William Grey Walter.

Elmer and Elsie, Grey Walter's two robots, demonstrated various aspects of lifelike behavior, such as phototaxis, and were even able to "survive" by returning to their hutch to recharge their own batteries.

These attempts to simulate adaptive, explicitly biological behavior using robots or software agents have continued to the present day. More recent robots have been used to improve our understanding of such species-specific behaviors as phonotaxis in crickets (Webb, 1994) and navigation strategies in the desert ant (Lambrinos, 1995). However, these experiments in artificial ethology lie somewhat on the fringes of artificial life, and although they teach us a lot about biology and behavior that is hard to learn by analysis, they are not aimed at understanding life in general nor elucidating the principles of life's capacity for self-design.

Some of the earliest examples of lifelike self-organization, as opposed to explicit design, began around the time of the invention of digital computing and arose in the minds of two of the great pioneers of that field. Although Samuel Butler had suggested that machines already reproduced themselves, after a fashion, with mankind acting as an intermediary (Butler, 1872), it was John von Neumann who first rigorously considered how a machine might be constructed that could give rise to offspring of its own kind (von Neumann and Burks, 1966). The resulting abstract concept of the cellular automaton (borrowed from Stanislaw Ulam) had a deep influence on later work and on the philosophy of A-life—see below.

Rather more directly related to biology was Alan Turing's paper on a possible chemical basis for morphogenesis[1] (Turing, 1952). In this seminal paper, Turing considered the question of how an initially homogeneous egg cell might break symmetry and develop structure, and he devised an algorithmic method to simulate it. He also used this same reaction–diffusion principle to hypothesize about the development of patterned markings on animals. From the perspective of this chapter, Turing's paper was vitally important to the prehistory of artificial life in several ways.

Firstly, it brought deep biological questions into close proximity with computing. During the production of his paper, Turing computed the results by hand, but towards the end of his life, he was experimenting using actual code (Copeland, 2000). There can be no doubt that Turing was aware of the potential that computers held for the rapid, *qualitative* simulation of nonlinear dynamical systems such as these.

Secondly, the idea was distinctly bottom-up and biological in concept, involving massively parallel computations with simulated enzymes, instead of very unlifelike components such as cogwheels or abstract equations, and yet at the same time,

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[1] Turing also made perhaps the first foray into what today are called neural networks, although the paper was decried at the time as "a schoolboy essay" by his boss at the National Physical Laboratory (who was, rather ironically, Charles Darwin, the grandson of the naturalist), and it was only published after Turing's death.

it was also concerned with principles, rather than details. It asked questions about what generalized chemical-like substances could do, in order to have generalized lifelike results (in Turing's words, "To specify actual substances, concentrations and temperatures giving rise to these functions would settle the matter finally, but would be difficult and somewhat out of the spirit of the present inquiry"). In this respect, it was a true piece of artificial life research in the modern sense.

Thirdly, with his work on morphogenesis and "unorganized machines" (neural networks), Turing was perhaps feeling his way towards other forms of computation that are not bounded by the same rules as algorithms. Turing's ideas about digital computing derived from his earlier theoretical work on the limitations of mathematics and led to one of the greatest inventions of mankind. The digital computer has transformed the way we think, but it is at least possible that if Turing had lived to see this alternative, biologically inspired line of research through, it might have led to a very different computational world.

Lastly, the focus of Turing's exploration was on self-organization; how does a system "design itself," creating complexity out of simplicity? His goal was not to analyze patterns mathematically but to use mathematics to generate them.

Nothing epitomizes the self-designing nature of living systems better than evolution by natural selection, and it was not long before computers provided an opportunity to simulate this in the laboratory. Nils Aall Barricelli was almost as far ahead of his time as Turing, and, perhaps as a consequence, his groundbreaking experiments on the evolution of synthetic "genomes" (Barricelli, 1954) went largely unnoticed. The world was not yet ready for qualitative simulation nor for a proper understanding of complex, adaptive, bottom-up systems in general. Nevertheless, by the early 1960s, computer experiments on evolution were becoming relatively common and the concept of a genetic algorithm was born. For the first time, it became reasonable to program a computer to create something by itself. In other words, computer-based design no longer required a designer.

I well remember my own first experience of "design by computer evolution," during the late 1980s. I had to transfer some images from one type of computer to another, which had a very peculiar and nonlinear palette structure. One could choose the first 16 colors in the palette at will, but from the 17th onwards, each color had to be a variant of one of the first 16, making the first few choices critical. I could not think of a mathematical way to find the optimal color choices for rendering each of the images, so I let evolution solve the problem for me, by defining a population of "palette creatures," whose genomes represented an initially random set of possible color choices. The evolutionary fitness of these creatures was decided by how closely each was able to reproduce the original images, and a simple competition for survival among "reproducing" and "mutating" genomes ensured that the gene pool improved with each generation. It took a couple of hours to write the program and a couple more to let it converge on a suitable candidate, thus saving me days of effort or more mathematical angst than I could handle. The fact that I could design a system which was able to design something that I could not do myself made a strong impression on me and doubt-less has on many others who have taken advantage of the third thread in the artificial life tapestry: A-life as *technology*.

By the mid-1980s, all three threads were in a position to come together: the use of computers to simulate and study specific biological phenomena, the use of biological ideas in the theory and practice of computation, and the age-old search for the essence of life. The person who finally drew them together to form the modern field of artificial life was Christopher Langton, who organized an eponymous conference at the Los Alamos National Laboratory, in 1987:

> The workshop itself grew out of my frustration with the fragmented nature of the literature on biological modeling and simulation. For years I had prowled around libraries, sifted through computer-search results, and haunted bookstores, trying to get an overview of a field which I sensed existed but which did not seem to have any coherence or unity. (Langton, 1989)

Langton's aim was merely to "see what was out there," but although the workshop produced a surprising diversity in terms of application areas and techniques, it also revealed a surprising coherence in terms of the way people were thinking. In the preface to the Proceedings, he felt able to characterize this as:

> based on bottom-up rather than top-down modeling, local control rather than global control, simple rather than complex specifications, emergent rather than prespecified behavior, [and] population rather than individual specification.

Despite his initial hesitancy about the respectability of this motley collection of biological models, Langton was further able to articulate the central idea of what was undoubtedly a new field in its own right, and not merely a branch of mathematical biology:

> Perhaps, however, the most fundamental idea to emerge at the workshop was the following: Artificial systems which exhibit lifelike behaviors are worthy of investigation on their own rights, whether or not we think that the processes that they mimic have played a role in the development or mechanics of life as we know it to be. Such systems can help us expand our understanding of life as it could be. By allowing us to view the life that has evolved here on Earth in the larger context of possible life, we may begin to derive a truly general theoretical biology capable of making universal statements about life wherever it may be found and whatever it may be made of.

## 3. Discussion

Possibly the most contentious part of the above quotation is the phrase, "and whatever it may be made of." The interpretation of this divides artificial life into two camps, closely analogous to the Strong and Weak stances in artificial intelligence.

Weak AI is the intent to automate tasks that would require intelligence if they were performed by a human being. It can be seen that this definition does not necessarily require the automatic systems to be intelligent; for instance, nobody today would regard a pocket calculator as intelligent, even though it performs a role once confined to human mental activity. Weak AI is thus the attempt to replace certain aspects of intelligence by "smart" software, but there is no expectation that the result is actually acting like a human brain in any philosophically or psychologically meaningful sense, least of all that it is conscious. The claim of Strong AI, on the other hand, is that real, general-purpose artificial intelligence, up to and possibly including first-person conscious experiences on the part of the artifact, is at least theoretically possible. Weak AI takes no particular stance on this issue and concerns itself only with practicalities; Strong AI is unapologetically mechanistic in its philosophy.

Artificial life can be divided along much the same lines in regard to life (and by extension may have things to say about the schism in artificial intelligence, too). The distinction between Weak and Strong A-life is less often debated and somewhat more blurred than its counterpart in AI, but nevertheless, many A-life researchers see their craft as a straightforward mathematical abstraction of life for the purposes of better understanding biology, while some are at least willing to accept (if not pursue) the idea that an artificial system may be truly alive, even though it may exist solely in software. Some of this latter group appear to take a "black box" stance and believe that, if it currently quacks like a duck and defecates like a duck, the design will sooner or later become good enough for it to be regarded as a duck. Meanwhile, others hold that real artificial life can only exist under certain circumstances, for instance, if it arises spontaneously from some more-or-less primitive starting condition. Either way, this question has a bearing on the meanings of both "design" and "nature" and is thus relevant to the title of this book.

Even though we have no satisfactory definition of life, we still tend to be "spooked" when something occurs that hints at its existence in an artifact. In many cases, we have simply been fooled into ascribing autonomy to something because our brains are tuned to recognize such cues. We can barely stop ourselves from naming boats or blaming our cars for not starting, so it is not surprising, when a robot gets stuck and runs out of power before reaching its recharging station, that many of us find ourselves feeling a little sad for it. And yet sometimes that sense of the "spooky" seems much more profound, as if we are on the edge of a huge realization about the nature of existence. Few classes of machine evoke such a sensation more profoundly than cellular automata.

Von Neumann's work on self-replicating cellular automata patterns surfaced again during the mid-1980s in Langton's own research (Langton, 1984). Langton was able to simplify von Neumann's complex replicating pattern considerably, resulting in an eight-state cellular automaton with an initial pattern like the letter "d." This pattern is capable of "exuding" new, identical loops and grows in a way reminiscent of a colonial organism. Langton says he sometimes felt a sense of a "presence" when working with such CAs, and I, too, can vouch for their uncanny nature.

The most commonly used variety of CA is John Conway's *Life*, a two-state automaton devised in 1970 and capable of creating a startling variety of patterns from simple initial states (Gardener, 1970). There is much to say about *Life*, but for our purposes, I want to draw attention to one particular pattern, which made the hair stand up on my neck the first time I saw it and led to something of a personal epiphany. This pattern is called the glider. It consists of a simple group of five "lit" cells, which gives rise in subsequent generations to three other patterns before repeating the first one, except this time it is displaced one square diagonally from its original position. The sequence of patterns thus "walks" in an amoeba-like fashion across the grid of cells until it collides with something and is disrupted. What startled me so much is that *something* is clearly moving across the grid, and yet *no thing* is moving: The cells remain static and only switch from state 1 to state 0 or vice versa. No central controller moves the pattern; it persists and moves all by itself. By any honest appraisal, the glider is a real *thing*, even though it is not a material object.

This realization quite changed my worldview. Almost immediately it dawned on me that organisms are things of a very similar nature. They are not material objects either; they are patterns in time and space which maintain their form despite and because of the fact that matter is flowing through them. Almost every atom in an organism is replaced many times over during its lifetime, so an organism is clearly not the "stuff" of which it is made: It has its own, emergent identity and constitutes another "level of being," above and beyond that of the atoms that presently make it up. At the same time, I realized that this is true of many phenomena that we call "things," including clouds, hurricanes, and, most notably, perhaps even matter itself. An electron can be visualized as a self-maintaining disturbance in a system of fields, rather like a whirlpool on the surface of water, instead of being thought of as a discrete, solid "lump" sitting in space.

Given this viewpoint, it became increasingly obvious to me that everything in the universe consists of *form*; from elementary particles, through molecules, through organisms to minds and even populations such as societies. Each is a new level of form that persists because it has some feedback mechanism that prevents its dispersion or disruption. An organism has vastly more sophisticated mechanisms for ensuring its persistence than an electron does, and each new level of being relies on the one beneath to create novel properties for it to exploit, but all forms of existence in the universe are nevertheless just that: forms. They are patterns in something else, which exist because they have the property of persistence. Patterns that lack such a property simply vanish, and the things we see around us and give names to are what remain.

Each new level of being emerges because of the affordances of the level beneath. For instance, organisms survive by reproducing, by evolving, and by adapting to or predicting potentially detrimental change, but they can do these things only by virtue of the properties of chemistry and hence molecules, which in turn only persist because of the properties of atoms, and so on down. Each level is *emergent*—a new class of self-maintaining form that arises spontaneously and remains, once the universe has the necessary properties available. This perspective shines a light on the Strong A-life stance and ultimately has a bearing on the question of design in nature.

