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GREEK MATHEMATICS

I

SELECTIONS
ILLUSTRATING THE HISTORY OF
GREEK MATHEMATICS

WITH AN ENGLISH TRANSLATION BY
IVOR THOMAS

FORMERLY SCHOLAR OF ST. JOHN'S AND SENIOR DEMY
OF MAGDALEN COLLEGE, OXFORD

IN TWO VOLUMES

I

FROM THALES TO EUCLID



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TO
M. E. B.

PREFACE

THE story of Greek mathematics is the tale of one of the most stupendous achievements in the history of human thought. It is my hope that these selections, which furnish a reasonably complete picture of the rise of Greek mathematics from earliest days, will be found useful alike by classical scholars, desiring easy access to a most characteristic aspect of the Greek genius, and by mathematicians, anxious to learn something about the origins of their science. In these days of specialization the excellent custom which formerly prevailed at Oxford and Cambridge whereby men took honours both in classics and in mathematics has gone by the board. It is now rare to find a classical scholar with even an elementary knowledge of mathematics, and the mathematician's knowledge of Greek is usually confined to the letters of the alphabet. By presenting the main Greek sources side by side with an English translation, reasonably annotated, I trust I have done something to bridge the gap.

For the classical scholar Greek mathematics is a brilliant after-glow which lightened the sky long after the sun of Hellas had set. Greek mathematics sprang from the same impulse as Greek philosophy, but Greek philosophy reached its maturity in the fourth century before Christ, the century of Plato and Aristotle, and thereafter never spoke with like con-

PREFACE

viction until the voice of Plato became reincarnate in the schools of Egypt. Yet such was the vitality of Hellenic thought that the autumn flowering of Greek philosophy in Aristotle was only the spring of Greek mathematics. It was Euclid, following hard on the heels of Aristotle in point of time, but teaching in distant Alexandria, who first transformed mathematics from a number of uncoordinated and loosely-proved theorems into an articulated and surely-grounded science; and in the succeeding hundred years Archimedes and Apollonius raised mathematics to heights not surpassed till the sixteenth century of the Christian era.

To the mathematician his Greek predecessors are deserving of study in that they laid the foundations on which all subsequent mathematical science is based. Names still in everyday use testify to this origin—Euclidean geometry, Pythagoras's theorem, Archimedes' axiom, the quadratrix of Hippias or Dinostratus, the cissoid of Diocles, the conchoid of Nicomedes. I cannot help feeling that mathematicians will welcome the opportunity of learning the reasons for these names, and that the extracts which follow will enable them to do so more easily than is now possible. In perusing these extracts they will doubtless be impressed by three features. The first is the rigour with which the great Greek geometers demonstrated what they set out to prove. This is most noticeable in their treatment of the indefinitely small, a subject whose pitfalls had been pointed out by Zeno in four arguments of remarkable acuteness. Archimedes, for example, carries out operations equivalent to the integral calculus, but he refuses to posit the existence of infinitesimal quanti-

viii

PREFACE

ties, and avoids logical errors which infected the calculus until quite recent times. The second feature of Greek mathematics which will impress the modern student is the dominating position of geometry. Early in the present century there was a powerful movement for the "arithmetization" of all mathematics. Among the Greeks there was a similar impulse towards the "geometrization" of all mathematics. Magnitudes were from earliest times represented by straight lines, and the Pythagoreans developed a geometrical algebra performing operations equivalent to the solution of equations of the second degree. Later Archimedes evaluated by purely geometrical means the area of a variety of surfaces, and Apollonius developed his awe-inspiring geometrical theory of the conic sections. The third feature which cannot fail to impress a modern mathematician is the perfection of form in the work of the great Greek geometers. This perfection of form, which is another expression of the same genius that gave us the Parthenon and the plays of Sophocles, is found equally in the proof of individual propositions and in the ordering of those separate propositions into books; it reaches its height, perhaps, in the *Elements* of Euclid.

In making the selections which follow I have drawn not only on the ancient mathematicians but on many other writers who can throw light on the history of Greek mathematics. Thanks largely to the labours of a band of Continental scholars, admirable standard texts of most Greek mathematical works now exist, and I have followed these texts, indicating only the more important variants and emendations. In the selection of the passages, in their arrangement and at

PREFACE

innumerable points in the translation and notes I owe an irredeemable debt of gratitude to the works of Sir Thomas Heath, who has been good enough, in addition, to answer a number of queries on specific points. These works, covering almost every aspect of Greek mathematics and astronomy, are something of which English scholarship may justly feel proud. His *History of Greek Mathematics* is unexcelled in any language. Yet there may still be room for a work which will give the chief sources in the original Greek together with a translation and sufficient notes.

In a strictly logical arrangement the passages would, no doubt, be grouped wholly by subjects or by persons. But such an arrangement would not be satisfactory. I imagine that the average reader would like to see, for example, all the passages on the squaring of the circle together, but would also like to see the varied discoveries of Archimedes in a single section. The arrangement here adopted is a compromise for which I must ask the reader's indulgence where he might himself have made a different grouping. The contributions of the Greeks to arithmetic, geometry, trigonometry, mensuration and algebra are noticed as fully as possible, but astronomy and music, though included by the Greeks under the name mathematics, have had to be almost wholly excluded.

I am greatly indebted to Messrs. R. and R. Clark for the skill and care shown in the difficult task of making this book.

I. T.

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CONTENTS OF VOLUME I

	PAGE
I. INTRODUCTORY—	
(a) Mathematics and its divisions—	
(i) Origin of the name	2
(ii) The Pythagorean quadrivium	4
(iii) Plato's scheme	6
(iv) Logistic	16
(v) Later classification	18
(b) Mathematics in Greek Education	20
(c) Practical calculation—	
(i) Enumeration by fingers	28
(ii) The abacus	34
 II. ARITHMETICAL NOTATION AND THE CHIEF ARITHMETICAL OPERATIONS—	
(a) English notes and examples	41
(b) Division	50
(c) Extraction of the square root	52
(d) Extraction of the cube root	60
 III. PYTHAGOREAN ARITHMETIC—	
(a) First principles	66
(b) Classification of numbers	72
(c) Perfect numbers	74
	xi

CONTENTS

	PAGE
(d) Figured numbers—	
(i) General	86
(ii) Triangular numbers	90
(iii) Oblong and square numbers	94
(iv) Polygonal numbers	94
(v) Gnomons of polygonal numbers	98
(e) Some properties of numbers—	
(i) The “sieve” of Eratosthenes	100
(ii) Divisibility of squares	102
(iii) A theorem about cube numbers	104
(iv) A property of the <i>pythmen</i>	106
(f) Irrationality of the square root of 2	110
(g) The theory of proportion and means—	
(i) Arithmetic, geometric and harmonic means	110
(ii) Seven other means	114
(iii) Pappus’s equations between means	124
(iv) Plato on means between two squares or two cubes	128
(v) A theorem of Archytas	130
(h) Algebraic equations—	
(i) Side- and diameter-numbers	132
(ii) The “bloom” of Thymaridas	138
 IV. PROCLUS’S SUMMARY	 144
 V. THALES	 164
 VI. PYTHAGOREAN GEOMETRY—	
(a) General	172
(b) Sum of the angles of a triangle	176
(c) “Pythagoras’s theorem”	178

CONTENTS

	PAGE
(<i>d</i>) The application of areas	186
(<i>e</i>) The irrational	214
(<i>f</i>) The five regular solids	216
VII. DEMOCRITUS	228
VIII. HIPPOCRATES OF CHIOS—	
(<i>a</i>) General	234
(<i>b</i>) Quadrature of lunes	234
(<i>c</i>) Two mean proportionals	252
IX. SPECIAL PROBLEMS—	
1. Duplication of the Cube—	
(<i>a</i>) General	256
(<i>b</i>) Solutions given by Eutocius—	
(<i>i</i>) "Plato"	262
(<i>ii</i>) Heron	266
(<i>iii</i>) Diocles : the Cissoïd	270
(<i>iv</i>) Menaechmus : solution by conics	278
(<i>v</i>) Archytas : solution in three dimensions	284
(<i>vi</i>) Eratosthenes	290
(<i>vii</i>) Nicomedes : the Conchoid	296
2. Squaring of the Circle—	
(<i>a</i>) General	308
(<i>b</i>) Approximation by polygons—	
(<i>i</i>) Antiphon	310
(<i>ii</i>) Bryson	314
(<i>iii</i>) Archimedes	316
(<i>c</i>) Solutions by higher curves—	
(<i>i</i>) General	334
(<i>ii</i>) The Quadratrix	336

CONTENTS

	PAGE
3. Trisection of an Angle—	
(a) Types of geometrical problems	346
(b) Solution by means of a verging	352
(c) Direct solutions by means of conics	356
X. ZENO OF ELEA	366
XI. THEAETETUS—	
(a) General	378
(b) The five regular solids	378
(c) The irrational	380
XII. PLATO—	
(a) General	386
(b) Philosophy of mathematics	390
(c) The <i>diorismos</i> in the <i>Meno</i>	394
(d) The nuptial number	398
(e) Generation of numbers	400
XIII. EUDOXUS OF CNIDOS—	
(a) Theory of proportion	408
(b) Volume of pyramid and cone	408
(c) Theory of concentric spheres	410
XIV. ARISTOTLE—	
(a) First principles	418
(b) The infinite	424
(c) Proof differing from Euclid's	428
(d) Mechanics—	
(i) Principle of the lever	430
(ii) Parallelogram of velocities	432

CONTENTS

	PAGE
XV. EUCLID—	
(a) General	436
(b) The <i>Elements</i> —	
(i) Foundations	436
(ii) Theory of proportion	444
(iii) Theory of incommensurables	450
(iv) Method of exhaustion	458
(v) Regular solids	466
(c) The <i>Data</i>	478
(d) The <i>Porisms</i>	478
(e) The <i>Conics</i>	486
(f) The <i>Surface Loci</i>	490
(g) The <i>Optics</i>	502

ABBREVIATIONS

- Heath, *H.G.M.* Sir Thomas Heath, *A History of Greek Mathematics*, 2 vols., Oxford 1921.
- Diels, *Vors.*⁵ Hermann Diels, *Die Fragmente der Vorsokratiker*, 3 vols., 5th ed., edited by Walther Kranz, Berlin 1934–1937.

Both cited by volume and page.

References to modern editions of classical texts are by volume (where necessary), page and line, *e.g.*, Eucl. ed. Heiberg-Menge vii. 14. 1—16. 5 refers to *Euclidis Opera Omnia*, edited by I. L. Heiberg and H. Menge, vol. vii., page 14 line 1 to page 16 line 5.

I. INTRODUCTORY

I. INTRODUCTORY

(a) MATHEMATICS AND ITS DIVISIONS

(i.) *Origin of the Name*

Anatolius ap. Her. Def., ed. Heiberg 160. 8-162. 2

Ἐκ τῶν Ἀνατολίου . . .

“ Ἀπὸ τίνος δὲ μαθηματικὴ ὠνομάσθη;

“ Οἱ μὲν ἀπὸ τοῦ Περιπάτου φάσκοντες ῥητορικῆς μὲν καὶ ποιητικῆς συμπάσης τε τῆς δημῶδους μουσικῆς δύνασθαι τινα συνεῖναι καὶ μὴ μαθόντα, τὰ δὲ καλούμενα ἰδίως μαθήματα οὐδένα εἰς εἶδησιν λαμβάνειν μὴ οὐχὶ πρότερον ἐν μαθήσει γενόμενον τούτων, διὰ τοῦτο μαθηματικὴν καλεῖσθαι τὴν περὶ τούτων θεωρίαν ὑπελάμβανον. θέσθαι δὲ λέγονται τὸ τῆς μαθηματικῆς ὄνομα ἰδιαίτερον ἐπὶ μόνῃς γεωμετρίας καὶ ἀριθμητικῆς οἱ ἀπὸ τοῦ Πυθαγόρου· τὸ γὰρ πάλαι χωρὶς ἑκατέρα τούτων ὠνομάζετο, κοινὸν δὲ οὐδὲν ἦν ἀμφῶν ὄνομα.”

^a Anatolius was bishop of Laodicea about A.D. 280. In a letter by Michael Psellus he is said to have written a concise treatise on the Egyptian method of reckoning.

^b *i.e.* singing or playing, as opposed to the mathematical study of musical intervals.

^c The word *μάθημα*, from *μαθεῖν*, means in the first place “that which is learnt.” In Plato it is used in the general sense for any subject of study or instruction, but with a tendency to restrict it to the studies now called mathematics. By the time of Aristotle this restriction had become established.

I. INTRODUCTORY

(a) MATHEMATICS AND ITS DIVISIONS

(i.) *Origin of the Name*

Anatolius, cited by Heron, *Definitions*, ed. Heiberg
160. 8-162. 2

From the works of Anatolius^a . . .

“ Why is mathematics so named ?

“ The Peripatetics say that rhetoric and poetry and the whole of popular music^b can be understood without any course of instruction, but no one can acquire knowledge of the subjects called by the special name *mathematics* unless he has first gone through a course of instruction in them ; and for this reason the study of these subjects was called *mathematics*.^c The Pythagoreans are said to have given the special name *mathematics* only to geometry and arithmetic ; previously each had been called by its separate name, and there was no name common to both.”^d

^a The esoteric members of the Pythagorean school, who had learnt the Pythagorean theory of knowledge in its entirety, are said to have been called *mathematicians* (μαθηματικοί), whereas the exoteric members, who merely knew the Pythagorean rules of conduct, were called *hearers* (ἀκουσματικοί). See Iamblichus, *De Vita Pythag.* 18. 81, ed. Deubner 46. 24 ff.

GREEK MATHEMATICS

(ii.) *The Pythagorean Quadrivium*

Archytas ap. Porphyry, in *Ptol. Harm.*, ed. Wallis, *Opera Math.* iii. 236. 40-237. 1; Diels, *Vors.* 1⁵. 431. 26-432. 8

Παρακείσθω δὲ καὶ νῦν τὰ Ἀρχύτα τοῦ Πυθαγορείου, οὗ μάλιστα καὶ γνήσια λέγεται εἶναι τὰ συγγράμματα· λέγει δὲ ἐν τῷ Περὶ μαθηματικῆς εὐθὺς ἐναρχόμενος τοῦ λόγου τάδε.

“Καλῶς μοι δοκοῦντι τοῖς περὶ τὰ μαθήματα διαγνώμεναι, καὶ οὐδὲν ἄτοπον ὀρθῶς αὐτούς, οἷά ἐντι, περὶ ἐκάστων φρονέειν· περὶ γὰρ τῆς τῶν ὄλων φύσιος καλῶς διαγνόντες ἔμελλον καὶ περὶ τῶν κατὰ μέρος, οἷά ἐντι, καλῶς ὀψείσθαι. περὶ τε δὴ τῆς τῶν ἄστρον ταχυτάτος καὶ ἐπιτολᾶν καὶ δυσίων παρέδωκαν ἡμῖν σαφῆ διάγνωσιν καὶ περὶ γαμετρίας καὶ ἀριθμῶν καὶ σφαιρικᾶς καὶ οὐχ ἥκιστα περὶ μουσικᾶς. ταῦτα γὰρ τὰ μαθήματα δοκοῦντι ἡμεν ἀδελφεά.”

^a Archytas lived in the first half of the fourth century B.C. at Taras (Tarentum) in Magna Graecia. He is said to have dissuaded Dionysius from putting Plato to death. For seven years he commanded the forces of his city-state, though the law forbade anyone to hold the post normally for more than one year, and he was never defeated. He is said to have been the first to write on mechanics, and to have invented a mechanical dove which would fly. For such of his mathematical discoveries as have survived, see pp. 112-115, 130-133, 284-289.

INTRODUCTORY

(ii.) *The Pythagorean Quadrivium*

Archytas, cited by Porphyry in his *Commentary on Ptolemy's Harmonics*, ed. Wallis, *Opera Mathematica* iii. 236. 40-237. 1; Diels, *Vors.* i⁹. 431. 26-432. 8

Let us now cite the words of Archytas ^a the Pythagorean, whose writings are said to be mainly authentic. In his book *On Mathematics* right at the beginning of the argument he writes thus :

"The mathematicians seem to me to have arrived at true knowledge, and it is not surprising that they rightly conceive the nature of each individual thing ; for, having reached true knowledge about the nature of the universe as a whole, they were bound to see in its true light the nature of the parts as well. Thus they have handed down to us clear knowledge about the speed of the stars, and their risings and settings, and about geometry, arithmetic and sphaeric, and, not least, about music ; for these studies appear to be sisters." ^b

^b *Sphaeric* is clearly identical with astronomy, and is aptly defined by Heath, *H.G.M.* i. 11 as "the geometry of the sphere considered solely with reference to the problem of accounting for the motions of the heavenly bodies." The same *quadrivium* is attributed to the Pythagoreans by Nicomachus, Theon of Smyrna and Proclus, but in the order arithmetic, music, geometry and sphaeric. The logic of this order is that arithmetic and music are concerned with number (*ποσόν*), arithmetic with number in itself and music with number in relation to sounds ; while geometry and sphaeric are concerned with magnitude (*πηλίκον*), geometry with magnitude at rest, sphaeric with magnitude in motion.

GREEK MATHEMATICS

(iii.) *Plato's Scheme*

Plat. *Rep.* vii. 525 A-530 D

(a) *Logistic and Arithmetic*

Ἄλλὰ μὴν λογιστικὴ τε καὶ ἀριθμητικὴ περὶ ἀριθμὸν πᾶσα.

Καὶ μάλα.

Ταῦτα δέ γε φαίνεται ἀγωγὰ πρὸς ἀλήθειαν.

Ὑπερφυῶς μὲν οὖν.

Ὡν ζητοῦμεν ἄρα, ὡς ἔοικε, μαθημάτων ἂν εἴη· πολεμικῶ μὲν γὰρ διὰ τὰς τάξεις ἀναγκαῖον μαθεῖν ταῦτα, φιλοσόφῳ δὲ διὰ τὸ τῆς οὐσίας ἀπτέον εἶναι γενέσεως ἐξαναδύντι, ἢ μηδέποτε λογιστικῶ γενέσθαι. . . .

Τί οὖν οἶει, ὦ Γλαύκων, εἴ τις ἔροιτο αὐτούς· “Ὡ θαυμάσιοι, περὶ ποίων ἀριθμῶν διαλέγεσθε, ἐν οἷς τὸ ἐν οἶον ὑμεῖς ἀξιοῦτέ ἐστιν, ἴσον τε ἕκαστον πᾶν παντὶ καὶ οὐδὲ σμικρὸν διαφέρον, μῦρον τε ἔχον ἐν ἑαυτῷ οὐδέν;” τί ἂν οἶει αὐτοὺς ἀποκρίνασθαι;

Τοῦτο ἔγωγε, ὅτι περὶ τούτων λέγουσιν ὦν διανοηθῆναι μόνον ἐγχωρεῖ, ἄλλως δ' οὐδαμῶς μεταχειρίζεσθαι δυνατόν. . . .

Τί δέ; τόδε ἤδη ἐπεσκέψω, ὡς οἷ τε φύσει

* The passage is taken from the section dealing with the education of the Guardians. The speakers in the dialogue are Socrates and Glaucon. It is made clear in *Rep.* 537 B-D that the Guardians would receive their chief mathematical training between the ages of twenty and thirty, after two or three years spent in the study of music and gymnastic and as a preliminary to five years' study of dialectic. Plato's scheme, it will be noticed, is virtually identical with the Pythagorean *quadrivium* except for the addition of stereo-

INTRODUCTORY

(iii.) *Plato's Scheme*

Plato, *Republic* vii. 525 A-530 D ^a

(a) *Logistic and Arithmetic*

Now logistic and arithmetic treat of the whole of number.

Yes.

And, apparently, they lead us towards truth.

They do, indeed.

It would appear, therefore, that they must be among the studies we seek ; for the soldier finds it necessary to learn them in order to draw up his troops, and the philosopher because he is bound to rise out of Becoming and cling to Being on pain of never becoming a reasoner. . . .^b

Now what would you expect, Glaucon, if someone were to ask them : " My good people, what kind of numbers are you discussing ? What are these numbers such as you describe, every unit being equal, each to each, without the smallest difference, and containing within itself no part ? " What answer would you expect them to make ?

I should expect them to say that the numbers they discuss are capable of being conceived only in thought, and can be dealt with in no other way. . . .

Again ; have you ever noticed that those who are metry ; and the addition is more formal than real since stereometrical problems were certainly investigated by the Pythagoreans—not least by Archytas—as part of geometry. Plato also distinguishes *logistic* from *arithmetic* (for which see the extract given below on pp. 16-19), and speaks of *harmonics* (ἁρμονία) not *music* (μουσική), thus avoiding confusion with *popular music* (τὸ δημῶδες μουσικόν).

^b There is a play on the Greek word, which could mean either " reasoner " or " calculator."

GREEK MATHEMATICS

λογιστικοὶ εἰς πάντα τὰ μαθήματα ὡς ἔπος εἰπεῖν ὀξεῖς φύνται, οἳ τε βραδεῖς, ἂν ἐν τούτῳ παιδευθῶσιν καὶ γυμνάσωνται, κἄν μηδὲν ἄλλο ὠφεληθῶσιν, ὅμως εἰς γε τὸ ὀξύτεροι αὐτοὶ αὐτῶν γίγνεσθαι πάντες ἐπιδιδόασιν;

Ἔστιν, ἔφη, οὕτω.

Καὶ μὴν, ὡς ἐγὼμαι, ἃ γε μείζω πόνον παρέχει μαθάνοντι καὶ μελετῶντι, οὐκ ἂν ῥαδίως οὐδὲ πολλὰ ἂν εὔροις ὡς τοῦτο.

Οὐ γὰρ οὖν.

Πάντων δὴ ἕνεκα τούτων οὐκ ἀφετέον τὸ μάθημα, ἀλλ' οἱ ἄριστοι τὰς φύσεις παιδευτέοι ἐν αὐτῷ.

Σύμφημι, ἦ δ' ὅς.

(β) *Geometry*

Τοῦτο μὲν τοίνυν, εἶπον, ἐν ἡμῖν κείσθω· δευτερον δὲ τὸ ἐχόμενον τούτου σκεψώμεθα ἄρα τι προσήκει ἡμῖν.

Τὸ ποῖον; ἢ γεωμετρίαν, ἔφη, λέγεις;

Αὐτὸ τοῦτο, ἦν δ' ἐγώ.

Ὅσον μὲν, ἔφη, πρὸς τὰ πολεμικὰ αὐτοῦ τείνει, δῆλον ὅτι προσήκει. . . .

Ἄλλ' οὖν δῆ, εἶπον, πρὸς μὲν τὰ τοιαῦτα καὶ βραχύ τι ἂν ἐξαρκοῖ γεωμετρίας τε καὶ λογισμῶν μόριον· τὸ δὲ πολὺ αὐτῆς καὶ πορρωτέρω προῖον σκοπεῖσθαι δεῖ εἴ τι πρὸς ἐκείνο τείνει, πρὸς τὸ ποιεῖν κατιδεῖν ῥᾶον τῆν τοῦ ἀγαθοῦ ιδέα. . . . οὐ τοίνυν τοῦτό γε, ἦν δ' ἐγώ, ἀμφισβητήσουσιν ἡμῖν ὅσοι καὶ σμικρὰ γεωμετρίας ἔμπειροι, ὅτι

INTRODUCTORY

by nature apt at calculation are—not to make a short matter long—naturally sharp at all studies, and that the slower-witted, if they be trained and exercised in this discipline, even supposing they derive no other advantage from it, at any rate all progress so far as to become sharper than they were before ?

Yes, that is true, he said.

And I am of opinion, also, that you would not easily find many sciences which give the learner and the student greater trouble than this.

No, indeed.

For all these reasons, then, this study must not be rejected, but all the finest spirits must be educated in it.^a

I agree, he said.

(β) *Geometry*

Then let us consider this, I said, as one point settled. In the second place let us examine whether the science bordering on arithmetic concerns us.

What is that ? Do you mean geometry ? he said.

Exactly, I replied.

So far as it bears on military matters, he said, it obviously concerns us. . . .

But for these purposes, I observed, a trifling knowledge of geometry and calculations would suffice ; what we have to consider is whether a more thorough and advanced study of the subject tends to facilitate contemplation of the Idea of the Good. . . . Well, even those who are only slightly conversant with geometry will not dispute us in saying that this

^a Plato's final reason may strike contemporary educationists as somewhat odd.

GREEK MATHEMATICS

αὕτη ἢ ἐπιστήμη πᾶν τούναντίον ἔχει τοῖς ἐν αὐτῇ λόγοις λεγομένοις ὑπὸ τῶν μεταχειριζομένων.

Πῶς; ἔφη.

Λέγουσι μὲν που μάλα γελοίως τε καὶ ἀναγκαίως· ὡς γὰρ πράττοντές τε καὶ πράξεως ἔνεκα πάντας τοὺς λόγους ποιούμενοι λέγουσιν τετραγωνίζειν τε καὶ παρατείνειν καὶ προστιθέναι καὶ πάντα οὕτω φθειγγόμενοι, τὸ δ' ἔστι που πᾶν τὸ μάθημα γνώσεως ἔνεκα ἐπιτηδευόμενον. . . .

(γ) Stereometry

Τί δέ; τρίτον θῶμεν ἀστρονομίαν; ἢ οὐ δοκεῖ; Ἐμοὶ γοῦν, ἔφη. . . .

Νυνδὴ γὰρ οὐκ ὀρθῶς τὸ ἐξῆς ἐλάβομεν τῇ γεωμετρίας.

Πῶς λαβόντες; ἔφη.

Μετὰ ἐπίπεδον, ἦν δ' ἐγώ, ἐν περιφορᾷ ὄν ἤδη στερεὸν λαβόντες, πρὶν αὐτὸ καθ' αὐτὸ λαβεῖν· ὀρθῶς δὲ ἔχει ἐξῆς μετὰ δευτέραν αὐξήν τρίτην λαμβάνειν. ἔστι δέ που τοῦτο περὶ τὴν τῶν κύβων αὐξήν καὶ τὸ βάθους μετέχον.

Ἔστι γάρ, ἔφη· ἀλλὰ ταῦτά γε, ὦ Σώκρατες, δοκεῖ οὕπω ἠρύησθαι.

Διττὰ γάρ, ἦν δ' ἐγώ, τὰ αἴτια· ὅτι τε οὐδεμία πόλις ἐντίμως αὐτὰ ἔχει, ἀσθενῶς ζητεῖται χαλεπὰ ὄντα, ἐπιστάτου τε δέονται οἱ ζητοῦντες, ἀνευ οὗ οὐκ ἂν εὖροιεν, ὄν πρῶτον μὲν γενέσθαι χαλεπόν,

^a It is useful to know that these terms, which are regularly found in Euclid, were already in technical use in Plato's day.

^b Lit. "increase of cubes," where the word "increase" is the same as that translated above by "dimension."

INTRODUCTORY

science holds a position the very opposite from that implied in the language of those who practise it.

How so ? he asked.

They speak, I gather, in an exceedingly ridiculous and poverty-stricken way. For they fashion all their arguments as though they were engaged in business and had some practical end in view, speaking of squaring and producing and adding^a and so on, whereas in reality, I fancy, the study is pursued wholly for the sake of knowledge. . . .

(γ) *Stereometry*

Again ; shall we put astronomy third, or do you think otherwise ?

That suits me, he said. . . .

We were wrong just now in what we took as the study next in order after geometry.

What did we take ? he asked.

After dealing with plane surfaces, I replied, we proceeded to consider solids in motion before considering solids in themselves ; the correct procedure, after the second dimension, is to consider the third dimension. This brings us, I believe, to cubical increase^b and to figures partaking of depth.

Yes, he replied ; but these subjects, Socrates, do not appear to have been yet investigated.

The reasons, I said, are twofold. In the first place, no state holds them in honour and so, being difficult, they are investigated only in desultory manner. In the second place, the investigators lack a director, and without such a person they will make no discoveries. Now to find such a person is a diffi-

There is probably a playful reference to the problem of doubling the cube, for which see *infra*, pp. 256-309.

GREEK MATHEMATICS

ἔπειτα καὶ γενομένου, ὡς νῦν ἔχει, οὐκ ἂν πείθοντο οἱ περὶ ταῦτα ζητητικοὶ μεγαλοφρονοῦμενοι. εἰ δὲ πόλις ὄλη συνεπιστατοῖ ἐντίμως ἄγουσα αὐτά, οὗτοί τε ἂν πείθοντο καὶ συνεχῶς τε ἂν καὶ ἐντόνως ζητούμενα ἐκφανῆ γένοιτο ὅπη ἔχει· ἐπεὶ καὶ νῦν ὑπὸ τῶν πολλῶν ἀτιμαζόμενα καὶ κολουόμενα, ὑπὸ δὲ τῶν ζητούιτων λόγον οὐκ ἔχόντων καθ' ὅτι χρήσιμα, ὅμως πρὸς ἅπαντα ταῦτα βία ὑπὸ χάριτος αὐξάνεται, καὶ οὐδὲν θαυμαστὸν αὐτὰ φανῆναι.

Καὶ μὲν δὴ, ἔφη, τό γε ἐπίχαρι καὶ διαφερόντως ἔχει. ἀλλὰ μοι σαφέστερον εἶπέ ἃ νυνδὴ ἔλεγες. τὴν μὲν γάρ που τοῦ ἐπιπέδου πραγματείαν γεωμετρίαν ἐτίθεις.

Ναί, ἦν δ' ἐγώ.

Εἰτά γ', ἔφη, τὸ μὲν πρῶτον ἀστρονομίαν μετὰ ταύτην, ὕστερον δ' ἀνεχώρησας.

Σπεύδων γάρ, ἔφην, ταχὺ πάντα διεξελθεῖν μᾶλλον βραδύνω· ἐξῆς γὰρ οὖσαν τὴν βάθους αὐξῆς μέθοδον, ὅτι τῇ ζητήσῃ γελοίως ἔχει, ὑπερβὰς αὐτὴν μετὰ γεωμετρίαν ἀστρονομίαν ἔλεγον, φορὰν οὖσαν βάθους.

Ὅρθως, ἔφη, λέγεις.

^a These words (ὡς νῦν ἔχει) can be taken either with what goes before or with what comes after. In the former case Plato (or Socrates) will be referring to a distinguished contemporary (such as Endoxus or Archytas) who had already made discoveries in solid geometry.

^b This passage has been thought to have some bearing on the question whether the Socrates of the dialogue is meant to be the Socrates of history or not. The condition of stereometry, as described in the dialogue, certainly does not fit

INTRODUCTORY

cult task, and even supposing one appeared on the scene, as matters now stand,^a those who are investigating these problems, being swollen with pride, would pay no heed to him. But if a whole state were to honour this study and constitute itself the director thereof, they would pay heed, and the subject, being continuously and earnestly investigated, would be brought to light. For even now, neglected and curtailed as it is, not only by the many but even by professed students, who can suggest no use for it, nevertheless in the face of all these obstacles it makes progress on account of its elegance, and it would not be astonishing if it were fully unravelled.

It is certainly an exceedingly fascinating subject, he said. But pray tell me more clearly what you were saying just now. I think you defined geometry as the investigation of plane surfaces.

Yes, I said.

Then, he observed, you first placed astronomy after it, but later drew back.

The more I hasten to cover the ground, I said, the more slowly I travel; the study of solid bodies comes next in order, but because of the absurd way in which it is investigated I passed it over and spoke of astronomy, which involves the motion of solid bodies, as next after geometry.

You are quite right, he said.^b

Plato's generation, when Archytas and Eudoxus were making brilliant discoveries in solid geometry; but, even during the lifetime of Socrates, Democritus and Hippocrates had made notable contributions to the same science. This passage cannot help, therefore, towards the solution of that problem. All that Plato meant, it would appear, was that stereometry had not been made a formal element in the curriculum but was treated as part of geometry.

GREEK MATHEMATICS

(δ) *Astronomy*

Τέταρτον τοίνυν, ἣν δ' ἐγώ, τιθῶμεν μάθημα ἀστρονομίαν, ὡς ὑπαρχούσης τῆς νῦν παραλειπομένης, ἐὰν αὐτὴν πόλις μετίη. . . . ταῦτα μὲν τὰ ἐν τῷ οὐρανῷ ποικίλματα, ἐπεὶπερ ἐν ὄρατῷ πεποίκιλται, κάλλιστα μὲν ἡγεῖσθαι καὶ ἀκριβέστατα τῶν τοιούτων ἔχειν, τῶν δὲ ἀληθινῶν πολὺ ἐνδεῖν, ἄς τὸ ὄν τάχος καὶ ἡ οὐσα βραδυτῆς ἐν τῷ ἀληθινῷ ἀριθμῷ καὶ πᾶσι τοῖς ἀληθέσι σχήμασι φοράς τε πρὸς ἄλληλα φέρεται καὶ τὰ ἐνόητα φέρει, ἃ δὴ λόγῳ μὲν καὶ διανοίᾳ ληπτὰ, ὄψει δ' οὐ ἢ σὺ οἶει;

Οὐδαμῶς γε, ἔφη.

Οὐκοῦν, εἶπον, τῇ περὶ τὸν οὐρανὸν ποικιλία παραδείγμασι χρηστέον τῆς πρὸς ἐκεῖνα μαθήσεως ἕνεκα, ὁμοίως ὥσπερ ἂν εἴ τις ἐντύχοι ὑπὸ Δαιδάλου ἢ τινος ἄλλου δημιουργοῦ ἢ γραφέως διαφερόντως γεγραμμένοις καὶ ἐκπεπονημένοις διαγράμμασιν. . . . προβλήμασιν ἄρα, ἣν δ' ἐγώ, χρώμενοι ὥσπερ γεωμετρίαν οὕτω καὶ ἀστρονομίαν μέτιμεν, τὰ δ' ἐν τῷ οὐρανῷ ἐάσομεν, εἰ μέλλομεν ὄντως ἀστρονομίας μεταλαμβάνοντες χρήσιμον τὸ φύσει φρόνιμον ἐν τῇ ψυχῇ ἐξ ἀχρήστου ποιήσιν. . . .

* There seems little doubt that in this passage Plato wished astronomy to be regarded as the pure science of bodies in motion, of which the heavenly bodies could at best afford only one example. Burnet has made desperate efforts to save Plato from himself. According to his contention, Plato meant that astronomy should deal with the true, as opposed to the apparent, motions of the heavenly bodies; it is tempt-

INTRODUCTORY

(8) *Astronomy*

Let us then put astronomy as the fourth study, regarding that now passed over as waiting only until some state shall take it up. . . . Those broideries yonder in the heaven, forasmuch as they are broidered on a visible ground, are rightly held to be the most beautiful and perfect of visible things, but they are nevertheless far inferior to those that are true, far inferior to those revolutions which absolute speed and absolute slowness, in true number and in all true forms, accomplish relatively to each other, carrying their contents with them—which can indeed be grasped by reason and intelligence, but not by sight. Or do you think otherwise ?

No, indeed, he replied.

Therefore, I said, we should use the broideries round the heaven as examples to help the study of those true objects, just as we might use, if we met with them, diagrams surpassingly well drawn and elaborated by Daedalus or any other artist. . . . Hence, I said, we shall approach astronomy, as we do geometry, by means of problems, but we shall leave the starry heavens alone, if we wish to obtain a real grasp of astronomy, and by that means to make useful, instead of useless, the natural intelligence of the soul. . . .^a

ing but difficult to reconcile this with the decisive language of the text. Fortunately Plato's own pupils in the Academy, notably Eudoxus and Heraclides of Pontus, adopted a different attitude, using mathematics to account for the actual motion of the heavenly bodies ; and Plato himself does not appear to have held consistently to the belief here expressed, for he is said to have put to his pupils the question by what combination of uniform circular revolutions the apparent movements of the heavenly bodies can be explained.

GREEK MATHEMATICS

(ε) *Harmonics*

Κινδυνεύει, ἔφην, ὡς πρὸς ἀστρονομίαν ὄμματα πέπηγεν, ὡς πρὸς ἐναρμόνιον φοράν ὄτα παγῆναι, καὶ αὐταὶ ἀλλήλων ἀδελφαὶ τινες αἱ ἐπιστῆμαι εἶναι, ὡς οἷ τε Πυθαγόρειοί φασι καὶ ἡμεῖς, ὦ Γλαύκων, συγχωροῦμεν.

(iv.) *Logistic*

Schol. in Plat. *Charm.* 165 E

Λογιστικὴ ἐστὶ θεωρία τῶν ἀριθμητῶν, οὐχὶ δὲ τῶν ἀριθμῶν μεταχειριστικὴ, οὐ τὸν ὄντως ἀριθμὸν λαμβάνουσα, ἀλλ' ὑποτιθεμένη τὸ μὲν ἐν ὡς μονάδα, τὸ δὲ ἀριθμητὸν ὡς ἀριθμὸν, οἷον τὰ τρία τριάδα εἶναι καὶ τὰ δέκα δεκάδα· ἐφ' ὧν ἐπάγει τὰ κατὰ ἀριθμητικὴν θεωρήματα. θεωρεῖ οὖν τοῦτο μὲν τὸ κληθὲν ὑπ' Ἀρχιμήδους βοεικὸν πρόβλημα, τοῦτο δὲ μηλίτας καὶ φιαλίτας ἀριθμούς, τοὺς μὲν ἐπὶ φιαλῶν, τοὺς δὲ ἐπὶ ποιίμνης· καὶ ἐπ' ἄλλων δὲ γενῶν τὰ πλήθη τῶν αἰσθητῶν σωμάτων σκοποῦσα, ὡς περὶ τελείων ἀποφαίνεται. ὕλη δὲ αὐτῆς πάντα τὰ ἀριθμητὰ· μέρη δὲ αὐτῆς αἱ Ἑλληνικαὶ καὶ Αἰγυπτιακαὶ καλούμεναι μέθοδοι ἐν πολλαπλασια-

^a See the fragment from Archytas, *supra*, pp. 4-5.

^b Socrates proceeds to censure the Pythagoreans for committing the same error as the astronomers: they investigate the numerical ratios subsisting between audible concords, but do not apply themselves to problems, in order to examine what numbers are consonant and what not, and to find out the reason for the difference (ἐπισκοπεῖν τίνες σύμφωνοι ἀριθμοὶ καὶ τίνες οὐ, καὶ διὰ τί ἑκάτεροι).

^c In the cattle-problem Archimedes sets himself to find the number of bulls and cows of each of four colours. The problem, stripped of its trimmings, is to find eight unknown

INTRODUCTORY

(ε) *Harmonics*

It would appear, I said, that just as our eyes were intended for astronomy, so our ears were intended for harmonious movements, and that these are in a manner sister sciences,^a as the Pythagoreans assert and as we, Glaucon, agree.^b

(iv.) *Logistic*

Scholium to Plato's *Charmides* 165 E

Logistic is the science that treats of numbered objects, not of numbers ; it does not consider number in the true sense, but it works with 1 as unit and the numbered object as number, *e.g.*, it regards 3 as a triad and 10 as a decad, and applies the theorems of arithmetic to such cases. It is, then, logistic which treats on the one hand the problem called by Archimedes the cattle-problem,^c and on the other hand *melite* and *phialite* numbers, the latter appertaining to bowls, the former to flocks^d ; in other types of problem too it has regard to the number of sensible bodies, treating them as absolute. Its subject-matter is everything that is numbered ; its branches include the so-called Greek and Egyptian methods in multiplications and divisions, as well as the addi-

quantities connected by seven simple equations and subject to two other conditions. It involves the solution of a " Pellian " equation in numbers of fantastic size, and it is unlikely that Archimedes completed the solution. See vol. ii. pp. 202 ff. ; T. L. Heath, *The Works of Archimedes*, pp. 319-326, and for a complete discussion, A. Anthor, *Zeitschrift für Math. u. Physik (Hist.-litt. Abtheilung)*, xxv. (1880), pp. 153-171, supplementing an article by B. Krumbiegel (pp. 121-136) on the authenticity of the problem.

^d He should probably have said " apples ".

GREEK MATHEMATICS

σμοῖς καὶ μερισμοῖς, καὶ αἱ τῶν μορίων συγκεφαλαιώσεις καὶ διαιρέσεις, αἷς ἰχνεύει τὰ κατὰ τὴν ὕλην ἐμφωλευόμενα τῶν προβλημάτων τῇ περὶ τοὺς τριγώνους καὶ πολυγώνους πραγματείᾳ. τέλος δὲ αὐτῆς τὸ κοινωνικὸν ἐν βίῳ καὶ χρήσιμον ἐν συμβολαίοις, εἰ καὶ δοκεῖ περὶ τῶν αἰσθητῶν ὡς τελείων ἀποφαίνεσθαι.

(v.) *Later Classification*

Anatolius ap. Her. *Def.*, ed. Heiberg 164. 9-18

“ Πόσα μέρη μαθηματικῆς;

“ Τῆς μὲν τιμιωτέρας καὶ πρώτης ὄλοσχερέστερα μέρη δύο, ἀριθμητικὴ καὶ γεωμετρία, τῆς δὲ περὶ τὰ αἰσθητὰ ἀσχολουμένης ἕξ, λογιστικὴ, γεωδαισία, ὀπτική, κανονικὴ, μηχανικὴ, ἀστρονομικὴ. ὅτι οὔτε τὸ τακτικὸν καλούμενον οὔτε τὸ ἀρχιτεκτονικὸν οὔτε τὸ δημῶδες μουσικὸν ἢ τὸ περὶ τὰς φάσεις, ἀλλ’ οὐδὲ τὸ ὁμωνύμως καλούμενον μηχανικόν, ὡς οἴονται τινες, μέρη μαθηματικῆς εἶσι, προϊόντος δὲ τοῦ λόγου σαφῶς τε καὶ ἐμμεθόδως δείξομεν.”

^a *i.e.*, that which deals with non-sensible objects.

^b Geminus, according to Proclus *in Eucl.* i. (ed. Friedlein 38. 8-12), gives the same classification, only in the order

INTRODUCTORY

tion and splitting up of fractions, whereby it explores the secrets lurking in the subject-matter of the problems by means of the theory of triangular and polygonal numbers. Its aim is to provide a common ground in the relations of life and to be useful in making contracts, but it appears to regard sensible objects as though they were absolute.

(v.) *Later Classification*

Anatolius, cited by Heron, *Definitions*, ed. Heiberg
164. 9-18

“ How many branches of mathematics are there ?

“ There are two main branches of the prime and more honourable type of mathematics,^a arithmetic and geometry ; and there are six branches of that type of mathematics concerned with sensible objects, logistic, geodesy, optics, canonic, mechanics and astronomy.^b That the so-called study of tactics and architecture and popular music and the study of [lunar] phases,^c or even the mechanics so called homonymously,^d are not branches of mathematics, as some think, we shall show clearly and methodically as the argument proceeds.”

arithmetic, geometry, mechanics, astronomy, optics, geodesy, canonic, logistic. Geodesy means the practical measurement of surfaces and volumes ; canonic is the theory of musical intervals ; logistic is the art of calculation, as opposed to arithmetic, by which is meant what we should call the theory of numbers. Geminus proceeds to give an elaborate analysis of the various branches.

^c According to Heiberg, this means “ das Kalenderwesen.”

^d Heiberg interprets this as “ die praktische Mechanik, die sich im Namen von der theoretischen nicht unterscheidet.”

GREEK MATHEMATICS

(b) MATHEMATICS IN GREEK EDUCATION

Iambl. *De Vita Pythag.* 18. 89, ed. Deubner 52. 8-11

Λέγουσι δὲ οἱ Πυθαγόρειοι ἐξηγητέχθαι γεωμετρίαν οὕτως. ἀποβαλεῖν τινα τὴν οὐσίαν τῶν Πυθαγορείων· ὡς δὲ τοῦτο ἠτύχησε, δοθῆναι αὐτῷ χρηματίσασθαι ἀπὸ γεωμετρίας. ἐκαλεῖτο δὲ ἡ γεωμετρία πρὸς Πυθαγόρου ἱστορία.

Plat. *Leg.* vii. 817 E-820 D

ΑΘΗΝΑΙΟΣ ΞΕΝΟΣ. Ἔτι δὴ τοίνυν τοῖς ἐλευθέροις ἔστιν τρία μαθήματα, λογισμοὶ μὲν καὶ τὰ περὶ ἀριθμοὺς ἐν μάθημα, μετρητικὴ δὲ μήκους καὶ ἐπιπέδου καὶ βάθους ὡς ἐν αὐτῷ δεύτερον, τρίτον δὲ τῆς τῶν ἀστρῶν περιόδου πρὸς ἄλληλα ὡς πέφυκεν πορεύεσθαι. ταῦτα δὲ σύμπαντα οὐχ ὡς ἀκριβείας ἐχόμενα δεῖ διαπονεῖν τοὺς πολλοὺς ἀλλὰ τινὰς ὀλίγους—οὓς δέ, προϊόντες ἐπὶ τῷ τέλει φράσομεν· οὕτω γὰρ πρέπον ἂν εἶη—τῷ πλήθει δέ, ὅσα αὐτῶν ἀναγκαῖα καὶ πῶς ὀρθότατα λέγεται μὴ ἐπίστασθαι μὲν τοῖς πολλοῖς αἰσχρὸν, δι' ἀκριβείας δὲ ζητεῖν πάντα οὔτε ῥάδιον οὔτε τὸ παράπαν δυνατόν. . . .

Τοσάδε τοίνυν ἐκάστων χρῆ φάναι μαθάνειν δεῖν τοὺς ἐλευθέρους, ὅσα καὶ πάμπολυς ἐν Αἰγύπτῳ παίδων ὄχλος ἅμα γράμμασι μαθάνει. πρῶτον μὲν γὰρ περὶ λογισμοὺς ἀτεχνῶς παισὶν ἐξηυρημένα μαθήματα μετὰ παιδιᾶς τε καὶ ἡδονῆς μαθάνειν,

^a Plato is thought to have redeemed this promise towards the end of the *Laws*, where he describes the composition of the Nocturnal Council, whose members are required to have considerable knowledge of mathematics.

^b The Greek word is derived from the same root as the

INTRODUCTORY

(b) MATHEMATICS IN GREEK EDUCATION

Iamblichus, *On the Pythagorean Life* 18. 89, ed. Deubner
52. 8-11

The Pythagoreans say that geometry was divulged in this manner. A certain Pythagorean lost his fortune ; and when this befell him, he was permitted to make money from geometry. But geometry was called by Pythagoras "inquiry."

Plato, *Laws* vii. 817 E-820 D

ATHENIAN STRANGER. Then there are, of course, still three subjects for the freeborn to study. Calculations and the theory of numbers form one subject ; the measurement of length and surface and depth make a second ; and the third is the true relation of the movement of the stars one to another. To pursue all these studies thoroughly and with accuracy is a task not for the masses but for a select few—who these should be we shall say later towards the end of our argument, where it would be appropriate ^a—for the multitude it will be proper to learn so much of these studies as is necessary and so much as it can rightly be described a disgrace for the masses not to know, even though it would be hard, or altogether impossible, to pursue with precision all of those studies. . . .

Well then, the freeborn ought to learn as much of these things as a vast multitude of boys in Egypt learn along with their letters. First there should be calculations of a simple type devised for boys, which they should learn with amusement ^b and pleasure,

Greek word for "boy," and Plato is playing on the two words.

GREEK MATHEMATICS

μήλων τέ τινων διανομαὶ καὶ στεφάνων πλείοσιν ἅμα καὶ ἐλάττοσιν ἀρμοττόντων ἀριθμῶν τῶν αὐτῶν, καὶ πυκτῶν καὶ παλαιστῶν ἐφεδρείας τε καὶ συλλήξεως ἐν μέρει καὶ ἐφεξῆς καὶ ὡς πεφύκασι γίνεσθαι. καὶ δὴ καὶ παίζοντες, φιάλας ἅμα χρυσοῦ καὶ χαλκοῦ καὶ ἀργύρου καὶ τοιούτων τινῶν ἄλλων κεραυνύντες, οἱ δὲ καὶ ὅλας πως διαδιδόντες, ὅπερ εἶπον, εἰς παιδιὰν ἐναρμόττοντες τὰς τῶν ἀναγκαίων ἀριθμῶν χρήσεις, ὠφελούσι τοὺς μανθάνοντας εἰς τε τὰς τῶν στρατοπέδων τάξεις καὶ ἀγωγὰς καὶ στρατείας καὶ εἰς οἰκονομίας αὖ, καὶ πάντως χρησιμωτέρους αὐτοὺς αὐτοῖς καὶ ἐγρηγορότας μᾶλλον τοὺς ἀνθρώπους ἀπεργάζονται· μετὰ δὲ ταῦτα ἐν ταῖς μετρήσεσιν, ὅσα ἔχει μήκη καὶ πλάτη καὶ βάθη, περὶ ἅπαντα ταῦτα ἐνοῦσάν τινα φύσει γελοίαν τε καὶ αἰσχροὴν ἄγνοιαν ἐν τοῖς ἀνθρώποις πᾶσιν, ταύτης ἀπαλλάτουσιν.

ΚΛΕΙΝΙΑΣ. Ποίαν δὴ καὶ τίνα λέγεις ταύτην;

ΑΘ. ὦ φίλε Κλεινία, παντάπασί γε μὴν καὶ αὐτὸς ἀκούσας ὀψέ ποτε τὸ περὶ ταῦτα ἡμῶν πάθος ἐθαύμασα, καὶ ἔδοξέ μοι τοῦτο οὐκ ἀνθρώπινον ἀλλὰ ὑηνῶν τινων εἶναι μᾶλλον θρεμμάτων, ἤσχυνθην τε οὐχ ὑπὲρ ἑμαυτοῦ μόνον, ἀλλὰ καὶ ὑπὲρ ἀπάντων τῶν Ἑλλήνων.

• Heath (*H.G.M.* i. 20 n. 1) first satisfactorily explained the construction of this sentence.

• The Athenian Stranger, generally taken to mean Plato

INTRODUCTORY

such as distributions of apples and crowns wherein the same numbers are divided among more or fewer, or distributions of the competitors in boxing and wrestling matches by the method of byes and drawings, or by taking them in consecutive order, or in any of the usual ways.^a Again, the boys should play with bowls containing gold, bronze, silver and the like mixed together, or the bowls may be distributed as wholes. For, as I was saying, to incorporate in the pupils' play the elementary applications of arithmetic will be of advantage to them later in the disposition of armies, in marches and in campaigns, as well as in household management, and will make them altogether more useful to themselves and more awake. After these things there should be measurements of objects having length, breadth and depth, whereby they would free themselves from that ridiculous and shameful ignorance on all these topics which is the natural condition of all men.

CLEINIAS. And in what, pray, does this ignorance consist?

ATHENIAN STRANGER. My dear Cleinias, when I heard, somewhat belatedly, of our condition in this matter,^b I also was astonished; such ignorance seemed to me worthy, not of human beings, but of swinish creatures, and I felt ashamed, not for myself alone, but for all the Greeks.

himself, proceeds to explain at length that he is referring to the problem of incommensurability. The Greek (*ἀκούσας ὀψέ ποτε*) could mean that he had only lately heard either of incommensurability itself or of the prevalent Greek ignorance about incommensurability. A. E. Taylor comments that in view of references to incommensurability in quite early dialogues it seems better to take the words in the latter sense.

GREEK MATHEMATICS

ΚΛ. Τοῦ πέρι; λέγ' ὅτι καὶ φήσ, ὦ ξένε.

ΑΘ. Λέγω δὴ· μᾶλλον δὲ ἐρωτῶν σοι δείξω.
καὶ μοι σμικρὸν ἀπόκριναι· γινώσκεις ποῦ μῆκος;

ΚΛ. Τί μῆν;

ΑΘ. Τί δέ; πλάτος;

ΚΛ. Πάντως.

ΑΘ. Ἡ καὶ ταῦτα ὅτι δὴ ἐστόν, καὶ τρίτον
τούτων βάθος;

ΚΛ. Πῶς γὰρ οὐ;

ΑΘ. Ἄρ' οὖν οὐ δοκεῖ σοι ταῦτα εἶναι πάντα
μετρητὰ πρὸς ἄλληλα;

ΚΛ. Ναί.

ΑΘ. Μῆκός τε οἶμαι πρὸς μῆκος, καὶ πλάτος
πρὸς πλάτος, καὶ βάθος ὡσαύτως δυνατὸν εἶναι
μετρεῖν φύσει.

ΚΛ. Σφόδρα γε.

ΑΘ. Εἰ δ' ἔστι μήτε σφόδρα μήτε ἡρέμα δυνατὰ
ἔνια, ἀλλὰ τὰ μὲν, τὰ δὲ μή, σὺ δὲ πάντα ἡγή, πῶς
οἶει πρὸς ταῦτα διακεῖσθαι;

ΚΛ. Δῆλον ὅτι φαύλως.

ΑΘ. Τί δ' αὖ μῆκός τε καὶ πλάτος πρὸς βάθος,
ἢ πλάτος τε καὶ μῆκος πρὸς ἄλληλα; ἄρ' οὐ
διανοούμεθα περὶ ταῦτα οὕτως Ἕλληνες πάντες,
ὡς δυνατὰ ἔστι μετρεῖσθαι πρὸς ἄλληλα ἀμῶς
γέ πως;

ΚΛ. Παντάπασι μὲν οὖν.

ΑΘ. Εἰ δ' ἔστιν αὖ μῆδαμῶς μῆδαμῆ δυνατὰ,
πάντες δ', ὅπερ εἶπον, Ἕλληνες διανοούμεθα ὡς
δυνατὰ, μῶν οὐκ ἄξιον ὑπὲρ πάντων αἰσχυρθέντα
εἰπεῖν πρὸς αὐτούς· “ ὦ βέλτιστοι τῶν Ἑλλήνων,
ἐν ἐκείνων τοῦτ' ἔστιν ὧν ἔφαμεν αἰσχυρὸν μὲν

INTRODUCTORY

CLEIN. Why? Please explain, sir, what you are saying.

ATH. I will indeed do so; or rather I will make it plain to you by asking questions. Pray, answer me one little thing; you know what is meant by *line*?

CLEIN. Of course.

ATH. And again by *surface*?

CLEIN. Certainly.

ATH. And you know that these are two distinct things, and that *volume* is a third distinct from them?

CLEIN. Even so.

ATH. Now does not it appear to you that they are all commensurable one with another?

CLEIN. Yes.

ATH. I mean, that line is in its nature measurable by line, and surface by surface, and similarly with volume.

CLEIN. Most assuredly.

ATH. But suppose this cannot be said of some of them, neither with more assurance nor with less, but is in some cases true, in others not, and suppose you think it true in all cases; what you do think of your state of mind in this matter?

CLEIN. Clearly, that it is unsatisfactory.

ATH. Again, what of the relations of line and surface to volume, or of surface and line one to another; do not all we Greeks imagine that they are commensurable in some way or other?

CLEIN. We do indeed.

ATH. Then if this is absolutely impossible, though all we Greeks, as I was saying, imagine it possible, are we not bound to blush for them all as we say to them, "Worthy Greeks, this is one of the things of which we said that ignorance is a disgrace and that

GREEK MATHEMATICS

γεγονέναι τὸ μὴ ἐπίστασθαι, τὸ δ' ἐπίστασθαι τὰναγκαῖα οὐδὲν πάνυ καλόν;''

κλ. Πῶς δ' οὐ;

αθ. Καὶ πρὸς τούτοις γε ἄλλα ἔστιν τούτων συγγενῆ, ἐν οἷς αὐτὰ πολλά ἁμαρτήματα ἐκείνων ἀδελφὰ ἡμῖν ἐγγίγνεται τῶν ἁμαρτημάτων.

κλ. Ποῖα δὴ;

αθ. Τὰ τῶν μετρητῶν τε καὶ ἀμέτρων πρὸς ἀλλήλα ἦτινι φύσει γέγονεν· ταῦτα γὰρ δὴ σκοποῦντα διαγιγνώσκειν ἀναγκαῖον ἢ παντάπασιν εἶναι φαῦλον, προβάλλοντά τε ἀλλήλοις αἰεὶ, διατριβὴν τῆς πεττείας πολὺ χαριεστέραν πρεσβυτῶν διατριβοντα, φιλονικεῖν ἐν ταῖς τούτων ἀξίαισι σχολαῖς.

κλ. Ἴσως· ἔοικεν γοῦν ἢ τε πεττεία καὶ ταῦτα ἀλλήλων τὰ μαθήματα οὐ πάμπολυ κεχωρίσθαι.

Isoc. *Panathenaicus* 26-28, 238 B-D

Τῆς μὲν οὖν παιδείας τῆς ὑπὸ τῶν προγόνων καταλειφθείσης τοσοῦτου δέω καταφρονεῖν, ὥστε καὶ τὴν ἐφ' ἡμῶν κατασταθεῖσαν ἐπαινώ, λέγω δὲ

* Plato is probably censuring a belief that if two squares are commensurable, their sides are also commensurable; and if two cubes are commensurable, their surfaces and sides are also commensurable. The discovery that this is not necessarily so would arise in such problems as that propounded in *Meno* 82 B—85 B (doubling of a square) and in the duplication of the cube (see *infra*, pp. 256-309). The only difficulty is that commensurability is not always impossible (*μηδαμῶς μηδαμῇ δυνατά*). A belief that areas and volumes can be expressed in linear measure would meet this stipulation, but it seems too elementary to call for elaborate refutation by Plato.

INTRODUCTORY

to know such necessary matters is no great achievement" ?^a

CLEIN. Certainly.

ATH. In addition to these, there are other related points, which often give rise to errors akin to those lately mentioned.

CLEIN. What kind of errors do you mean ?

ATH. The real nature of commensurables and incommensurables towards one another.^b A man must be able to distinguish them on examination, or must be a very poor creature. We should continually put such problems to each other—it would be a much more elegant occupation for old people than draughts—and give our love of victory an outlet in pastimes worthy of us.

CLEIN. Perhaps so ; it would seem that draughts and these studies are not so widely separated.

Isocrates, *Panegyric of Athens* 26-28, 238 B-D^c

So far from despising the education handed down by our ancestors, I even approve that established in

^b According to A. E. Taylor, this means that "behind the more special problems of the commensurability of specific areas and volumes there lies the problem of constructing a general 'theory of incommensurables.'" He calls in the evidence of *Epinomis*, 990 B—991 B, for which see *infra*, pp. 400-405. For further references to the problem see *infra*, pp. 110-111, 214-215.

^c Isocrates began this last of his orations in his ninety-fourth year and it was published in his ninety-eighth. He expresses similar sentiments about mathematics in *Antidosis* §§ 261-268 ; see also Xenophon, *Memorabilia* iv. 7. 2 ff. Heath's dry comment (*H.G.M.* i. 22) is : "It would appear therefore that, notwithstanding the influence of Plato, the attitude of cultivated people in general towards mathematics was not different in Plato's time from what it is to-day."

GREEK MATHEMATICS

τὴν τε γεωμετρίαν καὶ τὴν ἀστρολογίαν καὶ τοὺς διαλόγους τοὺς ἐριστικούς καλουμένους, οἷς οἱ μὲν νεώτεροι μᾶλλον χαίρουσι τοῦ δέοντος, τῶν δὲ πρεσβυτέρων οὐδεὶς ἔστιν, ὅστις ἂν ἀνεκτοὺς αὐτοὺς εἶναι φήσειεν.

Ἄλλ' ὅμως ἐγὼ τοῖς ὠρμημένοις ἐπὶ ταῦτα παρακελεύομαι πονεῖν καὶ προσέχειν τὸν νοῦν ἅπασι τούτοις, λέγων, ὡς εἰ καὶ μηδὲν ἄλλο δύναται τὰ μαθήματα ταῦτα ποιεῖν ἀγαθόν, ἀλλ' οὖν ἀποτρέπει γε τοὺς νεωτέρους πολλῶν ἄλλων ἀμαρτημάτων. τοῖς μὲν οὖν τηλικούτοις οὐδέποτ' ἂν εὐρεθῆναι νομίζω διατριβὰς ὠφελιμωτέρας τούτων οὐδὲ μᾶλλον πρεπούσας· τοῖς δὲ πρεσβυτέροις καὶ τοῖς εἰς ἄνδρας δεδοκιμασμένοις οὐκέτι φημὶ τὰς μελέτας ταύτας ἀρμόττειν. ὁρῶ γὰρ εἰῖους τῶν ἐπὶ τοῖς μαθήμασι τούτοις οὕτως ἀπηκριβωμένων ὥστε καὶ τοὺς ἄλλους διδάσκειν, οὐτ' εὐκαίρως ταῖς ἐπιστήμαις αἷς ἔχουσι χρωμένους, ἔν τε ταῖς ἄλλαις πραγματείαις ταῖς περὶ τὸν βίον ἀφρονεστέρους ὄντας τῶν μαθητῶν· ὀκνῶ γὰρ εἰπεῖν τῶν οἰκετῶν.

(c) PRACTICAL CALCULATION

(i.) Enumeration by Fingers

Aristot. *Prob.* xv. 3, 910 b 23–911 a 1

Διὰ τί πάντες ἄνθρωποι, καὶ βάρβαροι καὶ Ἕλληνες, εἰς τὰ δέκα καταριθμοῦσι, καὶ οὐκ εἰς ἄλλον ἀριθμόν, οἷον β, γ, δ, ε, εἶτα πάλιν ἐπαναδιπλοῦσιν, ἐν πέντε, δύο πέντε, ὥσπερ ἔνδεκα, δώδεκα; . . . ἢ ὅτι πάντες ὑπήρξαν ἄνθρωποι ἔχοντες δέκα δακτύλους; οἷον οὖν ψήφους ἔχοντες

INTRODUCTORY

our own times—I mean geometry, astronomy, and the so-called eristic dialogues, in which our young men delight more than they ought, though there is not one of the older men who would pronounce them tolerable.

Nevertheless I urge those who are inclined to these disciplines to work hard and apply their mind to all of them, saying that even if these studies can do no other good, they at least keep the young out of many other things that are harmful. Indeed, for those who are at this age I maintain that no more helpful or fitting occupations can be found; but for those who are older and those admitted to man's estate I assert that these disciplines are no longer suitable. For I notice that some of those who have become so versed in these studies as to teach others fail to use opportunely the sciences they know, while in the other activities of life they are more unpractical than their pupils—I shrink from saying than their servants.

(c) PRACTICAL CALCULATION

(i.) *Enumeration by Fingers*

Aristotle, *Problems* xv. 3, 910 b 23-911 a 1

Why do all men, both barbarians and Greeks, count up to ten and not up to any other number, such as 2, 3, 4 or 5, whence they would start again, saying, for example, one *plus* five, two *plus* five, just as they say one *plus* ten, two *plus* ten? ^a . . . Is it that all men were born with ten fingers? Having the

^a The Greek words for 11 and 12 mean literally *one-ten*, *two-ten*.

GREEK MATHEMATICS

τοῦ οἰκείου ἀριθμοῦ, τούτῳ τῷ πλήθει καὶ τὰ ἄλλα ἀριθμοῦσιν.

Nicolas Rhabdas, ed. Tannery, *Notices et extraits des manuscrits de la Bibliothèque Nationale*, vol. xxxii. pt. 1, pp. 146-152

Ἐκφασίς τοῦ δακτυλικοῦ μέτρου

Ἐν δὲ ταῖς χερσὶ καθέξεις τοὺς ἀριθμοὺς οὕτως· καὶ ἐν μὲν τῇ λαιᾷ, ὀφείλεις ἀεὶ τοὺς μοναδικούς καὶ δεκαδικούς κρατεῖν ἀριθμούς, ἐν δὲ τῇ δεξιᾷ τοὺς ἑκατονταδικούς καὶ χιλιονταδικούς, τοὺς δὲ ἐπέκεινα τούτων χαράττειν ἐν τινι· οὐ γὰρ ἔχεις ὅπως καθέξεις ἐν ταῖς χερσὶ.

Συστελλομένου τοῦ πρώτου καὶ μικροῦ δακτύλου, τοῦ μύωπος καλουμένου, τῶν δὲ τεσσάρων ἐκτεταμένων καὶ ἰσταμένων ὀρθίων, κατέχεις ἐν μὲν τῇ ἀριστερᾷ χερσὶ μονάδα μίαν, ἐν δὲ τῇ δεξιᾷ χιλιοντάδα μίαν.

Καὶ πάλιν συστελλομένου καὶ τούτου καὶ τοῦ μετ' αὐτὸν δευτέρου δακτύλου, τοῦ παραμέσου καὶ ἐπιβάτου καλουμένου, τῶν δὲ λοιπῶν τριῶν ὡς ἔφημεν ἠπλωμένων, κρατεῖς ἐν μὲν τῇ εὐωνύμῳ δύο, ἐν δὲ τῇ δεξιᾷ δισχίλια.

Τοῦ δ' αὖ τρίτου συστελλομένου, ἦτοι τοῦ σφακέλου καὶ μέσου, κειμένων καὶ τῶν ἐτέρων δύο, τῶν

^a The word *πεμπάζειν* ("to five"), used by Homer (*Od.* iv. 412) in the sense "to count," would appear to be a relic of a quinary system of reckoning. The Greek *χείρ*, like the Latin *manus*, is used to denote "a number" of men, e.g., Herodotus vii. 157, viii. 140; Thucydides iii. 96.