The "if it quacks like a duck it is a duck" hypothesis is rather unsatisfying because merely emulating the behavior of a thing does not seem sufficient for it to become an instance of that thing. An actor playing the part of Napoleon is not Napoleon; a portrait is not a person; a machine that translates Chinese as effectively as a human mind does not necessarily possess a mind (although this is a more vexing example). But there is, it seems to me, a way in which a genuine instance of a thing, in this case a living thing, might exist in a radically different form, or rather in the *same* form but on a radically different substrate.

If we try to make a mechanical creature by emulating each aspect of its behavior separately, from quacking to defecating, we have not made a real creature. If the quack emanates from a tape recording and the defecation is a contrived mechanism and not the inevitable result of a production line that extracts energy and nutrients from food, then the resulting duck is clearly just a sham. At the other extreme, if we were able to copy a duck slavishly, molecule by individual molecule, then the result would be expected to quack, defecate, and all the rest, and we would be forced, unless we were Cartesian dualists, to admit that the result was a real duck, even though it had been made by hand. The latter is a demonstration (although not a proof) that artificial life is possible, at least in principle. Given current developments in synthetic biology and the attempt to construct artificial bacterial cells, that principle is soon likely to be demonstrated in practice. So at one extreme we have only a shallow imitation of a creature with no right to be called alive, while at the other we have a real creature, albeit a slavishly copied one. Where does the boundary exist between the two, if indeed there is one?

Moreover, from the perspective of Strong A-life, we are primarily concerned with computer simulations, not molecular hardware. Intuitively, most people balk at the idea that software is capable of constructing anything real at all—a program is just a list of instructions, executed blindly by the machine. How can a simulated object be real?

In addition, A-life is not really concerned with slavishly copying biology at any scale, least of all at the molecular level; it is about illuminating the *principles* of biology—what Langton called "life as it could be." How much is it permissible to diverge from a slavishly copied design and yet still describe the result as alive?

It seems to me that the glider pattern in Conway's *Life* hints at answers to all three questions.

First of all, the glider has a simple kind of coherence, making it philosophically defensible to call it a *thing*, even though it is not a material object. As already discussed, organisms and even electrons are no more "real" than this—each is a persistent form, and it is the form itself that constitutes the thing, not the substance from which it is made. In the case of the glider, it exists as a thing in software (or more accurately in an alternate universe that we may reasonably call "cyberspace," since the glider is, in its essence, a pattern on a grid and not part of the code that defines the grid's properties), but it would be perfectly possible to make Conway's *Life* in hardware, even as a purely mechanical device, and yet the glider configuration would still work. Unquestionably, the "cyberspace" and "physical space" gliders are ontologically equivalent. It really does not matter which universe the pattern exists in, as long as that universe has the same key properties. It is not even meaningful, with respect to the glider, to say that one universe is real and the other fake.

If the behavior of the glider was merely *emulated* by devious means (say by a human hand drawing it, erasing it, and then drawing it again in a new position), then this would not be a real glider. Equally, if a duck's behavioral properties are emulated through cunning use of cogs and levers, it is not a real duck. But if the glider's properties *emerge* from the same set of rules in each universe, it does not matter how those rules are actually implemented; it will still be a real glider. It seems to me that the same is true of a duck.

Suppose we create a computer simulation of chemistry. Have we made real molecules? Of course not—they are fake. But we have created a new universe—a universe whose properties are chemical. If these properties conspire, without explicit programming, to create new phenomena that also exist in the so-called "real" universe of chemicals, are these phenomena not the same thing? If we create such a computer simulation of atomic behavior and define some patterns made from simulated hydrogen and oxygen atoms, have we made real water molecules? Certainly not. But if those fake water molecules spontaneously and collectively flow downhill in a gushing torrent (as we would expect them to do if our simulation of atomic behavior is good enough), is it not a real river? If the fake water molecules find themselves attracted to a hydrophilic surface made from fake molecules of another kind, is that not real wetness? If our fake elements spontaneously assemble themselves into molecular species, with properties identical to (or potentially only analogous to) real organic and inorganic molecules, and some of these molecules then react with each other to create a chemical network that happens to metabolize other fake "nutrients" and turn them into more of the network's constituents; if these networks surround themselves in membranes made from lipid-like structures, and the resulting mélange spontaneously demonstrates chemotaxis so as to seek out more nutrients; if, as a result, the bubble of fake ingredients grows larger and splits in two, and each daughter bubble continues to metabolize, react, and replicate like its parent, perhaps even in a template-driven manner that can suffer mutations and thus develop greater levels of persistence through natural selection, is this not real life?

A number of people object to such extrapolations. "No, it's still not *real*," they say, "it's just software." But as far as I can see, this simply means they have not grasped the true nature of reality. Either that or they fail to appreciate the difference between the software running inside the computer and the pure forms which exist in the cyberspace that the software produces. It is a subtle distinction that flies counter to the way we were brought up to think about computing, so it can be hard to grasp unless you happen to be an object-oriented programmer with experience in bottom-up computer simulation.

More often, I have heard people insist (quite vocally) that "a virtual aircraft cannot carry me to Seattle" or "a virtual rainstorm does not make me wet." But this is to confuse the two universes. A virtual aircraft (of the emergent kind described above) would be perfectly capable of carrying a *virtual* you to a virtual Seattle. It is a mistake to expect the reality of one universe to extend over into the other. These are, I submit, problems of perception, and perhaps even a lingering form of vitalism, *not* problems with the logic. We fail to grasp the fact that the so-called "real" universe is itself a kind of software; it, too, is constructed essentially from patterns. Come to that, even the hardware of a computer is really software: A silicon chip is, after all, nothing more than a highly specific pattern drawn in the silicon using impurities. Unfortunately, we also find it hard to let go of the idea, perhaps even the hope, that "real" life depends upon some kind of magic ingredient, even if it is only the presence of "real" matter or some quantum-mechanical property that cannot in principle be simulated on a computer.

Regardless of whether artificial systems in a software substrate can really be alive, the glider pattern has something to say about our two other questions: Where does the threshold lie along the continuum between a slavish copy of life and a shallow imitation, and how far can we move away in the perpendicular direction, from terrestrial biology into what Langton called "life as it could be"? Both are questions about abstraction.

Firstly, Conway's *Life* and Langton's self-replicating loops show that profoundly lifelike phenomena can certainly exist in a radically different universe. In no sense is a replicating pattern in a CA copy of terrestrial biology, and yet it *does* replicate. Simpler finite-state automata have often been used as both the genotype and phenotype (i.e., the FSA performs some function that depends on the numbers in its state and output tables) in artificial evolutionary systems. In no sense is a state table of a direct facsimile of DNA, nor do its state transitions represent a phenotype in the conventional sense, and yet it *does* evolve. Cellular automata (among other mechanisms) can create processes that grow and develop structure, or represent networks of chemical-like systems that perform something like metabolism. Most of the individual features characteristic of life on Earth have emergent counterparts in the world of cellular automata that are by no means similar in structure. So far, nobody has put these things together to create a cohesive organism (more on this below), but it seems that "life as it could be" might be a very broad category indeed. This takes us nearer to understanding the underlying essence of "life as it is."

Secondly, we can see from the ontology of the glider that emergence is a fundamental idea in artificial life. If the behavior of the whole is explicitly encoded in one or a few of the parts, then we have something that merely *appears* to be a duck. No matter how cunning the mechanism, it will not actually be a duck unless the behavior, along with all its peculiarities and pathologies, emerges holistically from the system. This is especially important if the Strong hypothesis is to hold true: Simulated atoms are not atoms; a simulated mind is not a mind, but when essentially similar phenomena arise from two different substrates in the same way, we surely have to concede that this is the same phenomenon in both cases, and the two are therefore equally real. Strong A-life aside, however, there is an important sense in which the structural decomposition of the system should not map directly onto the functional decomposition. The richness of life does not and cannot emerge from a system where one module equates to one function, and if we want to design systems that exhibit the richness of life, we must simulate more deeply than the properties in which we are interested; preferably several levels more deeply. This has design implications for both A-life and AI.

For artificial intelligence, it suggests that seeking an entirely abstract "algorithm of thought" is futile. Listing the many and various properties of intelligence and then trying to write code that tackles each one of them individually leads to a combinatorial explosion at best and a bunch of subsystems that are quite incompatible with each other at worst. Brains are made from neurons, and only a design that captures the essential structural characteristics of such a neural system is likely to exhibit the full range of properties we expect from a brain. AI needs to be biologically inspired and take proper account of the A-life canon: bottom-up, local, simple, emergent, and population-based.

A-life, too, has things to learn about design that it has so far paid little attention to. For one thing, embryology is singularly underrepresented in A-life designs. Genetic algorithms have been studied to death, but for the most part, they employ 1:1 mappings between genotype and phenotype. So many of the emergent properties and evolutionary dynamics available to real evolving creatures are lost in such trivial systems. It is only when the actions of genes are multiplied by interaction with each other and with the environment that the true creative power of evolution becomes apparent. If nothing else, the field of embryology stands to gain from the abstracted yet still determinedly bottom-up approach of artificial life. Artificial embryologies may have much to teach us about the essential principles that underlie the undoubted complexity of real embryogenesis.

In a similar vein, it is in the nature of scientists that we tend to isolate one area of study from the others, but life is not just evolution, not just metabolism or reproduction or adaptation. Life is all of these put together, including the rich interactions between them. In my own work, I try to create complete artificial creatures (e.g., Grand et al., 1997), whose behavior, learning, and evolution are an emergent consequence of the interactions between networks of simulated neurons, enzymes, sensory cells, receptors, genes, etc. My particular interest is in biologically inspired AI, and so I revel in the richness that such complex networks produce. To the A-life purist (especially those in the Weak camp), this is probably overkill because I am in danger of creating something almost as complex as real biology, thus defeating the point. Nevertheless, many of the "essences" of life exist in things that make little sense in isolation. Certain kinds of regulatory network, for instance, are ubiquitous in the chemical and electrical systems of the body and brain, but in isolation, they teach us very little. It is only when you can see them actually functioning that their significance becomes clear. In building my various artificial creatures, I have gained a good deal of insight into nature's designs and often found myself solving a difficult problem, only to discover that the same solution was there in nature all along but I did not recognize it for what it is. Of course, this is only an operational understanding and it would often be hard for me to translate this intimate knowledge into a form worthy of a theory or even a descriptive paper, but as I have said, sometimes an operational understanding is the best we can hope for.

Finally, there is the question of design versus emergence. Ideally, artificial life research would involve defining an initial universe (a virtual Miller-Urey experiment, of sorts) and letting it sort things out for itself. If we get the conditions right, life will emerge spontaneously, and this time around, we would have the privilege of watching it unfold before our eyes. We could restart the experiment with different conditions and see what basins of attraction exist in the space of "life as it could be." It is certainly worth trying, but evolution is very, very slow, and the numbers of molecular species, organisms, and niches in the natural world is very, very huge. There is no good reason to suppose that we could speed up the process more than a few orders of magnitude compared to nature, even in a minimally complex universe, and still hope for anything informatively rich and realistic to occur. Even with a model that has the scale and hence the exploratory potential of Earth, and an acceleration factor of a million, we might still be waiting around for a 1,000 years before anything much happened. So it seems to me that we must perforce play God and design things for ourselves a lot of the time. The art is to design them in such a way that we develop and utilize our growing operational understanding of life, in other words, to design them in such a way that they *could* have evolved by themselves. And then we need to let them go; let their behavior emerge; let them act autonomously and take control of their own destinies. Only then will they have any right to be called alive. Only then, by virtue of playing God, will we have the right to think of ourselves as truly understanding the essence of life, which has fascinated and eluded ancient Egyptians, medieval alchemists, Regency novelists, and modern biologists alike.

> God is not dead but alive and well and working on a much less ambitious project.
>
> – Anonymous, Graffito

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# PART VII:
# DESIGN IN THE SOCIAL SCIENCES

**Rodgers**
**Stillwaggon**

Water drops on a leaf taken by Glen Mendels.

Biodata of **Diane M. Rodgers**, author of "***The Socially Constructed Natural Origins of Self-Organization***."

**Dr. Diane M. Rodgers** is currently an assistant professor of Sociology at Northern Illinois University. She obtained her Ph.D. from the University of Missouri-Columbia in 2006. Dr. Rodger's research interests are science and technology studies (STS); theory; organizations; and social movements. She is the author of *Debugging the Link Between Social Theory and Social Insects* (2008 Louisiana State University Press).

E-mail: **drodgers@niu.edu**

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# THE SOCIALLY CONSTRUCTED NATURAL ORIGINS OF SELF-ORGANIZATION

**DIANE M. RODGERS**
*Northern Illinois University, DeKalb, IL, USA*

From traffic flows to architecture, inspiration for understanding the design patterns of nature has been discovered in the behavior and structures of ant, bees, wasps, and termites. These patterns are viewed as emerging from self-organization, with each member of the group having little information yet contributing to the overall ability to create distinct, complex design from simple collective behavior. The concept of "swarm intelligence" further identifies this behavior of social insects as one that may also apply to human systems, revolutionizing our systems to match the more flexible, decentralized models of social insects. A paradigm shift in viewing social systems has occurred based on the understanding of these exemplars of natural self-organized systems.

As exciting as this paradigm shift is, the fact that it is a shift underscores that until recently these same social insects inspired a very different type of understanding of design in nature – that of rigid, specialized patterns of hierarchical structure. It is not that fundamental laws of nature have now changed, rather our perception of them has, and it is in this sense that they are socially constructed. Scientific discourse on the origins of nature's design is always framed within a social context and with outcomes for social structures that should be made transparent instead of naturalized.

## 1. Introduction

Self-organizing has been used to explain everything from the flow of traffic, termite mounds, snowflake patterns, and even the inner workings of a computer network. Kauffman (1993) presented self-organizing as a factor in evolution alongside natural selection, responsible for spontaneous order that emerges from complex systems. Although acknowledging that the idea of self-organizing goes back as far as Kant, Kaufman suggested in the early 1990s that a coherent theory of self-organization needed to be formulated out of the work of the many disciplines that had been involved in the phenomena. One of these disciplines that proved to be a significant source for the idea of self-organization would be the field of cybernetics and the work of Ashby (1947). The new field of complex adaptive systems developed from these ideas in cybernetics and began to be applied within various disciplines. A new self-organizing theory to explain the origins of design in nature had been interdisciplinary from its early beginnings.

The conception of emergence is tied to the idea of self-organization but not synonymous with it. A complex system is viewed as emerging from far simpler units and ending up with collective properties much greater than any of these individual units. The explanation of self-organizing proposes design in nature as emerging from nonlinear, dynamic systems. Design does not rely on a one-to-one correspondence of structure and function but rather the process that connects them. Self-organizing identifies the pattern of complex design from within and not external to the organization (Kauffman, 1996). For instance, a flock of birds uses simple behavioral rules of spacing to form what may look like a preplanned design. A single leader does not guide the flock, and there is no overall plan or understanding of the larger pattern by each bird. Instead, each bird is simply adhering to simple behavioral rules and forming a larger complex pattern that emerges from the local interaction of individuals with those around them (Camazine et al., 2001).

Studying self-organizing patterns and understanding the interactions involved in the emergence of complex adaptive systems have been paired with mathematical modeling and computer simulations. In the late 1980s, Craig Reynolds designed a computer program based on the self-organizing of a flock of birds. Computer-generated “boids” followed three simple rules to recreate the very complex design we see as a group of birds fly together in what appears to be an ordered pattern. The boids in the computer program needed to avoid collisions with each other, maintain a similar speed and direction as those next to them, and also stay close to those in their immediate surrounding area (Reynolds, 1987). Kennedy and Eberhart (1995) created an algorithm, particle swarm optimization (PSO), based on this self-organizing flocking pattern of birds. They identified the concept of “swarm intelligence” as a way to describe the interactions between the simple units making up a larger complex design (Kennedy et al., 2001). Particle swarm optimization (PSO) has also been illustrated frequently with the swarming behavior that occurs in bee and ant colonies. Self-organizing algorithms of social insect behavior and organization are currently being applied to human design and social structures.

In this chapter, I use the example of self-organizing and social insects to show how the conception of natural design is socially constructed. The history of scientific discourse on the design of social insects offers insights into how our ideas on the design of nature are socially constructed. Initially viewed as a rigid hierarchical social structure, a paradigm shift has occurred that currently recognizes self-organizing as the pattern of social insect organization. The interpretation of social insect behavior and organization has a history of being linked to our understanding of human behavior and social structure. This link continues to co-construct scientific discourse on the shared patterns of social insect and human self-organizing. The past may serve as a guide or cautionary tale about the extent that these models can be viewed as universal. I begin with an explanation of how the social construction of nature can provide important context to evaluate our knowledge claims of nature. Next, a history of knowledge claims about social insect organization is presented from a social constructionist vantage point. Assessing the contemporary research on self-organization and social insects and particularly how these are linked to human self-organization follows the epistemological opening made by acknowledging that knowledge claims are socially constructed.

## 2. Social Construction of Nature

A perceived problem with applying social construction to nature is that it somehow undermines the reality of nature. This chapter does not contest or question the reality of nature but rather how we make claims about it. Manicas (1987) frames the positivist view on nature as that of a minimalist realism which accepts that "trees and rocks" exist outside our human perception. If it is true that trees and rocks have an independent existence beyond the human mind, our knowledge claims about trees and rocks do not. In particular when stating knowledge claims about laws or processes of nature, it is tempting to forget this social lens exists. Nature becomes a legitimating reference point (Harvey, 1996; Wright, 1992). The ideas we have about nature are seen as somehow more authentic because of their link to "real" matter. Knowledge claims about nature are presented as discoveries that mirror the reality of nature. However, these knowledge claims are representations of what is observed about nature by humans. The truths they propose are mediated through a human perspective.

Specifically, what does it mean to say that nature and our ideas of self-organizing are socially constructed rather than a value-free account based on human observation? At a basic level, social constructionism can serve as a simple reminder that claims about knowledge are constructed through a social lens. Social construction has often been criticized as an absolutely relativizing concept, but it need not be. To show the social construction of an idea is not equivalent to denying the validity of the idea, it only questions the epistemological grounds for how that validity has been framed. As Donna Haraway argues, all knowledge is socially situated (1988); it has a social and historical context. For example, the commonly accepted view that Darwin was influenced by the social context and political economic ideas of Victorian England does not discredit evolution; it only allows us to better evaluate it (Greene, 1981; Hess, 1995; Young, 1985). The philosophy and history of science exposed some of the subjective aspects in the development of scientific theories, most notably Thomas Kuhn's (1962) classic on the paradigm shifts of "normal science." The post-Kuhnian laboratory studies more emphatically revealed the social construction of knowledge in the daily practices and assumptions of scientists (Knorr-Cetina, 1981; Latour and Woolgar, 1979). Science and technology studies (STS) have continued to supply accounts of the social construction of science and technology.

Any discussion of the origin of design in nature is enhanced by first presenting a brief historical context of the most influential ideas concerning nature. For living systems, an important point in history to begin with would be Aristotle's conception of the Scala Naturae, or the "ladder of nature." The design of nature was viewed as purposive, fixed, and hierarchical with a direct correspondence between structure and function. Each form was striving toward perfection within its own range. The design of nature included the designer at the very top of the scale, God. Aristotle's ideas were supported by the Church and became the dominant philosophy on the pattern of nature. This notion of the "Great Chain of Being" reflected ideas of higher and lower grades of perfection in form. This sense of fixed hierarchy was compatible with the social structure of the time period.

As the eighteenth century had brought an end to the idea of a predetermined chain of being, conceptions based on more evolutionary scales ushered in a significant transition to holistic thought concerning social and natural patterns of living organisms that would further develop in the nineteenth century (Levine, 1995). The earlier ideas of perfectibility were retained in the later evolutionary schemes such as the widely adopted Lamarckian theory espousing the inheritance of acquired traits. This maintained the hierarchical design of social and natural systems while deemphasizing the spiritual component (Lovejoy, 1936). Greene (1981) points to the dovetailing of ideas about political economy with the formation of both biological and social evolution in the eighteenth century: "In less than a decade the idea of progress through competitive struggle was elevated from the status of a principle of political economy to that of a law governing biological and social evolution. The 'Lamarckian' principle of inheritance of acquired characters, far from constituting a rival principle of explanation, was viewed as cooperating with the law of natural selection in bringing about the gradual improvement of the human race. Finally, the sense of Western, and more especially British or Anglo-Saxon, superiority over other nations and races seemed confirmed by the findings of science as well as the progress of history" (122).

Darwin's theory of evolution introduced natural selection as the mechanism of evolution. The idea developed from Darwin's exposure to Thomas Malthus' *An Essay on the Principle of Population* and Herbert Spencer's concept of "survival of the fittest"; Darwin applied both of these social ideas to the natural world. These social concepts combined with Darwin's evolutionary ideas were applied to human society and created what is referred to as social Darwinism (Hofstadter, 1955). The struggle of survival and natural selection translated into justifications for inequality and went so far as to suggest ideas of eugenics to artificially select those most fit. The criteria for what constituted fit were based on social biases of the time. But the idea of natural and social order determined by competition and natural selection of the fittest individuals was not universally shared. In particular, Russian zoologists and sociologists rejected this notion and instead supported a modified Darwinian evolutionary theory, with mutual aid instead of survival of the fittest as the ultimate law of nature. Natural selection operated on the group and cooperation was the key to survival. This split in understanding nature's design was not just a difference in social or political vantage points, but was explained as the accurate representation of what Russian zoologists observed out in the field as they searched to verify a Hobbesian nature "red in tooth and claw" (Kropotkin, 1902).

Both time and place have an influence on the creation of ideas about nature. The possibility that there are national styles of science has been examined (Abend, 2006; Graham and Kantor, 2006; Harwood, 1987). Sapp (1994) chronicles the history of the concept of symbiosis in evolution, showing how these ideas developed in various countries over time but remained marginalized. Cell theory originated in nineteenth century in Germany, and there is some speculation that this was due to the philosophical influence of German Idealism (36). Cell theory provoked various conceptions of the cell from scientists, although the Russian scientist Merezhkovskii was the one to coin the term symbiogenesis and to claim a fully developed theory of symbiosis. Sapp asks why this symbiotic theory was not developed in Germany and refers to Merezhkovskii's estimation that the German style of science emphasized data collection and precluded theory building that was necessary to move the idea forward (56–57). However, Sapp contends that career building was a part of Merezhkovskii's denial of other work on symbiosis and that previous interpretation of Russian symbiotic theory as a simple transfer to the West is an overly simplistic history of the idea. The rise and fall of the meaning that this cooperative design of nature implied was fraught with social, political, and national social constructions.

Knowledge claims of nature offer a multitude of social constructions, sometimes complimentary, sometimes competing and contested. We tend to view the latest construction as the "true" description of nature; however, acknowledging that social constructions of nature may coexist is more accurate. Escobar (1999) distinguishes three types of constructions of nature, arguing for a way to present all three as interacting and viewed from an antiessentialist position. He views the dominant Western construction of "capitalist" nature as reinforcing a binary between society and nature. He then contrasts this modern construction with more local, nonmodern constructions of an "organic" nature that does not separate nature and culture or society. These constructions, along with a more postmodern "technonature," may coexist and form a plurality of constructions or combine into hybrid nature. Although it was claimed by Kuhn that a new paradigm must always supplant an old one, post-Kuhnian science studies question such large transitions. Sandra Mitchell (2002) proposes an "integrative pluralism" that moves away from the image of one universal truth replacing another, thereby breaking with the idea of "normal" science in the positivist vein. She believes that a pluralistic model is more realistic because "…unification at the theoretical level is unlikely to be very robust. The reason is found in the evolved complexity characterizing the domain of phenomena studied by biology. It is the diversity of the 'solutions' to adaptive problems and the historical contingencies influencing those variable paths that preclude global, theoretical unification" (67). Mitchell claims that the concept of the division of labor is not as unified as it is described. By grouping particular insects into levels of sociality and applying a standard for division of labor to these levels, more subtle differences go undetected. Rather than replacing one model for another, she suggests that an integrative pluralistic approach to models is possible. Using social insects as a case study for biological phenomena, she proposes that explanations for the division of labor may be different for each species and subspecies, and therefore varying explanations could coexist.