^b Nicolas Artavasdas of Smyrna, called Rhabdas, lived in the fourteenth century A.D. He is the author of two letters

INTRODUCTORY

equivalent of pebbles to the number of their own fingers, they came to use this number for counting everything else as well.^a

Nicolas Rhabdas,^b ed. Tannery, *Notices et extraits des manuscrits de la Bibliothèque Nationale*, vol. xxxii. pt. 1, pp. 146-152

Exposition of finger-notation ^c

This is how numbers are represented on the hands: The left hand is always used for the units and tens, and the right hand for the hundreds and thousands, while beyond that some form of characters must be used, for the hands are not sufficient.

Closing the first finger—the little one, called *myope*—and keeping the other four stretched out straight, you have on the left hand 1 and on the right hand 1000.^d

Again, closing this finger together with that next after it—the second, called *next the middle* and *epibate*—and keeping the remaining three fingers open, as we said, you have on the left hand 2 and on the right hand 2000.

Once more, closing the third finger—called *sphaelos* and *middle*—and keeping the other two as

edited by Tannery, of which the second can be dated to the year 1341 by a calculation of Easter. He edited the arithmetical manual of the monk Maximus Planudes.

^a A similar system is explained by the Venerable Bede, *De temporum ratione*, c. i., "De computo vel loquela digitorum." He implies that St. Jerome (*ob.* A.D. 420) was also acquainted with the system.

^d In the Greek the numerals are sometimes written in full, sometimes in the alphabetic notation, for which see *infra*, p. 43.

δὲ λοιπῶν δύο ἐκτεταμένων, τοῦ λιχανοῦ λέγω καὶ τοῦ ἀντίχειρος, εἰσὶν ἄπερ κρατεῖς ἐν μὲν τῇ λαιᾷ, γ, ἐν δὲ τῇ δεξιᾷ, γ̄.

Πάλιν συστελλομένων τῶν δύο, τοῦ μέσου καὶ παραμέσου, ἦγον τοῦ δευτέρου καὶ τρίτου, καὶ τῶν ἄλλων ὄντων ἐξηπλωμένων, τοῦ ἀντίχειρος λέγω, τοῦ λιχανοῦ καὶ τοῦ μύωπος, εἰσὶν ἄπερ κρατεῖς ἐν μὲν τῇ λαιᾷ, δ, ἐν δὲ τῇ δεξιᾷ, δ̄.

Πάλιν τοῦ τρίτου, τοῦ καὶ μέσου, συνεσταλμένου, καὶ τῶν λοιπῶν τεσσάρων ἐκτεταμένων, δηλοῦσιν ἄπερ κρατεῖς (ἐν μὲν τῇ λαιᾷ)¹ ε, ἐν δὲ τῇ δεξιᾷ, ε̄.

Τοῦ ἐπιβάτου πάλιν, τοῦ καὶ δευτέρου, συνεσταλμένου καὶ τῶν λοιπῶν (τεσσάρων)² ἠπλωμένων, κρατεῖς ἐν μὲν τῇ εὐωνύμῳ ς, ἐν δὲ τῇ ἐτέρᾳ, ς̄.

Τοῦ μύωπος πάλιν, τοῦ καὶ πρώτου, ἐκτεταμένου καὶ τῇ παλάμῃ προσψαύοντος, τῶν δὲ λοιπῶν ἰσταμένων ὀρθίως, εἰσὶν ἄπερ κατέχεις, ζ, ἐν δὲ τῇ ἄλλῃ, ζ̄.

Τοῦ δευτέρου πάλιν, τοῦ καὶ παραμέσου, ὁμοίως ἐκτεταμένου καὶ κλίνοντος ἄχρις οὗ τῇ κυάθῳ τελείως προσεγγίση, τῶν δὲ λοιπῶν τριῶν, τοῦ τρίτου, τοῦ τετάρτου καὶ τοῦ πέμπτου, ὡς προεῖρηται ἰσταμένων ὀρθίων, τὸ γενόμενον σχῆμα ἐν μὲν τῇ λαιᾷ δηλοῖ η, ἐν δὲ τῇ δεξιᾷ, η̄.

Οὕτως οὖν καὶ τοῦ τρίτου γενομένου, κειμένων καὶ τῶν ἄλλων δύο, τοῦ πρώτου καὶ δευτέρου, κατὰ τὸ αὐτὸ σχῆμα, ἐν μὲν τῇ ἀριστερᾷ δηλοῦσιν θ, ἐν δὲ τῇ ἄλλῃ, θ̄.

Πάλιν τοῦ ἀντίχειρος ἠπλωμένου, οὐχὶ δ' ὑπερ-

¹ ἐν . . . λαιᾷ add. Morel.

² τεσσάρων add. Tannery.

INTRODUCTORY

before, with the remaining two held out straight—I mean the forefinger^a and thumb^b—you have on the left hand 3 and on the right hand 3000.

Again, closing the two fingers called *middle* and *next the middle*, that is, the second and third, and keeping the others open—I mean the thumb and forefinger and that called *myope*, you have on the left hand 4 and on the right hand 4000.

Again, closing the third finger—the *middle*—and keeping the remaining four straight, the fingers will represent on the left hand 5 and on the right hand 5000.

Closing, again, the *epibate* finger—the second—and keeping the remaining four open, you have on the left hand 6 and on the other 6000.

Again, by extending the finger called *myope*—the first—so as to touch the palm, and keeping the others stretched out straight, you have 7 and on the other hand 7000.

If the second finger—that called *next the middle*—is extended in a similar manner and bent until it nearly touches the hollow of the hand, while the remaining three fingers—the third, fourth and fifth—are stretched out straight as aforesaid, the resulting figure will represent on the left hand 8 and on the right hand 8000.

If the third finger also is bent in this manner, the other two—the first and second—remaining as before, the fingers will represent on the left hand 9 and on the other 9000.

Again, if the thumb is kept open, not raised verti-

^a The Greek word means literally the “licking” finger.

^b The Greek word means literally “that which is opposite”
sc. the four fingers.

GREEK MATHEMATICS

αιρομένου, ἀλλὰ πλαγίως πως, καὶ τοῦ λιχανοῦ ὑποκλινομένου ἄχρις ἂν τῷ τοῦ ἀντίχειρος προτέρω ἄρθρῳ συμπέσῃ, ἕως ἂν γένηται σίγματος σχῆμα, τῶν δὲ λοιπῶν τριῶν φυσικῶς ἠπλωμένων καὶ μὴ χωριζομένων ἀπ' ἀλλήλων, ἀλλὰ συνημμένων, τὸ τοιοῦτον ἐν μὲν τῇ εὐωνύμῳ χειρὶ σημαίνει δέκα, ἐν δὲ τῇ δεξιᾷ ῥ.

(ii.) *The Abacus*

Herod. ii. 36. 4

Γράμματα γράφουσι καὶ λογίζονται ψήφοισι Ἑλληνες μὲν ἀπὸ τῶν ἀριστερῶν ἐπὶ τὰ δεξιὰ φέροντες τὴν χεῖρα, Αἰγύπτιοι δὲ ἀπὸ τῶν δεξιῶν ἐπὶ τὰ ἀριστερά· καὶ ποιεῦντες ταῦτα αὐτοὶ μὲν φασι ἐπὶ δεξιὰ ποιέειν, Ἑλλήνας δὲ ἐπ' ἀριστερά.

* It is perhaps unnecessary to follow this trifle to its end. Rhabdas proceeds to show how the tens from 20 to 90, and the hundreds from 200 to 900, can be represented in similar manner. Details are given in Heath, *H.G.M.* ii. 552.

I have not found it possible to give a satisfactory rendering of Rhabdas's names for the fingers. Possibly *μύψ* should be translated *spur* (though this seems a more natural name for the thumb than the first finger) and *ἐπιβάτης rider*; *σφάκελος* (*σφάκελλος* in the mss.) can mean spasms or convulsions, and Mr. Colin Roberts tentatively suggests (to my mind convincingly) that the middle finger is so called because it is joined with the thumb in cracking the fingers.

† The only ancient abaci which have been preserved and can definitely be identified as such are Roman. It is disputed whether the famous Salaminian table, discovered by

INTRODUCTORY

cally but somewhat aslant, and the forefinger is bent until it touches the first joint of the thumb, so that they resemble the letter σ , while the remaining three fingers are kept open in their natural position and not separated from each other but kept together, the figure so formed will signify on the left hand 10 and on the right hand 100.^a

(ii.) *The Abacus* ^b

Herodotus ii. 36. 4

In writing and in reckoning with pebbles the Greeks move the hand from left to right, but the Egyptians from right to left^c; in so doing they maintain that they move the hand to the right, and that it is the Greeks who move to the left.

Rangabé and described by him in 1846 (*Revue archéologique* iii.), is an abacus or a game-board; the table now lies in the Epigraphical Museum at Athens and is described and illustrated by Kubitschek (*Wiener numismatische Zeitschrift*, xxxi., 1899, pp. 393-398, with Plate xxiv.), Nagl (*Abhandlungen zur Geschichte der Mathematik*, ix., 1899, plate after p. 357) and Heath, *H.G.M.* i. 49-51. The essence of the Greek abacus, like the Roman, was an arrangement of the columns to denote different denominations, *e.g.*, in the case of the decimal system units, tens, hundreds, and thousands. The number of units in each denomination was shown by pebbles. When the pebbles collected in one column became sufficient to form one or more units of the next highest denomination, they were withdrawn and the proper number of pebbles substituted in the higher column.

^a This implies that the columns were vertical.

GREEK MATHEMATICS

Diog. Laert. i. 59

Ἐλεγε δὲ τοὺς παρὰ τοῖς τυράννοις δυναμένους παραπλησίους εἶναι ταῖς ψήφοις ταῖς ἐπὶ τῶν λογισμῶν. καὶ γὰρ ἐκείνων ἐκάστην ποτὲ μὲν πλείω σημαίνειν, ποτὲ δὲ ἥττω· καὶ τούτων τοὺς τυράννους ποτὲ μὲν ἕκαστον μέγαν ἄγειν καὶ λαμπρόν, ποτὲ δὲ ἄτιμον.

Polyb. *Histor.* v. 26. 13

Ὅντως γὰρ εἰσιν οὗτοι παραπλήσιοι ταῖς ἐπὶ τῶν ἀβακίων ψήφοις· ἐκεῖναί τε γὰρ κατὰ τὴν τοῦ ψηφίζοντος βούλησιν ἄρτι χαλκοῦν καὶ παραυτίκα τάλαντον ἰσχύουσιν, οἳ τε περὶ τὰς αὐλὰς κατὰ τὸ τοῦ βασιλέως νεῦμα μακάριοι καὶ παρὰ πόδας ἐλεεινοὶ γίνονται.

INTRODUCTORY

Diogenes Laertius i. 59

He [Solon] used to say that men who surrounded tyrants were like the pebbles used in calculations; for just as each pebble stood now for more, now for less, so the tyrants would treat each of their courtiers now as great and famous, now as of no account.

Polybius, *History* v. 26. 13

These men are really like the pebbles on reckoning-boards. For the pebbles, according to the will of the reckoner, have the value now of an eighth of an obol, and the next moment of a talent^a; while courtiers, at the nod of the king, are now happy, and the next moment lying piteously at his feet.

^a In the Salaminian table (see *supra*, p. 34 n. b) the extreme denominations on one side are actually the talent and the χαλκοῦς ($\frac{1}{8}$ obol).

II. ARITHMETICAL NOTATION AND THE CHIEF ARITHMETI- CAL OPERATIONS

II. ARITHMETICAL NOTATION AND THE CHIEF ARITHMETICAL OPERATIONS

(a) ENGLISH NOTES AND EXAMPLES

FROM earliest times the Greeks followed the decimal system of enumeration. At first, no doubt, the words for the different numbers were written out in full, and many inscriptions bear witness to this practice. But the development of trade and of mathematical interests would soon have caused the Greeks to search for some more convenient symbolic method of representing numbers. The first system of symbols devised for this purpose is sometimes known as the Attic system, owing to the prevalence of the signs in Attic inscriptions. In it | represents the unit, and may be repeated up to four times. There are only five other distinct symbols, each being the first letter of the word representing a number. They are

∏ (the first letter of πέντε)	=	5
Δ (δέκα)	=	10
Η (ἑκατόν)	=	100
Χ (χίλιοι)	=	1000
Μ (μύριοι)	=	10000

Like |, each of these signs may be repeated up to

GREEK MATHEMATICS

four times. Four other symbols are formed by compounding two of the simple signs.

$$\text{Ϟ} (\text{Γ and } \Delta) = 50$$

$$\text{Ϟ} (\text{Γ and H}) = 500$$

$$\text{Ϟ} (\text{Γ and X}) = 5000$$

$$\text{Ϟ} (\text{Γ and M}) = 50000$$

By combinations of these signs it is possible to represent any number from 1 to 50000. For example, $\text{ϞXHHH}\Delta\Delta\text{ΓIIII} = 6329$.

Notwithstanding the opinion of Cantor,^a there is very little to be said for this cumbrous notation. A second system devised by the Greeks made use of the letters of the alphabet, with three added letters, as numerals. It is not certain when this system came into use,^b but it had completely superseded the older system long before the time of the writers with whom we shall be concerned, and for the purposes of this book it is the only system which need be noticed. In it an alphabet of 27 letters is used: the first nine letters represent the units from 1 to 9, the second nine represent the tens from 10 to 90, and the third nine represent the hundreds from 100 to 900. To show that a numeral is indicated, a horizontal stroke

^a *Vorlesungen über Geschichte der Mathematik*, i³, p. 129.

^b For a full consideration of the date given by Larfeld (end of eighth century B.C.) and that given by Keil (550-425 B.C.), see Heath, *H.G.M.* i. 33-34.

ARITHMETICAL NOTATION

is generally placed above the letter in cursive writing, as in the following scheme ^a

$\bar{\alpha} = 1$	$\bar{\iota} = 10$	$\bar{\rho} = 100$
$\bar{\beta} = 2$	$\bar{\kappa} = 20$	$\bar{\sigma} = 200$
$\bar{\gamma} = 3$	$\bar{\lambda} = 30$	$\bar{\tau} = 300$
$\bar{\delta} = 4$	$\bar{\mu} = 40$	$\bar{\upsilon} = 400$
$\bar{\epsilon} = 5$	$\bar{\nu} = 50$	$\bar{\phi} = 500$
$\bar{\zeta} = 6$	$\bar{\xi} = 60$	$\bar{\chi} = 600$
$\bar{\eta} = 7$	$\bar{\omicron} = 70$	$\bar{\psi} = 700$
$\bar{\theta} = 8$	$\bar{\pi} = 80$	$\bar{\omega} = 800$
$\bar{\delta} = 9$	$\bar{\varsigma} = 90$	$\bar{\chi} = 900$

The horizontal stroke is often omitted for convenience in printed texts.

In this system there are three letters ς (Stigma, a form of the digamma), ζ or φ (Koppa) and χ (Sampi) which had been taken over by the Greeks from the Phoenician alphabet but had dropped out of literary use. As there is no record of this alphabet of 27 letters in this order being in use at any time, it seems to have been deliberately framed by someone for the purposes of mathematics.^b Though more concise than the Attic system, it suffers from the disadvantage of giving no indication of place-value; the connexion between ϵ , ν and ϕ , for example, does not leap to the eye as in the Arabic notation 5, 50, 500.

^a In some texts the method of indicating that a letter stands for a numeral is an accent placed above the letter and to the right, in the following manner :

$$\alpha' = 1, \iota' = 10, \rho' = 100.$$

A double accent is used to indicate submultiples, e.g.,

$$\gamma'' = \frac{1}{3}, \lambda'' = \frac{1}{3}\sigma, \tau'' = \frac{1}{3}\delta\sigma.$$

^b Gow, *A Short History of Greek Mathematics*, pp. 45-46.

GREEK MATHEMATICS

Opinions differ greatly on the facility with which it could be used, but the balance of opinion is in favour of the view that it was an obstacle to the development of arithmetic by the Greeks.

By combination of these letters, it is possible to represent any number from 1 to 999. Thus $\overline{\rho\nu\gamma} = 153$. For the thousands from 1000 to 9000 the letters α to θ are used again with a distinguishing mark, generally a stroke subscribed to the letter a little to the left, in addition to the horizontal stroke above the letter.

Thus $\bar{\alpha} = 1000, \bar{\beta} = 2000, \dots, \bar{\theta} = 9000$.

For tens of thousands the sign M is used, generally with the number of myriads written above it.

Thus $\overset{\alpha}{M} = 10000, \overset{\beta}{M} = 20000$, and so on (Eutocius).

Another method is to use the sign M or $\overset{Y}{M}$ for the myriad and to put the number of myriads after it, separated by a dot from the thousands.

Thus

$\overset{Y}{M}\rho\delta. \overline{\eta\phi\sigma} = 1048576$ (Diophantus vi. 22, ed. Tannery 446. 11).

In a third method the symbol M is not used, but the symbol representing the number of myriads has two dots placed over it.

Thus

$\overline{\ddot{\alpha}}\eta\phi\zeta\sigma = 18596$ (Heron, *Geometrica* xvii. 33, ed. Heiberg 348. 35).

Heron commonly wrote the word $\mu\nu\rho\iota\acute{\alpha}\delta\epsilon\varsigma$ in full.

To express still higher numbers, powers of myriads were used. Apollonius and Archimedes invented

ARITHMETICAL NOTATION

systems of "tetrads" and "octads" respectively to indicate powers of 10000 and 100000000.

There was no single Greek system for representing fractions. With submultiples, the orthodox method was to write the letter for the corresponding number with an accent instead of a horizontal dash, *e.g.*, $\delta' = \frac{1}{4}$. There were special signs, \angle' and C' , for $\frac{1}{2}$, and ω' for $\frac{2}{3}$. The Greeks, like the Egyptians, tried to express ordinary proper fractions as the sum of two or more submultiples. Thus $\angle' \delta' = \frac{1}{2} + \frac{1}{4} = \frac{3}{4}$, $\angle' \xi \delta' = \frac{1}{2} + \frac{1}{8} = \frac{5}{8}$ (Eutocius). There was a limit to what could be done in this way, and the Greeks devised several methods of representing ordinary proper fractions. The most convenient is that used by Diophantus, and occasionally by Heron. The numerator is written underneath the denominator, which is the reverse of our modern practice. Thus $\lambda \epsilon \sigma = \frac{1}{6} \frac{5}{6}$. A method commonly used in Heron's works was to write the denominator twice and with an accent, *e.g.*, $\bar{\delta} \zeta' \zeta' = \frac{4}{7}$, $\bar{i} \beta \zeta' \zeta' = \frac{1}{7} \frac{2}{7}$. Sometimes the word $\lambda \epsilon \pi \tau \acute{\alpha}$ ("fractional parts") was added, *e.g.*, $\lambda \epsilon \pi \tau \acute{\alpha} \nu \alpha' \nu \alpha' \bar{\lambda} \epsilon = \frac{3}{5} \frac{5}{1}$. There is no fixed order of preference for numerator and denominator. In Aristarchus of Samos we find $\delta \acute{\upsilon} \omicron \mu \epsilon'$ for $\frac{2}{45}$ and in Archimedes $\bar{i} \omicron \alpha'$ for $\frac{1}{71}$, where only the context will show that $10 \frac{1}{71}$ is not intended.

Several fragments illustrating elementary mathematical operations have come to light among the Egyptian papyri.^a The following tables (2nd cent. A.D.) show how fractions can be represented as sums of submultiples. The Greek is set out in columns. The

^a I am indebted to Mr. Colin Roberts for drawing my attention to them.

GREEK MATHEMATICS

first two columns give the numerator of the fraction to be split up. The denominator is not explicitly announced in the table, but it is implicit in the first line. Fractions are marked with signs like accents, usually but not always over every letter. The sign Δ for $\frac{1}{4}$ will be noted. Dots under letters indicate doubtful readings.

Michigan Papyri, No. 145, vol. iii. (*Humanistic Series*, vol. xl.) p. 36

I, ii

A Table of Twenty-thirds

τ η ς	α	κ' γ'		
[τ ω ν	β]	ι' β'	σ ο' ς'	
[τ ω ν	γ]	ι'	μ' ς'	ρ' ι' ε'
[τ ω ν	δ	ς']	ρ' λ' η'	
[τ ω ν	ε	ς'	κ' γ']	ρ λ' [η']

Equivalent in Arabic Notation

$$\begin{aligned} \frac{1}{23} &= \frac{1}{23} \\ \frac{2}{23} &= \frac{1}{12} + \frac{1}{276} \\ \frac{3}{23} &= \frac{1}{10} + \frac{1}{46} + \frac{1}{115} \\ \frac{4}{23} &= \frac{1}{6} + \frac{1}{138} \\ \frac{5}{23} &= \frac{1}{6} + \frac{1}{23} + \frac{1}{138} \end{aligned}$$

ii

A Table of Twenty-ninths

τ ω ν	ι β	Δ	η'	κ θ'	σ λ' β'	
[τ ω ν]	ι γ	γ'	ι' ε'	[κ' θ'	π'] ζ'	ι [λ' ε']
[τ ω ν]	ι δ	Δ	ε'	[ν'] η'	ρ ι ς'	ρ μ' ε'
[τ ω ν]	ι ε	∠	ν' η'			
[τ ω ν	ι ς]	∠	[∠	κ'] θ'	ν' η'	
[τ ω ν	ι ζ	∠		ι' β']	τ' μ' η'	

ARITHMETICAL NOTATION

Equivalent in Arabic Notation

$$\begin{aligned} \frac{12}{29} &= \frac{1}{4} + \frac{1}{8} + \frac{1}{29} + \frac{1}{232} \\ \frac{13}{29} &= \frac{1}{3} + \frac{1}{15} + \frac{1}{29} + \frac{1}{87} + \frac{1}{435} \\ \frac{14}{29} &= \frac{1}{4} + \frac{1}{5} + \frac{1}{58} + \frac{1}{116} + \frac{1}{145} \\ \frac{15}{29} &= \frac{1}{2} + \frac{1}{58} \\ \frac{16}{29} &= \frac{1}{2} + \frac{1}{29} + \frac{1}{58} \\ \frac{17}{29} &= \frac{1}{2} + \frac{1}{12} + \frac{1}{348} \end{aligned}$$

The Greeks had no sign corresponding to 0, and never rose to the conception of 0 as a number.^a Having no need of a sign to indicate decimal position, they wrote such a number as 1007 in only two letters— $\overline{\alpha\zeta}$.

By means of these devices the Greeks had a complete system of enumeration. Here are a few examples of complicated numbers taken from Eutocius :

$$\overline{\text{M}}^{\rho\lambda\zeta} \overline{\gamma\mu\gamma} \text{ } \zeta' \xi\delta' = 1373943\frac{1}{2}\frac{1}{8}\frac{1}{4} = 1373943\frac{33}{84}.$$

$$\overline{\text{M}}^{\phi\mu\zeta} \overline{\beta\varsigma} \text{ } \zeta' \iota\varsigma' = 5472090\frac{1}{2}\frac{1}{18} = 5472090\frac{9}{18}.$$

With these symbols the Greeks conducted the chief mathematical operations in much the same manner, and with much the same facility, as we do. The following is an example of multiplication from

^a In his sexagesimal notation, Ptolemy used the symbol **O** to stand for *οὐδεμία μοῖρα* or *οὐδὲν ἐξήκοστόν*. The diverse views which have been held on this symbol from the time of Delambre are summed up by Loria (*Le scienze esatte nell' antica Grecia*, p. 761) in the words: "In base ai documenti scoperti e decifrati sino ad oggi, siamo autorizzati a negare che i Greci usassero lo zero nel senso e nel modo in cui lo adoperiamo noi."

GREEK MATHEMATICS

Eutocius's commentary on Archimedes' *Measurement of a Circle* (Archim., ed. Heiberg iii. 242):

$\overline{\rho\nu\gamma}$	153		
$\xi\pi\iota \overline{\rho\nu\gamma}$	$\times 153$		
$\overset{\alpha}{\text{M}} \overline{\epsilon\tau}$	15300		
$\overline{\epsilon} \overline{\beta\phi} \overline{\rho\nu}$	5000	2500	150
$\overline{\tau} \overline{\rho\nu\theta}$		300	159
$\delta\mu\omicron\upsilon \overset{\beta}{\text{M}} \overline{\gamma\nu\theta}$	Total	23409	

The operation, it will be noticed, is split up into a number of simple operations. 153 is first multiplied by 100, then 100, 50 and 3 are separately multiplied by 50, and lastly 100 and 53 are separately multiplied by 3. The products are finally all added together to make the total of 23409.

Only one example of long division fully worked out survives in the whole of the extant corpus of Greek mathematical writings—in Theon's *Commentary on the Syntaxis of Ptolemy*. The same work contains an example of the extraction of a square root. Both passages will be reproduced, but as the notation is sexagesimal a few words of explanation are necessary.

The sexagesimal notation had its origin among the Babylonians and was used by the Greeks in astronomical calculations. It appears fully developed in the *Syntaxis* of Ptolemy and the *Commentaries* of Theon and Pappus.^a In this system the circumference of a

^a Theon of Alexandria (to be distinguished from Theon of Smyrna) is dated by Suidas in the reign of Theodosius I (A.D. 379-395). His commentary on Ptolemy's *Syntaxis* is in eleven books, and his famous daughter Hypatia assisted in its revision. Pappus of Alexandria flourished in the reign of

ARITHMETICAL NOTATION

circle, and with it the four right angles at the centre, are divided into 360 equal parts by radial lines. Each of these 360 *degrees* (μοίραι or τμήματα) is divided into 60 equal parts called πρῶτα ἐξηκοστή, frequently represented as α' ἐξηκοστή, *first sixtieths* or *minutes*. In turn each of these parts is divided into 60 δεύτερα ἐξηκοστή, or β' ἐξηκοστή, *second sixtieths* or *seconds*. By further subdivision we obtain τρίτα ἐξηκοστή, or γ' ἐξηκοστή, and so on. In similar manner the diameter of the circle is divided into 120 τμήματα, *segments*, each of these into sixtieths, and so on. The circular associations of the system tended to be forgotten, and it offered a convenient method for representing any number consisting of an integral number of units with fractional parts. The denominations of the parts might be written out in full (e.g., πρῶτα ἐξηκοστή $\overline{\gamma}$ = 900 minutes, α' ἐξηκοστή $\overline{\sigma}$ καὶ β' $\overline{\iota\epsilon}$ = 200 minutes and 15 seconds), or a number consisting of degrees, minutes and seconds might be written down in three sets of numerals without any indication of the denominations other than is provided by the context (e.g., $\overline{\alpha\phi\iota\epsilon}$ $\overline{\kappa}$ $\overline{\iota\epsilon}$ = 1515° 20' 15").

After explaining the advantages of the notation owing to the large number of factors of 60, and noting the result of multiplying or dividing minutes by degrees, minutes by minutes, and so on, Theon gives an example of multiplication and then the two interesting passages which are now to be reproduced and translated :

Diocletian (A.D. 284–305). His chief work was his *Synagoge* or *Collection*, a handbook to Greek geometry which is now one of our main sources for the subject and will be extensively used in these pages.

GREEK MATHEMATICS

(b) DIVISION

Theon Alex. in Ptol. Math. Syn. Comm. i. 10, ed. Rome, *Studi e Testi*, lxxii. (1936), 461. 1-462. 17

Ἐστω δὲ καὶ ἀνάπαλιν δοθέντα ἀριθμὸν μερίσαι παρά τε μοίρας καὶ πρῶτα καὶ δεύτερα ἐξηκοστά. ἔστω ὁ δοθεὶς ἀριθμὸς ὁ $\overline{\alpha\phi\iota\epsilon\ \bar{\kappa}\ \bar{\iota}\bar{\epsilon}}$. καὶ δέον ἔστω μερίσαι αὐτὸν παρὰ τὸν $\overline{\bar{\kappa}\bar{\epsilon}\ \bar{\iota}\bar{\beta}\ \bar{\iota}}$, τουτέστιν εὐρεῖν ποσάκις ἔστιν ὁ $\overline{\bar{\kappa}\bar{\epsilon}\ \bar{\iota}\bar{\beta}\ \bar{\iota}}$ ἐν τῷ $\overline{\alpha\phi\iota\epsilon\ \bar{\kappa}\ \bar{\iota}\bar{\epsilon}}$.

Μερίζομεν αὐτὸν πρῶτον παρὰ τὸν $\bar{\xi}$, ἐπειδήπερ ὁ παρὰ τὸν $\bar{\xi}\alpha$ ὑπερπίπτει καὶ ἀφαιροῦμεν ἐξηκοντάκι τὸν τε $\overline{\bar{\kappa}\bar{\epsilon}}$ καὶ τὸν $\overline{\bar{\iota}\bar{\beta}}$, καὶ ἔτι τὸν $\bar{\iota}$. καὶ πρότερον τὸν $\overline{\bar{\kappa}\bar{\epsilon}}$, καὶ γίνονται $\overline{\alpha\phi}$. εἶτα ἐπὶ τῶν λοιπῶν μοιρῶν $\bar{\iota}\bar{\epsilon}\ \bar{\kappa}\ \bar{\iota}\bar{\epsilon}$ ἀναλύσαντες τὰς $\bar{\iota}\bar{\epsilon}$ μοίρας εἰς πρῶτα ἐξηκοστά καὶ προσθέντες αὐτοῖς τὰ πρῶτα ἐξηκοστά $\bar{\kappa}$ ἀπὸ τῶν γενομένων $\overline{\lambda\kappa}$ πρῶτα πάλιν ἐξηκοστά ἀφαιροῦμεν ἐξηκοντάκις τὰ $\overline{\bar{\iota}\bar{\beta}}$, τουτέστιν $\overline{\psi\kappa}$. καὶ ἔτι ἀπὸ τῶν λοιπῶν πρῶτων ἐξηκοστῶν $\bar{\sigma}$ καὶ δευτέρων $\bar{\iota}\bar{\epsilon}$ ἀφαιροῦμεν ἐξηκοντάκις πάλιν τὰ $\bar{\iota}$. γίνεται δεύτερα μὲν ἐξηκοστά

* We may exhibit Theon's working as follows :

$$\begin{array}{r}
 \text{1st division} \quad 25^{\circ} 12' 10'' \overline{) 1515^{\circ} \quad 20' \quad 15'' \overline{) 60^{\circ}} \\
 \underline{25^{\circ}.60^{\circ} = 1500^{\circ}} \\
 \phantom{25^{\circ} 12' 10'' \overline{) 1515^{\circ} \quad 20' \quad 15'' \overline{) 60^{\circ}}} 15^{\circ} = 900' \\
 \phantom{25^{\circ} 12' 10'' \overline{) 1515^{\circ} \quad 20' \quad 15'' \overline{) 60^{\circ}}} \phantom{15^{\circ} = 900'} 20' \\
 \phantom{25^{\circ} 12' 10'' \overline{) 1515^{\circ} \quad 20' \quad 15'' \overline{) 60^{\circ}}} \phantom{15^{\circ} = 900'} 920' \\
 \phantom{25^{\circ} 12' 10'' \overline{) 1515^{\circ} \quad 20' \quad 15'' \overline{) 60^{\circ}}} \underline{12'.60^{\circ} = 720'} \\
 \phantom{25^{\circ} 12' 10'' \overline{) 1515^{\circ} \quad 20' \quad 15'' \overline{) 60^{\circ}}} \phantom{15^{\circ} = 900'} 200' \quad 15'' \\
 \phantom{25^{\circ} 12' 10'' \overline{) 1515^{\circ} \quad 20' \quad 15'' \overline{) 60^{\circ}}} \underline{10''.60^{\circ} = 10'}
 \end{array}$$

GREEK MATHEMATICS

$\bar{\chi}$, πρῶτα δὲ $\bar{\iota}$. εἶτα πάλιν τὰ ὑπολιπέντα¹ πρῶτα ἐξηκοστὰ $\bar{\rho}\zeta$ καὶ δεύτερα $\bar{\iota}\epsilon$ μερίζομεν παρὰ τὸν $\bar{\kappa}\epsilon$, καὶ γίνεται ὁ μερισμὸς παρὰ $\bar{\zeta}$. ὑπερπίπτε γὰρ παρὰ τὸν $\bar{\eta}$. καὶ τὰ γενόμενα ἐκ τῆς παραβολῆς ἐξηκοστὰ πρῶτα $\bar{\rho}\sigma\epsilon$ ἀφείλομεν ἀπὸ τῶν $\bar{\rho}\zeta$ πρώτων ἐξηκοστῶν. ἔπειτα τὰ λοιπὰ $\bar{\iota}\epsilon$ πρῶτα ἐξηκοστὰ ἀναλύσαντες εἰς δεύτερα $\bar{\lambda}$ καὶ προσθέντες αὐτοῖς τὰ δεύτερα ἐξηκοστὰ $\bar{\iota}\epsilon$, ἀπὸ τῶν γενομένων $\bar{\lambda}\iota\epsilon$ ἀφαιροῦμεν ἐπτάκις τὰ $\bar{\iota}\beta$ πρῶτα ἐξηκοστά, τουτέστιν $\bar{\pi}\delta$ δεύτερα ἐξηκοστά, διὰ τὸ καὶ τὰ $\bar{\zeta}$ πρῶτα εἶναι ἐξηκοστά. καὶ ὑπολείπεται λοιπὰ ὦλα δεύτερα ἐξηκοστά. καὶ ἔτι ἀφελοῦμεν ὁμοίως ἐπτάκις καὶ τὰ $\bar{\iota}$ δεύτερα ἐξηκοστά, ἃ γίνεται τρίτα ἐξηκοστά $\bar{\sigma}$, τουτέστιν δεύτερον $\bar{\alpha}$ καὶ τρίτα $\bar{\iota}$. καὶ λοιπὰ ὑπελίπη δεύτερα ἐξηκοστά $\bar{\omega}\kappa\theta$ καὶ τρίτα $\bar{\nu}$. ταῦτα πάλιν παρὰ τὸν $\bar{\kappa}\epsilon$. καὶ γίνεται ὁ μὲν μερισμὸς παρὰ τὸν $\bar{\lambda}\gamma$, ἐκ δὲ τῆς παραβολῆς $\bar{\omega}\kappa\epsilon$ δεύτερα ἐξηκοστά. καὶ λοιπὰ ὑπελίπη δεύτερα ἐξηκοστά $\bar{\delta}$, τρίτα δὲ $\bar{\nu}$, ὁμοῦ δὲ τρίτα $\bar{\sigma}\zeta$. ἔπειτα πάλιν ἀφείλομεν τὰ $\bar{\iota}\beta$ πρῶτα ἐξηκοστὰ τριακοντάκι καὶ τρίς καὶ γίνεται τρίτα $\bar{\tau}\zeta\varsigma$, ὡς ποιεῖν ἔγγιστα τὸν μερισμὸν τὸν ἀφιε $\bar{\kappa}$ $\bar{\iota}\epsilon$ παρὰ τὸν $\bar{\kappa}\epsilon$ $\bar{\iota}\beta$ $\bar{\iota}$, $\bar{\xi}$ $\bar{\zeta}$ $\bar{\lambda}\gamma$, ἐπεὶ καὶ ἐὰν ταῦτα πολλαπλασιάσωμεν ἐπὶ τὰ $\bar{\kappa}\epsilon$ $\bar{\iota}\beta$ $\bar{\iota}$ συνάγεται ὁ ἀφιε $\bar{\kappa}$ $\bar{\iota}\epsilon$ ἔγγιστα.

$\bar{\alpha}\phi\iota\epsilon \bar{\kappa} \bar{\iota}\epsilon \qquad \bar{\kappa}\epsilon \bar{\iota}\beta \bar{\iota} \qquad \bar{\xi} \bar{\zeta} \bar{\lambda}\gamma$

(c) EXTRACTION OF SQUARE ROOT

Ibid. 469. 16-473. 8

Τούτων θεωρηθέντων, ἐξῆς ἂν εἴη διαλαβεῖν πῶς
 52

ARITHMETICAL NOTATION

sixty times $10''$; that is $600''$, or $10'$. The remainder is $190' 15''$, and, making a new start, we divide by 25° ; the quotient is $7'$, for $8'$ is too big. The number resulting from this division is $175'$, which we subtract from the $190'$. There is a remainder of $15'$, which we split up into $900''$ and to it add the $15''$; from the resulting $915''$ we subtract seven times $12'$, which is $84''$ on account of the seven being minutes; there is left a remainder $831''$. Similarly we subtract seven times $10''$, which is $70'''$, or $1'' 10'''$. The remainder is $829'' 50'''$. We divide this in turn by 25° . The quotient is $33''$, and the number resulting from the division is $825''$, leaving a remainder of $4'' 50'''$, or $290'''$. Next we subtract thirty-three times $12'$, which is $396'''$. Thus the quotient obtained by dividing $1515^\circ 20' 15''$ by $25^\circ 12' 10''$ is approximately $60^\circ 7' 33''$, inasmuch as, if we multiply this quotient by $25^\circ 12' 10''$, the result will be approximately $1515^\circ 20' 15''$.

$$1515^\circ 20' 15'' \quad 25^\circ 12' 10'' \quad 60^\circ 7' 33''$$

(c) EXTRACTION OF SQUARE ROOT

Ibid. 469. 16–473. 8

After this demonstration the next step is to inquire

¹ "Forme suspecte. Voir pourtant Hirt, *Handbuch der griechischen Laut- und Formenlehre*, 2^e éd., Heidelberg, 1912, p. 506."—Rome.

GREEK MATHEMATICS

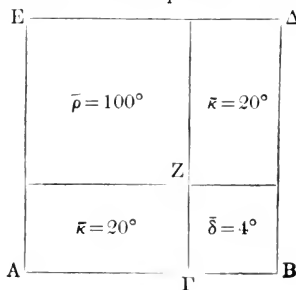
ἂν δοθέντος χωρίου τινὸς τετραγώνου μὴ ἔχοντος
 πλευρὰν μήκει ῥητὴν τὴν σύνεγγυς αὐτοῦ τετραγω-
 νικὴν πλευρὰν ἐπιλογισώμεθα. καὶ ἔστιν τὸ τοιοῦ-
 τον δῆλον ἐπὶ ῥητὴν ἔχοντος πλευρὰν, ἐκ τοῦ δ'
 θεωρήματος τοῦ β' βιβλίου τῶν Στοιχείων, οὗ ἡ
 πρότασις ἔστιν τοιαύτη· ἂν εὐθεία γραμμὴ τμηθῇ
 ὡς ἔτυχεν, τὸ ἀπὸ τῆς ὅλης τετράγωνον ἴσον ἔστιν
 τοῖς τε ἀπὸ τῶν τμημάτων τετραγώνοις καὶ τῷ δις
 ὑπὸ τῶν τμημάτων περιεχομένῳ ὀρθογωνίῳ. ἂν
 γὰρ ἔχοντες δοθέντα ἀριθμὸν τετράγωνον ὡς τὸν
 $\rho\mu\delta$, ῥητὴν ἔχοντα πλευρὰν ὡς τὴν AB εὐθείαν, καὶ
 λαβόντες αὐτοῦ ἐλάσσονα τετράγωνον τὸν ρ , οὗ
 ἔστιν πλευρὰ $\bar{\iota}$, καὶ ὑποθέμενοι τὴν AG $\bar{\iota}$, διπλα-
 σιάσαντες αὐτὴν [καὶ]¹ διὰ τὸ δις ὑπὸ τῶν AG ,
 GB , <παρὰ>² τὰ γενόμενα $\bar{\kappa}$ παραβάλωμεν [παρὰ]³
 τὰ λοιπὰ $\mu\delta$, τῶν ὑπολειπομένων δ ἔσται τὸ ἀπὸ
 τῆς GB , αὕτη δὲ μήκει $\bar{\beta}$. ἦν δὲ καὶ ἡ AG $\bar{\iota}$. καὶ
 ὅλη ἄρα ἡ AB ἔσται μοιρῶν $\bar{\iota}\bar{\beta}$, ὅπερ ἔδει δεῖξαι.

¹ καὶ om. Rome.

² παρὰ add. Rome.

³ παρὰ om. Rome.

• The diagram will make the procedure clear. The square



ARITHMETICAL NOTATION

in what manner, given the area of a square whose side is irrational, we may make an approximation to its side. In the case of a square with a rational side the method is clear from the fourth theorem of the second book of the *Elements*, whose enunciation is as follows : *If a straight line be cut at random, the square on the whole is equal to the squares on the segments, and twice the rectangle contained by the segments.* For if the given number is a square such as 144, having a rational side AB, we take the square 100, which is less than 144 and has 10 as its side, and make AΓ equal to 10. Doubling it, because the rectangle contained by AΓ, ΓB is taken twice, we get 20, and by this number we divide the remainder 44, obtaining a remainder 4 as the square on ΓB, whose length will therefore be 2. Now AΓ was 10, and therefore the whole AB is 12, which was to be proved.^a

AΔ is divided up into the squares EZ, BZ and the equal rectangles AZ, ZΔ.

Thus, square AΔ = square EZ + 2 rect. AZ + square BZ or $144 = 10^2 + 2 \cdot 10 \cdot 2 + 2^2$. Generally, if a given square number A is equal to $(a + x)^2$, where a^2 is a first approximation, then

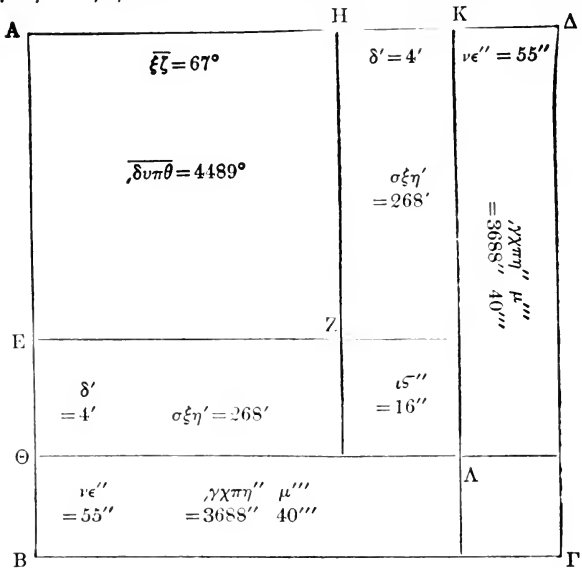
$$A = a^2 + 2ax + x^2$$

and we find the value of x by dividing $2a$ into the remainder when a^2 is subtracted from A.

If A is not a square number, then this gives a method of finding an approximation, $a + x$, to the square root.

GREEK MATHEMATICS

Ἴνα δὲ καὶ ἐπὶ τινος τῶν ἐν τῇ Συντάξει παρακειμένων ἀριθμῶν ὑπ' ὅψιν ἡμῖν γένηται ἢ τῆς κατὰ μέρος ἀφαιρέσεως διάκρισις, ποιησόμεθα τὴν ἀπόδειξιν ἐπὶ τοῦ $\overline{\delta\phi}$ ἀριθμοῦ, οὗ τὴν πλευρὰν ἐξέθετο μοιρῶν $\overline{\xi\zeta}$ δ' $\overline{\nu\epsilon}$. ἐκκείσθω χωρίον τετράγωνον τὸ ΑΒΓΔ, δυνάμει μόνον ῥητόν, οὗ τὸ ἔμβαδόν ἔστω μοιρῶν $\overline{\delta\phi}$, καὶ δέον ἔστω τὴν σύνεγγυς αὐτοῦ



τετραγωνικὴν πλευρὰν ἐπιλογίσασθαι. ἐπεὶ οὖν ὁ

^a The method which Theon proposes to use may be summarized as follows. A first approximation to the square root

ARITHMETICAL NOTATION

In order to show visually, for one of the numbers in the *Syntaxis*, this extraction of the root by taking away the parts, we shall construct the proof for the number 4500°, whose side he [Ptolemy] made 67° 4' 55". Let ABΓΔ be a square area, the square alone being rational, and let its contents be 4500°, and let it be required to calculate the side of a square approximating to it.^a Since the square

of 4500 is 67, for $67^2 = 4489$. (This suggests that Theon may have had a table of squares before him.) Theon proposes to find the square root of 4500 in the form $67 + \frac{x}{60} + \frac{y}{60^2}$. That is,

$$\sqrt{4500} = \sqrt{67^2 + 11} = 67 + \frac{x}{60} + \frac{y}{60^2}.$$

It follows from Euclid ii. 4 that $\frac{2.67x}{60}$ must be less than 11, or x must be less than $\frac{660}{2.67}$. The nearest whole number obtained by dividing 2.67 into 660 is 4, and we try 4 for the value of x . On trial it is found that 4 satisfies the conditions of the problem, for $\left(67 + \frac{4}{60}\right)^2$ is less than 4500, the remainder being $\frac{7424}{60^2}$. Theon proves this geometrically. If AE = 67, then the square AZ = 4489 and the gnomon BZZΔ is therefore 11, or $\frac{660}{60}$. Putting EΘ = HK = $\frac{4}{60}$, we have rect. ΘZ = rect. ZK = $\frac{4.67}{60} = \frac{268}{60}$. Their sum is $\frac{536}{60}$ and this we subtract from $\frac{660}{60}$, getting $\frac{124}{60}$ or $\frac{7440}{60^2}$. From this we subtract $\frac{16}{60^2}$, being the value of the square ZΛ, and so get $\frac{7424}{60^2}$ for the remaining gnomon BΛΛΔ, as was stated above. This remainder now serves as a basis to obtain the third term y of the quotient. Since $\left\{\left(67 + \frac{4}{60}\right) + \frac{y}{60^2}\right\}^2$ is approximately 4500, we have by

GREEK MATHEMATICS

σύνεγγυς τοῦ $\overline{\delta\phi}$ τετράγωνος ῥητὴν ἔχων πλευρὰν ὄλων μονάδων ἐστὶν $\overline{\delta\psi\theta}$ ἀπὸ πλευρᾶς τοῦ $\overline{\xi\zeta}$, ἀφηρήσθω ἀπὸ τοῦ $\overline{AB\Gamma\Delta}$ τετραγώνου τὸ \overline{AZ} τετράγωνον μονάδων $\overline{\delta\psi\theta}$, οὗ ἡ πλευρὰ ἔστω μονάδων $\overline{\xi\zeta}$. ὁ λοιπὸς ἄρα ὁ $\overline{BZZ\Delta}$ γνώμων ἔσται μονάδων $\overline{\iota\alpha}$, ἃς ἀναλύσαντες εἰς πρῶτα ἐξηκοστὰ $\overline{\chi\xi}$ ἐκθησόμεθα. ἔπειτα διπλασιάσαντες τὴν \overline{EZ} διὰ τὸ δις ὑπὸ \overline{EZ} , ὡσπερ ἐπ' εὐθείας τῆς \overline{EZ} τὴν \overline{ZH} λαμβάνοντες, παρὰ τὰ γενόμενα $\overline{\rho\lambda\delta}$ παραβαλοῦμεν τὰ $\overline{\chi\xi}$ ἐξηκοστὰ πρῶτα, καὶ τῶν γενομένων ἐκ τῆς παραβολῆς δ πρώτων ἐξηκοστῶν ἔξομεν ἑκατέραν τῶν $\overline{E\Theta}$, \overline{HK} . καὶ ἀναπληρώσαντες τὰ $\overline{\Theta Z}$, \overline{ZK} παραλληλόγραμμα ἔξομεν καὶ αὐτὰ $\overline{\phi\lambda\sigma}$ πρώτων ἐξηκοστῶν, ἑκάτερον δὲ ὄν $\overline{\sigma\xi\eta}$. εἶτα πάλιν τὰ ὑπολιπέντα $\overline{\rho\kappa\delta}$ πρῶτα ἐξηκοστὰ ἀναλύσαντες εἰς δευτέρα $\overline{\zeta\upsilon\mu}$, ἀφελοῦμεν καὶ τὸ $\overline{Z\Lambda}$ ἀπὸ πρώτων δ γενόμενον ἐξηκοστῶν δευτέρων $\overline{\iota\sigma}$, ἵνα γνώμονα περιθέντες τῷ ἐξ ἀρχῆς τετραγώνῳ τῷ \overline{AZ} ἔχωμεν τὸ $\overline{A\Lambda}$ τετράγωνον ἀπὸ πλευρᾶς $\overline{\xi\zeta}$ δ συναγόμενον μοιρῶν $\overline{\delta\upsilon\zeta\zeta}$ $\overline{\nu\sigma}$ $\overline{\iota\sigma}$. καὶ λοιπὸν πάλιν τὸν $\overline{B\Lambda\Lambda\Delta}$ γνώμονα μοιρῶν $\overline{\beta}$ $\overline{\gamma}$ $\overline{\mu\delta}$, τουτέστιν δευτέρων ἐξηκοστῶν $\overline{\zeta\upsilon\kappa\delta}$. ἔτι δὲ πάλιν διπλασιάσαντες τὴν $\overline{\Theta\Lambda}$ ὡς ἐπ' εὐθείας τυγχανούσης τῇ $\overline{\Theta\Lambda}$ τῆς $\overline{\Lambda K}$, καὶ παρὰ τὰ γινόμενα $\overline{\rho\lambda\delta}$ η μερίσαντες τὰ $\overline{\zeta\upsilon\kappa\delta}$ δευτέρα ἐξηκοστά, τῶν ἐκ τῆς παραβολῆς γενομένων $\overline{\nu\epsilon}$ ἔγγιστα δευτέρων ἐξηκοστῶν ἔχομεν

Euclid ii. 4 that $2\left(67 + \frac{4}{60}\right) \cdot \frac{y}{60^2} + \left(\frac{y}{60^2}\right)^2$ is approximately $\frac{7424}{60^2}$,

and we obtain a trial value for y by dividing $2\left(67 + \frac{4}{60}\right)$ or

ARITHMETICAL NOTATION

which approximates to 4500° but has a rational side and consists of a whole number of units is 4489° on a side of 67° , let the square AZ, with area 4489° and side 67° , be taken away from the square $AB\Gamma\Delta$. The remainder, the gnomon $BZZ\Delta$, will therefore be 11° , which we reduce to $660'$ and set out. Then we double EZ, because the rectangle on EZ has to be taken twice, as though we regarded ZH as on the straight line EZ, divide the result 134° into $660'$, and by the division get $4'$, which gives us each of E Θ , HK. Completing the parallelograms ΘZ , ZK, we have for their sum $536'$, or $268'$ each. Continuing, we reduce the remainder, $124'$, into $7440''$, and subtract from it also the complement Z Λ , which is $16''$, in order that by adding a gnomon to the original square AZ we may have the square $\Lambda\Lambda$ on a side $67^\circ 4'$ and consisting of $4497^\circ 56' 16''$. The remainder, the gnomon $B\Lambda\Lambda\Delta$, consists of $2^\circ 3' 44''$, that is, $7424''$. Continuing the process, we double $\Theta\Lambda$, as though ΛK were in a straight line with $\Theta\Lambda$ and equal to it, divide the product $134^\circ 8'$ into $7424''$, and the result is approximately $55''$, which gives

$\left(134 + \frac{8}{60}\right)$ into 7424 , which yields $y = 55$. Putting $\frac{55}{60^2}$ as the value of ΘB , $K\Lambda$, we get the value $\frac{3688}{60^2} + \frac{40}{60^3}$ for each of the rectx. $B\Lambda$, $\Lambda\Delta$, or $\frac{7377}{60^2} + \frac{20}{60^3}$ for their sum. Subtracting this from $\frac{7424}{60^2}$ we get $\frac{46}{60^2} + \frac{40}{60^3}$, which Theon notes will be approximately the value of the square $\Lambda\Gamma$, or $\left(\frac{55}{60^2}\right)^2$. As a matter of fact, $\frac{46}{60^2} + \frac{40}{60^3} = \frac{2800}{60^3} = \frac{16800}{60^4}$ while $\left(\frac{55}{60^2}\right)^2 = \frac{3025}{60^4}$.

GREEK MATHEMATICS

ἔγγιστα ἐκάτεραν τῶν ΘΒ, ΚΔ. καὶ συμπληρώσαντες τὰ ΒΑ, ΛΔ παραλληλόγραμμα, ἔξομεν καὶ αὐτὰ ἐξηκοστῶν δευτέρων μὲν ζτο καὶ τρίτων $\bar{\upsilon}\bar{\mu}$, ἐκάτερον δὲ δευτέρων μὲν ἐξηκοστῶν γχπε καὶ τρίτων $\bar{\sigma}\bar{\kappa}$.¹ καὶ λοιπὰ ὑπελίπη ἐξηκοστὰ δεύτερα $\bar{\mu}\bar{\varsigma}$ καὶ τρίτα $\bar{\mu}$, ἅπερ ἔγγιστα ποιεῖ τὸ ΛΓ τετράγωνον, ἀπὸ πλευρᾶς τυγχάνον $\bar{\nu}\bar{\epsilon}$ δευτέρων ἐξηκοστῶν, καὶ ἔσχομεν τὴν πλευρὰν τοῦ ΑΒΓΔ τετραγώνου, μοιρῶν τυγχάνοντος δφ, ξξ δ $\bar{\nu}\bar{\epsilon}$ ἔγγιστα.

“Ὡστε καὶ καθόλου ἐὰν ζητῶμεν ἀριθμοῦ τινος τὴν τετραγωνικὴν πλευρὰν ἐπιλογίσασθαι, λαμβάνομεν πρῶτον τοῦ σύνεγγυς τετραγώνου ἀριθμοῦ τὴν πλευρὰν. εἶτα ταύτην διπλασιάσαντες καὶ παρὰ τὸν γινόμενον ἀριθμὸν μερίσαντες τὸν λοιπὸν ἀριθμὸν ἀναλυθέντα εἰς πρῶτα ἐξηκοστά, καὶ ἀπὸ τοῦ ἐκ τῆς παραβολῆς γενομένου ἀφελούμεν τετράγωνον, καὶ ἀναλύοντες πάλιν τὰ ὑπολειπόμενα εἰς δεύτερα ἐξηκοστά, καὶ μερίζοντες παρὰ τὸν διπλασίονα τῶν μοιρῶν καὶ ἐξηκοστῶν, ἔξομεν ἔγγιστα τὸν ἐπιζητούμενον τῆς πλευρᾶς τοῦ τετραγώνου χωρίου ἀριθμόν.

(d) EXTRACTION OF CUBE ROOT

Heron, *Metr.* iii. 20, ed. Schöne 178. 3-16

Ὡς δὲ δεῖ λαβεῖν τῶν $\bar{\rho}$ μονάδων κυβικὴν πλευρὰν $\bar{\nu}\bar{\upsilon}\bar{\nu}$ ἐροῦμεν.

¹ So the oldest ms. In others the numbers are worked out to the equivalent forms ζτοζ' κ'', γχπη' μ''.

^a In the Greek of the oldest ms. the numbers are given as 7370' 440''' and 3685'' 220''', in which form Theon would first

ARITHMETICAL NOTATION

us an approximation to ΘB , $K\Delta$. Completing the parallelograms BA , $\Lambda\Delta$, we shall have for their joint area $7377'' 20'''$, or $3688'' 40'''$ each.^a The remainder is $46'' 40'''$, which approximates to the square $\Lambda\Gamma$ on a side of $55''$, and so we obtain for the side of the square $AB\Gamma\Delta$, consisting of 4500° , the approximation $67^\circ 4' 55''$.

In general, if we seek the square root of any number, we take first the side of the nearest square number, double it, divide the product into the remainder reduced to minutes, and subtract the square of the quotient; proceeding in this way we reduce the remainder to seconds, divide it by twice the quotient in degrees and minutes, and we shall have the required approximation to the side of the square area.^b

(d) EXTRACTION OF CUBE ROOT

Heron, *Metrics* iii. 20, ed. Schöne 178. 3-16

We shall now inquire into the method of extracting the cube root of 100.

obtain them. In other mss. the numbers are worked out to the form $7377'' 20'''$, $3688'' 40'''$.

^b In his Table of Chords Ptolemy gives the approximation

$$\sqrt[3]{3} = \frac{103}{60} + \frac{55}{60^2} + \frac{23}{60^3},$$

which is equivalent to 1.7320509 and is correct to six decimal places. This formula could be obtained by a slight adaptation of Theon's method.

Archimedes gives, without any explanation, the following approximation :

$$\frac{1351}{780} > \sqrt[3]{3} > \frac{265}{153}.$$

The formula opens up a wide field of conjecture. See Heath, *The Works of Archimedes*, pp. lxxx-xcix.

GREEK MATHEMATICS

Λαβὲ τὸν ἔγγιστα κύβον τοῦ $\bar{\rho}$ τὸν τε ὑπερβάλλοιτα καὶ τὸν ἐλλείποντα· ἔστι δὲ ὁ $\overline{\rho\kappa\epsilon}$ καὶ ὁ $\overline{\xi\delta}$. καὶ ὅσα μὲν ὑπερβάλλει, μονάδες $\overline{\kappa\epsilon}$, ὅσα δὲ ἐλλείπει, μονάδες $\overline{\lambda\sigma}$. καὶ ποιήσον τὰ $\bar{\epsilon}$ ἐπὶ τὰ $\overline{\lambda\sigma}$. γίγνεται $\overline{\rho\pi}$. καὶ τὰ $\bar{\rho}$ γίγνεται $\overline{\sigma\pi}$. (καὶ παράβαλε id'

τὰ $\overline{\rho\pi}$ παρὰ τὰ $\overline{\sigma\pi}$.)¹ γίγνεται θ . πρόσβαλε τῇ [κατὰ] τοῦ ἐλάσσονος κύβου πλευρᾶ, τουτέστι τῷ id'

$\bar{\delta}$. γίγνεται μονάδες $\bar{\delta}$ καὶ θ τοσοῦτων ἔσται ἡ τῶν $\bar{\rho}$ μοιᾶδων κυβικὴ πλευρὰ ὡς ἔγγιστα.

¹ καὶ παράβαλε τὰ $\overline{\rho\pi}$ παρὰ τὰ $\overline{\sigma\pi}$ supplevit H. Schöne.

^a If p^3 and q^3 are the two cube numbers between which A lies, and $A = p^3 - a = q^3 + b$, then Heron's formula can be generalized as follows :

$$\sqrt[3]{A} = q + \frac{b\sqrt{a}}{A + b\sqrt{a}}$$

It is unlikely that Heron worked with this general formula ; his method was probably empirical. The subject is discussed

ARITHMETICAL NOTATION

Take the nearest cube in excess of 100 and also the nearest which is deficient ; they are 125 and 64. The excess of the former is 25, the deficiency of the latter 36. Now multiply 36 by 5 ; the result is 180 ; and adding 100 gives 280. Dividing 180 by 280 gives $\frac{9}{14}$. Add this to the side of the lesser cube, that is, to 4, and the result is $4\frac{9}{14}$. This ^a is the closest approximation to the cube root of 100.

by M. Curtze, *Quadrat- und Kubikwurzeln bei den Griechen nach Herons neu aufgefundenen Μετρικά* (*Zeitschrift f. Math. u. Phys.* xlii., 1897, *Hist.-lit. Abth.*, pp. 113-120), G. Wertheim, *Herons Ausziehung der irrationalen Kubikwurzeln* (*ibid.* xliv., 1899, *Hist.-lit. Abth.*³, pp. 1-3), and G. Eneström, *Bibliotheca Mathematica*, viii., 1907-1908, pp. 412-413. The actual value of $(4\frac{9}{14})^3$ is $100\frac{2}{27}\frac{5}{14}$.

There is no example in Greek mathematics of the extraction of a cube root fully worked out by means of the formula $(a+x)^3 = a^3 + 3a^2x + 3ax^2 + x^3$, corresponding to Theon's method for square roots : but by means of this formula Philon of Byzantium (*Mech. Synt.* iv. 6-7, ed. R. Schöne) appears to have approximated to the cube roots of 1500, 2000, 3000, 5000 and 6000. Heron (*Metrica* iii. 22, ed. H. Schöne 184. 1-2) gives without explanation 46 as the cube root of 97 050.

III. PYTHAGOREAN ARITHMETIC

III. PYTHAGOREAN ARITHMETIC

(a) FIRST PRINCIPLES

Eucl. *Elem.* vii.

Ὅροι

α'. Μονάς ἐστίν, καθ' ἣν ἕκαστον τῶν ὄντων ἐν λέγεται.

β'. Ἀριθμὸς δὲ τὸ ἐκ μονάδων συγκείμενον πλῆθος.

γ'. Μέρος ἐστὶν ἀριθμὸς ἀριθμοῦ ὁ ἐλάσσων τοῦ μείζονος, ὅταν καταμετρηῇ τὸν μείζονα.

δ'. Μέρη δέ, ὅταν μὴ καταμετρηῇ.

ε'. Πολλαπλάσιος δὲ ὁ μείζων τοῦ ἐλάσσονος, ὅταν καταμετρηῇται ὑπὸ τοῦ ἐλάσσονος.

ς'. Ἄρτιος ἀριθμὸς ἐστὶν ὁ δίχα διαιρούμενος.

ζ'. Περισσὸς δὲ ὁ μὴ διαιρούμενος δίχα ἢ [ὁ] μονάδι διαφέρων ἀρτίου ἀριθμοῦ.

η'. Ἀρτιάκις ἄρτιος ἀριθμὸς ἐστὶν ὁ ὑπὸ ἀρτίου ἀριθμοῦ μετρούμενος κατὰ ἄρτιον ἀριθμόν.

* The theory of numbers is treated by Euclid in Books vii.-x. The definitions prefixed to Book vii. are wholly Pythagorean in their outlook, though there are differences in

III. PYTHAGOREAN ARITHMETIC

(a) FIRST PRINCIPLES

Euclid, *Elements* vii.

DEFINITIONS ^a

1. A *unit* is that in virtue of which each of the things that exist is called one.

2. A *number* is a multitude composed of units.

3. A number is a *part* of a number, the less of the greater, when it measures the greater.

4. But *parts*, when it does not measure it.

5. The greater number is a *multiple* of the less when it is measured by the less.

6. An *even number* is one that is divisible into two equal parts.

7. An *odd number* is one that is not divisible into two equal parts, or that differs from an even number by a unit.

8. An *even-times even number*^b is one that is measured by an even number according to an even number.

detail. Heath's notes (*The Thirteen Books of Euclid's Elements*, vol. ii. pp. 279-295) are invaluable.

^b It is a consequence of this definition that an even-times even number may also be even-times odd, as 24 is both 6×4 and 8×3 (*cf.* Euclid ix. 34, where it is proved that this must be so for certain numbers). Three later writers, Nicomachus, Theon of Smyrna and Iamblichus, defined an even-times even number differently, as a number of the form 2^p .

GREEK MATHEMATICS

θ'. Ἄρτιάκῃς δὲ περισσός ἐστιν ὁ ὑπὸ ἀρτίου ἀριθμοῦ μετρούμενος κατὰ περισσὸν ἀριθμόν.

[ι'. Περισάκῃς ἄρτιός ἐστιν ὁ ὑπὸ περισσοῦ ἀριθμοῦ μετρούμενος κατὰ ἄρτιον ἀριθμόν.]¹

ια'. Περισάκῃς δὲ περισσός ἀριθμός ἐστιν ὁ ὑπὸ περισσοῦ ἀριθμοῦ μετρούμενος κατὰ περισσὸν ἀριθμόν.

ιβ'. Πρῶτος ἀριθμός ἐστιν ὁ μονάδι μόνῃ μετρούμενος.

ιγ'. Πρῶτοι πρὸς ἀλλήλους ἀριθμοί εἰσιν οἱ μονάδι μόνῃ μετρούμενοι κοινῶ μέτρῳ.

ιδ'. Σύνθετος ἀριθμός ἐστιν ὁ ἀριθμῶ τινι μετρούμενος.

ιε'. Σύνθετοι δὲ πρὸς ἀλλήλους ἀριθμοί εἰσιν οἱ ἀριθμῶ τινι μετρούμενοι κοινῶ μέτρῳ.

¹ ι'. περισάκῃς . . . ἀριθμόν om. Heiberg.

^a Instead of Euclid's term ἀρτιάκῃς περισσός, Nicomachus, Theon and Iamblichus used the single word ἀρτιοπέριττος. According to Nicomachus (*Arith. Introd.* i. 9) such a number, when divided by 2, leaves an odd number as the quotient, *i.e.*, it is of the form $2(2n+1)$. In this later subdivision an *odd-even* (περισσάρτιος) number is one which can be halved twice or more successively, but the final quotient is always an odd number and not unity, *i.e.*, a number of the form $2^{p+1}(2n+1)$. We thus have three mutually exclusive classes of even numbers: (1) *even-even*, of the form 2^p ; (2) *even-odd*, of the form $2(2n+1)$; and (3) *odd-even*, of the form $2^{p+1}(2n+1)$, where (1) and (3) are extremes and (2) partakes of the nature of both. The *odd-odd* is not defined by Nicomachus and Iamblichus, but according to a curious usage in Theon it is one of the names applied to prime numbers, for these have two odd factors, 1 and the number itself.