If there is not a unified, linear understanding of the construction of nature, then why does it sometimes appear to be unfolding in such a manner? Scientific knowledge claims, although presented as objective, include the subjective elements of persuasion and rhetoric. The dominant discourse portrays scientific knowledge claims as truths once they gain acceptance from the scientific community. Therefore another area to examine concerning claims of nature and social construction is the act of description through language. This chapter cannot elaborate fully on this; however, it is important to note that our observations and representations of science are communicated through scientific and public discourse. This discourse is influenced by and influences the larger social and political context. As Barnes and Shapin elaborate, "Any perceived pattern or organized system in nature is liable to be employed to express and comment upon social order and social experience. In being so employed, the perceived pattern is itself liable to be developed and reconstituted to better fit it to its functions. The pattern in question may be of many kinds: the overall order of the cosmos, the system of natural kinds of plants and animals, the general organization of the earth's crust, even the humdrum routines of the honeybee" (1979:15).

The way nature is represented in scientific and public discourse matters (Gilbert and Mulkay, 1984; Hess, 1995). For instance, a long-standing common term in entomology for a particular species of ants is "slavemaker," and descriptions of their behavior include references to their treatment of other ants as "slaves." Entomologist Joan Herbers (2006) asserts that the loaded language of entomological science may bring about negative associations to human institutions that are not even accurate portrayals of insect behavior. How is the new language of self-organizing shaping our views of nature and human organization? Looking specifically at the development of scientific ideas about social insect organization can provide some clues as to the social construction of ideas concerning the design in nature and how we choose to describe this new paradigm.

## 3. Brief History of Knowledge Claims About Social Insect Organization

Perhaps the first key idea to examine is the one that privileges social insects over other insects as a model of social organization. In the Western classification scheme, social insects, that is, ants, bees, wasps, and termites, are considered "eusocial." This places them as the highest socially evolved insect. To exhibit eusociality, an insect species has to pass the following criteria: (1) presence of a caste system, including reproductive division of labor; (2) an overlap of generations; and (3) existence of parental care (Oster and Wilson, 1978). This definition became more specific over time and more exclusive. Those insects that are not considered eusocial are ranked in less evolved social terms as “quasi-” or “semi-” social. Communal behavior, aggregations, and of course solitary behavior make up the decreasing levels of social organization. This may reflect the legacy of hierarchical ordering found in the Great Chain of Being and early evolutionary theories. The idea of ranking insect sociality into higher and lower has been contested within entomology (Costa and Fitzgerald, 2005; Sherman et al., 1995; Wcislo, 1997).

To choose social insects as the model to study self-organizing is by itself a presumption about the importance of social insects to a particular culture. Not all cultures look to social insects as models of behavior or even see them as exceptional among insects (Gurung, 2003). The description of social insect organization also varies cross-culturally (Ellen, 1993; Novellino, 2000). For instance, the Nuaulu of central Seram do not conceive of “deep hierarchies” in social organization according to Ellen (1993). A description of eusocial insects as hierarchically superior to others does not exist. In other cultures, the eusocial category may not contain the same set of insects as the Western category. Wasps in particular are seen as important and serve as a model of social organization for the Kayapó of Brazil. The origin of social structure design is seen reflected in the nest design of a wasp as it contains a sky layer and an earth layer within a circular universe. However, there is also a lower layer, and all those deemed worthless live on this layer. Termites live on this layer; they are seen as “worthless” because they are “weak” and “cowardly” unlike wasps (Posey, 2002:92). The idea of layers structuring the design of the universe is similar to the social insect model adopted by indigenous Palawan of the Philippines as described by Novellino (2000).

Therefore to what extent does a perceived natural model influence the creation of social structure? Or rather is it the social structure that influences the perception of the natural model? Review of the ethnoentomological literature reveals that if the culture itself has hierarchical terms for their social organization, then those specific terms might be used to describe social insects, and conversely if a culture does not have any terms for hierarchical relationships, then social insects will not be seen to have hierarchical relationships within their social structure. We might surmise that there is no one natural structure for social insects, just as there is no one social structure for humans. Descriptions of social insects will be influenced by this variation in human social structure because culture plays a role in scientific description.

Just as culture plays a role, the idea of what social insect organization is comprised of has not always been viewed the same way over time. A historical look at the ideas of social insect organization within the dominant Western scientific discourse reveals a conception of hierarchical structure. The comparison of natural systems to human social structure has been used to explain a rigid division of labor and race, gender and class hierarchies (Rodgers, 2008). Even within this idea of hierarchical structure, the makeup of this hierarchy has changed over time. With few exceptions, up until Jan Swammerdam's observations under a microscope in the late 1600s, most thought that a bee colony was headed by a king bee. Burke (1997) argues that it was not only the new technology of the microscope but also Swammerdam's lack of investment in the political structure of the monarchy that allowed him to see past the assumption of the bee as king, thereby realizing that the sex of the prominent bee was female. Even after the switch to a queen ruler, the idea that the other bees were loyal subjects in a monarchy was still used to reinforce a sense that this hierarchical social structure was a desirable natural model to emulate (Burke, 1997; Merrick, 1988; Ransome, 1937).

Some precursors to the notion that something more complex was behind the organization of the colony other than the orders of a queen can be found in the work of natural historians and early entomologists. Maurice Maeterlinck's (1901) "Spirit of the Hive," Eugene Marias' (1937) "soul of the termitary," and Henry C. McCook's (1909) "occult force" are examples of an attempt to reference organization that was indirect, diffuse, and not attributable to a leader. According to some scientific accounts, the behavior of the entire colony was under some type of influence that could not be identified as direct instruction from a ruler. And yet, the unidentified force usually organized the colony in a very rigid and obedient manner. This mysterious quality of order was not explained in very scientific terms at this point.

Other attempts at understanding the complexity of social insect organization came out of the organicist ecological paradigm. William Morton Wheeler (1911) applied the concept of the superorganism to the social insect colony, thereby providing a scientific basis to the sense of group order. The concept originated with Herbert Spencer in his description of modern human society being an aggregate of individuals connected through language and the specialization of functions. Charlotte Sleigh (2002) points out another association with human society in Wheeler's theories of social insect organization. Wheeler termed the mutual act of ants feeding each other their regurgitated fluids "trophallaxis," naming this behavior as the mechanism of communication within the superorganism. Trophallaxis not only connected the inner colony but extended to the larger environment through contact with food resources for the colony. Sleigh places Wheeler's insights within the backdrop of the Depression and Hoover's policies of food distribution. "The success of both Hoover and Wheeler hinged on the circulation of food, and there is more to this connection than mere chance. Both were caught in a dilemma between the need for social management and a fervent belief in individualism. Both attempted to resolve the dilemma through an understanding of socioeconomics; specifically, both modeled recession in the same manner. Their rooting in a common political and cultural environment is embodied by Dora Emerson Wheeler's active participation in Hoover's presidential campaign, and a consequent acquaintanceship between the two couples" (2007:82). The interrelation between nature and culture is not easy to disentangle; however, Wheeler's work illustrates the presence of a social filter in the creation of his theories of nature.

The influence of interactions happens to also be featured in the idea of emergent evolution that Wheeler adopted from C. Loyd Morgan (Worster 1985:322). According to Morgan, evolution creates new forms completely unique from those previously existing. This new synthesis cannot be explained or studied by the same methods used to study the entities from which it emerges. Emergence became a key idea for the Chicago Ecology Group during the 1930s and the 1940s, and they placed an ecological emphasis on a process of evolution that occurred on varying group levels (Redfield, 1942; Worster, 1985:326). Warder Clyde Allee and Alfred E. Emerson felt that this idea of emergence had significance for cooperation in human society. However, during World War II, the idea of group selection became associated with the repression of the individual under Nazi Germany and became a politically unfavorable theory in America (Mitman, 1992; Worster, 1985). This is interesting for the historical lesson it imparts, especially in regard to studies that focus on group behavior. The tension between individualism and the collective is generally infused with political meaning. Similar to the marginalization of symbiosis, the interest in emergence and group level selection became associated with anti-individualism on a sociopolitical scale.

A more ideologically acceptable notion appeared with Hamilton's (1964) proposal of kin selection as an explanation for the group sacrifice exhibited in social insect colonies. The "problem" of altruism in social insects grappled with since Darwin's *Origin of Species* was resolved. Because of the coefficient of relatedness between workers in a colony, inclusive fitness was viewed as supplying genetic benefits for nonreproductives who selflessly contributed to the reproductive success of others in the colony. Individual selection could still be asserted despite what appeared to be the contrary evidence of altruistic behavior. Kin selection has had its critics, including E. O. Wilson; however, it has remained a dominant force in descriptions of social insect organization.

The factory-fortress model developed by Oster and Wilson (1978) drew upon the earlier idea of the superorganism. Oster and Wilson further developed this through the use of economic metaphors (21). They imagined the colony as needing to protect its reproductive investments through defense. The fortress surrounded the factory within the colony. Because the losses sustained in defense while attempting to maintain reproduction must be managed somehow to maintain fitness, a rigid division of labor that relied on specialized castes was offered as the solution. This model is based on ideas of optimization and was seen as generalizable (22). Deborah Gordon questioned the efficiency of such a rigid and specialized division of labor among ants. Instead she proposed that the concept of task allocation best describes the way work gets accomplished in a colony (1989). Gordon further noted that human work models had turned to less specialization from a new belief that flexible production was most efficient and that rigid specialization may never have explained the efficiency of ants. Our own images of how humans organize work influenced the way we interpreted ant behavior. This earlier interpretation overlooked other ways of understanding how ants organize. One of these possibilities was self-organizing.

## 4. Self-Organization of Social Insects

The description of social insect colonies as self-organizing began to be more widely accepted beginning in the 1990s. The first significant change one can detect in the literature is the lack of a hierarchical leader giving out directions in a colony. As Camazine et al. (2001:191) describe honeybee foraging: "…the mechanisms appear to arise entirely from the actions and interactions between forager bees rather than on guidance from an external, directing influence. Studies have failed to find any supervisory leader of the foragers." Foragers are described as on their own in finding food sources, and the researchers find no centralization within the organization as opposed to the previous belief that the queen bee was the centralizing force. This process is termed a "decentralized, self-organized mechanism of foraging" (Camazine et al., 2001:192–193).

The self-organizing of foraging has been identified in ants as well. Gordon (1989) found a parallel-distributed model of foraging in the harvester ants she studied. She refuted Oster and Wilson's (1978) explanation that foraging behavior is carried out by individual ants who are genetically preprogrammed to be foraging specialists in a hierarchical division of labor. Deneubourg et al. (1990) concurred that self-organizing explained the process of foraging and considered the pheromones to serve as positive feedback for guiding the other ants who are not specialists but share the same level of local information and ability.

The architectural designs of social insect nests also began to be viewed through self-organizing (Franks and Deneubourg, 1997; Bonabeau et al., 1998; Karsai and Pénzes, 1998). Early work in this field applied Grassé's (1959) idea of stigmergy and developed computer models to quantitatively test this approach toward the construction of social insect nests. Grassé's idea of stigmergy explained the behavioral patterns that went into building and maintaining a foot-high termite mound. Each individual action of laying down material triggered another individual to follow and add to this; an accumulation of actions following this pattern was able to produce a large structure without any preconceived blueprint for design.