^b According to this definition, any even-times odd number would also be odd-times even. The definition appears to have been known to Iamblichus, but there can be little doubt

PYTHAGOREAN ARITHMETIC

9. An *even-times-odd number*^a is one that is measured by an even number according to an odd number.

[10. An *odd-times even number* is one that is measured by an odd number according to an even number.]^b

11. An *odd-times odd number* is one that is measured by an odd number according to an odd number.

12. A *prime number* is one that is measured by the unit alone.

13. Numbers *prime to one another* are those which are measured by a unit alone as a common measure.

14. A *composite number* is one that is measured by some number.

15. Numbers *composite to one another* are those which are measured by some number as a common measure.^c

that it is an interpolation. If both definitions are genuine, one is not only pointless but the enunciations of ix. 33 and ix. 34 become difficult to understand, and were, indeed, read differently by Iamblichus from what we find in our mss. We have to choose between accepting Iamblichus's reading in all three places and rejecting Def. 10 as interpolated. I agree with Heiberg (*Euklid-Studien*, pp. 198 *et seq.*) that the definition was probably interpolated by someone who was unaware of the difference between the Euclidean and the later Pythagorean classifications, but noticed the absence of a definition by Euclid of an odd-times even number and tried to supply one.

^c Euclid's definition of prime and composite numbers differs greatly from the classification of Nicomachus (*Arith. Introd.* i. 11-13) and Iamblichus. To match the three classes of even numbers, they devised three classes of odd numbers: (1) *πρῶτον καὶ ἀσύνθετον*, *prime and incomposite*, which is a prime number in the Euclidean sense; (2) *δεύτερον καὶ σύνθετον*, *secondary and composite*, which appears to be the product of prime numbers; and (3) *ὁ καθ' ἑαυτὸ μὲν δεύτερον καὶ σύνθετον, πρὸς ἄλλο δὲ πρῶτον καὶ ἀσύνθετον*, *that which is secondary and composite in itself, but prime and incomposite in relation to another*, where all the factors must

GREEK MATHEMATICS

ις'. Ἄριθμὸς ἀριθμὸν πολλαπλασιάζειν λέγεται, ὅταν, ὅσαι εἰσὶν ἐν αὐτῷ μονάδες, τοσαυτάκις συντεθῆ ὁ πολλαπλασιαζόμενος, καὶ γένηται τις.

ιζ'. Ὄταν δὲ δύο ἀριθμοὶ πολλαπλασιάσαντες ἀλλήλους ποιῶσί τινα, ὁ γενόμενος ἐπίπεδος καλεῖται, πλευραὶ δὲ αὐτοῦ οἱ πολλαπλασιάσαντες ἀλλήλους ἀριθμοί.

ιη'. Ὄταν δὲ τρεῖς ἀριθμοὶ πολλαπλασιάσαντες ἀλλήλους ποιῶσί τινα, ὁ γενόμενος στερεός ἐστιν, πλευραὶ δὲ αὐτοῦ οἱ πολλαπλασιάσαντες ἀλλήλους ἀριθμοί.

ιθ'. Τετράγωνος ἀριθμὸς ἐστὶν ὁ ἰσάκις ἴσος ἢ [ὁ] ὑπὸ δύο ἴσων ἀριθμῶν περιεχόμενος.

κ'. Κύβος δὲ ὁ ἰσάκις ἴσος ἰσάκις ἢ [ὁ] ὑπὸ τριῶν ἴσων ἀριθμῶν περιεχόμενος.

κα'. Ἄριθμοι ἀνάλογόν εἰσιν, ὅταν ὁ πρῶτος τοῦ δευτέρου καὶ ὁ τρίτος τοῦ τετάρτου ἰσάκις ἢ πολλαπλάσιος ἢ τὸ αὐτὸ μέρος ἢ τὰ αὐτὰ μέρη ᾧσιν.

κβ'. Ὅμοιοι ἐπίπεδοι καὶ στερεοὶ ἀριθμοὶ εἰσιν οἱ ἀνάλογον ἔχοντες τὰς πλευράς.

κγ'. Τέλειος ἀριθμὸς ἐστὶν ὁ τοῖς ἑαυτοῦ μέρεσιν ἴσος ᾧν.

be odd and prime. The classification is defective, as (2) includes (3). Another defect is that the term *composite* is restricted to odd numbers instead of being given, as by Euclid, its general signification. For an earlier and different use of the terms by Speusippus, see *infra*, p. 78 n. a.

^a For figured numbers, see *infra*, pp. 86-99.

^b "Ἀνάλογον, though usually written in one word, is equivalent to ἀνά λόγον, *in proportion*. It comes, however, in

PYTHAGOREAN ARITHMETIC

16. A number is said to *multiply* a number when that which is multiplied is added to itself as many times as there are units in the other, and so some number is produced.

17. And when two numbers have multiplied each other so as to make some number, the resulting number is called *plane*, and its sides are the numbers which have multiplied each other.^a

18. And when three numbers have multiplied each other so as to make some number, the resulting number is *solid*, and its sides are the numbers which have multiplied each other.

19. A *square number* is equal multiplied by equal, or one that is contained by two equal numbers.

20. And a *cube* is equal multiplied by equal and again by equal, or a number that is contained by three equal numbers.

21. Numbers are *proportional* ^b when the first is the same multiple, or the same part, or the same parts, of the second as the third is of the fourth.

22. *Similar plane* and *solid* numbers are those which have their sides proportional.

23. A *perfect number* ^c is one that is equal to [the sum of] its own parts.

Greek mathematics to be used practically as an indeclinable adjective. . . . Sometimes it is used adverbially" (Heath, *The Thirteen Books of Euclid's Elements*, vol. ii. p. 129).

This definition, inasmuch as it depends on the notion of a part of a number, is applicable only to commensurable magnitudes. A new definition, applicable to incommensurable as well as commensurable magnitudes, and due in substance though not necessarily in form to Eudoxus, is given by Euclid in *Elements* v. Def. 5 (see *infra*, pp. 444-447).

^c The term "perfect number" was apparently not used in this sense before Euclid. The subject is treated *infra*, pp. 74-87.

GREEK MATHEMATICS

(b) CLASSIFICATION OF NUMBERS

Philolaus ap. Stob. *Ecl.* i. 21. 7c, ed. Wachsmuth 188, 9-12 ;
Diels, *Forss.* i⁵. 108. 7-10

Ἐκ τοῦ Φιλολάου Περὶ κόσμου . . .

“Ὁ γὰρ μὲν ἀριθμὸς ἔχει δύο μὲν ἴδια εἶδη, περισσὸν καὶ ἄρτιον, τρίτον δὲ ἀπ’ ἀμφοτέρων μειχθέντων ἀρτιοπέριπτον· ἑκατέρω δὲ τῷ εἶδος πολλαὶ μορφαί, ὡς ἕκαστον αὐταυτὸ σημαίνει.”

Nicom. *Arith. Introd.* i. 7, ed. Hoche 13. 7-14. 12

Ἀριθμὸς ἐστὶ πλήθος ὠρισμένον ἢ μονάδων σύστημα ἢ ποσότητος χύμα ἐκ μονάδων συγκείμενον, τοῦ δὲ ἀριθμοῦ πρώτη τομὴ τὸ μὲν ἄρτιον, τὸ δὲ περιπτόν. ἔστι δὲ ἄρτιον μὲν, ὃ οἶόν τε εἰς δύο ἴσα διαιρεθῆναι μονάδος μέσον μὴ παρεμπιπτούσης, περιπτόν δὲ τὸ μὴ δυνάμενον εἰς δύο ἴσα μερισθῆναι διὰ τὴν προειρημένην τῆς μονάδος μεσιτείαν. οὗτος μὲν οὖν ὁ ὅρος ἐκ τῆς δημῶδους ὑπολήψεως· κατὰ δὲ τὸ Πυθαγορικὸν ἄρτιος ἀριθμὸς ἐστὶν ὃ τὴν εἰς τὰ μέγιστα καὶ τὰ ἐλάχιστα κατὰ ταῦτὸ τομὴν ἐπιδεχόμενος, μέγιστα μὲν πηλικότητι, ἐλάχιστα δὲ ποσότητι, κατὰ φυσικὴν τῶν δυὸ τούτων γενῶν ἀντιπεπόνθησιν, περισσὸς δὲ ὃ μὴ δυνάμενος τοῦτο παθεῖν, ἀλλ’ εἰς ἄνισα δύο τεμνόμενος. ἑτέρω δὲ τρόπῳ κατὰ τὸ παλαιὸν

^a The “ even-odd ” would seem to mean here the product of odd and even numbers. This agrees with Euclid’s usage in *Elem.* vii. Def. 9. For the later specialized Pythagorean meaning, see *supra*, p. 68 n. a.

^b If an odd number is set out as $2n+1$ units in a straight line, then it can be divided into two sections of n units

PYTHAGOREAN ARITHMETIC

(b) CLASSIFICATION OF NUMBERS

Philolaus, cited by Stobaeus, *Extracts* i. 21. 7c, ed. Wachsmuth 188. 9-12; Diels, *Fors.* i⁵. 408. 7-10

From Philolaus's book *On the Universe* . . .

“Number is of two special kinds, odd and even, with a third, even-odd,^a arising from a mixture of both; and of each kind there are many forms, which each thing exhibits in itself.”

Nicomachus, *Introduction to Arithmetic* i. 7, ed. Hoche 13. 7-14. 12

Number is a determinate multitude or collection of units or flow of quantity made up of units, and the first division of number is into the even and odd. Now the even is that which can be divided into two equal parts, without a unit inserting itself in the middle, while the odd is that which cannot be divided into two equal parts owing to the unit inserting itself as aforesaid.^b This is the definition commonly accepted; but according to the Pythagoreans an even number is that which is divided, by one and the same operation, into the greatest and the least parts, greatest in size but least in quantity,^c in accordance with a natural reciprocity of the two species, while an odd number cannot be so divided but is only divisible into two unequal parts. There is another ancient way of defining an even number

measured from either end, with a single unit left over in the middle; but an even number of $2n$ units can be divided into two equal sections with no unit left over in the middle.

^c *i.e.* into two halves, for there cannot be any part greater than half nor fewer parts than two.

GREEK MATHEMATICS

ἄρτιός ἐστιν ὁ καὶ εἰς δύο ἴσα τμηθῆναι δυνάμενος καὶ εἰς ἄνισα δύο, πλὴν τῆς ἐν αὐτῷ ἀρχοειδοῦς δυάδος θάτερον τὸ διχοτόμημα μόνον ἐπιδεχομένης τὸ εἰς ἴσα, ἐν ἧτινι οὖν τομῇ παρεμφαίνων τὸ ἕτερον εἶδος μόνον τοῦ ἀριθμοῦ, ὅπως ἂν διχασθῆ, ἀμέτοχον τοῦ λοιποῦ· περισσὸς δέ ἐστιν ἀριθμὸς ὁ καθ' ἣντιναοῦν τομὴν εἰς ἄνισα πάντως γινομένην ἀμφοτέρα ἅμα ἐμφαίνων τὰ τοῦ ἀριθμοῦ δυὸ εἶδη οὐδέποτε ἄκρατα ἀλλήλων, ἀλλὰ πάντοτε σὺν ἀλλήλοις. ἐν δὲ τῷ δι' ἀλλήλων ὄρω περιττός ἐστιν ὁ μονάδι ἐφ' ἑκάτερα διαφέρων ἀρτίου ἀριθμοῦ, τουτέστιν ἐπὶ τὸ μείζον καὶ ἔλαττον, ἄρτιος δὲ ὁ μονάδι διαφέρων ἐφ' ἑκάτερον περισσοῦ ἀριθμοῦ, τουτέστι μονάδι μείζων καὶ μονάδι ἐλάσσων.

(c) PERFECT NUMBERS

[Jambl.] *Theol. Arith.*, ed. de Falco 82. 10-85. 23; Diels, *Vors.* i⁵. 400. 22-402. 11

Ὅτι καὶ Σπεύσιππος, ὁ Πρωτῶν μὲν υἱὸς τῆς τοῦ Πλάτωνος ἀδελφῆς, διάδοχος δὲ Ἀκαδημείας πρὸ Ξενοκράτου, ἐκ τῶν ἐξαιρέτως σπουδασθεισῶν αἰεὶ Πυθαγορικῶν ἀκροάσεων, μάλιστα δὲ τῶν

^a It is probable that we have here a trace of an original conception according to which 2 (the dyad) was regarded as being, not a number, but the principle or beginning of the even, just as 1 was not regarded as a number, but the principle or beginning of number; for the qualification about the dyad seems clearly to be a later addition to the original definition. It must, however, have been pre-Platonic, for in *Parm.* 143 D Plato speaks of 2 as even. Aristotle, who adds (*Topics* Θ 2, 157 a 39) that 2 is the only even number which is prime, says (*Met.* A 5, 986 a 19) the Pythagoreans regarded the One as

PYTHAGOREAN ARITHMETIC

according to which it can be divided both into two equal parts and into two unequal parts, save in the case of the fundamental dyad, which can be divided only into two equal parts^a; but howsoever it be divided, it must have its two parts of the same kind,^b without partaking of the other kind; while the odd is that which, howsoever it be divided, always yields two unequal parts and so exhibits at one and the same time both species of number, never independent of one another but always together.^c To give a definition in terms one of another, the odd is that which differs from even number by a unit in both directions, that is, in the direction both of the greater and of the lesser, while the even is that which differs by a unit from odd number in either direction, that is, it is greater by a unit and less by a unit.

(c) PERFECT NUMBERS

[Iamblichus], *Theologumena Arithmeticae*, ed. de Falco
82. 10-85. 23; Diels, *Vors.* i⁵. 400. 22-402. 11

Speusippus, the son of Potone, sister of Plato, and his successor in the Academy before Xenocrates, was always full of zeal for the teachings of the Pythagoreans, and especially for the writings of Philolaus,

both odd and even. For this question, as well as many others arising in Greek arithmetic, the student may profitably consult *Nicomachus of Gerasa: Introduction to Arithmetic*, translated by Martin Luther D'Ooge, with studies in Greek arithmetic by Frank Egleston Robbins and Louis Charles Karpinski.

^b *i.e.* both odd or both even.

^c *i.e.* an odd number can be divided only into an odd number and an even number, never into two odd or two even numbers.

GREEK MATHEMATICS

Φιλολάου συγγραμμάτων, βιβλιδίων τι συντάξας
 γλαφυρὸν ἐπέγραψε μὲν αὐτὸ Περὶ Πυθαγορικῶν
 ἀριθμῶν, ἀπ' ἀρχῆς δὲ μέχρι ἡμίσεως περὶ τῶν ἐν
 αὐτοῖς γραμμικῶν ἐμμελέστατα διεξελθὼν πολυ-
 γωνίων τε καὶ παντοίων τῶν ἐν ἀριθμοῖς ἐπιπέδων
 ἅμα καὶ στερεῶν, περὶ τε τῶν πέντε σχημάτων, ἃ
 τοῖς κοσμικοῖς ἀποδίδονται στοιχείοις, ἰδιότητός
 <τε>¹ αὐτῶν καὶ πρὸς ἀλλήλα κοινότητος, <περὶ>²
 ἀναλογίας τε καὶ ἀντακολουθίας,³ μετὰ ταῦτα
 λοιπὸν θάτερον [τὸ]⁴ τοῦ βιβλίου ἡμισυ περὶ δεκάδος
 ἄντικρυς ποιεῖται, φυσικωτάτην αὐτὴν ἀποφαίνων
 καὶ τελεστικωτάτην τῶν ὄντων, οἷον εἶδος τι τοῖς
 κοσμικοῖς ἀποτελέσμασι τεχνικὸν ἀφ' ἑαυτῆς (ἀλλ'
 οὐχ ἡμῶν νομισάντων ἢ ὡς ἔτυχε) θεμέλιον ὑπ-
 ἀρχουσαν καὶ παράδειγμα παντελέστατον τῷ τοῦ
 παντός ποιητῆ θεῷ προεκκειμένην. λέγει δὲ τὸν
 τρόπον τοῦτον περὶ αὐτῆς.

“Ἔστι δὲ τὰ δέκα τέλειος <ἀριθμός>,⁵ καὶ ὀρθῶς
 τε καὶ κατὰ φύσιν εἰς τοῦτον καταπτῶμεν παντοίως
 ἀριθμοῦντες Ἕλληνές τε καὶ πάντες ἄνθρωποι
 οὐδὲν αὐτοῖ ἐπιτηδεύοντες· πολλὰ γὰρ ἴδια ἔχει, ἃ
 προσήκει τὸν οὕτω τέλειον ἔχειν, πολλὰ δὲ ἴδια μὲν
 οὐκ ἔστιν αὐτοῦ, δεῖ δὲ ἔχειν αὐτὰ τέλειον.

“Πρῶτον μὲν οὖν ἄρτιον δεῖ εἶναι, ὅπως ἴσοι
 ἐνῶσιν οἱ περιττοί τε καὶ ἄρτιοι, καὶ μὴ ἕτερο-
 μερῶς⁶. ἐπεὶ γὰρ πρότερος αἰεὶ ἔστιν ὁ περιττός τοῦ

¹ <τε> add. Diels.

² <περὶ> add. de Falco.

³ ἀντακολουθίας Lang : ἀνακολουθίας Ast, Tannery, Diels.

⁴ [τὸ] om. Diels.

⁵ ἀριθμός add. Diels.

⁶ ἕτερομερεῖς Diels.

^a For the five cosmic or Platonic figures, see *infra*, pp. 216-225.

PYTHAGOREAN ARITHMETIC

and he compiled a neat little book which he entitled *On the Pythagorean Numbers*. From the beginning up to half way he deals most elegantly with linear and polygonal numbers and with all the kinds of surfaces and solids in numbers ; with the five figures which he attributes to the cosmic elements,^a both in respect of their special properties and in respect of their similarity one to another ; and with proportion and reciprocity.^b After this he immediately devotes the other half of the book to the decad, showing it to be the most natural and most initiative of realities, inasmuch as it is in itself (and not because we have made it so or by chance) an organizing idea of cosmic events, being a foundation stone and lying before God the Creator of the universe as a pattern complete in all respects. He speaks about it to the following effect.

“Ten is a perfect number, and it is both right and according to Nature that we Greeks and all men arrive at this number in all kinds of ways when we count, though we make no effort to do so ; for it has many special properties which a number thus perfect ought to have, while there are many characteristics which, while not special to it, are necessary to its perfection.

“In the first place it must be even, in order that the odds and evens in it may be equal and not disparate. For since the odd is always prior to the even, unless

^b If, with Ast, Tannery and Diels we read ἀνακολουθίας for ἀντακολουθίας, the rendering is “proportion continuous and discontinuous,” but it is not easy to interpret this, though Tannery makes a valiant effort to do so. His French translation, notes and comments should be studied (*Pour l'histoire de la science hellène*, 2nd ed., pp. 374 seq., 386 seq., and *Mémoires scientifiques*, vol. i. pp. 281-289).

GREEK MATHEMATICS

ἀρτίου, εἰ μὴ ἄρτιος εἶη ὁ συμπεραίνων, πλεονεκτήσει ὁ ἕτερος.

“Εἶτα δὲ ἴσους ἔχειν χρή τοὺς πρώτους καὶ ἀσυνθέτους καὶ τοὺς δευτέρους καὶ συνθέτους· ὁ δὲ δέκα ἔχει ἴσους, καὶ οὐδεὶς ἄν ἄλλος ἐλάττων τῶν δέκα τοῦτο ἔπαθεν ἀριθμός, πλείων δὲ τάχα (καὶ γὰρ ὁ $\bar{\iota}\beta$ καὶ ἄλλοι τινές), ἀλλὰ πυθμὴν αὐτῶν ὁ δέκα· καὶ πρῶτος τοῦτο ἔχων καὶ ἐλάχιστος τῶν ἐχόντων τέλος τι ἔχει, καὶ ἴδιόν πως αὐτοῦ τοῦτο γέγονε τὸ ἐν πρώτῳ αὐτῷ ἴσους ἀσυνθέτους τε καὶ συνθέτους ὡφθαι.

“Ἐχων τε τοῦτο ἔχει πάλιν <ἴσους>¹ καὶ τοὺς πολλαπλασίους καὶ τοὺς ὑποπολλαπλασίους, ὧν εἰσι πολλαπλάσιοι· ἔχει μὲν γὰρ ὑποπολλαπλασίους τοὺς μεχρὶ πέντε, τοὺς δὲ ἀπὸ τῶν ἕξ μέχρι τῶν δέκα [οἱ]² πολλαπλασίους αὐτῶν· ἐπεὶ δὲ τὰ ζ οὐδενός, ἐξαιρετέον, καὶ τὰ δ ὡς πολλαπλάσια τοῦ $\bar{\beta}$, ὥστε ἴσους εἶναι πάλιν [δεῖ].³

“Ἐπι πάντες οἱ λόγοι ἐν τῷ $\bar{\iota}$, ὃ τε τοῦ ἴσου καὶ τοῦ μείζονος καὶ τοῦ ἐλάττονος καὶ τοῦ ἐπι-

¹ ἴσους add. Lang.

² οἱ om. Diels.

³ δεῖ om. Diels. He points out that the original reading may have been δ' , indicating the fourth property of the decad.

* One of the most noteworthy features of this passage is the early use of the terms *πρῶτοι καὶ ἀσύνθετοι* (*prime and incomposite*), *δευτέροι καὶ σύνθετοι* (*secondary and composite*), for which see *supra*, p. 69 n. c. The use is different from that of Nicomachus and Iamblichus. It seems that *prime and incomposite* numbers are prime numbers in the ordinary sense, including 2, as is the case with Euclid and Aristotle (*Topics* Θ 2, 157 a 39). *Secondary and composite* numbers

PYTHAGOREAN ARITHMETIC

the even were joined with it the other would predominate.

“ Next it is necessary that the prime and incomposite and the secondary and composite ^a should be equal ; now they are equal in the case of 10, and in the case of no other number which is less than 10 is this true, though numbers greater than 10 having this property (such as 12 and certain others ^b) can soon be found, but their base is 10. As the first number with this property and the least of those possessing it 10 has a certain perfection, and it is a property peculiar to itself that it is the first number in which the incomposite and the composite are equal.

“ In addition to this property it has an equal number of multiples and submultiples of those multiples ; for it has as submultiples the numbers up to 5, while those from 6 to 10 are multiples of them ; since 7 is a multiple of no number, it has to be omitted, but 4 must also be dropped as a multiple of 2, and so this brings about equality once more.^c

“ Furthermore all the ratios are in 10, for the equal and the greater and the less and the superparticular

are all composite numbers, the term not being limited to odd numbers as with Nicomachus. There is no suggestion of a third mixed class. The two equal classes according to Speusippus are 1, 2, 3, 5, 7 and 4, 6, 8, 9, 10. According to the later terminology the *prime and incomposite* numbers would be 3, 5, 7, while the only *secondary and composite* number would be 9.

^b Actually 10, 12 and 14 are the only numbers possessing this property.

^c In the series 1, 2 . . . 10 the submultiples are 1, 2, 3, 5 and the multiples are 6, 8, 9, 10. It is curious that though 1 is counted as a submultiple, all the other numbers are not counted as multiples of it ; to have admitted them as such would have destroyed the scheme.

GREEK MATHEMATICS

μορίου καὶ τῶν λοιπῶν εἰδῶν ἐν αὐτῷ, καὶ οἱ γραμμικοὶ <καὶ>¹ οἱ ἐπίπεδοι καὶ οἱ στερεοί. τὸ μὲν γὰρ α στιγμή, τὰ δὲ β γραμμή, τὰ δὲ γ τρίγωνον, τὰ δὲ δ πυραμῖς· ταῦτα δὲ πάντα ἐστὶ πρῶτα καὶ ἀρχαὶ τῶν καθ' ἕκαστον ὁμογενῶν. καὶ ἀναλογιῶν δὲ πρώτη αὕτη ἐστὶν ἢ ἐν αὐτοῖς ὀφθείῃσα, ἢ τὸ ἴσον μὲν ὑπερέχουσα, τέλος δὲ ἔχουσα ἐν τοῖς δέκα. ἔν τε ἐπιπέδοις καὶ στερεοῖς πρῶτά ἐστι ταῦτα, στιγμή, γραμμή, τρίγωνον, πυραμῖς· ἔχει δὲ ταῦτα τὸν τῶν δέκα ἀριθμὸν καὶ τέλος ἴσχει. τετρὰς μὲν γὰρ ἐν πυραμίδος γωνίαις ἢ βάσεσιν, ἐξὰς δὲ ἐν πλευραῖς, ὥστε δέκα· τετρὰς δὲ πάλιν ἐν στιγμῆς καὶ γραμμῆς διαστήμασι καὶ πέρασι, ἐξὰς δὲ ἐν τριγώνου πλευραῖς καὶ γωνίαις, ὥστε πάλιν δέκα. καὶ μὴν καὶ ἐν τοῖς σχήμασι κατ' ἀριθμὸν σκεπτομένῳ συμβαίνει². πρῶτον γὰρ ἐστὶ τρίγωνον τὸ ἰσόπλευρον, ὃ ἔχει μίαν πως

¹ καὶ add. Lang.

² <ταῦτό> συμβαίνει Lang (in adn.), de Falco.

^a Speusippus asserts that among the numbers 1, 2 . . . 10 all the different kinds of ratio can be found. The *super-particular* ratio is the ratio of the whole + an aliquot fraction, $1 + \frac{1}{n}$ or $\frac{n+1}{n}$, typified by the ratio known as ἐπίτριτος, or $\frac{4}{3}$. Tannery sees here an allusion to the ten kinds of proportion outlined by Nicomachus (see *infra*, pp. 114-124), and a proof of their ancient origin.

^b *i.e.*, 1, 2, 3, 4 form an arithmetical progression having 1 as the common difference and 10 as the sum.

^c *i.e.*, a pyramid has 4 angles (or 4 faces) and 6 sides, and so exhibits the number 10.

^d The reasoning is not very clear. Taking first a line and a point outside it, Speusippus notes that the line has 2 extremities and between the point and these 2 extremities are

PYTHAGOREAN ARITHMETIC

and the remaining varieties are in it,^a and so are the linear and plane and solid numbers. For 1 is a point, 2 is a line, 3 is a triangle and 4 is a pyramid ; all these are elements and principles of the figures like to them. In these numbers is seen the first of the progressions, that in which the terms exceed by an equal amount, and they have 10 for their sum.^b In surfaces and solids these are the elements—point, line, triangle, pyramid. The number 10 exhibits them and possesses perfection. For 4 is to be found in the angles or faces of a pyramid, and 6 in the sides,^c so making 10 ; again 4 is to be found in the intervals and extremities of the point and line, while 6 is in the sides and angles of a triangle,^d so as again to make 10. This also comes about in figures regarded from the point of view of number.^e For the first triangle is the equilateral, which has one side and angle ; I say one

2 intervals. This gives the number 4. A triangle has 3 sides and 3 angles, giving the number 6. Combining the point, the line and the triangle we thus get 10.

^e A very difficult passage follows, but Tannery seems successfully to have unravelled its meaning. There seems to be here, he notes, an ill-developed Pythagorean conception. The point or monad is necessarily simple. The line is a dyad with two species, straight and curved. The triangle is a triad with three kinds. The pyramid is a tetrad with four kinds. Clearly the three species of triangle are the equilateral, the isosceles and the scalene, where the number of different elements are respectively 1, 2, 3. Speusippus does not consider isosceles and scalene triangles in general, but takes particular cases, and it is worthy of note that the three triangles he considers are used in the *Timaeus* of Plato.

By analogy, the pyramids can be divided into four kinds : (1) all solid angles equal ; (2) three solid angles equal ; (3) two solid angles equal ; (4) all solid angles unequal. Here again Speusippus takes special cases, but he goes astray by giving the second class a square base, and has to force the analogy.

GREEK MATHEMATICS

γραμμὴν καὶ γωνίαν· λέγω δὲ μίαν, διότι ἴσας ἔχει·
 ἄσχιστον γὰρ αἰεὶ καὶ ἐνοειδὲς τὸ ἴσον· δεύτερον δὲ
 τὸ ἡμιτετράγωνον· μίαν γὰρ ἔχον παραλλαγὴν
 γραμμῶν καὶ γωνιῶν ἐν δυάδι ὁράται· τρίτον δὲ τὸ
 τοῦ ἰσοπλεύρου ἡμισυ τὸ καὶ ἡμιτρίγωνον· πάντως
 γὰρ ἄνισον καθ' ἕκαστον, τὸ δὲ πάντῃ¹ αὐτοῦ τρία
 ἐστί· καὶ ἐπὶ τῶν στερεῶν εὐρίσκοις ἂν ἄχρι τῶν
 τεττάρων προῖόν τὸ τοιοῦτο, ὥστε δεκάδος καὶ
 οὕτως ψαύει· γίνεται γὰρ πως ἡ μὲν πρώτη πυραμὶς
 μίαν πως γραμμὴν τε καὶ ἐπιφάνειαν ἐν ἰσότητι
 ἔχουσα, ἐπὶ τοῦ ἰσοπλεύρου ἰσταμένη· ἡ δε δευτέρα
 δύο, ἐπὶ² τετραγώνου ἐνηγερμένη, μίαν παραλλαγὴν
 ἔχουσα² παρὰ τῆς ἐπὶ τῆς βάσεως γωνίας, ὑπὸ
 τριῶν ἐπιπέδων περιεχομένη, τὴν κατὰ κορυφὴν
 ὑπὸ τεττάρων συγκλειομένη, ὥστε ἐκ τούτου δυάδι
 εἰοικέναι· ἡ δὲ τρίτη τριάδι, ἐπὶ ἡμιτετραγώνου
 βεβηκυῖα καὶ σὺν τῇ ὀφθείσῃ μιᾷ ὡς ἐν ἐπιπέδῳ
 τῇ ἡμιτετραγώνῳ ἔτι καὶ ἄλλην ἔχουσα διαφορὰν
 τὴν τῆς κορυφαίας γωνίας, ὥστε τριάδι ἂν ὁμοιοῖτο,
 πρὸς ὀρθὰς τὴν γωνίαν ἔχουσα τῇ τῆς βάσεως
 μέσῃ πλευρᾷ· τετράδι δὲ ἡ τετάρτη κατὰ ταυτά,
 ἐπὶ ἡμιτριγώνῳ³ βάσει συνισταμένη, ὥστε τέλος ἐν
 τοῖς δέκα λαμβάνειν τὰ λεχθέντα· τὰ αὐτὰ δὲ καὶ
 ἐν τῇ γενέσει· πρώτη μὲν γὰρ ἀρχὴ εἰς μέγεθος
 στιγμῆ, δευτέρα γραμμῆ, τρίτη ἐπιφάνεια, τέταρτον
 στερεόν.”

¹ πάντῃ Lang, de Falco; πᾶν [τι] Diels; Lang would like to read τὰ δὲ πάντα.

² ἐπὶ . . . ἔχουσα. Only one manuscript has these words; many emendations have been offered.

³ The manuscripts have ἡμιτετραγώνῳ, but ἡμιτριγώνῳ is required, as Tannery recognized.

PYTHAGOREAN ARITHMETIC

because they are equal ; for the equal is always indivisible and uniform. The second triangle is the half-square ; for with one difference in the sides and angles it corresponds to the dyad. The third is the half-triangle, which is half of the equilateral triangle ; for being completely unequal in every respect, its elements number three. In the case of solids, you would find this property also, but going up to four, so that the decad is reached in this way also. For the first pyramid, which is built upon an equilateral triangle, is in some sense unity, since by reason of its equality it has one side and one face ; the second pyramid, which is raised upon a square, has the angles at the base enclosed by three planes and that at the vertex by four, so that from this difference it resembles the dyad. The third resembles a triad, for it is set upon a half-square ; together with the one difference that we have seen in the half-square as a plane figure it presents another corresponding to the angle at the vertex ; there is therefore a resemblance between the triad and this pyramid, whose vertex lies on the perpendicular to the middle of the hypotenuse^a of the base. In the same way the fourth, rising upon a half-triangle as base, resembles a tetrad, so that the aforesaid figures find completion in the number 10. The same result is seen in their generation. For the first principle of magnitude is point, the second is line, the third is surface, the fourth is solid.”^b

^a Lit. “ side.”

^b The abrupt end suggests that the passage went on in this strain for some time ; but the historian of mathematics need not feel much disappointment.

GREEK MATHEMATICS

Theon Smyr., ed. Hiller 45. 9-46. 19

Ἔτι τε τῶν ἀριθμῶν οἱ μὲν τινες τέλειοι λέγονται, οἱ δ' ὑπερτέλειοι, οἱ δ' ἑλλιπείς. καὶ τέλειοι μὲν εἰσιν οἱ τοῖς αὐτῶν μέρεσιν ἴσοι, ὡς ὁ τῶν $\bar{\epsilon}$ · μέρη γὰρ αὐτοῦ ἡμισυ $\bar{\gamma}$, τρίτον $\bar{\beta}$, ἕκτον $\bar{\alpha}$, ἅτινα συντιθέμενα ποιεῖ τὸν $\bar{\epsilon}$. γεννῶνται δὲ οἱ τέλειοι τοῦτον τὸν τρόπον. εἴαν ἐκθῶμεθα τοὺς ἀπὸ μονάδος διπλασίους καὶ συντιθῶμεν αὐτούς, μέχρις οὗ ἂν γένηται πρῶτος καὶ ἀσύνθετος ἀριθμὸς, καὶ τὸν ἐκ τῆς συνθέσεως ἐπὶ τὸν ἔσχατον τῶν συντιθεμένων πολλαπλασιάσωμεν, ὁ ἀπογεννηθεὶς ἔσται τέλειος. οἷον ἐκκείσθωσαν διπλάσιοι $\bar{\alpha}$ $\bar{\beta}$ $\bar{\delta}$ $\bar{\eta}$ $\bar{\iota\varsigma}$. συνθῶμεν οὖν $\bar{\alpha}$ καὶ $\bar{\beta}$ · γίνεται $\bar{\gamma}$ · καὶ τὸν $\bar{\gamma}$ ἐπὶ τὸν ὑστερον τὸν ἐκ τῆς συνθέσεως πολλαπλασιάσωμεν, τουτέστιν ἐπὶ τὸν $\bar{\beta}$ · γίνεται $\bar{\epsilon}$, ὅς ἐστι πρῶτος τέλειος. ἂν πάλιν τρεῖς τοὺς ἐφεξῆς διπλασίους συνθῶμεν, $\bar{\alpha}$ καὶ $\bar{\beta}$ καὶ $\bar{\delta}$, ἔσται $\bar{\zeta}$ · καὶ τοῦτον ἐπὶ τὸν ἔσχατον τῶν τῆς συνθέσεως πολλαπλασιάσωμεν, τὸν $\bar{\zeta}$ ἐπὶ τὸν $\bar{\delta}$ · ἔσται ὁ $\bar{\kappa\eta}$, ὅς ἐστι δεῦτερος τέλειος. σύγκειται ἐκ τοῦ ἡμίσεος τοῦ $\bar{\iota\delta}$, τετάρτου τοῦ $\bar{\zeta}$, ἐβδόμου τοῦ $\bar{\delta}$, τεσσαρακαιδεκάτου τοῦ $\bar{\beta}$, εἰκοστοῦ ὀγδόου τοῦ $\bar{\alpha}$.

Ἐπερτέλειοι δὲ εἰσιν ὧν τὰ μέρη συντεθέντα μείζονά ἐστι τῶν ὅλων, οἷον ὁ τῶν $\bar{\iota\beta}$ · τούτου γὰρ ἡμισύ ἐστιν $\bar{\epsilon}$, τρίτον $\bar{\delta}$, τέταρτον $\bar{\gamma}$, ἕκτον $\bar{\beta}$, δωδέκατον $\bar{\alpha}$, ἅτινα συντεθέντα γίνεται $\bar{\iota\varsigma}$, ὅς ἐστι μείζων τοῦ ἐξ ἀρχῆς, τουτέστι τῶν $\bar{\iota\beta}$.

Ἐλλιπείς δὲ εἰσιν ὧν τὰ μέρη συντεθέντα ἐλάττονα τὸν ἀριθμὸν ποιεῖ τοῦ ἐξ ἀρχῆς προτεθέντος

^a In other words, if $S_n = 1 + 2 + 2^2 + \dots + 2^{n-1}$, and S_n is prime, then $S_n \cdot 2^{n-1}$ is a perfect number. This is proved in 84

PYTHAGOREAN ARITHMETIC

Theon of Smyrna, ed. Hiller 45. 9-46. 19

Furthermore certain numbers are called *perfect*, some *over-perfect*, others *deficient*. Perfect numbers are those that are equal to their own parts, such as 6 ; for its parts are the half 3, the third 2 and the sixth 1, which added together make 6. Perfect numbers are produced in this manner. If we take successive double numbers starting from the unit and add them until a prime and incomposite number is found, and then multiply the sum by the last of the added terms, the resulting number will be perfect.^a For example, let the doubles be 1, 2, 4, 8, 16. We therefore add together 1 and 2 ; the result is 3 ; and we multiply 3 by the last of the added terms, that is by 2 ; the result is 6, which is the first perfect number. Again, if we add together three doubles in order, 1 and 2 and 4, the result will be 7 ; and we multiply this by the last of the added terms, that is, we multiply 7 by 4 ; the result will be 28, which is the second perfect number. It is composed out of its half 14, its fourth part 7, its seventh part 4, its fourteenth part 2 and its twenty-eighth part 1.

Over-perfect numbers are those whose parts added together are greater than the wholes, such as 12 ; for the half of this number is 6, the third is 4, the fourth is 3, the sixth is 2 and the twelfth 1, which added together produce 16, and this is greater than the original number, 12.

Deficient numbers are those whose parts added together make a number less than the one originally

Euclid ix. 36. Even the algebraic proof is too long for reproduction here, but for such a proof the reader may be referred to Heath, *The Thirteen Books of Euclid's Elements*, vol. ii. pp. 424-425.

GREEK MATHEMATICS

ἀριθμοῦ, οἷον ὁ τῶν η . τούτου γὰρ ἤμισυ δ , τετάρτον β , ὄγδοον ἔν· τὸ αὐτὸ δὲ καὶ τῶ ι συμβέβηκεν, ὄν καθ' ἕτερον λόγον τέλειον ἔφασαν οἱ Πυθαγορικοί, περὶ οὗ κατὰ τὴν οἰκείαν χώραν ἀποδώσομεν. λέγεται δὲ καὶ ὁ γ τέλειος, ἐπειδὴ πρῶτος ἀρχὴν καὶ μέσα καὶ πέρασ ἔχει· ὁ δ' αὐτὸς καὶ γραμμὴ ἔστι καὶ ἐπίπεδον, τρίγωνον γὰρ ἰσόπλευρον ἐκάστην πλευρὰν δυεῖν μονάδων ἔχον, καὶ πρῶτος δεσμὸς καὶ στερεοῦ δύναμις· ἐν γὰρ τρισὶ διαστάσεσι τὸ στερεὸν νοεῖσθαι.

(d) FIGURED NUMBERS

(i.) General

Nicom. *Arith. Introd.* ii. 7. 1-3, ed. Hoche 86. 9-87. 6

Ἔστιν οὖν σημεῖον ἀρχὴ διαστήματος, οὐ διάστημα δέ, τὸ δ' αὐτὸ καὶ ἀρχὴ γραμμῆς, οὐ γραμμὴ

^a There were in use among the Greeks two ways of representing numbers geometrically. One, used by Euclid and implied in Plato, *Theaetetus* 147 D—148 B (see *infra*, p. 380), is to represent numbers by straight lines proportional in length to the numbers they represent. If two such lines are made adjacent sides of a rectangle, then the rectangle represents their product; if three such lines are made sides of a rectangular parallelepiped then the parallelepiped is the product. The other way of representing numbers was by dots or alphas for the units disposed along straight lines so as to form geometrical patterns, a method greatly developed by the Pythagoreans. Any number could be represented as a straight line, and prime numbers only as

86

PYTHAGOREAN ARITHMETIC

put forth, such as 8 ; for the half of this number is 4, the fourth 2, the eighth 1. The same property is shown by 10, which the Pythagoreans called perfect for a different reason, and this we shall discuss in the proper place. The number 3 is also called perfect, since it is the first number which has a beginning and middle and end. It is moreover both a line and a surface, for it is an equilateral triangle in which each side is two units, and it is the first bond and power of the solid ; for in three dimensions is the solid conceived.

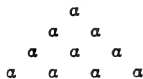
(d) FIGURED NUMBERS ^a

(i.) General

Nicomachus, *Introduction to Arithmetic* ii. 7. 1-3,
ed. Hoche 86. 9-87. 6

Point is therefore the principle of dimension, but is not dimension, while it is also the principle of line,

straight lines, whence Thymaridas spoke of them as "rectilinear *par excellence*" (Plato would have represented a prime number such as 7 by 7×1 , an oblong). The unit, being the source of all number, can be taken as a triangle, a pentagon, a hexagon, and so on. The first number after 1 which can be represented as a triangle is 3, and the sum of the first n natural numbers can always be represented as a triangle; the adjoining figure, a famous Pythagorean symbol, shows how this is done for $1 + 2 + 3 + 4 = 10$.

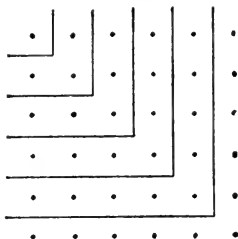


Square numbers can be represented in similar fashion, and the square of side $n + 1$ can be obtained from the square of side n by adding a gnomon of $2n + 1$ dots round the side (the term "gnomon" originally signified an upright stick which cast shadows on a plane or hemispherical surface, and so

GREEK MATHEMATICS

δέ· καὶ γραμμὴ ἀρχὴ ἐπιφανείας, οὐκ ἐπιφάνεια δέ, καὶ ἀρχὴ τοῦ διχῆ διαστατοῦ, οὐ διχῆ δὲ διαστατόν. καὶ εἰκότως ἢ ἐπιφάνεια ἀρχὴ μὲν σώματος, οὐ σῶμα δέ, καὶ ἢ αὐτὴ ἀρχὴ μὲν τοῦ τριχῆ διαστατοῦ, οὐ τριχῆ δὲ διαστατόν. οὕτως δὴ καὶ ἐν τοῖς ἀριθμοῖς ἢ μὲν μονὰς ἀρχὴ παντὸς ἀριθμοῦ ἐφ' ἓν διάστημα κατὰ μονάδα προβιβαζομένου, ὁ δὲ γραμμικὸς ἀριθμὸς ἀρχὴ ἐπιπέδου ἀριθμοῦ ἐφ' ἕτερον διάστημα ἐπιπέδως πλατυνομένου, ὁ δὲ ἐπίπεδος ἀριθμὸς ἀρχὴ στερεοῦ ἀριθμοῦ ἐπὶ τρίτον

could be used for telling the time ; it was later used of an

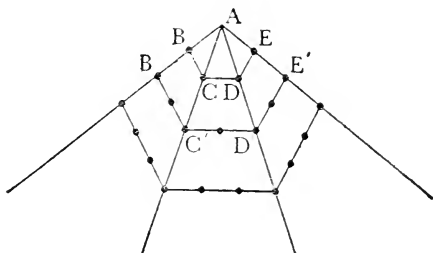


instrument for drawing right angles).

The first number after 1 which can be represented as a pentagon is 5. If it be represented as ABCDE, then we can form another pentagon AB'C'D'E, equivalent to 10, by adding the "gnomon of the pentagon," a row of an extra 7 dots arranged round three of the sides of the original pentagon. The gnomons to be added to form the successive pentagonal numbers 1, 5, 12, 22 . . . are respectively 4, 7, 10 . . ., or the successive terms of an arithmetical progression having 3 as the common difference. In the case of the hexagon the successive gnomonic numbers differ by 4, and in general, if n is the number of sides in the polygon, the successive gnomonic numbers differ by $n - 2$.

PYTHAGOREAN ARITHMETIC

but is not line ; and line is the principle of surface, but is not surface, and is the principle of the two-dimensional, but is not two-dimensional. Naturally also surface is the principle of body, but is not body, while it is the principle of the three-dimensional, but is not three-dimensional. Similarly among numbers the unit is the principle of every number set out by units in one dimension, while linear number is the principle of plane number broadened out in another dimension in the manner of a surface, and plane number is the principle of solid number, which acquires a certain depth in a third dimension [at



So much for plane numbers. There are similar varieties of solid numbers (cubes, pyramids, truncated pyramids, etc.). The curious reader will find the whole subject treated exhaustively by Nicomachus (*Arith. Introd.* ii. 7-20), Theon of Smyrna (ed. Hiller 26-42) and Iamblichus (*in Nicom. Arith. Introd.*, ed. Pistelli 58. 7 *et seq.*). It is of importance for the student of Greek mysticism, but has little interest for the modern mathematician.

GREEK MATHEMATICS

διάστημα πρὸς τὰ ἐξ ἀρχῆς βάθος τι προσκτω-
μένου· οἶον καθ' ὑποδιαίρεσιν γραμμικοὶ μὲν εἰσιν
ἀριθμοὶ ἀπλῶς ἅπαντες οἱ ἀπὸ δυάδος ἀρχόμενοι
καὶ κατὰ μονάδος πρόσθεσιν ἐπὶ ἓν καὶ τὸ αὐτὸ
προχωροῦντες διάστημα, ἐπίπεδοι δὲ οἱ ἀπὸ τριάδος
ἀρχόμενοι ἀρχικωτάτης ρίζης καὶ διὰ τῶν ἐξῆς
συνεχῶν ἀριθμῶν προϊόντες, λαμβάνοντες καὶ τὴν
ἐπωνυμίαν κατὰ τὴν αὐτὴν τάξιν· πρῶτιστοι γὰρ
τρίγωνοι, εἶτα μετ' αὐτοὺς τετράγωνοι, εἶτα μετ'
αὐτοὺς πεντάγωνοι, εἶτα ἐπὶ τούτοις ἑξάγωνοι καὶ
ἐπτάγωνοι καὶ ἐπ' ἄπειρον.

(ii.) *Triangular Numbers*

Luc. Vit. auct. 4

ΠΥΘΑΓΟΡΑΣ. Εἶτ' ἐπὶ τουτέοισιν ἀριθμέειν.

ΑΓΟΡΑΣΤΗΣ. Οἶδα καὶ νῦν ἀριθμεῖν.

ΠΥΘ. Πῶς ἀριθμέεις;

ΑΓΟ. Ἐν, δύο, τρία, τέτταρα.

ΠΥΘ. Ὅρας; ἃ σὺ δοκέεις τέσσαρα, ταῦτα
δέκα ἐστὶ καὶ τρίγωνον ἐντελὲς καὶ ἡμέτερον
ὄρκιον.

Procl. in Eucl. i., ed. Friedlein 428. 7-429. 8

Παραδέδονται δὲ καὶ μέθοδοί τινες τῆς εὐρέσεως
τῶν τοιούτων τριγώνων, ὧν τὴν μὲν εἰς Πλάτωνα

* This celebrated Pythagorean symbol was known as the
90

PYTHAGOREAN ARITHMETIC

right angles] to the dimensions of the surface. For example, by subdivision linear numbers are all numbers without exception beginning from two and proceeding by the addition of a unit in one and the same dimension, while plane numbers begin from three as their fundamental root and advance through an orderly series of numbers, taking their designation according to their order. For first come triangles, then after them are squares, then after these are pentagons, then succeeding these are hexagons and heptagons and so on to infinity.

(ii.) *Triangular Numbers*

Lucian, *Auction of Souls* 4

PYTHAGORAS. After this you must count.

AGORASTES. Oh, I know how to do that already.

PYTH. How do you count?

AGO. One, two, three, four.

PYTH. Do you see? What you think is four is ten, a perfect triangle and our oath.^a

Proclus, *on Euclid* i., ed. Friedlein 428. 7-429. 8

There have been handed down certain methods for the discovery of such triangles,^b of which one is

τετρακτύς. It was alternatively called the "principle of health" (Lucian, *De Lapsu in Salutando* 5). The sum of any number of successive terms (beginning with the first) of the series of natural numbers $1 + 2 + 3 + \dots + n$ is therefore a triangular number, and the general formula for a triangular number is $\frac{1}{2}n(n+1)$.

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^b *i.e.*, triangles having the square on one side equal to the sum of the squares on the other two. Proclus is commenting on Euclid i. 47, for which see *infra*, pp. 178-185.

GREEK MATHEMATICS

ἀναπέμπουσι, τὴν δὲ εἰς Πυθαγόραν. καὶ ἡ μὲν Πυθαγορικὴ ἀπὸ τῶν περιπτῶν ἐστὶν ἀριθμῶν. τίθησι γὰρ τὸν δοθέντα περιπτὸν ὡς ἐλάσσονα τῶν περὶ τὴν ὀρθὴν, καὶ λαβοῦσα τὸν ἀπ' αὐτοῦ τετραγώνον καὶ τούτου μονάδα ἀφελούσα τοῦ λοιποῦ τὸ ἥμισυ τίθησι τῶν περὶ τὴν ὀρθὴν τὸν μείζονα· προσθεῖσα δὲ καὶ τούτῳ μονάδα τὴν λοιπὴν ποιεῖ τὴν ὑποτείνουσαν· οἶον τὸν τρία λαβοῦσα καὶ τετραγωνίσασα καὶ ἀφελούσα τοῦ ἐννέα μονάδα τοῦ ἦ λαμβάνει τὸ ἥμισυ τὸν δ, καὶ τούτῳ προστίθησι πάλιν μονάδα καὶ ποιεῖ τὸν ε, καὶ εὔρηται τρίγωνον ὀρθογώνιον ἔχον τὴν μὲν τριῶν, τὴν δὲ τεσσάρων, τὴν δὲ πέντε.

Ἡ δὲ Πλατωνικὴ ἀπὸ τῶν ἀρτίων ἐπιχειρεῖ. λαβοῦσα γὰρ τὸν δοθέντα ἄρτιον τίθησιν αὐτὸν ὡς μίαν πλευρὰν τῶν περὶ τὴν ὀρθὴν, καὶ τοῦτον

^a i.e., if n is the given odd number, the sides of the triangle are

$$n, \frac{n^2 - 1}{2}, \frac{n^2 + 1}{2}$$

and the formula is an assertion that

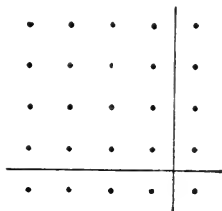
$$n^2 + \left(\frac{n^2 - 1}{2}\right)^2 = \left(\frac{n^2 + 1}{2}\right)^2.$$

PYTHAGOREAN ARITHMETIC

referred to Plato and one to Pythagoras. The Pythagorean method starts from the odd numbers. For it sets the given odd number as the lesser of the sides about the right angle, takes its square and subtracts a unit therefrom, and sets half the result as the greater of the sides about the right angle. Adding a unit to this it makes the resulting number the hypotenuse.^a For example, starting from 3 and squaring, the method obtains 9; a unit is subtracted, making 8, and the half of 8 is taken, making 4: to this a unit is added, giving 5, and in this way there is found a right-angled triangle having as its respective sides 3, 4 and 5.

The Platonic method starts from the even numbers. For taking the given even number it sets it as one of the sides about the right angle, divides

Heath (*H.G.M.* i. 80) shows how Pythagoras probably arrived at this formula by a system of dots forming a square. Starting with a square of side m , the square of side $m+1$ can be formed by adding a gnomon-like array of $2m+1$ dots round two sides. To obtain his formula, Pythagoras would only have to assume that $2m+1$ (necessarily an odd number) is a square.



Let

$$2m + 1 = n^2$$

then

$$m = \frac{n^2 - 1}{2}$$

$$m + 1 = \frac{n^2 + 1}{2}$$

and the array of dots shows that

$$n^2 + \left(\frac{n^2 - 1}{2}\right)^2 = \left(\frac{n^2 + 1}{2}\right)^2.$$

GREEK MATHEMATICS

διελούσα δίχα καὶ τετραγωνίσασα τὸ ἥμισυ, μονάδα μὲν τῷ τετραγώνῳ προσθείσα ποιεῖ τὴν ὑποτείνουσαν, μονάδα δὲ ἀφελούσα τοῦ τετραγώνου ποιεῖ τὴν ἑτέραν τῶν περὶ τὴν ὀρθήν· οἷον τὸν τέσσαρα λαβοῦσα καὶ τούτου τὸ ἥμισυ τὸν β̄ τετραγωνίσασα καὶ ποιήσασα αὐτὸν δ. ἀφελούσα μὲν μονάδα ποιεῖ τὸν γ̄, προσθείσα δὲ ποιεῖ τὸν ε̄, καὶ ἔχει τὸ αὐτὸ γενόμενον τρίγωνον, ὃ καὶ ἐκ τῆς ἑτέρας ἀπετελείτο μεθόδου. τὸ γὰρ ἀπὸ τούτου ἴσον τῷ ἀπὸ τοῦ γ̄ καὶ τῷ ἀπὸ τοῦ δ̄ συντεθείσιν.

(iii.) *Oblong and Square Numbers*

Aristot. *Phys.* Γ 4, 203 a 13-15

Περιτιθεμένων γὰρ τῶν γνωμόνων περὶ τὸ ἐν καὶ χωρὶς ὅτε μὲν ἄλλο αἰεὶ γίνεσθαι τὸ εἶδος, ὅτε δὲ ἔν.

(iv.) *Polygonal Numbers*

Nicom. *Arith. Introd.* ii. 12. 2-4, ed. Hoche 96. 11-97. 17

Δύο δὴ, οὓς ἂν θέλης, τριγώνους συνεχεῖς ἀλ-

^a *i.e.*, if $2n$ is the given even number, the sides of the triangle are $2n$, $n^2 + 1$, $n^2 - 1$, and the formula asserts that

$$(2n)^2 + (n^2 - 1)^2 = (n^2 + 1)^2.$$

Heath (*H.G.M.* i. 81) shows how this formula, like that of Pythagoras, could have been obtained from gnomons of dots. Both formulae can be deduced from Euclid ii. 5, a Pythagorean proposition (see *infra*, p. 194 n. a). A more general formula, including both the Pythagorean and Platonic methods, is given in the lemma to Euclid x. 28, which is equivalent to the assertion

$$m^2 n^2 p^2 q^2 + \left(\frac{mnp^2 - mnq^2}{2} \right)^2 = \left(\frac{mnp^2 + mnq^2}{2} \right)^2.$$

PYTHAGOREAN ARITHMETIC

this in two and squares the half, adds a unit to the square so as to make the hypotenuse and subtracts a unit from the square so as to make the other side about the right angle.^a For example, taking 4 and squaring the half, 2, it makes 4 again. Subtracting a unit it obtains 3, and adding one it makes 5, and yields the same triangle as that furnished by the other method. For the triangle constructed by this method is equal to that from 3 and from 4.

(iii.) *Oblong and Square Numbers*

Aristotle, *Physics* Γ 4, 203 a 13-15

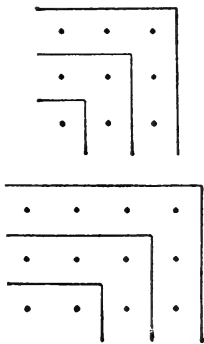
For when gnomons are placed round 1 the resulting figures are in one case always different, in the other they preserve one form.^b

(iv.) *Polygonal Numbers*

Nicomachus, *Introduction to Arithmetic* ii. 12. 2-4,
ed. Hoche 96. 11-97. 17

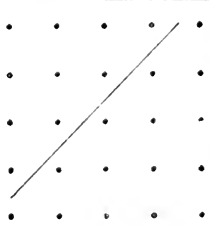
By taking any two successive triangular numbers

^b As was indicated on p. 86 n. a, when gnomons consisting of an *odd* number of dots are placed round 1 the result is always a square. When gnomons consisting of an *even* number of dots are placed round 2 the result is an oblong, and the successive oblongs are always different in form. This is probably what Aristotle refers to, but he does not indicate that the starting-point is in one case 1 and in the other 2; and the interpretation is modern, Themistius and Simplicius having other (and less attractive) explanations. The subject is fully discussed by W. D. Ross in his notes *ad loc.* (*Aristotle's Physics*, pp. 542-544).



GREEK MATHEMATICS

λήλοις συνθεῖς πάντως τετράγωνον ποιήσεις καὶ ὄντιν οὖν τετράγωνον ἄρα διαλύσας δυνήσῃ δύο ἀπ' αὐτῶν τριγώνους ποιήσαι· καὶ πάλιν παντὶ τετραγώνῳ σχήματι τρίγωνον προσζευχθὲν ὀθενοῦν πεντάγωνον ποιεῖ, οἷον τῷ δ̄ τετραγώνῳ ὁ \bar{a} τρίγωνος προσζευχθεὶς τὸν $\bar{\epsilon}$ πεντάγωνον ποιεῖ καὶ τῷ $\bar{\theta}$ τῷ ἐξῆς ὁ ἐξῆς προστεθείς, δηλονότι ὁ $\bar{\gamma}$, πεντάγωνον τὸν $\bar{\iota\beta}$ ποιεῖ, τῷ δὲ $\bar{\iota\varsigma}$ ὄντι ἀκολουθῶ ὁ $\bar{\sigma}$ ἀκόλουθος ἐπισυντεθείς τὸν $\bar{\kappa\beta}$ ἀκόλουθον ἀποδίδωσιν καὶ τῷ $\bar{\kappa\epsilon}$ ὁ $\bar{\iota}$ τὸν $\bar{\lambda\epsilon}$ καὶ αἰεὶ οὕτως. κατὰ δὲ τὰ αὐτὰ καὶ τοῖς πενταγώνοις οἱ τρίγωνοι προστιθοῖντο τῇ αὐτῇ τάξει, τοὺς εὐτάκτους γεννήσουσιν ἐξαγώνους καὶ πάλιν ἐκείνοις οἱ αὐτοὶ προσπλεκόμενοι τοὺς ἐν τάξει ἑπταγώνους ποιήσουσι καὶ μετ' ἐκείνους τοὺς ὀκταγώνους καὶ τοῦτο ἐπ' ἄπειρον. πρὸς δὲ ὑπόμνησιν ἐκκείσθωσαν ἡμῖν πολυγώνων στίχοι παραλλήλως γεγραμμένοι οἷδε, ὁ πρῶτος τρίγωνων, ὁ μετ' αὐτὸν τετραγώνων, μετὰ δὲ ἀμφοτέρους πενταγώνων, εἶτα ἐξαγώνων, εἶτα ἑπταγώνων, εἶτα, εἰ ἐθέλοι τις, καὶ τῶν ἐξῆς πολυγώνων·



^a In other words $\frac{1}{2}(n-1)n + \frac{1}{2}n(n+1) = n^2$, as may easily be seen from an array of dots. Here the square, of side n , is split up into two triangular numbers of side $n-1$, n whose values are therefore $\frac{1}{2}(n-1)n$, $\frac{1}{2}n(n+1)$. Theon of Smyrna (ed. Hiller 41. 3-8) gives the same theorem.

^b The general formula for an a -gonal number of side n is $n + \frac{1}{2}n(n-1)(a-2)$,

PYTHAGOREAN ARITHMETIC

you please and adding them one to another you will make the whole into a square, and whatsoever square you split up you will be able to make two triangles from it.^a Again, a triangle joined to any square figure makes a pentagon ; for example, when the triangle 1 is added to the square 4 it makes the pentagon 5, and when the next triangle in order, which is plainly 3, is joined to 9, the next square, it makes 12, while 6, the next successive triangle, added to 16, the next successive square, will yield 22, the next successive pentagon, and 10 added to 25 will make 35, and so on without limit. In the same way if the triangles are added to the corresponding pentagons, they will produce the hexagons in an orderly series, and the triangles linked with them in turn will give the heptagons in order, and after them the octagons, and so on to infinity.^b To help the memory let the various polygonal numbers be written out in parallel rows, the first consisting of triangles, the next of squares, the next after these of pentagons, then of hexagons, then of heptagons, then, if it is so desired, of the other polygonal numbers in order.

as is proved below, p. 98 n. a, and Nicomachus's assertion is equivalent to saying

$$n + \frac{1}{2}n(n-1)(a-2) = n + \frac{1}{2}n(n-1)(a-3) + \frac{1}{2}n(n-1).$$

GREEK MATHEMATICS

μήκος καὶ πλάτος

τρίγωνοι	α	γ	ς	ι	ιε	κα	κη	λς	με	νε	βάθος
τετράγωνοι	α	δ	θ	ις	κε	λς	μβ	ξδ	πα	ρ	
πεντάγωνοι	α	ε	ιβ	κβ	λε	να	ο	ςβ	ριζ	ρμε	
έξάγωνοι	α	ς	ιε	κη	με	ξς	ζα	ρκ	ρηγ	ρς	
έπτάγωνοι	α	ζ	ιη	λδ	νε	πα	ριβ	ρμη	ρπθ	σλε	

(v.) Gnomons of Polygonal Numbers

Iambl. in *Nicom. Arith. Introd.*, ed. Pistelli 62. 10-18

Καὶ ἐν τῇ σχηματογραφίᾳ δὲ τῶν πολυγώνων δύο μὲν ἐπὶ πάντων αἱ αὐταὶ μενοῦσι πλευραὶ μηκυνόμεναι καθ' ἕκαστον, αἱ δὲ παρὰ ταύτας ἐναποληφθήσονται τῇ τῶν γνωμόνων περιθέσει αἰεὶ ἀλλασσόμεναι, μία μὲν ἐν τριγώνῳ, δύο δὲ ἐν τετραγώνῳ καὶ τρεῖς ἐν πενταγώνῳ καὶ ὁμοίως ἐπ' ἄπειρον, κατὰ δυνάδος κἀνταῦθα διαφορὰν τῆς κλήσεως τῶν πολυγώνων πρὸς τὴν ποσότητα τῶν ἀλλασσομένων γινομένης.

* *i.e.*, the principle will be made clear from the figures for the gnomons of the square and pentagon given on pp. 86-89 *n. a.* The general formula is that in a polygon of a sides, the number of sides changed to form the next highest polygon

PYTHAGOREAN ARITHMETIC

BREADTH AND LENGTH

Triangles	1	3	6	10	15	21	28	36	45	55	depth
Squares	1	4	9	16	25	36	49	64	81	100	
Pentagons	1	5	12	22	35	51	70	92	117	145	
Hexagons	1	6	15	28	45	66	91	120	153	190	
Heptagons	1	7	18	34	55	81	112	148	189	235	

(v.) *Gnomons of Polygonal Numbers*

Iamblichus, *On Nicomachus's Introduction to Arithmetic*,
ed. Pistelli 62. 10-18

Now in the representation of the polygons two of the sides always remain the same but are produced, while the sides intercepted between them are continually changed when the gnomons are placed round, one being changed in the triangle, two in the square, three in the pentagon and so on to infinity, the difference between the designation of the polygons and the number of sides changed being two.^a

is $a-2$. (This leads Iamblichus to introduce immediately Thymaridas's rule for solving n simultaneous equations, as the factor $a-2$ occurs in this also. For this rule see *infra*, pp. 138-141).

From Iamblichus's account it follows that the successive gnomons to a polygon of a sides are

$$1, 1+(a-2), 1+2(a-2), \dots, 1+(r-1)(a-2),$$

and the a -gonal number of side n is the sum of n terms this series, or

$$n + \frac{1}{2}n(n-1)(a-2).$$

GREEK MATHEMATICS

(e) SOME PROPERTIES OF NUMBERS

(i.) *The " Sieve " of Eratosthenes*

Nicom. *Arith. Introd.* i. 13. 2-4, ed. Hoche 29. 17-32. 18

Ἡ δὲ τούτων γένεσις ὑπὸ Ἐρατοσθένους καλεῖται κόσκινον, ἐπειδὴ ἀναπεφυρμένους τοὺς περισσοὺς λαβόντες καὶ ἀδιακρίτους ἐξ αὐτῶν τῆ τῆς γενέσεως μεθόδῳ ταύτῃ διαχωρίζομεν, ὡς δι' ὀργάνου ἢ κοσκίνου τινὸς καὶ ἰδίᾳ μὲν τοὺς πρῶτους καὶ ἀσυνθέτους, ἰδίᾳ δὲ τοὺς δευτέρους καὶ συνθέτους, χωρὶς δὲ τοὺς μικτοὺς εὐρίσκομεν. ἔστι δὲ ὁ τρόπος τοῦ κοσκίνου τοιοῦτος· ἐκθέμενος τοὺς ἀπὸ τριάδος πάντας ἐφεξῆς περισσοὺς ὡς δυνατὸν μάλιστα ἐπὶ μήκιστον στίχον, ἀρξάμενος ἀπὸ τοῦ πρώτου ἐπισκοπῶ, τίνας οἴος τέ ἐστι μετρεῖν, καὶ εὐρίσκω δυνατὸν ὄντα τοὺς δύο μέσους παραλείποντας μετρεῖν, μέχρις οὗ ἂν προχωρεῖν ἐθέλωμεν, οὐχ ὡς ἔτυχε δὲ καὶ εἰκῆ μετροῦντα, ἀλλὰ τὸν μὲν πρώτως κείμενον, τουτέστι τὸν δύο μέσους ὑπερβαίνοντα κατὰ τὴν τοῦ πρωτίστου ἐν τῷ στίχῳ κειμένου ποσότητα μετρήσει, τουτέστι κατὰ τὴν ἑαυτοῦ· τρὶς γάρ· τὸν δ' ἀπ' ἐκείνου δύο

* Nicomachus has been discussing the different species of odd numbers, which are explained above on p. 69 n. c.