If self-organizing could be used to explain foraging and building, could it explain group decision-making? Combining the study of foraging patterns with the concept of collective intelligence or swarm intelligence was used to illustrate the self-organizing of army ants. Swarm intelligence describes the ability of a group to adapt its behavior to meet its goals in the most efficient manner. No individual in the group knows the overall plan but is able to act with the group to achieve the larger goals. The swarming of army ants is seen to be a perfect model for observing swarm intelligence. Descriptions of army ants have varied over time and place and can be examined for the social context involved in applying self-organizing to their behavior and organization.

"Army ants" is a common term used for Old World and New World species of ants that share a particular type of social organization and behavior. They are nomadic and conduct swarm raids in search of prey. The swarms of thousands of individuals follow a seemingly efficient pattern, despite the limited sight and intelligence of each individual. There are many different species of army ants; however, the most studied are *Eciton burchellii* and *Eciton hamatum* and those in the genus *Dorylus*. How these ants organize their predatory raids has long been of interest to naturalists and scientists. Naturalist William Beebe described the army ants as "directed, ordered, commanded by scent and odor alone," although he did identify scouts as helping to forge a path (1921:62). Although Beebe described the overall effect of an army ant swarm as being systematic in its coverage and predation, he did not particularly see the ants as efficient in their individual movements. He claimed that "Unlike penguins and human beings, army ants have no rule of the road as to right and left, and there is no lessening of pace or turning aside for a heavily laden drogher. Their blindness caused them to bump squarely into every individual, often sending load and carrier tumbling to the bottom of a vertical path" (Beebe, 1921:70).

Other naturalists such as Thomas Belt interpreted the army ants as having a hierarchical division of labor with officers directing the march of soldiers. The column raiding of certain army ants was compared to the precision of the British Army (Belt, 1911). Army ant organization and behavior have a history of being described in terms of hierarchical military rankings and military maneuvers (Gotwald, 1995). Franks and Partridge (1993) have even applied a mathematical model derived from human armies to explain the benefits of raiding patterns in reducing the number of ant casualties for the colony. The social construction of these military metaphors can be shown against the contrasting indigenous descriptions of swarms as the "visiting ants" who rid the village of other invertebrate and vertebrate pests (Réaumur, 1926). Similar to Escobar's notion of hybrid natures, the descriptions in the literature often overlapped between Western modern scientific terms and indigenous terms for these ants.

Some early scientific explanations of the raids of army ants proposed that the raids originated from "inner drives," in particular, the belief that instinctual needs to swarm were due to area food depletion. Thomas Schneirla, during his studies of army ants in Panama, claimed that the queen was the "pacemaker" of the raids connected to brood reproduction and worker interaction with the brood (1944). Schneirla was a critic of instinct theories and contested this long held belief as the cause of the swarms. Instead he identified a pattern of nomadic and statary periods related to this internal influence of a brood cycle (queen as pacemaker) that occurred within the environmental influence of the rainy season. Schneirla employed Wheeler's concept of trophallaxis in explaining how the tactile and chemical stimulation derived from interaction with the brood led to the raids. Despite the differences in raiding patterns between *Eciton hamatum* and *Eciton burchellii*, Schneirla claimed that the queen was the pacemaker for both species. Schneirla also noted the differences of patterns between swarm raids and column raids, identifying a "pushing party" as guiding the forward direction of the mass of ants for column raiders. The swarm raiders' movement was directed in another manner; the "flanking" actions of the ants provide a type of rudder.

"This alternate flanking movement of the raiding swarm is mainly responsible for the meandering course that is taken by the eventual consolidation trail. The phenomenon occurs principally as a result of the manner in which contact among individuals limits and directionalizes the spreading of a mass of eccentrically running workers over an area; but the process is complicated by other factors as well, and varies greatly at times" (1934:319).

Scientific and technological advances influenced changes in how army ant behavior was studied and described. A turn toward chemical explanations emerged in the late 1950s with the new scientific area of pheromones. The role of pheromones was examined in all social insects. Of particular interest, due to their nomadic and swarming behavior, army ant organization was seen as integral to these chemical signals they used to lay down and follow trails or to activate alarms (Blum and Portocarrro, 1964; Gotwald, 1995; Torgerson and Akre, 1970). Pheromones became a way to explain social insect queen control of the colony as well (Wilson, 1965). Although pheromones offered an explanation for the "spirit of the hive" that had proved so elusive to scientists, questions still remained as to the dynamics of organization. With the advent of computer simulation, often paired with mathematical modeling and robotics, the behavior of army ants began to be modeled artificially. "Computer simulation allows the investigation of more complex cases, by simulating both the animal and the environment, and so allowing the external consequences of the model animal's behavior to be fed back to the model animal. In this type of work the simulated agent is often called an animat" (Holland and McFarland, 2001:14). Modeling army ant raids became of special interest to social insect researchers. And although the importance of pheromones was still acknowledged, the new concept of self-organizing came to include a focus on optimization models.

Deneubourg et al. (1989) created a computer simulation of army ants to predict how swarm raid patterns were determined by simple pheromone trail laying and following behavior. Their model was seen to provide evidence of self-organizing patterns in the swarm raids. Building on this work, Solé et al. (2000) quantified the model to judge if the patterns reflected optimal solutions to foraging. The algorithm they developed in the simulation for three army ant species was claimed to achieve optimal foraging strategies under varying ecological conditions. Further, this model was viewed to be similar enough to actual colony behavior to contribute to knowledge about the role of self-organization on group selection and individual behaviors that were directed toward optimal foraging. Franks et al. (1991) tested the Deneubourg et al. model through experiments and mathematical modeling, also concluding that self-organization was at work in the traffic patterns that emerge from trail pheromones and prey distribution. An interest in the self-organized movements of army ants resulted in computer simulations and optimization models of their traffic patterns. Couzin and Franks (2003) concluded that army ants were highly efficient due to the self-organization of thousands of individuals creating extra lanes to avoid blockages in traffic and collisions.

Interpretations of army ant behavior and organization have followed along with the more general changes over time in the descriptions of social insects, and yet they are a unique group to analyze in the social construction of the self-organizing paradigm. Their swarm raids in particular are considered well suited to study self-organizing patterns. Several interesting shifts in thinking about army ants illustrate the social construction of ideas about their natural organization patterns, in particular, the description of individual behavior, explanation for the driving force of colony movement, and of course the influence of larger scientific theories and technology in framing research questions and methods used to study them.

The movement of army ants was not always viewed as rationally efficient as it has come to be through the use of mathematical models and computer simulations. In maze studies that Schneirla (1943) conducted, he determined that rats were more efficient in negotiating mazes than ants. He also compared the *Eciton* migration to bird flocking and believed that for birds, the individual has more to do with the "highly specialized superstructure" (1945:192). *Eciton* on the other hand has what Schneirla considers to be a "primitive or rudimentary migration" precisely because of a lack of individual specialization (1945:192). There are current questions about individual behavior for army ants and also other social insects. Dornhaus and Franks (2008) claim that the assumption of individual simplicity in self-organizing models may be overstated. They cite both classic and contemporary texts that refer to cognition for individual social insects and the role of the larger environment shaping individual behavior.

A hallmark of self-organizing has been the feature of a leaderless, nonhierarchical organization made up of simple units creating an overall complex whole. This is an interesting parallel to the decentralized social organizations found currently in human society as a "flexible" workplace became the norm. In the above case of the army ants, the idea of leadership or the driving force behind the colony behavior changed over time and place. The queen had previously been seen as a driving force, similar to the general view of social insect organization. This leader-driven hierarchical model also matched our own human organizational structure at the time. This speaks to the socially constructed possibilities for how we view nature through our own organizational lens. Another example is provided by the description of military organization that began with naturalists from the West describing species of ants in a colonized country and comparing them to the colonizing army. In an opposing conception, the indigenous population did not describe the ants in this way but instead viewed their raids as useful pest control.

The explanation for the driving force within a colony can also be influenced by current trends in science and technology. Instinct had been a widely popular area of study in science until behaviorism took hold; the "inner drives" of the swarm raids no longer seemed an adequate explanation. Likewise, the role of pheromones as driving force developed as the focus on chemicals became predominant in science. Computers have also made their mark on scientific investigations into social insect behavior. Although mathematical models and computer simulations may be limited in their ability to recreate reality, they are currently relied on in most self-organization studies. Models typically focus on only one aspect of colony behavior, and individual units are assigned behavioral rules that are more restricted and fixed than in nature (Camazine et al., 2001; Gordon, 2010). An interest in understanding rational efficiency has inspired particular models, such as Dorigo and Gambardella's (1997) ant colony optimization model (ACO), created to solve the traveling salesperson problem by modeling ant routes to food sources. These biologically inspired models reflect what we currently find the most useful to know about social insects, not necessarily the entirety of their organizational design. Self-organizing is a paradigm, and like all paradigms, it is socially constructed; the social and historical contexts give us perspective on the possibilities and limits of the stated knowledge claims.

## 5. Self-organization as a General Model

Can the principles of self-organization studies with social insects transfer to human organizations? In the coproduction of ideas about social organization such generalities may be difficult. Gordon demonstrated the problem with applying a human concept of division of labor onto ant societies. Ascribing hierarchy and centralization where it rarely exists obscures the type of organization that ant societies actually have that differs from human societies. Likewise, to apply self-organizing principles inspired by social insect studies to explain aspects of human structures may obscure important issues such as power, inequality, and sociohistorical context. To explain simple crowd behavior through self-organizing may be one thing; explaining the rise and fall of the British Empire or modern urban resource allocation by way of self-organizing is something else altogether (Adams, 1982; Allen, 1997; Robinson, 1986). The danger is in oversimplification and naturalization of human social structures. For instance, Adams' account of Britain Imperialism contends that "expanding social systems are entirely a part of nature and…their ultimate elements are no different from those composing the more easily visible physical world. Their inevitable expansion carries the emergence of higher levels of hierarchy, and these must be recognized as real dissipative structures that will take on their own behavior. In the present case, the lesser components lose their autonomy of action; they lose the ability to respond individualistically to an unstructured environment because they now confront one that is structured. In the nature of social structure, they become subordinated to the larger expanding dissipative structure that encompasses them" (129). Adams is specifically comparing human social systems with a natural principle of self-organizing complexity.

The expansion of an insect colony, the growth of a termite mound, overpopulation leading to a swarm of bees, and the raids of army ants into new territories may seem ripe for analogies to social systems. In fact, these have a history of being compared to human social systems, as previously discussed. Yet, as

Lewotin (1991) states, “what happens is that human categories are laid on animals by analogy, partly as a matter of convenience of language, and then these traits are ‘discovered’ in animals and laid back on humans as if they had a common origin. There is in fact not a shred of evidence that the anatomical, physiological, and genetic basis of what is called aggression in rats has anything in common with the German invasion of Poland in 1939” (95–96). Schneirla argued for a more complex view of understanding similar adaptive functions in two different organisms considering that the process of arriving at that adaptation may not be the same. He compared insects, rats, birds, and humans, finding each to have separate processes even when it appeared there were similar adaptations (Lerner, 2001). Currently, however, self-organizing models tend to be viewed as contributing to a universal explanation of design for many species including humans. Whether ideas about social insects shift from hierarchical organizational structures to self-organizing does not have a direct effect on their behavior. There are some social constructions of insects that may have more direct impact on insects themselves, such as whether an insect is framed as a pest or an important part of biodiversity. However, in accepting the challenges of understanding insect behavior, we should also be more cautious about making facile comparisons to human society.

Although ideas about self-organizing are being modified to include more cognition for individuals, as a general model, it proposes that the individual is not a conscious actor and instead is a unit contributing to the larger global pattern. As Kelly (1994) describes it: “The whole 50-pound hive organ emerges with its own identity from the tiny bee parts. …Ants, too, have hive mind. A colony of ants on the move from one nest site to another exhibits the Kafkaesque underside of emergent control…A typical day at the office…Without any visible decision making at a higher level, it chooses a new nest site, signals workers to begin building, and governs itself. The marvel of ‘hive mind’ is that no one is in control, and yet an invisible hand governs, a hand that emerges from very dumb members” (Kelly, 1994:12). The lack of visible control, as Kelly plays off the metaphor, is Smith’s invisible hand of the market. Self-organizing has been evoked to make comparisons between social insect organization and the human postindustrial economy just as earlier analogies naturalized a hierarchical division of labor. It is interesting to note that the political economic discourse for humans has changed along with our natural models. The division of labor is now described as global and complex. Self-organizing becomes an apolitical, ahistorical explanation of the economy, the way that organizations have downsized, decentralized, and shed responsibility for workers is posed as an organic process that is surprisingly similar to current interpretations of social insect behavior.

As the new idea of self-organizing spans the disciplines, it creates a dominant discourse of complex adaptive systems. The link between social and natural reinforces the legitimation of this discourse; it appears to “make sense.” Kennedy et al. (2001) in their speculation as to the newfound interest in swarms cite Mark Millonas, an ant swarm researcher who states that “in the end perhaps the most pervasive appeal of swarms centers on a kind of emotional attractiveness of the subject" (Millonas in Kennedy et al., 2001:108–109). Kennedy et al. admit their interest in swarm intelligence is "motivated in part by the uninformed suspicion there is wisdom to be gained from it, and by the feeling that there is something about the orderly interactions of dumb actors and their achievements that is just, well, fascinating. It seems that there is something profound and meaningful in these phenomena, something that transcends the compulsive rationality imposed by our intellectual tradition" (109). This admission speaks to the element of subjectivity in our choice of research topics. When there appears to be an intuitive match between the research idea and our own understandings, the social and political context informs that sense of natural fit. Reactions to excessive rationality, decentralized systems in nature that are similar to computer networks, and a naturalized postindustrial economy all "make sense" in a particular time and place. Our ideas about design in nature are socially constructed.

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Biodata of **Eileen Stillwaggon,** author of "***Complex Epidemics, Simplistic Tools: The Failure of AIDS Policy in Africa***."

**Eileen Stillwaggon** is Professor of Economics and Harold G. Evans-Eisenhower Professor at Gettysburg College, Pennsylvania. She received her Ph.D. in Economics at American University in 1979 and a Diploma in Economics from the University of Cambridge in 1977. As a development economist, she naturally approaches complex emergencies and chronic needs in the context in which people live and work. Author of *AIDS and the Ecology of Poverty* (Oxford University Press, 2006), Stillwaggon has written extensively on HIV/AIDS in developing nations for scholarly journals, including the *Journal of the International AIDS Society, Development and Change, Feminist Economics, South African Journal of Economics,* and popular media. She also wrote the 1998 book, *Stunted Lives, Stagnant Economies: Poverty, Disease, and Underdevelopment*, about the interaction of poor health and poverty, based on years of research and work in informal settlements and public clinics and hospitals in Argentina. Stillwaggon is Secretary of the International AIDS Economics Network (IAEN) and a member of the Editorial Board of *AIDS Care*. Her current work involves the modeling of complex systems of disease dynamics to devise effective health and development policies.

E-mail: **stillwaggon@gettysburg.edu**

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# COMPLEX EPIDEMICS, SIMPLISTIC TOOLS: THE FAILURE OF AIDS POLICY IN AFRICA

**EILEEN STILLWAGGON**
*Department of Economics, Gettysburg College,*
*Gettysburg, PA 17325, USA*

## 1. Introduction

Over the past 25 years, global AIDS prevention policy has remained largely isolated from mainstream epidemiology, which recognizes that epidemics arise from the interaction of multiple biological characteristics of the host, pathogen, and environment. The result has been an implicit (and often explicit) theory of HIV causation that treats AIDS as a special case, unrelated to the context of malnutrition or parasitic and infectious disease in which the epidemic flourishes.

Health economics uses tools such as cost-effectiveness analysis to evaluate alternative interventions for prevention and treatment. Just as AIDS policy is isolated from the conventional understanding of disease interactions, health economics has remained isolated from an expanding toolkit in other fields of economics that recognize interaction and incorporate externalities and increasing returns. Thus, it is poorly equipped to evaluate interventions that have spillover benefits, such as when treating one disease or condition improves the efficacy of interventions to prevent or treat other conditions.

This chapter discusses how the limitations of health economics reinforce the errors caused by a simplistic theory of HIV causation and artificially isolate AIDS programming from other health-promotion priorities. It suggests better integration of complex models of epidemiology with economic models of increasing returns to develop more effective AIDS interventions through a broader health-systems approach.

Although HIV is sexually transmitted in probably the majority of cases in poor populations in developing countries, exclusive focus on the proximate cause of infection (sexual contact) does not provide an explanation for the divergence in incidence among populations. Sexual behavior, of course, is important in determining individual risk, but differences in sexual behavior between countries do not correlate with differences in HIV prevalence or incidence. Numerous empirical studies demonstrate that rich countries have higher rates of most risky behaviors – early initiation of sex, short-term concurrent relationships, unprotected sex, multiple partners, and premarital sex – that are not matched by high rates of

HIV (Billy et al., 1993; Grinstead et al., 1993; Kost and Forrest, 1992; MacDonald et al., 1990; Reinisch et al., 1992; Singh and Darroch, 1999; Singh et al., 2000; Smith, 1991; Stillwaggon, 2006; Turner, 1993; Wellings et al., 2006). Nevertheless, the presumption that there must be something exceptional about African sexuality still dominates AIDS-causation scenarios and HIV-prevention policy. The latest variant of the behavioral explanation of AIDS in Africa is that long-term concurrent relationships are more common in parts of sub-Saharan Africa and drive HIV epidemics in the region (Halperin and Epstein, 2004, 2007; Mah and Halperin, 2010; Morris and Kretzschmar, 2000). National rates of multiple concurrent partnerships, however, do not correlate with rates of HIV (Mishra and Bignami-Van Assche, 2009). A systematic review has demonstrated that the concurrency hypothesis is without empirical or logical basis. Even under extremely unrealistic assumptions (such as every person having sex with every partner every day), mathematical modeling shows that concurrent sexual relationships cannot increase HIV prevalence by more than a trivial amount (Sawers and Stillwaggon, 2010).

Without coinfections or other conditions that raise per-contact transmission rates, there is no evidence that African concurrency or networks are more risky than sexual networks elsewhere. The appropriate comparison for Africa is not with a hypothetical case of no sexual networks, but with real sexual networks, such as are reported on North American university campuses, with extensive short-term concurrency and high rates of sexually transmitted infections (STIs) (Billy et al., 1993; MacDonald et al., 1990; Reinisch et al., 1992), and yet low rates of HIV.

Almost 30 years into the epidemic, prevention policy for HIV/AIDS in Africa is still not evidence-based. In spite of accumulating survey evidence that national or regional rates of HIV do not correlate with rates of risky behaviors (Cleland et al., 1995; UNAIDS (Joint United Nations Programme on HIV/AIDS), 1999; Wellings et al., 2006), AIDS policy still emphasizes sexual behavior to the exclusion of other factors that influence individual and national vulnerability to HIV. To devise effective prevention strategies, we need to understand why HIV spreads at different rates in different populations.

## 2. What Is Driving the Spread of HIV in Poor Populations?

A growing body of scientific literature demonstrates that host and ecological factors play an important role in determining an individual's vulnerability to HIV infection and the contagiousness of HIV-infected partners (and mothers). Sexual contact with an infected person represents only a necessary, but not sufficient, condition for infection through sex. Similarly, being born to an HIV-infected mother does not always lead to infection of the infant. Vertical transmission, before introduction of maternal prophylaxis, ranged from 14% of infants of HIV-infected mothers in Europe to 40% in sub-Saharan Africa (World Bank, 1997).

Moreover, in the absence of other factors, transmission of HIV in industrialized countries has been insufficient to maintain a heterosexual epidemic. In the

United States and western Europe and in otherwise healthy populations elsewhere, HIV transmission will occur in about 1 out of 1,000 contacts (Boily et al., 2009; Chan, 2005; Deuchert and Brody, 2007; Gray et al., 2001). Clearly, other factors play a role in determining individual infection and divergence in incidence of HIV in different regions.

In the 1990s, STIs were recognized as potential cofactors for HIV transmission, and STI treatment has been included in some HIV-prevention programs (Grosskurth et al., 1995). Some skeptics cite an STI treatment trial in Rakai, Uganda (Wawer et al., 1999), which did not seem to confirm the role of STIs in HIV transmission, but that trial had serious flaws, including the absence of a true control group. Rakai's "control" group was treated with deworming medication and a vitamin/mineral supplement, with results not significantly different from treating STIs. (For additional discussion and sources, see Stillwaggon, 2006.)

Later it was recognized that antiretroviral therapy (ART), by reducing viral load, could reduce transmission (Auvert et al., 2004). More recently, male circumcision has been added to prevention programs, although there is still some scientific dispute regarding the efficacy of the procedure for HIV prevention (de Witte et al., 2007; Green et al., 2008). AIDS policy, however, does not yet address the widespread nutritional, parasitic, and infectious conditions that can act as cofactors of HIV transmission. The following section discusses prevalence of cofactors primarily in sub-Saharan Africa because HIV is much higher there than elsewhere. The divergence in HIV epidemics in different world regions suggests a complex etiology for generalized epidemics and the need for systemic solutions that solve multiple problems simultaneously.

## 2.1. NUTRITIONAL DEFICIENCIES

From 1988 to 1998, when nascent or concentrated AIDS epidemics developed into generalized epidemics in sub-Saharan Africa, 30% of the population of the region was malnourished (World Bank, 1998). Malnutrition increases vulnerability to infectious and parasitic diseases generally, and it increases HIV viral load and viral shedding, thereby increasing sexual and vertical transmission of HIV (Beisel, 1996; Chandra, 1997; Fawzi and Hunter, 1998; Friis and Michaelsen, 1998; John et al., 1997; Landers, 1996; Nimmagadda et al., 1998; Pelletier et al., 1995; Semba et al., 1994; Stillwaggon, 2006).

## 2.2. MALARIA

More than 90% of acute malaria infections worldwide occur in tropical Africa. Africa accounts for the majority of malaria deaths, including about 3,000 deaths per day of children under the age of 5. Survivors suffer chronic immune activation through repeated reinfection, increasing individual susceptibility of HIV-negative persons (WHO (World Health Organization), 2009a). Malaria increases HIV viral load as much as tenfold, increasing contagiousness of HIV-infected persons and affecting the dynamics of the epidemic at the population level (Abu-Raddad et al., 2006; Bloland et al., 1995; Corbett et al., 2002; Hoffman et al., 1999; Stillwaggon, 2006; Whitworth et al., 2000; Xiao et al., 1998). Individuals in malaria-endemic areas have a higher probability of sexual contact with persons who are infected with both malaria and HIV and who thus have high viral load. Models of malaria-HIV interaction estimate a threefold increase in HIV transmission in malaria-endemic populations and increased malaria transmission due to HIV coinfection (Abu-Raddad et al., 2006).

### 2.3. FILARIASIS AND GEOHELMINTHES

Lymphatic filariasis afflicts over 40 million people in sub-Saharan Africa. Prevalence is increasing in Africa because breeding areas for mosquitoes proliferate with unplanned urban growth (WHO (World Health Organization), 2000). Helminthic infections (various kinds of worms) are widespread in developing countries and virtually ubiquitous in shanty towns and rural communities. Worldwide, nearly 1.5 billion people are infected with ascariasis, 1.3 billion with hookworm, and more than 1 billion with trichuriasis (Partnership for Parasite Control). Lymphatic filariasis and soil-transmitted helminthes have also been shown to suppress immune response in HIV-negative persons and increase viral load in HIV-infected persons, affecting individual transmission and population dynamics (Borkow and Bentwich, 2006; Gopinath et al., 2000; Montresor et al., 2001; Nacher, 2002; Partnership for Parasite Control, 2002; Stillwaggon, 2006; Wolday et al., 2002). A recent double-blind, controlled trial found that treating ascariasis in HIV-infected persons results in a statistically significant increase in CD4 counts (Walson et al., 2008). That suggests that a simple, inexpensive (2 US cents) and effective deworming medication (albendazole) could allow HIV-infected people to postpone ART. On an individual and population basis, the benefits of postponing first-line ART are substantial. A systematic review of studies of cofactor treatment for HIV-infected persons found that 12 of the 14 studies with variance data reported significant HIV viral-load differences before and after treatment. They report that even small changes in viral load have been shown to slow HIV progression and could translate into population-level lowering of HIV transmission risk (Modjarrad and Vermund, 2010).