^b That is, Eratosthenes, for whom see p. 156 n. a, set out the odd numbers beginning with 3 in a column. For convenience we will set them out horizontally as follows :

3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31, 33, 35.

PYTHAGOREAN ARITHMETIC

(e) SOME PROPERTIES OF NUMBERS

(i.) *The " Sieve " of Eratosthenes*

Nicomachus, *Introduction to Arithmetic* i. 13. 2-4,
ed. Hoche 29. 17-32. 18

The method of obtaining these ^a is called by Eratosthenes a sieve, since we take the odd numbers mixed together and indiscriminate, and out of them by this method, as though by some instrument or sieve, we separate the prime and incomposite by themselves, and the secondary and composite by themselves, and also find those that are mixed. The nature of the sieve is as follows : I set forth in as long a column as possible all the odd numbers, beginning with three, and, starting with the first, I examine which numbers in the series it will measure, and I find it will measure the numbers obtained by passing over two intermediate numbers, so far as we care to proceed, not measuring them at random and by hap-hazard, but it will measure the number first found by this process, that is, the one obtained by passing over two intermediate numbers, according to the magnitude of the number lying at the head of the column, that is, according to the magnitude of itself ; for it will measure it thrice.^b It will measure the number

We now strike out from this list the multiples of 3, because they will not be prime numbers, and this is done by passing over two numbers at a time and striking out the next. That is, we pass over 5 and 7 and strike out 9, we pass over 11 and 13 and strike out 15, and so on without limit. As Nicomachus notes in a rather cumbrous way, the numbers struck out, 3, 9, 15, 21, 27 . . ., when divided by 3 gives us in order the numbers in the original column 3, 5, 7, 9 There is here the foundation for a logical theory of the infinite, but it was left for Russell and Whitehead to develop it.

GREEK MATHEMATICS

διαλείποντα κατὰ τὴν τοῦ δευτέρου τεταγμένου πεντάκις γάρ· τὸν δὲ περαιτέρω πάλιν δύο διαλείποντα κατὰ τὴν τοῦ τρίτου τεταγμένου· ἐπτάκις γάρ· τὸν δὲ ἔτι περαιτέρω ὑπὲρ δύο κείμενον κατὰ τὴν τοῦ τετάρτου τεταγμένου· ἐνάκις γάρ· καὶ ἐπ' ἄπειρον τῷ αὐτῷ τρόπῳ. εἶτα μετὰ τοῦτον ἀπ' ἄλλης ἀρχῆς ἐπὶ τὸν δεύτερον ἐλθὼν σκοπῶ, τίνος οἷός τέ ἐστι μετρεῖν, καὶ εὐρίσκω πάντας τοὺς τετράδα διαλείποντας, ἀλλὰ τὸν μὲν πρῶτον κατὰ τὴν τοῦ ἐν τῷ στίχῳ πρώτου τεταγμένου ποσότητα· τρεῖς γάρ· τὸν δὲ δεύτερον κατὰ τὴν τοῦ δευτέρου πεντάκις γάρ· τὸν δὲ τρίτον κατὰ τὴν τοῦ τρίτου ἐπτάκις γάρ· καὶ τοῦτο ἐφεξῆς αἰεί.

(ii.) *Divisibility of Squares*

Theon Smyr., ed. Hiller 35. 17-36. 2

Ἰδίως δὲ τοῖς τετραγώνοις συμβέβηκεν ἥτοι τρίτον ἔχειν ἢ μονάδος ἀφαιρεθείσης τρίτον ἔχειν πάντως, ἢ πάλιν τέταρτον ἔχειν ἢ μονάδος ἀφαιρεθείσης τέταρτον ἔχειν πάντως· καὶ τὸν μὲν μονάδος ἀφαιρεθείσης τρίτον ἔχοντα ἔχειν καὶ τέταρτον

- The numbers obtained by passing over four numbers are

15, 25, 35 . . .

and can all be divided by 5, leaving

3, 5, 7 . . .

which is the original series of odd numbers.

Nicomachus proceeds to pass over six numbers at a time, beginning from 7, but we need not follow him. Clearly in this way he will eventually be able to remove from the series of odd numbers all that are not prime. The general formula is that we obtain all multiples of a prime number n by skip-

PYTHAGOREAN ARITHMETIC

obtained by passing over two from that one according to the magnitude of the second number in order ; for it will measure it five times. The number obtained by passing over two numbers yet again it will measure according to the magnitude of the third number in order ; for it will measure it seven times. The number that lies yet two places beyond it will measure according to the magnitude of the fourth number in order ; for it will measure it nine times ; and we may proceed without limit in this manner. After this I make a fresh start with the second number in the series and examine which numbers it will measure, and I find it will measure all the numbers obtained by passing over four,^a and will measure the first number so obtained according to the magnitude of the first number in the column ; for it will measure it thrice. It will measure the second according to the magnitude of the second, that is, five times ; the third according to the magnitude of the third, that is, seven times ; and so on in order for ever.

(ii.) *Divisibility of Squares*

Theon of Smyrna, ed. Hiller 35. 17-36. 2

It is a property of squares to be divisible by three, or to become so divisible after subtraction of a unit ; likewise they are divisible by four, or become so divisible after subtraction of a unit ; even squares that after subtraction of a unit are divisible by three

ping $n - 1$ terms at a time. But to make sure that any odd number $2n + 1$ left in the series is prime we should have to try to divide it by all the prime numbers up to $\sqrt{2n + 1}$, and the method is not a practicable way of ascertaining whether any large number is prime.

GREEK MATHEMATICS

πάντως, ὡς ὁ δ, τὸν δὲ μονάδος ἀφαιρεθείσης τέταρτον ἔχοντα ἔχειν τρίτον πάντως, ὡς ὁ θ, ἢ τὸν αὐτὸν πάλιν καὶ τρίτον ἔχειν καὶ τέταρτον, ὡς ὁ λζ [ἢ μηδέτερον τούτων ἔχοντα τοῦτον μονάδος ἀφαιρεθείσης τρίτον ἔχειν πάντως],¹ ἢ μήτε τρίτον μήτε τέταρτον ἔχοντα μονάδος ἀφαιρεθείσης καὶ τρίτον ἔχειν καὶ τέταρτον, ὡς ὁ κε.

(iii.) *A Theorem about Cube Numbers*

Nicom. *Arith. Introd.* ii. 20. 5, ed. Hoche 119. 12-18

Ἐκτεθέντων γὰρ τῶν ἀπὸ μονάδος ἐπ' ἄπειρον συνεχῶν περισσῶν ἐπισκόπει οὕτως, ὁ πρῶτος τὸν δυνάμει κύβον ποιεῖ, οἱ δὲ δύο μετ' ἐκείνον συντεθέντες τὸν δεύτερον, οἱ δὲ ἐπὶ τούτοις τρεῖς τὸν τρίτον, οἱ δὲ συνεχεῖς τούτοις τέσσαρες τὸν τέταρτον, οἱ δὲ ἐφεξῆς τούτοις πέντε τὸν πέμπτον

¹ ἢ . . . πάντως om. Bullialdus, Hiller.

* Any number may be written as $3n$, $3n \pm 1$ or $3n \pm 2$, and its square takes the form

$$9n^2 \text{ or } 9n^2 \pm 6n + 1 \text{ or } 9n^2 \pm 12n + 4.$$

In the first case, the square is divisible by three; in the second and third cases it becomes so divisible after subtraction of a unit.

PYTHAGOREAN ARITHMETIC

can be divided by four, such as 4 itself ; those that after subtraction of a unit are divisible by four can be divided by three, such as 9 ; while there are yet again squares divisible both by three and by four, such as 36 ; and others that are divisible neither by three nor by four but can be divided, after subtraction of a unit, by both three and four, such as 25.^a

(iii.) *A Theorem about Cube Numbers*

Nicomachus, *Introduction to Arithmetic* ii. 20. 5,
ed. Hoche 119. 12-18

When the odd numbers beginning with one are set out in succession *ad infinitum* this property can be noticed, that the first makes a cube, the sum of the next two after it makes the second cube, the next three following them make the third cube, the next four succeeding these make the fourth cube, the next five in order after these makes the fifth cube,

As for division by four, the square of an even number $2n$ is necessarily divisible by 4. The square of an odd number $2n \pm 1$ may be written $4n^2 \pm 4n + 1$ and becomes divisible by four after subtraction of a unit. Karpinski observes (*Nicomachus of Gerasa*, by M. L. D'Ooge, p. 58) : " Apparently Theon desired to divide all square numbers into four classes, viz., those divisible by three and not by four ; by four and not by three ; by three and four ; and by neither three nor four. In modern mathematical phraseology all square numbers are termed congruent to 0 or 1, modulus 3, and congruent to 0 or 1, modulus 4. This is written :

$$\begin{aligned}n^2 &\equiv 1 \pmod{3}, \\n^2 &\equiv 0 \pmod{3}, \\n^2 &\equiv 0 \text{ or } 1 \pmod{4}.\end{aligned}$$

" This is the first appearance of any work on congruence which is fundamental in the modern theory of numbers."

GREEK MATHEMATICS

καὶ οἱ ἐξῆς ἕξ τὸν ἕκτον καὶ τοῦτο μέχρι αἰεί.

(iv.) *A Property of the Pythmen*

Iambl. in *Nicom. Arith. Introd.*, ed. Pistelli 103. 10-104. 13

Ἐπεὶ δὲ ἐξάδος ἀποτελεσματικὴ ἐστὶν ἡ πρώτη παρ' οὐδὲν ἀπὸ μονάδος συζυγία, ἡ πρώτη $\bar{\alpha}$ $\bar{\beta}$ $\bar{\gamma}$ εἰδοποιήσῃ τὰς ἐξῆς αὐτῇ, μηδενὸς ὄρου κοινουῦ λαμβανομένου μηδὲ μὴν παρελλειπομένου, ἀλλὰ μετὰ τὴν $\bar{\alpha}$ $\bar{\beta}$ $\bar{\gamma}$ λαμβανομένης τῆς δ $\bar{\epsilon}$ $\bar{\zeta}$, εἶτα $\bar{\eta}$ $\bar{\theta}$ καὶ ἐξῆς ἀκολουθῶς. πᾶσαι γὰρ αὐταὶ ἐξάδες γενήσονται μεταλαμβανούσης τὸν μονάδος τόπον αἰεί τῆς δεκάδος, τουτέστιν εἰς μονάδα ἀναγομένης· οὕτως γὰρ αὐτὴν καὶ δευτερωδομένην μονάδα καλεῖσθαι ἐλέγομεν πρὸς τῶν Πυθαγορείων,

^a That is to say, $1 = 1^3$, $3 + 5 = 2^3$, $7 + 9 + 11 = 3^3$, $13 + 15 + 17 + 19 = 4^3$, $21 + 23 + 25 + 27 + 29 = 5^3$, $31 + 33 + 35 + 37 + 39 + 41 = 6^3$, and so on to infinity, the general formula being

$$\{n(n-1)+1\} + \{n(n-1)+3\} + \dots + \{n(n-1)+2n-1\} = n^3.$$

By putting $n=1, 2, 3 \dots r$ in this formula and adding the results it is easily shown that

$$1^3 + 2^3 + 3^3 + \dots + r^3 = \left\{\frac{1}{2}r(r+1)\right\}^2,$$

a formula which was known to the Roman *agrimensores* and probably to Nicomachus. Heath (*H.G.M.* i. 109-110) shows how it was proved by the Arabian algebraist Alkarkhī in a book *Al-Fakhrī* written in the tenth or eleventh century. The proof depends on Nicomachus's theorem.

^b Iamblichus has been considering various groups of three numbers which can be formed from the series of natural numbers, by passing over a specified number of terms, so as to become polygonal numbers. Thus $1 + 2 + 3 = 6$ (triangle), $1 + 3 + 5 = 9$ (square), $3 + 4 + 5 = 12$ (pentagon), $1 + 4 + 7 = 12$ (pentagon), $1 + 5 + 9 = 15$ (hexagon).

GREEK MATHEMATICS

καὶ τριωδομένην τὴν ἑκατοντάδα, καὶ τετρωδομένην τὴν χιλιάδα. ἡ μὲν γὰρ δ̄ ε̄ ε̄ ποιεῖ ἀριθμὸν τὸν ιε̄· ἀναγομένης δὲ τῆς δεκάδος εἰς μονάδα, ὁ πέντε προσλαβὼν αὐτὴν ἐξάς γίνεται. πάλιν ἡ ξ̄ ἢ θ̄ συνθεῖσα ποιεῖ τὸν κδ̄ ἀριθμὸν, οὗ τὰ κ̄ εἰς δύο μονάδας ἀναγαγὼν προστίθῃμι τῷ δ̄, καὶ ἔχω πάλιν ἐξάδα. πάλιν ῑ ῑᾱ ιβ̄ συνθεῖς ποιῶ λγ̄, ὧν τὰ λ̄ τριάς ἐστίν, ἣν προσθεῖς τοῖς τρισὶν ἔχω ὁμοίως ἐξάδα, καὶ τοῦτο ὁμοίως ἔσται δι' ὅλου. καὶ ἡ μὲν πρώτη ἐξὰς οὐκ ἔχει μετάθεσιν δεκάδος εἰς μονάδα, ὡς ἂν εἰδοποιὸς καὶ στοιχεῖον τῶν μετ' αὐτὴν ὑπάρχουσα· ἡ δὲ δευτέρα μιᾶς μονάδος μετάθεσιν ἔξει, ἡ δὲ τρίτη δυεῖν καὶ ἡ τετάρτη τριῶν καὶ ἡ πέμπτη τεσσάρων καὶ ἐξῆς ἀκολουθῶς. ὅσαι δ' ἂν ὦσιν αἱ μετατιθέμεναι δεκάδες, τοσαῦται καὶ αἱ ἐννεάδες ἀφαιρεθήσονται ἐκ τοῦ ὅλου συστήματος, ἵνα τὸ λείπον ὁμοίως ἐξὰς ἦ· τοῦ γὰρ ιε̄ μιᾶς δεκάδος ἔχοντος μετάθεσιν, ἐὰν ἀφέλω μίαν ἐννεάδα, λειφθήσεται ἐξὰς. τοῦ δὲ κδ̄ δύο ἔχοντος δεκάδας τὰς μεταποιουμένας ἐὰν ἀφέλω δύο ἐννεάδας, λειφθήσεται πάλιν ἐξὰς, καὶ τοῦτο δι' ὅλου συμβήσεται.

$$\begin{aligned} 10 + 20 + 30 + \dots + 100 + 90 + 80 + \dots + 30 + 20 + 10 &= 10^3 \\ 100 + 200 + 300 + \dots + 1000 + 900 + 800 + \dots + 300 + 200 + 100 &= 10^4 \end{aligned}$$

and so on. It was in virtue of these relations that the Pythagoreans spoke of 10 as the *unit of the second course* (δευτεροδομένη μονάς), 100 as the *unit of the third course* (τριωδομένη μονάς) and so on.

^a The truth of Iamblichus's proposition is proved generally by Loria (*Le scienze esatte nell' antica Grecia*, pp. 841-842) in the following manner.

$$\text{Let} \quad N = n_0 + 10n_1 + 10^2n_2 + \dots$$

PYTHAGOREAN ARITHMETIC

was called the unit of the third course and 1000 the unit of the fourth course. Now 4, 5, 6 make the number 15. Reducing the 10 to a unit, and adding it to the 5 we get 6. Again, 7, 8, 9 when added together make the number 24, in which I reduce the 20 to two units, add them to the 4 and so again have 6. Once more, adding 10, 11, 12, I make 33, in which the 30 yields 3, and adding this to the 3 units I likewise have 6, with a similar result in all cases. The first 6 does not suffer a change of the 10 into a monad, being a kind of image and element of those that succeed it. The second has a change of one monad, the third of two, the fourth of three, the fifth of four and so on in order. The number of 10s that have to be changed is also the number of 9s that have to be taken away from the whole sum in order that the result may likewise be 6. In the case of 15, where there is one 10 to be changed, if I take away one 9 the remainder will be 6. In the case of 24, where there are two 10s to be changed, if I take away two 9s the remainder will again be 6, and this will happen in all cases.^a

be a number written in the decimal system. Let $S(N)$ be the sum of its digits, $S^{(2)}(N)$ the sum of the digits of $S(N)$, and so on.

$$\text{Now} \quad N - S(N) = 9(n_1 + 11n_2 + 111n_3 + \dots)$$

$$\text{whence} \quad N \equiv S(N) \pmod{9}.$$

$$\text{Similarly} \quad S(N) \equiv S^{(2)}N \pmod{9}$$

and so on.

$$\text{Let} \quad S^{(k-1)}(N) \equiv S^k N \pmod{9}$$

be the last possible relation of this kind; $S^{(k)}N$ will be a number $N' \leq 9$.

Adding all the congruences we get

$$N \equiv N' \pmod{9}, \text{ where } N' \leq 9.$$

GREEK MATHEMATICS

(f) IRRATIONALITY OF THE SQUARE ROOT OF 2

Aristot. *Anal. Pr.* i. 23, 41 a 26-27

Πάντες γὰρ οἱ διὰ τοῦ ἀδύνατου περαίνοντες τὸ μὲν ψεῦδος συλλογίζονται, τὸ δ' ἐξ ἀρχῆς ἐξ ὑποθέσεως δεικνύουσιν, ὅταν ἀδύνατόν τι συμβαίῃ τῆς ἀντιφάσεως τεθείσης, οἷον ὅτι ἀσύμμετρος ἡ διάμετρος διὰ τὸ γίνεσθαι τὰ περιττὰ ἴσα τοῖς ἀρτίοις συμμέτρου τεθείσης. τὸ μὲν οὖν ἴσα γίνεσθαι τὰ περιττὰ τοῖς ἀρτίοις συλλογίζεται, τὸ δ' ἀσύμμετρον εἶναι τὴν διάμετρον ἐξ ὑποθέσεως δεικνύουσιν, ἐπεὶ ψεῦδος συμβαίνει διὰ τὴν ἀντίφασιν.

(g) THE THEORY OF PROPORTION AND MEANS

(i.) *Arithmetic, Geometric and Harmonic Means*

Iambl. in *Nicom. Arith. Introd.*, ed. Pistelli 100. 19-25

Μόνοι δὲ τὸ παλαιὸν τρεῖς ἦσαν μεσότητες ἐπὶ Πυθαγόρου καὶ τῶν κατ' αὐτὸν μαθηματικῶν, ἀριθ-

Now, if N is the sum of three consecutive numbers of which the greatest is divisible by 3, we can write

$$N = (3p + 1) + (3p + 2) + (3p + 3),$$

and the above congruence becomes

$$9p + 6 = N' \pmod{9}$$

so that $N' \equiv 6 \pmod{9}$, with the condition $N' \leq 9$. But the only number ≤ 9 which is divisible by 6 is 6 itself.

Therefore $N' = 6$.

^a It is generally believed that the Pythagoreans were aware of the irrationality of $\sqrt{2}$ (Theodorus, for example, when proving the irrationality of numbers began with $\sqrt{3}$), and that Aristotle has indicated the method by which they proved it. The proof, interpolated in the text of Euclid as

PYTHAGOREAN ARITHMETIC

(f) IRRATIONALITY OF THE SQUARE ROOT OF 2

Aristotle, *Prior Analytics* i. 23, 41 a 26-27

For all who argue *per impossibile* infer by syllogism a false conclusion, and prove the original conclusion hypothetically when something impossible follows from a contradictory assumption, as, for example, that the diagonal [of a square] is incommensurable [with the side] because odd numbers are equal to even if it is assumed to be commensurate. It is inferred by syllogism that odd numbers are equal to even, and proved hypothetically that the diagonal is incommensurate, since a false conclusion follows from the contradictory assumption.^a

(g) THE THEORY OF PROPORTION AND MEANS

(i.) *Arithmetic, Geometric and Harmonic Means*

Iamblichus, *On Nicomachus's Introduction to Arithmetic*, ed. Pistelli 100. 19-25

In ancient days in the time of Pythagoras and the mathematicians of his school there were only three

x. 117 (Eucl., ed. Heiberg-Menge iii. 408-410), is roughly as follows. Suppose AC, the diagonal of a square, to be commensurable with its side AB, and let their ratio in its smallest terms be $a : b$.

$$\text{Now} \quad AC^2 : AB^2 = a^2 : b^2$$

$$\text{and} \quad AC^2 = 2AB^2, a^2 = 2b^2.$$

Hence a^2 , and therefore a , is even.

Since $a : b$ is in its lowest terms it follows that b is odd.

Let $a = 2c$. Then $4c^2 = 2b^2$, or $b^2 = 2c^2$, so that b^2 , and therefore b is even.

But b was shown to be odd, and is therefore odd and even, which is impossible. Therefore AC cannot be commensurable with AB.

GREEK MATHEMATICS

μητική τε καὶ ἡ γεωμετρικὴ καὶ ἡ ποτὲ μὲν ὑπεναντία λεγομένη τῇ τάξει τρίτη, ὑπὸ δὲ τῶν περὶ Ἀρχύταν αὐθις καὶ Ἰππασον ἀρμονικὴ μετακληθεῖσα, ὅτι τοὺς κατὰ τὸ ἡρμωσμένον καὶ ἐμμελὲς ἐφαίμετο λόγους περιέχουσα.

Archytas ap. Porph. in Ptol. Harm., ed. Wallis, *Opera Math.* iii. 267. 39-268. 9; Diels, *Vors.* i^o. 435. 18-436. 13

Ἀρχύτας δὲ περὶ τῶν μεσοτήτων λέγων γράφει ταῦτα·

“Μέσαι δὲ ἐντι τρεῖς τᾶ μουσικᾶ, μία μὲν ἀριθμητικά, δευτέρα δὲ γεωμετρικά, τρίτα δ’ ὑπεναντία, ἂν καλέοντι ἀρμονικάν. ἀριθμητικὰ μὲν, ὅκκα ἔωντι τρεῖς ὅροι κατὰ τὰν τοίαν ὑπεροχὰν ἀνὰ λόγον· ᾧ πρῶτος δευτέρου ὑπερέχει, τῷτῷ δευτέρου τρίτου ὑπερέχει. καὶ ἐν ταῦτα τᾶ ἀναλογία συμπίπτει εἶμεν τὸ τῶν μειζόνων ὄρων διάστημα μείον, τὸ δὲ τῶν μειόνων μείζον. γεωμετρικὰ δέ, ὅκκα ἔωντι οἷος ὁ πρῶτος ποτὶ τὸν δευτέρου, καὶ ὁ δευτέρου ποτὶ τὸν τρίτου. τούτων δὲ οἱ μείζονες ὅροι ἴσον ποιοῦνται τὸ διάστημα καὶ οἱ μείους. ἃ δὲ ὑπεναντία, ἂν καλοῦμεν ἀρμονικάν, ὅκκα ἔωντι <τοῖοι ᾧ>¹ ὁ πρῶτος ὅρος ὑπερέχει τοῦ δευτέρου αὐταύτου μέρει, τῷτῷ ὁ μέσος τοῦ τρίτου ὑπε-

¹ τοῖοι ᾧ add. Diels.

• i.e., b is the arithmetic mean between a and c if

$$a - b = b - c.$$

• The word διάστημα (*interval*) is here used in the musical sense; mathematically it must be understood as the *ratio*

PYTHAGOREAN ARITHMETIC

means, the arithmetic and the geometric and a third in order which was then called subcontrary, but which was renamed harmonic by the circle of Archytas and Hippasus, because it seemed to furnish harmonious and tuneful ratios.

Archytas, cited by Porphyry in his *Commentary on Ptolemy's Harmonics*, ed. Wallis, *Opera Mathematica* iii. 267. 39-268. 9 ; Diels, *Vors.* i⁵. 435. 18-436. 13

Archytas, in his discussion of means, writes thus :

“ Now there are three means in music : first the arithmetic, secondly the geometric, and thirdly the subcontrary, the so-called harmonic. The arithmetic is that in which three terms are in proportion in virtue of some difference : the first exceeds the second by the same amount as the second exceeds the third.^a And in this proportion it happens that the interval ^b between the greater terms is the lesser, while that between the lesser terms is the greater. The geometric mean is that in which the first term is to the second as the second is to the third. Here the greater terms make the same interval as the lesser.^c The subcontrary mean, which we call harmonic, is such that by whatever part of itself the first term exceeds the second, the middle term exceeds the between the two terms, not their arithmetical difference. Archytas asserts that

$$\frac{a}{b} < \frac{b}{c}.$$

^c *i.e.*, b is the geometric mean between a and c if

$$\frac{a}{b} = \frac{b}{c},$$

and what Archytas says about the interval is contained in the definition.

GREEK MATHEMATICS

ἔχει τοῦ τρίτου μέρει. γίνεται δὲ ἐν ταῦτα τῆ ἀναλογία τὸ τῶν μειζόνων ὄρων διάστημα μείζον, τὸ δὲ τῶν μειόνων μείον.”

(ii.) *Seven Other Means*

Nicom. *Arith. Introd.* ii. 28. 3-11, ed. Hoche 141. 4-144. 19

Τετάρτη μὲν ἢ καὶ ὑπεναντία λεγομένη διὰ τὸ ἀντικεῖσθαι καὶ ἀντιπεπονθέναι τῇ ἀρμονικῇ ὑπάρχει ὅταν ἐν τρισὶν ὄροις ὡς ὁ μέγιστος πρὸς τὸν ἐλάχιστον, οὕτως ἢ τῶν ἐλαττόνων διαφορά πρὸς τὴν τῶν μειζόνων ἔχῃ, οἷον

$$\bar{\gamma}, \bar{\epsilon}, \varsigma,$$

• *i.e.*, b is the harmonic mean between a and c if

$$\frac{a-b}{a} = \frac{b-c}{c},$$

which can be written $\frac{1}{c} - \frac{1}{b} = \frac{1}{b} - \frac{1}{a}$,

so that $\frac{1}{c}, \frac{1}{b}, \frac{1}{a}$

form an arithmetical progression, and Archytas goes on to assert that

$$\frac{a}{b} > \frac{b}{c}.$$

• It is easily seen how the Pythagoreans would have observed the three means in their musical studies (see A. E. Taylor, *A Commentary on Plato's Timaeus*, p. 95). They would first have noticed that when they took three vibrating strings, of which the first gave out a note an octave below the second, while the second gave out a note an octave below the third, the lengths of the strings would be proportional to 4, 2, 1. Here the *διάστημα* is in each case an octave. The Pythagoreans would then have noticed that if they took three

PYTHAGOREAN ARITHMETIC

third by the same part of the third.^a In this proportion the interval between the greater terms is the greater, that between the lesser terms is the lesser.”^b

(ii.) *Seven Other Means*

Nicomachus, *Introduction to Arithmetic* ii. 28. 3-11,
ed. Hoche 141. 4-144. 19

The fourth mean, which is also called subcontrary by reason of its being reciprocal and antithetical to the harmonic, comes about when of three terms the greatest bears the same ratio to the least as the difference of the lesser terms bears to the difference of the greater,^c as in the case of

3, 5, 6,

strings sounding a given note, its major fourth and its upper octave, the lengths of the strings would be proportional to 12, 8, 6, which are in harmonic progression. Finally they would have observed that if they took three strings sounding a note, its major fifth and its upper octave, the lengths of the strings would be proportional to 12, 9, 6, which are terms in arithmetical progression. But the fact that the means are consistently given in the order arithmetic, geometric, harmonic, and that the name “harmonic” was substituted by Archytas for the older name “subcontrary” suggests that these means had already been arithmetically defined before they were seen to be exemplified in the fundamental intervals of the octave.

^a *i.e.*, b will be the subcontrary mean to a, c , if

$$\frac{c}{a} = \frac{b-a}{c-b}.$$

In this and the succeeding examples, following the practice of Nicomachus, it is assumed that a, b, c are in ascending order of magnitude.

GREEK MATHEMATICS

ἐν γὰρ διπλασίῳ τὰ συγκριθέντα ὀράται· φανερόν δέ, καθ' ἃ ἠναντίωται τῇ ἀρμονικῇ· τῶν γὰρ αὐτῶν ἄκρων ἀμφοτέραις ὑπαρχόντων καὶ ἐν διπλασίῳ γε λόγῳ, ἐν μὲν τῇ πρὸ ταύτης ἢ τῶν μειζόνων ὑπεροχῇ πρὸς τὴν τῶν ἐλαττόνων τὸν αὐτὸν ἔσωζε λόγον, ἐν ταύτῃ δὲ ἀνάπαλιν ἢ τῶν ἐλαττόνων πρὸς τὴν τῶν μειζόνων· ἴδιον δὲ ταύτης ἰστέον ἐκείνο, τὸ διπλάσιον ἀποτελεῖσθαι τὸ ὑπὸ τοῦ μείζονος καὶ μέσου πρὸς τὸ ὑπὸ τοῦ μέσου καὶ ἐλαχίστου, τοῦ γὰρ πεντάκις $\bar{\gamma}$ διπλάσιον τὸ ἑξάκις $\bar{\epsilon}$.

Αἱ δὲ δύο μεσότητες πέμπτη καὶ ἕκτη παρὰ τὴν γεωμετρικὴν ἐπλάσθησαν ἀμφοτέραι, διαφέρουσι δ' ἀλλήλων οὕτως· ἡ μὲν πέμπτη ἔστιν, ὅταν ἐν τρισὶν ὄροις ὡς ὁ μέσος πρὸς τὸν ἐλάχιστον οὕτω καὶ ἡ αὐτῶν τούτων διαφορά πρὸς τὴν τοῦ μεγίστου πρὸς τὸν μέσον, οἶον

$$\bar{\beta}, \bar{\delta}, \bar{\epsilon}.$$

διπλάσιος γὰρ ὁ μὲν $\bar{\delta}$ τοῦ $\bar{\beta}$, μέσος ὄρος τοῦ ἐλαχίστου, ὁ δὲ $\bar{\beta}$ τοῦ $\bar{\alpha}$, ἐλαχίστων διαφορά πρὸς διαφοράν μεγίστων· ὁ δ' ὑπεναντίον αὐτὴν τῇ

^a An elaborate classification of ratios is given by Nicom. *Arith. Introd.* i. 17-23. They are given in a convenient form for reference by Heath, *H.G.M.* i. 101-104, with the Latin names used by Boethius in his *De Institutione Arithmetica*, which is virtually a translation of Nicomachus's work.

^b *i.e.*, in the harmonic mean

$$\frac{c}{a} = \frac{c-b}{b-a}$$

and in the subcontrary mean

$$\frac{c}{a} = \frac{b-a}{c-b}.$$

^c This property happens to be true of the particular

PYTHAGOREAN ARITHMETIC

for the ratios formed are both seen to be the double.^a It is clear in what way this mean is contrary to the harmonic; for whereas they both have the same extremes, standing in the double ratio, in the case of the former mean this was also the ratio of the difference of the greater terms towards that of the lesser, while in the case of the present mean it is the ratio of the difference of the lesser terms to that of the greater.^b This property peculiar to the present mean deserves to be known, that the product of the greater and middle terms is double the product of the middle and least terms, for six times five is double five times three.^c

The next two means, the fifth and sixth, were both fashioned after the geometric, and differ from each other in this way. The fifth exists when of three terms the middle bears to the least the same ratio as their difference bears to the difference between the greatest and the middle terms,^d as in the case of

$$2, 4, 5 ;$$

for 4 is double 2, that is, the middle term is double the least, and 2 is double 1, that is, the difference of the least terms is double the difference of the greatest.

numbers Nicomachus has chosen, but is not in general true of the subcontrary mean. What is universally true is that if

$$\frac{c}{a} = \frac{c-b}{b-a} = \tau,$$

then $ab\tau = ab \times \frac{c}{a} = bc.$

^d *i.e.*, b is the fifth mean of a, c , if

$$\frac{b}{a} = \frac{b-a}{c-b}.$$

GREEK MATHEMATICS

γεωμετρικῇ ποιεῖ, ἐκεῖνό ἐστιν, ὅτι ἐπὶ μὲν ἐκείνης ὡς ὁ μέσος πρὸς τὸν ἐλάττονα, οὕτως ἢ τοῦ μείζονος πρὸς τὸν μέσον ὑπεροχῇ πρὸς τὴν τοῦ μέσου πρὸς τὸν ἐλάττονα, ἐπὶ δὲ ταύτης ἀνάπαλιν ἢ τοῦ ἐλάττονος πρὸς τὴν τοῦ μείζονος· ἴδιον δ' ὅμως καὶ ταύτης ἐστὶ τὸ διπλάσιον γίνεσθαι τὸ ὑπὸ τοῦ μεγίστου καὶ μέσου τοῦ ὑπὸ τοῦ μεγίστου καὶ ἐλαχίστου, τὸ γὰρ πεντάκις δ' διπλάσιον τοῦ πεντάκις β'.