### 2.4. SCHISTOSOMIASIS

Urinary schistosomiasis (*S. hematobium*) afflicts almost 200 million people in sub-Saharan Africa (WHO (World Health Organization), 1996) and acts as a cofactor of HIV transmission in much the same way as do STIs. Acquired in contaminated lakes and streams, worms and ova of *S. hematobium* infect the reproductive tracts of both men and women. They create lesions, which are open portals for HIV, and inflammation of the genital area, which makes HIV transmission more efficient (Attili et al., 1983; Feldmeier et al., 1995; Leutscher et al., 1998; Marble and Key, 1995; Stillwaggon, 2006). In Zimbabwe, researchers found that genital lesions of schistosomiasis increased HIV risk in women threefold compared to women in the same communities without genital schistosomiasis (Kjetland et al., 2006). Furthermore, reports from developing countries indicate that neglecting to treat schistosomiasis, worms, and malaria contributes to failure of ART.

As we acquire new information about HIV transmission, we have to make sure we are asking the right questions in each regional context. Viral load is an important factor in determining the risk of infection (Quinn et al., 2000), and recent studies have concluded that the majority of new infections are transmitted by persons who were themselves recently infected and thus have high viral load (Brenner et al., 2007). That is probably true in poor populations as well.

In coinfected persons in poor populations, however, the burden of malnutrition, parasites, and infectious diseases also increases viral load, not just within the first weeks of HIV infection, but over the lifetime of the infected person. Malarial episodes, for example, increase viral load not just during febrile periods, but for 7 weeks afterward (Abu-Raddad et al., 2006; Hoffman et al., 1999; Kublin et al., 2005), and people in endemic zones are repeatedly infected.

We can expect to see a flurry of studies on how best to reach newly infected persons with elevated viral load. That will be very useful, of course, but we also need to consider the extended periods of elevated viral load in persons with malaria and other coinfections.

In light of the conventional epidemiological understanding of disease synergies and the evidence that interactions with specific parasites and infections increase vulnerability to and contagiousness of HIV, the exclusively behavioral focus of AIDS policy reveals a very simplistic notion of disease causation.

## 3. Limitations of the Behavioral Paradigm

The primary focus of HIV-prevention policy and the principal targets of spending continue to be various strategies for changing sexual behavior. Substantial money and effort have been expended, thus far without success, on vaccine and microbicide development, but those efforts also reflect a focus on proximate cause.

That the major political debates on AIDS policy have revolved around promoting abstinence or providing condoms attests to the behavioral focus of HIV-prevention policy. Comprehensive lists of standard interventions (Hogan et al., 2005; Schwartlander et al., 2001; Stover et al., 2002) name various behavior-change strategies for sexual and needle-sharing behavior and strategies for reducing mother-to-child transmission. The additions of STI treatment and male circumcision may be important steps, but AIDS programming is still restricted to factors fairly obviously connected to a proximate cause, sexual contact.

While AIDS discourse does address social and economic factors, such as stigma, gender roles, and poverty, it is only to the extent that such factors influence risky sexual behaviors, closing off other useful lines of inquiry. Gender analysis of AIDS includes important issues, such as violence and inheritance practices, but not the mundane risks of gendered household tasks, such as washing clothes or gathering reeds in rivers and lakes, which affect susceptibility to HIV through genital lesions of schistosomiasis (Stillwaggon, 2008).

Studies of higher HIV prevalence among fisherfolk and car washers (who work standing in lake water) presume unobserved sexual networks at the lakeshore. They fail to consider that people who work in freshwater in Africa have high rates of schistosomiasis, which increases HIV transmission. We cannot examine AIDS in a laboratory where social and economic factors affect only sexual behavior. People have sex and bear children in a context of everyday risks – disease vectors, contaminated water, food insecurity, and job hazards – that make every sexual contact and every birth more risky in poor countries.

## 3.1. THE STANDARD MODEL OF HIV IN POLICY DOCUMENTS

In the policy literature, HIV-prevention interventions are justified on the basis of an extremely simplistic model of HIV transmission. The standard models for sexual transmission of HIV used by multilateral and bilateral donors, for example, AVERT, GOALS, and STDSIM (Bouey et al., 1998; Futures Group, 2012; van Vliet et al., 1998), do not incorporate what is known about the complexity of HIV transmission. They usually assume a universal dose–response, given in a constant per-contact transmission risk. The core of the standard model is as follows:

$$I = N \times P \times T,$$

where $I$ is probability of sexual infection, $N$ is the number of partners, $P$ is the prevalence in the population, and $T$ is the per-contact transmission risk, which is assumed to be the same for every population.

Each of the models is different, but the core variables included in each can be represented with this simple equation. AVERT includes number of sex partners, number of sex acts, prevalence of STIs, condom use, and related variables. GOALS includes various behavior-change interventions and can include blood-safety interventions.

Because the models include only population characteristics related to sexual behavior or sexual health, they explain incidence of infection through the behavioral variable, $N$, or number of partners. In circular fashion, the only policy conclusions that derive from this equation favor behavioral interventions. STDSIM, for example, could incorporate schistosomiasis along with STIs, but it does not. Omitting cofactors leads to biased estimations.

STDSIM was used to evaluate whether rates of male circumcision could explain the differences in rates of HIV in the Four Cities Study (UNAIDS (Joint United Nations Programme on HIV/AIDS), 1999), allowing for variation in other risk factors, such as frequenting commercial sex workers. The model was successfully fitted to the data, except for the case of Kisumu, Kenya, leading the authors to reject the behavioral data the men reported. Had they included prevalence of schistosomiasis for Kisumu, which is on Lake Victoria, their model might have predicted HIV in Kisumu better, and they would not have had to conclude that the men were lying about their sexual behavior (Orroth et al., 2007).

The implicit assumption underlying these models and most HIV-prevention strategies is that differences in sexual behavior, represented by $N$, explain differences in HIV rates, although the preponderance of evidence shows no correlation at the country level between rates of various sexual behaviors and rates of HIV.

$P$, prevalence, is a misleadingly simple concept. Transmission dynamics are influenced not just by the proportion of the population that is HIV-infected, but by the infectiousness of each person infected. $P$, thus, should not be a number, but an array of numbers representing the proportion of the population infected at each level of viral load. It matters a great deal at the individual and at the population level what the population viral load is.

In this equation, prevalence, $P$, represents the probability of a sexual contact being HIV-infected. But what matters more is the probability that a random sexual partner from that population has a viral load above the level at which transmission is likely to occur (Fideli et al., 2001; Quinn et al., 2000). Consequently, our understanding of the spread of HIV, in sub-Saharan Africa in particular, would be improved if we estimate $P$ as an array disaggregated by level of viral load. And our prevention of transmission would be enhanced by interventions that reduce viral load in infected partners and mothers.

Transmission risk, $T$, should include per-contact risk of infection for the HIV-negative person (vulnerability) and per-contact risk of transmission for the HIV-infected person (contagiousness). Both vulnerability and contagiousness could be increased by infection with helminthes, malaria, malnutrition, tuberculosis, STIs, and schistosomiasis. (To avoid double-counting the enhanced contagiousness of the HIV-infected person, we would include here only factors not captured in the estimate of viral load in the array of $P$. Genital sores of schistosomiasis or STIs in either partner would be included here, for example.)

Similarly, a new model for vertical transmission should include characteristics of mother and infant, including anemia and other nutritional deficiencies, geohelminth exposure, schistosomiasis, and STIs. Epidemic models for poor countries should also include primary transmission by contaminated medical instruments and blood. Even if such medical transmission produces only the

5–10% of primary infections conservatively estimated by UNAIDS (UNAIDS (Joint United Nations Programme on HIV/AIDS), 2004), they comprise an underestimated source of primary infection for women and infants in particular since both women and infants are more likely to undergo invasive medical procedures than are men (Gisselquist et al., 2003, 2004).

The standard model, with a scalar *P* and a constant *T*, assumes that one risk fits all individuals and all populations, abstracting from almost all the important biological variation between rich and poor, and temperate and tropical populations. Modifying *P* and *T* helps, but it does not begin to model the complex interactions among conditions or to estimate the effect of nonlinearities in the impact of one or more conditions on others. We would need more fully specified models to do that, although it may not be possible or mathematically meaningful to aggregate all conditions across all individuals.

The point is that if we use a model that assumes one risk fits all, as do most models used in AIDS policy, we cannot explain the global distribution of HIV and AIDS, and we cannot generate useful prevention policies for different regions. By cataloging all the endemic conditions that are known to influence the spread of HIV in poor populations, and accounting for the disease synergies, we can attempt to design HIV programs that address the differential risk of multiburdened populations.

That does not, however, mean that we should postpone treatment for widespread, debilitating conditions until we have the perfect model. We already have plenty of evidence that treating STIs, helminthes, malaria, and malnutrition are good things in themselves. The only barriers to addressing those problems have been a lack of political will and flawed economic models.

## 4. Complexity and HIV

We need new ways of thinking about HIV causation, and here, I outline one way to begin. The AIDS epidemic, like most epidemics, is a complex, contingent process. In complex adaptive (or contingent) systems, even small differences in initial conditions can result in widely different outcomes, and sudden or rapid change can produce bifurcations or changes in trajectory. Edward Lorenz observed such results in the 1960s when his modeling of weather conditions calculated at three decimal places produced widely different forecasts from his calculations at seven decimal places (Bird, 2003).

As epidemics unfold as complex, contingent processes, both the exposures (sexual contacts for HIV) and the infections themselves result from multiple, interacting causes. Sequential iterations produce new trajectories that are determined (not random), but unpredictable at the outset. In different countries and different regions, relevant conditions of hosts, environment, and sometimes the pathogen can differ not just by small amounts, but by several orders of magnitude.

In the United States and Europe, for example, malaria and schistosomiasis are extremely rare, whereas in Africa the number of malaria cases per year exceeds 25% of the population in 27 countries (WHO (World Health Organization), 2008) and the number of schistosomiasis cases exceeds 25% of the population in 22 countries (WHO (World Health Organization), 2009b). Differences in the burden of other parasitic diseases are similarly vast.

It is simplistic to assume that a large event, such as a generalized HIV epidemic, results from a single large cause, a lone gunman. It is more likely that large events are the result of the synergistic effect of multiple causes, each of which may show slight variation between regions. The divergence in HIV incidence between rich and poor countries and between temperate and tropical areas is affected by the interplay of malaria, STIs, helminthes, filariases, anemia, vitamin-A deficiency, and many other factors, for which the differences between rich and poor populations are great.

Moreover, even between western and southern Africa, the relative weights of each of those factors differ, although they are not differences in order of magnitude. As in weather patterns, it is quite plausible that very small differences in initial conditions of one or several factors can result in very different outcomes in incidence of diseases with multiple, interacting determinants.

### 4.1. BOOLEAN NETWORKS

One way to visualize how AIDS epidemics behave as complex systems with interacting variables is to use Boolean networks, employed by some biologists (Kauffman, 1991). In a system with $N$ elements (e.g., diseases or environmental factors), some of those elements interact and are called inputs, designated as $K$. In simple systems, of $K=2$ or $K=3$, stable outcomes can be expected. When every variable is connected to every other variable – a so-called $K=N$ network – outcomes are said to be completely random (Kauffman, 1991, 1993), although perhaps it should be said that they are determined but unpredictable.

A Boolean network seems to model HIV effectively. In developed countries, it may be that $K=2$ or $K=3$, and incidence would therefore be stable and predictable; this has generally been the case in western Europe and North America. In poor populations in tropical regions, with many interacting variables (malaria, malnutrition, worms, etc.), $K$ approaches $N$, and epidemics are unstable and unpredictable. The greater the number of factors, the more sensitive are the outcomes (epidemic trajectories) to initial conditions.

As Kauffman observed in reference to other $K=N$ systems, minimal changes typically cause extensive damage – alterations in the activity patterns – almost immediately (Kauffman, 1991, p. 81). This approach might be extremely useful when applied to HIV, considering the divergent evolutions of HIV epidemics in different populations. No other credible explanation has been offered for the near-explosive growth of HIV in southern Africa. And no single variable can explain the differences between regions, be it male circumcision, labor migration patterns, local sexual practices, or parasite burden.

Clearly, if $K = N$ or nearly so, policy makers must work with a reduced form of the model. They have to choose the most significant coinfections for interventions. But to make policy that is relevant to a real-world epidemic, and even to recognize the most significant coinfections, they need to bear in mind that such complex interactions of multiple factors determine the diverging trajectories in different regions.

The good news is that while disease interactions can accelerate epidemics, they also provide multiple entry points to interrupt transmission. Many of those opportunities, such as providing clean water and sanitation and deworming, are much more policy-sensitive than sexual behavior, and they have multiple beneficial effects.

## 5. The Poverty of Economics

Ignoring interacting and multiple-level variables has generated an inadequate theory of disease causation to inform AIDS policy. That problem is reinforced because of the limitations of health economics, and cost-effectiveness analysis in particular, in evaluating complex interventions. Unlike other fields of economics, health economics has not been drawn into the exploration of complexity, nonlinearity, and multiple equilibria.

Since disease interactions have nonlinear effects, multiple outcomes are not only possible, but quite likely in disease dynamics. But recognition of nonlinearities is rare in health economics. (In a search of all articles published in *Health Economics*, *Health Policy and Planning*, and *Journal of Health Economics* in the past 10 years, I found only three articles that made any reference to interaction variables or nonlinearities. None was based on a model of biological interaction.)

Clearly, policy makers must employ some method of evaluating interventions, and the principle of cost-effectiveness analysis is valid. Cost-effectiveness analysis, however, is best used when there are identical outcomes to alternative treatments or when it is easy to measure a single objective (outcome) of the intervention (Henderson, 1999).

In an epidemic with multiple, interacting causes, it is difficult to define interventions with identical outcomes or to evaluate treatments with only one kind of benefit. The use of simple cost-effectiveness analysis appears to validate the superiority of single-input interventions because, as it is currently employed, it cannot measure the benefits of programs with heterogeneous or diffuse benefits, unanticipated spillover benefits, or benefits that take some time to appear. With few notable exceptions (Chesson and Pinkerton, 2000), they fail to recognize increasing returns (decreasing costs) or other nonlinearities in interventions.

## 6. Increasing Returns: Economics in the Real World

The general equilibrium model that has dominated economics for more than a century assumes negative feedbacks (decreasing returns) that lead to a unique, stable equilibrium under perfect competition.

Since the 1980s, economists have attempted to model positive feedbacks in growth theory, trade theory, and other fields (Arthur, 1989; Romer, 1986, 1990, 1994). Positive feedbacks (increasing returns) generally provide a better description of actual economic conditions, especially of the past 200 years. They do not lead to a unique, stable equilibrium (are not boundary defending), but instead can have multiple possible outcomes (misleadingly called equilibria). Health economics, however, is based on the conventional economic model of the early twentieth century that assumes decreasing or constant returns (increasing or constant costs), although that is rarely stated explicitly.

Increasing returns can occur for various reasons. The simplest case is that of scale economies, where the fixed costs of a clinic, for example, are spread over a larger number of patients, and the marginal cost of additional patients is negligible. A second type is economies of scope, where fixed costs are spread over more services, and additional services are virtually costless. Where economies of scope are present, modeling a number of services together would give more valid estimates of cost-effectiveness than requiring each service to be justified independently, as is more generally the case in cost-effectiveness analysis.

Health economists tend to focus on short-run diminishing returns, rather than scale economies, and belabor the increasing cost of bringing treatment to ever more remote villages. But that is generally not the situation in the field.

In reality, tens of thousands of people in poor countries with generalized HIV epidemics die without any treatment even though they live in close proximity to health facilities. Reaching them does not entail rising costs per person. Many clinics can still expand the range of services and the number of people served with decreasing average cost. As word spreads about ART and treatment of coinfections, such as ascariasis, schistosomiasis, and malaria, outreach can be self-sustaining. And as the number of people receiving treatment grows, there are also population benefits (herd effects) for both prevention and treatment, which lower future costs.

Cost-effectiveness analysis and health economics generally would be more useful if they incorporated more health information. They need to be interdisciplinary, using economic tools but reflecting the underlying biological complexity of conditions they hope to address. To integrate the economics and the biology, I would add to the conventional economic notions of economies of scale and scope two categories of biologically based increasing returns arising from disease interactions.

One is the positive treatment spillover within the individual. For example, treatment for cofactor conditions, including worms, malnutrition, and malaria, makes HIV prevention and ART more effective for each individual. The second biologically driven cause of increasing returns is the population effect. Treatment for HIV, helminthes, TB, and malaria (among other things) reduces transmission in the population by reducing HIV viral load, parasite burden, and infectiousness of TB.

To calculate accurately the costs of delivering services for a population, we have to include the population spillovers (benefits) that reduce viral load, transmission, and subsequent costs of prevention and treatment. If we do not calculate conventional economies of scale and scope *and* intraindividual treatment benefits (such as deworming for HIV) *and* externalities (population effects), we seriously underestimate the benefits of complementary interventions, and we allocate resources improperly. Ultimately, we need to broaden the scope of what we consider treatment outcomes in calculating benefits of programs that affect multiple sectors. Deworming, for example, not only improves health, it also improves school attendance and cognitive development, but a health sector evaluation might not include those benefits.

The result of using simplistic cost-effectiveness analysis that can compare only very similar interventions is that the tool can identify only local maxima (minima). But the landscape of HIV transmission is very complex. If we only want to advise policy makers on whether it is better to hand out condoms in a community center or in a factory, or hand out condoms with or without lollipops as an inducement, the current methods are adequate. If, however, we want to reduce the significant relative risks in poor environments (compared to rich environments), those risk factors must be included in the models, and the benefits of complementary interventions have to be calculated.

The generation of local maxima is essentially a Type III error – we get very precise, and even correct, answers to the wrong questions (Schwartz and Carpenter, 1999). But it will not matter very much if one approach to condom distribution is marginally better than another if the larger reason that HIV spreads so rapidly in poor populations is the prevalence of endemic parasitic and infectious diseases.

## 7. Conclusion

HIV epidemics, like other complex systems, are influenced by multiple factors. The issue is not that sexual behavior is unimportant. It is that behavior explains so little about why poor people get sick, especially in tropical areas with little access to safe medical care, clean water, sanitation, and good housing to protect them from disease vectors.

Standard HIV-prevention policies, and thus cost-effectiveness analyses evaluating those interventions, have overlooked complementary investments for treating coinfections. Treatment for TB, schistosomiasis, malaria, malnutrition, and helminthes is relatively inexpensive, highly effective, and essential for improving immune status in HIV-negative persons and decreasing viral load in HIV-infected persons.

Such investments are not a diversion of funds from HIV prevention; they are necessary complements. Deworming is safe, effective, and easily dosed; it generates positive externalities (Miguel and Kremer, 2001), and it might also prevent the failure of first-line ART – at a cost of as little as 2 US cents per person. The cost of moving to second-line therapy will far exceed the cost of treating coinfections.

We need cost-effectiveness tools that reflect complexity and attempt to measure the costs of multiple inputs distributed over multiple outputs in which interactions play a prominent role. Those tools would recognize conventional economies of scale and scope, which are extensive in multipurpose programs, as well as biological externalities, both intraindividual and population-wide, that, if exploited, reduce overall cost. With those tools, we can achieve our goal of healthy individuals in healthy populations, rather than chasing after one virus, one person at a time.

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# PART VIII:
# Summary and Conclusions

### Swan

A rhubarb leaf with its red vessels taken by Glen Mendels.

Biodata of **Liz Stillwaggon Swan**, author of "**Summary and Conclusion of *Origin(s) of Design in Nature: A Fresh, Interdisciplinary Look at How Design Emerges in Complex Systems, Especially Life*.**"

**Liz Stillwaggon Swan** earned her Ph.D. in philosophy from the University of South Carolina in 2008, her M.A. in philosophy from San Francisco State University in 2002, and her B.A. in psychology from Loyola University in Maryland in 1995. Her multidisciplinary research is anchored by a desire to understand how and why organic mindedness emerged in the natural world. Swan is author or editor of over 20 academic and popular publications in the fields of biosemiotics, philosophy of science, cognitive science, artificial life, and yoga. She is a certified yoga instructor and enjoys teaching both yoga and philosophy classes in Colorado where she lives with her husband and baby, Freeman.

E-mail: **lizstillwaggonswan@gmail.com**

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# SUMMARY AND CONCLUSION OF *ORIGIN(S) OF DESIGN IN NATURE: A FRESH, INTERDISCIPLINARY LOOK AT HOW DESIGN EMERGES IN COMPLEX SYSTEMS, ESPECIALLY LIFE*

**LIZ STILLWAGGON SWAN**
*Longmont, CO, USA*

> *Last in deed, but first in thought*—from *Lecha Dodi*—a beautiful, inspiring song to the Sabbath by Rabbi Shlomo Alkabetz [sixteenth century, added by Joseph Seckbach].

Because the title of this volume is *Origins of Design in Nature*, one must ask—if one is philosophically inclined—is there design in nature? When we look, for example, at the intricate processes involved in the T4 virus' injection of DNA into a cell, there seems to be clear purpose at work here.[1] Everything from the structure of the virus itself, with its tentacle-like appendages that hook it into the target cell wall, to the timely release of its DNA through its tail-like structure and into the cytoplasmic interior of the cell, suggests a high degree of intricate planning, of cunning forethought, such that we are forced to think of this process as somehow "designed." But where, exactly, is the design in this albeit naturally elegant set of processes? And what do we mean by "design" anyway?

While there is symmetry between the relevant structures and processes in this example, to see this symmetry as the result of careful forethought and planning begs the question of whom or what conceived of the design. This observation is not new and in fact constitutes the theoretical demarcation between evolution and intelligent design. One could argue, however, that the debate concerning the origin of design in nature—whether divine or natural—constitutes an unnecessary dichotomy. There is a third possibility: the concept of design is a human conceptualization that we project onto nature. Both David Hume (Scottish historian and philosopher [1711–1776]) and Immanuel Kant (1724–1804, metaphysician and philosopher from Prussia, author of *Religion Within the Limits of Reason Alone* and *Critique of Judgment*) altered the contour of mind-world dualism from one of exclusion to one of projection, i.e., it is not that there is design in nature, and we try, to varying degrees of success, to discover, measure, and thus understand it; rather, the natural world just is as it is, and the human mind projects a reflection of its own structure onto the world and thus understands it in a quintessentially human way.

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[1] Thanks to Louis Goldberg for offering this poignant example from microbiology.

Or so one could argue. People tend to be intuitively inclined toward one of the philosophical positions outlined above in regard to the origin of design in nature: supernatural, natural, or particularly human.

In this book (volume 23 of *Cellular Origin, Life in Extreme Habitats and Astrobiology* series), the 42 chapters, each of which in a unique way addresses the question of where design in nature comes from, were selected in the spirit of fostering fruitful cross-disciplinary discussion of this unsolved scientific and philosophical problem which is still very much open to debate. No meaningful consensus could be drawn from the many selections in this book written by scholars from all over the world. It suffices instead to say that the question of design is alive and well in many academic disciplines today and that the editors of this volume hope to have made a valuable contribution to this problem that is central to both science and philosophy.

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