Ἡ δὲ ἕκτη γίνεται, ὅταν ἐν τρισὶν ὄροις ἢ ὡς ὁ μέγιστος πρὸς τὸν μέσον, οὕτως ἢ τοῦ μέσου παρὰ τὸν ἐλάχιστον ὑπεροχῇ πρὸς τὴν τοῦ μεγίστου παρὰ τὸν μέσον, οἶον

$$\bar{a}, \delta, \bar{c},$$

ἐν ἡμιολίῳ γὰρ ἐκάτεροι λόγῳ· εἰκυῖα δ' αἰτία καὶ ταύτη τῆς πρὸς τὴν γεωμετρικὴν ὑπεναντιότητος, ἀναστρέφει γὰρ κἀνταῦθα ἢ τῶν λόγων ὁμοιότης ὡς ἐπὶ τῆς πέμπτης.

Καὶ αἱ μὲν παρὰ τοῖς πρόσθεν θρυλλόμεναι ἕξ μεσότητες αἶδε εἰσὶ, τρεῖς μὲν αἱ πρωτότυποι μέχρι

^a *i.e.*, if b is the geometric mean between a and c ,

$$\frac{b}{a} = \frac{c}{b} = \frac{c-b}{b-a},$$

while if b is the fifth mean between a and c ,

$$\frac{b}{a} = \frac{b-a}{c-b}.$$

The property which Nicomachus notes about this mean needs generalizing as in the case of his similar remark about the fourth mean, *i.e.*, if

$$\frac{b}{a} = \frac{b-a}{c-b} = \tau,$$

then

$$ac\tau = ac \times \frac{b}{a} = ba.$$

PYTHAGOREAN ARITHMETIC

What makes it subcontrary to the geometric mean is this property, that in the case of the geometric mean the middle term bears to the lesser the same ratio as the excess of the greater term over the middle bears to that of the middle term over the lesser, while in the case of this mean a contrary relation holds. It is a peculiar property of this mean that the product of the greatest and middle terms is double the product of the greatest and least, for five times four is double of five times two.^a

The sixth mean comes about when of three terms the greatest bears the same ratio to the middle term as the excess of the middle term over the least bears to the excess of the greatest term over the middle,^b as in the case of

1, 4, 6,

for in each case the ratio is the sesquialter (3 : 2). No doubt, it is called subcontrary to the geometric mean because the ratios are reversed, as in the case of the fifth mean.^c

These are then what are commonly called the six means, three prototypes which came down to Plato

^b *i.e.*, b is the sixth mean between a and b if

$$\frac{c}{b} = \frac{b-a}{c-b}$$

^c *i.e.*, if b is the geometric mean between a and c ,

$$\frac{c}{b} = \frac{c-b}{b-a},$$

while if b is the sixth mean between a and c ,

$$\frac{c}{b} = \frac{b-a}{c-b}.$$

GREEK MATHEMATICS

Ἄριστοτέλους καὶ Πλάτωνος ἄνωθεν ἀπὸ Πυθαγόρου διαμείνασαι, τρεῖς δ' ἕτεραι ἐκείναις ὑπεναντία τοῖς μετ' ἐκείνους ὑπομνηματογράφοις τε καὶ αἰρετισταῖς ἐν χρήσει γινόμεναι· τέσσαρας δέ τινες ἐτέρας μετακινουῦντες τοὺς τούτων ὄρους τε καὶ διαφορὰς ἐπέξευρόν τινες οὐ πάνυ ἐμφανταζομένας τοῖς τῶν παλαιῶν συγγράμμασιν, ἀλλ' ὡς περιεργότερον λελεπτολογημένας, ἅς ὁμως πρὸς τὸ μὴ δοκεῖν ἀγνοεῖν ἐπιτροχαστέον τῆδ' ἐπισημῶς.

Πρώτη μὲν γὰρ αὐτῶν, ἐβδόμη δὲ ἐν τῇ πασῶν συντάξει ἔστιν, ὅταν ἡ ὡς ὁ μέγιστος πρὸς τὸν ἐλάχιστον, οὕτως καὶ ἡ τῶν αὐτῶν διαφορὰ πρὸς τὴν τῶν ἐλαττόνων, οἶον

$$\bar{\epsilon}, \bar{\eta}, \bar{\theta},$$

ἡμιόλιος γὰρ ὁ λόγος ἐκατέρου συγκρίσει ἐνορᾶται.

Ἐβδόμη δὲ μεσότης, ἣτις τούτων δευτέρα ἐστὶ, γίνεται, ὅταν ὡς ὁ μέγιστος πρὸς τὸν ἐλάχιστον, οὕτως ἡ διαφορὰ τῶν ἄκρων πρὸς τὴν τῶν μειζόνων διαφορὰν, οἶον

$$\bar{\epsilon}, \bar{\zeta}, \bar{\theta}.$$

καὶ αὕτη γὰρ ἡμιολίους ἔχει τοὺς δύο λόγους.

Ἡ δὲ ἐνάτη μὲν ἐν τῇ τῶν πασῶν συντάξει, τρίτη δὲ ἐν τῶ τῶν ἐφευρημένων ἀριθμῶ ὑπάρχει, ὅταν τριῶν ὄρων ὄντων, ὃν λόγον ἔχει ὁ μέσος πρὸς

* Iamblichus says (*in Nicom.*, ed. Pistelli 101. 1-5) that the school of Eudoxus discovered these means, but in other places (*ibid.* 116. 1-4, 113. 16-18) he gives the credit, in part at least, to Archytas and Hippiasus.

PYTHAGOREAN ARITHMETIC

and Aristotle from Pythagoras, and three others sub-contrary to these which came into use with later writers and partisans.^a By playing about with the terms and their differences certain men discovered four other means which do not find a place in the writings of the ancients, but which must nevertheless be treated briefly in some fashion, although they are superfluous refinements, in order not to appear ignorant.

The first of these, or the seventh in the complete list, exists when the greatest term bears the same relation to the least as their difference bears to the difference of the lesser terms,^b as in the case of

$$6, 8, 9,$$

for the ratio of each is seen by compounding the terms to be the sesquialter.

The eighth mean, or the second of these, comes about when the greatest term bears to the least the same ratio as the difference of the extremes bears to the difference of the greater terms,^c as in the case of

$$6, 7, 9 ;$$

for here the two ratios are the sesquialter.

The ninth mean in the complete series, and the third in the number of those more recently discovered, comes about when there are three terms and the

^b *i.e.*, b is the seventh mean between a and c if

$$\frac{c}{a} = \frac{c-a}{b-a}.$$

^c *i.e.*, b is the eighth mean between a and c if

$$\frac{c}{a} = \frac{c-a}{c-b}.$$

GREEK MATHEMATICS

τὸν ἐλάχιστον, τοῦτον καὶ ἡ τῶν ἄκρων ὑπεροχὴ
πρὸς τὴν τῶν ἐλαχίστων ἔχῃ, ὡς

$$\delta, \bar{\sigma}, \bar{\zeta}.$$

Ἡ δὲ ἐπὶ πάσαις δεκάτῃ μὲν συλλήβδην, τετάρτῃ
δὲ ἐν τῇ τῶν νεωτερικῶν ἐκθέσει ὀράται, ὅταν ἐν
τρισὶν ὄροις ἢ ὡς ὁ μέσος πρὸς τὸν ἐλάχιστον,
οὕτως καὶ ἡ διαφορὰ τῶν ἄκρων πρὸς τὴν διαφορὰν
τῶν μειζόνων, οἶον

$$\bar{\gamma}, \bar{\epsilon}, \bar{\eta}.$$

ἐπιδιμερῆς γὰρ ὁ ἐν ἑκατέρᾳ συζυγίᾳ λόγος.

Ἐπὶ κεφαλαίου τοίνυν οἱ τῶν δέκα ἀναλογιῶν
ὄροι ἐκκείσθωσαν ὑφ' ἐν παραδείγμα πρὸς τὸ
εὐσύνοπτον,

πρώτης	$\bar{a}, \bar{\beta}, \bar{\gamma},$
δευτέρας	$\bar{a}, \bar{\beta}, \bar{\delta},$
τρίτης	$\bar{\gamma}, \bar{\delta}, \bar{\sigma},$
τετάρτης	$\bar{\zeta}, \bar{\epsilon}, \bar{\sigma},$
πέμπτης	$\bar{\beta}, \bar{\delta}, \bar{\epsilon},$
ἕκτης	$\bar{a}, \bar{\delta}, \bar{\sigma},$

- *i.e.*, b is the ninth mean between a and c if

$$\frac{b}{a} = \frac{c-a}{b-a}.$$

- *i.e.*, b is the tenth mean between a and c if

$$\frac{b}{a} = \frac{c-a}{c-b}.$$

• Pappus (iii. 18, ed. Hultsch 84. 12-86. 14) gives a similar list, but in a different order after the sixth mean. Nos. 8, 9, 10 in Nicomachus's list are respectively Nos. 9, 10, 7 in that of Pappus. Moreover Pappus omits No. 7 in the list of Nicomachus and gives as No. 8 an additional mean

equivalent to the formula $\frac{c-a}{c-b} = \frac{c}{b}$. The two lists thus give

five means additional to the first six.

PYTHAGOREAN ARITHMETIC

middle bears to the least the same ratio as the difference between the extremes bears to the difference between the least terms,^a as

4, 6, 7.

Finally, the tenth in the complete series, and the fourth in the list set out by the moderns, is seen when in three terms the middle term bears to the least the same ratio as the difference between the extremes bears to the difference of the greater terms,^b as in the case of

3, 5, 8 ;

for the ratio in each couple is the superbipartient (5 : 3).

To sum up, then, let the terms of the ten proportions be set out in one figure so as to be taken in at a glance.^c

				$a < b < c$
First	1,	2,	3	$\frac{b-a}{c-b} = \frac{a}{b} = \frac{b}{c} = \frac{c}{a}$; arithmetic
Second	1,	2,	4	$\frac{b-a}{c-b} = \frac{b}{c} = \frac{a}{b}$; geometric
Third	3,	4,	6	$\frac{b-a}{c-b} = \frac{a}{c}$; harmonic
Fourth	3,	5,	6	$\frac{b-a}{c-b} = \frac{c}{a}$; subcontrary to harmonic
Fifth	2,	4,	5	$\frac{b-a}{c-b} = \frac{b}{a}$
Sixth	1,	4,	6	$\frac{b-a}{c-b} = \frac{c}{b}$
				} ; subcontrary to geometric

GREEK MATHEMATICS

έβδόμησ	$\varepsilon, \eta, \theta,$
ὀγδόησ	$\bar{\varepsilon}, \zeta, \theta,$
ένάτησ	$\delta, \bar{\varepsilon}, \zeta,$
δεκάτησ	$\bar{\gamma}, \bar{\varepsilon}, \eta.$

(iii.) *Pappus's Equations between Means*

Papp. *Coll.* iii. 18. 48, ed. Hultsch 88. 5-18

Τρεῖσ ἀνάλογον ἔστωσαν ὅροι οἱ Α, Β, Γ καὶ συναμφοτέρω μὲν τῶ Α, Γ μετὰ $\bar{\beta}$ τῶν Β ἴσος ἐκκείσθω ὁ Δ, συναμφοτέρω δὲ τῶ Β, Γ ὁ Ε, τῶ δὲ Γ ὁ Ζ· λέγω ὅτι καὶ οἱ Δ, Ε, Ζ ὅροι ἀνάλογόν εἰσιν.

Ἐπεὶ γὰρ ὡσ ὁ Α πρὸσ τὸν Β, οὕτωσ ὁ Β πρὸσ τὸν Γ, ἔσται καὶ συνθέντι ὡσ συναμφότεροσ ὁ Α, Β πρὸσ τὸν Β, οὕτωσ συναμφότεροσ ὁ Β, Γ πρὸσ τὸν Γ· καὶ πάντεσ ἄρα οἱ ἡγούμενοι πρὸσ πάντα τοὺσ ἐπομένουσ εἰσὶν ἐν τῶ αὐτῶ λόγῳ ὡσ συναμφότεροσ ὁ Α, Β μετὰ συναμφοτέρου τοῦ Β, Γ πρὸσ συναμφότερον τὸν Β, Γ, οὕτωσ συναμφότεροσ ὁ Β, Γ πρὸσ τὸν Γ. καὶ ἔστιν συναμφοτέρω μὲν τῶ Α, Β μετὰ συναμφοτέρου τοῦ Β, Γ ἴσος ὁ Δ, συναμφοτέρω δὲ

PYTHAGOREAN ARITHMETIC

Seventh	6,	8,	9	$\frac{c-a}{b-a} = \frac{c}{a}$
Eighth	6,	7,	9	$\frac{c-a}{c-b} = \frac{c}{a}$
Ninth	4,	6,	7	$\frac{c-a}{b-a} = \frac{b}{a}$
Tenth	3,	5,	8	$\frac{c-a}{c-b} = \frac{b}{a}$ or $c = a + b$

(iii.) Pappus's Equations between Means

Pappus, *Collection* iii. 18. 48, ed. Hultsch 88. 5-18

Let A, B, Γ be three terms in [geometric] proportion^a and let $\Delta = A + \Gamma + 2B$, $E = B + \Gamma$, $Z = \Gamma$; I say that Δ, E, Z are terms in [geometric] proportion.

For since $A : B = B : \Gamma$, it follows that $A + B : B = B + \Gamma : \Gamma$; and therefore all the antecedents bear to all the consequents^b the same ratio, so that $A + B + B + \Gamma : B + \Gamma = B + \Gamma : \Gamma$. Now $\Delta = A + B +$

^a According to Theon (ed. Hiller 106. 15-20), Adrastus said the geometric mean was called "both proportion *par excellence* and primary," though the other means were also commonly called proportion by some writers (τούτων δέ φησιν ὁ Ἀδραστος μίαν τὴν γεωμετρικὴν κυρίως λέγεσθαι καὶ ἀναλογίαν καὶ πρώτην . . . κοινότερον δέ φησι καὶ τὰς ἄλλας μεσότηας ὑπ' ἐνίων καλεῖσθαι ἀναλογίας).

^b The expressions "antecedents," literally "leading (terms)," and "consequents," or "following (terms)," are those used in Euclid v. Def. 11 *et seq.*

GREEK MATHEMATICS

τῶ Β, Γ ἴσος ὁ Ε, καὶ τῶ Γ ὁ Ζ. καὶ οἱ Δ, Ε, Ζ
ἄρα ἀνάλογόν εἰσιν.

Ibid. iii. 23. 57, ed. Hultsch 102

Μεσότητες	Α Β Γ	Οἱ περιέχοντες τὰς μεσότητας τρεῖς ἐλάχιστοι ἀριθμοὶ
ἀριθμητική	$\bar{\beta}$ $\bar{\gamma}$ $\bar{\alpha}$ $\bar{\alpha}$ β $\bar{\alpha}$ $\bar{\alpha}$ $\bar{\alpha}$	$\bar{\sigma}$ δ $\bar{\beta}$
γεωμετρική	$\bar{\alpha}$ $\bar{\beta}$ $\bar{\alpha}$ $\bar{\alpha}$ $\bar{\alpha}$ $\bar{\alpha}$	δ $\bar{\beta}$ α
ἀρμονική	$\bar{\beta}$ $\bar{\gamma}$ $\bar{\alpha}$ β $\bar{\alpha}$ $\bar{\alpha}$ $\bar{\alpha}$	$\bar{\sigma}$ $\bar{\gamma}$ $\bar{\beta}$
ὑπεναντία	$\bar{\beta}$ $\bar{\gamma}$ $\bar{\alpha}$ $\bar{\beta}$ β $\bar{\alpha}$ $\bar{\alpha}$ $\bar{\alpha}$	$\bar{\sigma}$ ϵ $\bar{\beta}$

^a This is one of a series of propositions given by Pappus to the following effect. If A, B, Γ are three terms in geometric proportion, it is possible to form from them three other terms Δ, Ε, Ζ, being linear functions of A, B, Γ, which satisfy the different proportions. In this case Δ, Ε, Ζ are also in geometric proportion, but in the other examples Δ, Ε, Ζ are made to satisfy the harmonic, the subcontrary, and the fifth, sixth, eighth, ninth and tenth means of Pappus's list. The problems are, of course, problems in indeterminate analysis of the second degree. Pappus does not include solutions for the arithmetic and seventh proportions. Tannery (*Mémoires scientifiques* i., pp. 97-98) suggests as the reason that in these cases the equations of the proportions, $\Delta + Z = 2E$ and, $\Delta = E + Z$, are already linear, there is no need to assume that

PYTHAGOREAN ARITHMETIC

$B + \Gamma$, $E = B + \Gamma$ and $Z = \Gamma$; and therefore Δ , E , Z are in [geometric] proportion.^a

Ibid. iii. 23. 57, ed. Hultsch 102

Means	Solution in terms of A, B, Γ	The three least numbers exhibiting the means
Arithmetic	$\begin{aligned} \Delta &= 2A + 3B + \Gamma \\ E &= A + 2B + \Gamma \\ Z &= B + \Gamma \end{aligned}$	6, 4, 2
Geometric	$\begin{aligned} \Delta &= A + 2B + \Gamma \\ E &= B + \Gamma \\ Z &= \Gamma \end{aligned}$	4, 2, 1
Harmonic	$\begin{aligned} \Delta &= 2A + 3B + \Gamma \\ E &= 2B + \Gamma \\ Z &= B + \Gamma \end{aligned}$	6, 3, 2
Subcontrary	$\begin{aligned} \Delta &= 2A + 3B + \Gamma \\ E &= 2A + 2B + \Gamma \\ Z &= B + \Gamma \end{aligned}$	6, 5, 2

$A\Gamma = B^2$, and consequently there is one indeterminate too many. But the complete results are shown in the table reproduced on these pages from Pappus (ed. Hultsch, p. 102, with explanation, pp. 100-104). The first column in the Greek table gives the means which Δ , E , Z are to satisfy. The second column gives the number of times A , B , Γ have to be taken to form Δ , E , Z respectively. In the case of the geometric progression already considered, the table shows that to form Δ we have to take A once, B twice and Γ once; to form E we have to take B once and Γ once; and to form Z we take Γ once. The third column gives the least integral values of Δ , E , Z satisfying the respective proportions (*i.e.* the values of Δ , E , Z , supposing A , B , Γ to be each unity); in the case of the geometric proportion the values are 4, 2, 1.

GREEK MATHEMATICS

Μεσότητες	Α	Β	Γ	Οί περιέχοντες τὰς μεσότητας τρεῖς ἐλάχιστοι ἀριθμοί
ε'	\bar{a} \bar{a}	$\bar{\gamma}$ $\bar{\beta}$ \bar{a}	\bar{a} \bar{a} \bar{a}	$\bar{\epsilon}$ $\bar{\delta}$ $\bar{\beta}$
ς'	\bar{a} \bar{a} \bar{a}	$\bar{\gamma}$ $\bar{\beta}$ \bar{a}	$\bar{\beta}$ \bar{a} \bar{a}	$\bar{\varsigma}$ $\bar{\delta}$ \bar{a}
ζ'	\bar{a}	\bar{a} \bar{a}	\bar{a} \bar{a} \bar{a}	$\bar{\zeta}$ $\bar{\beta}$ \bar{a}
η'	$\bar{\beta}$ \bar{a}	$\bar{\gamma}$ $\bar{\beta}$ $\bar{\beta}$	\bar{a} \bar{a} \bar{a}	$\bar{\eta}$ $\bar{\delta}$ $\bar{\gamma}$
θ'	\bar{a} \bar{a}	$\bar{\beta}$ \bar{a} \bar{a}	\bar{a} \bar{a} \bar{a}	$\bar{\theta}$ $\bar{\gamma}$ $\bar{\beta}$
ι'	\bar{a}	\bar{a} \bar{a}	\bar{a} \bar{a} \bar{a}	$\bar{\iota}$ $\bar{\beta}$ \bar{a}

(iv.) *Plato on Means between two Squares or two Cubes*

Plat. *Tim.* 31 v-32 v

Δύο δὲ μόνω καλῶς συνίστασθαι τρίτου χωρὶς οὐ δυνατόν· δεσμὸν γὰρ ἐν μέσῳ δεῖ τινα ἀμφοῖν συναγωγὸν γίνεσθαι. . . . εἰ μὲν οὖν ἐπίπεδον μὲν, βάθος δὲ μηδὲν ἔχον ἔδει γίνεσθαι τὸ τοῦ παντὸς σῶμα, μία μεσότης ἂν ἐξήρκει τά τε μεθ'

PYTHAGOREAN ARITHMETIC

Means	Solution in terms of A, B, Γ	The three least numbers exhibiting the means
Fifth	$\begin{aligned} \Delta &= A + 3B + \Gamma \\ E &= A + 2B + \Gamma \\ Z &= \quad B + \Gamma \end{aligned}$	5, 4, 2
Sixth	$\begin{aligned} \Delta &= A + 3B + 2\Gamma \\ E &= A + 2B + \Gamma \\ Z &= A + B - \Gamma \end{aligned}$	6, 4, 1
Seventh	$\begin{aligned} \Delta &= A + B + \Gamma \\ E &= \quad B + \Gamma \\ Z &= \quad \quad \Gamma \end{aligned}$	3, 2, 1
Eighth	$\begin{aligned} \Delta &= 2A + 3B + \Gamma \\ E &= A + 2B + \Gamma \\ Z &= \quad 2B + \Gamma \end{aligned}$	6, 4, 3
Ninth	$\begin{aligned} \Delta &= A + 2B + \Gamma \\ E &= A + B + \Gamma \\ Z &= \quad B + \Gamma \end{aligned}$	4, 3, 2
Tenth	$\begin{aligned} \Delta &= A + B + \Gamma \\ E &= \quad B + \Gamma \\ Z &= \quad \quad \Gamma \end{aligned}$	3, 2, 1

N.B.—For the differences between this list of means and that given by Nicomachus, see p. 122 n. c.

(iv.) *Plato on Means between two Squares or two Cubes*

Plato, *Timaeus* 31 B-32 B

But it is not possible that two things alone be joined without a third; for in between there must needs be some bond joining the two. . . . Now if the body of the All had had to come into being as a plane surface, having no depth, one mean would have

GREEK MATHEMATICS

αὐτῆς συνδεῖν καὶ ἑαυτήν, νῦν δὲ στερεοειδῆ γὰρ αὐτὸν προσῆκεν εἶναι, τὰ δὲ στερεὰ μία μὲν οὐδέποτε, δύο δὲ αἰεὶ μεσότητες συναρμόττουσιν.

(v.) *A Theorem of Archytas*

Archytas ap. Boeth. *De Inst. Mus.* iii. 11,
ed. Friedlein 285-286

Demonstratio Archytæ superparticularem in aequa dividi non posse.

Superparticularis proportio scindi in aequa medio proportionaliter interposito numero non potest. Id vero posterius firmiter demonstrabitur. Quam enim demonstrationem ponit Archytas, nimium fluxa est. Haec vero est huiusmodi. Sit, inquit, superparticularis proportio $\cdot A \cdot B \cdot$, sumo in eadem proportione minimos $\cdot C \cdot DE \cdot$. Quoniam igitur sunt minimi in eadem proportione $\cdot C \cdot DE \cdot$ et sunt superparticulares, $\cdot DE \cdot$ numerus $\cdot C \cdot$ numerum parte una sua eiusque transcendit. Sit haec $\cdot D \cdot$. Dico, quoniam $\cdot D \cdot$ non erit numerus, sed unitas. Si enim est nu-

^a In other words, one mean is sufficient to connect in continuous proportion two square numbers, but two are required to connect cube numbers. Plato's remarks are equivalent to saying that

$$\text{and} \quad \begin{array}{l} a^2 : ab = ab : b^2 \\ a^3 : a^2b = a^2b : ab^2 = ab^2 : b^3. \end{array}$$

^b The *superparticularis ratio* (ἐπιμόριος λόγος) is the ratio in which one number contains the other and an aliquot part of it, i.e., is the ratio $\frac{n+1}{n}$.

^c That is, a geometric mean. Archytas's proof as preserved by Boethius is substantially identical with that given by Euclid in his *Sectio Canonis*, prop. 3 (*Euclid*, ed. Heiberg-130

PYTHAGOREAN ARITHMETIC

sufficed to bind together both itself and its fellow-terms ; but now it is otherwise—for it behoved it to be solid in shape, and what brings solids into harmony is never one mean, but always two.^a

(v.) *A Theorem of Archytas*

Archytas as quoted by Boethius, *On Music* iii. 11,
ed. Friedlein 285-286

Archytas's proof that a superparticular ratio cannot be divided into equal parts.

A superparticular ratio ^b cannot be divided into equal parts by a mean proportional ^c placed between. That will later be more conclusively proved. For the proof which Archytas gives is very loose. It is after this manner. Let there be, he says, a superparticular ratio $A : B$.^d I take $C, D + E$ the least numbers in the same ratio.^e Therefore, since $C, D + E$, are the least numbers in the same ratio and are superparticulars, the number $D + E$ exceeds the number C by an aliquot part of itself and of C . Let the excess be D .^f I say that D is not a number but a unit. For, if D is a number and an aliquot

Menge viii. 162. 7-26). It is subsequently used by Euclid (prop. 16), to show that the musical tone, whose numerical value is $9 : 8$, cannot be divided into two or more equal parts.

^d Archytas writes the smaller number first instead of second, as Euclid does.

^e In Archytas's proof $D + E$ is represented by DE . Euclid, following his usual practice, takes a straight line divided into two parts. To find $C, D + E$, presupposes Euclid vii. 33.

^f *i.e.*, E is supposed equal to C .

GREEK MATHEMATICS

merus $\cdot D \cdot$ et pars est eius, qui est $\cdot DE \cdot$ metitur $\cdot D \cdot$ numerus $\cdot DE \cdot$ numerum; quocirca et $\cdot E \cdot$ numerum metietur, quo fit, ut $\cdot C \cdot$ quoque metiatur. Utrumque igitur $\cdot C \cdot$ et $\cdot DE \cdot$ numeros metietur $\cdot D \cdot$ numerus, quod est impossibile. Qui enim sunt minimi in eadem proportione quibuslibet aliis numeris, hi primi ad se invicem sunt, et solam differentiam retinent unitatem. Unitas igitur est $\cdot D \cdot$. Igitur $\cdot DE \cdot$ numerus $\cdot C \cdot$ numerum unitate transcendit. Quocirca nullus incidit medius numerus, qui eam proportionem aequaliter scindat. Quo fit, ut nec inter eos, qui eandem his proportionem tenent, medius possit numerus collocari, qui eandem proportionem aequaliter scindat.

(h) ALGEBRAIC EQUATIONS

(i.) *Side- and Diameter-numbers*

Theon Smyr., ed. Hiller 42. 10-44. 17

Ὡσπερ δὲ τριγωνικοὺς καὶ τετραγωνικοὺς καὶ πενταγωνικοὺς καὶ κατὰ τὰ λοιπὰ σχήματα λόγους ἔχουσι δυνάμει οἱ ἀριθμοί, οὕτως καὶ πλευρικοὺς καὶ διαμετρικοὺς λόγους εὕρομεν ἂν κατὰ τοὺς σπερματικοὺς λόγους ἐμφανιζομένους τοῖς ἀριθμοῖς. ἐκ γὰρ τούτων ῥυθμίζεται τὰ σχήματα. ὥσπερ οὖν πάντων τῶν σχημάτων κατὰ τὸν ἀνωτάτω καὶ σπερματικὸν λόγον ἡ μονὰς ἄρχει, οὕτως καὶ τῆς διαμέτρου καὶ τῆς πλευρᾶς λόγος ἐν τῇ μονάδι εὐρίσκεται. οἷον ἐκτίθενται δύο μονάδες, ὧν τὴν μὲν θῶμεν εἶναι διάμετρον, τὴν δὲ πλευράν, ἐπειδὴ

^a This presupposes Euclid vii. 22.

^b This is an inference from Euclid vii. 20. Heath (*H.G.M.*

PYTHAGOREAN ARITHMETIC

part of $D + E$, the number D measures the number $D + E$; therefore it measures the number E , that is, the number D measures C also. The number D therefore measures both C and $D + E$, which is impossible. For the least numbers which are in the same ratio as any other numbers whatsoever are prime to one another,^a and the only difference they retain is unity. Therefore D is a unit. Therefore the number $D + E$ exceeds the number C by a unit. Hence there is no number which is a mean between the two numbers. For this reason no mean can be placed between the numbers in the same proportion so as to divide that proportion equally.^b

(h) ALGEBRAIC EQUATIONS

(i.) *Side- and Diameter-numbers*

Theon of Smyrna, ed. Hiller 42. 10–44. 17

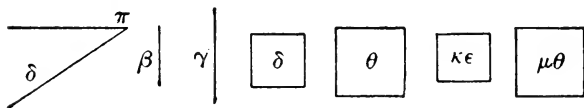
Even as numbers are invested with power to make triangles, squares, pentagons and the other figures, so also we find side and diameter^c ratios appearing in numbers in accordance with the generative principles; for it is these which give harmony to the figures. Therefore since the unit, according to the supreme generative principle, is the starting-point of all the figures, so also in the unit will be found the ratio of the diameter to the side. To make this clear, let two units be taken, of which we set one to be a diameter and the other a side, since the unit, as the

i. 90) considers that this proposition implies the existence, at least as early as the date of Archytas (about 430–365 B.C.), of an *Elements of arithmetic* in the form which we call Euclidean.

^c Or “diagonal.”

GREEK MATHEMATICS

τὴν μονάδα, πάντων οὖσαν ἀρχήν, δεῖ δυνάμει καὶ πλευρὰν εἶναι καὶ διάμετρον. καὶ προστίθεται τῇ μὲν πλευρᾷ διάμετρος, τῇ δὲ διαμέτρῳ δύο πλευραί, ἐπειδὴ ὅσον ἢ πλευρὰ δις δύναται, ἢ διάμετρος ἅπαξ. ἐγένετο οὖν μείζων μὲν ἢ διάμετρος, ἐλάττων δὲ ἢ πλευρά. καὶ ἐπὶ μὲν τῆς πρώτης πλευρᾶς τε καὶ διαμέτρου εἶη ἂν τὸ ἀπὸ τῆς μονάδος διαμέτρου τετράγωνον μονάδι μιᾷ ἔλαττον ἢ διπλάσιον τοῦ ἀπὸ τῆς μονάδος πλευρᾶς τετραγώνου· ἐν ἰσότητι γὰρ αἱ μονάδες· τὸ δ' ἐν τοῦ ἐνὸς μονάδι ἔλαττον ἢ διπλάσιον. προσθῶμεν δὴ τῇ μὲν πλευρᾷ διάμετρον, τουτέστι τῇ μονάδι μονάδα· ἔσται ἢ πλευρὰ ἄρα δύο μονάδων· τῇ δὲ διαμέτρῳ προσθῶμεν δύο πλευράς, τουτέστι τῇ μονάδι δύο μονάδας· ἔσται ἢ διάμετρος μονάδων τριῶν· καὶ τὸ μὲν ἀπὸ τῆς μονάδος πλευρᾶς τετράγωνον δ, τὸ δ' ἀπὸ τῆς τριάδος διαμέτρου τετράγωνον θ· τὸ θ



ἄρα μονάδι μείζων ἢ διπλάσιον τοῦ ἀπὸ τῆς β̄ πλευρᾶς.

Πάλιν προσθῶμεν τῇ μὲν β̄ πλευρᾷ διάμετρον τὴν τριάδα· ἔσται ἢ πλευρὰ ε̄· τῇ δὲ τριάδι διαμέτρῳ β̄ πλευράς, τουτέστι δις τὰ β̄· ἔσται ζ̄· ἔσται τὸ μὲν ἀπὸ τῆς (ε̄) πλευρᾶς τετράγωνον κε, τὸ δὲ ἀπὸ τῆς ζ̄ (διαμέτρου) μθ· μονάδι ἔλασσον ἢ διπλάσιον τοῦ κε ἄρα τὸ μθ. πάλιν ἂν τῇ (ε̄) πλευρᾷ προσθῆς τὴν ζ̄ διάμετρον, ἔσται ιβ̄. κὰν τῇ ζ̄ διαμέτρῳ

PYTHAGOREAN ARITHMETIC

beginning of all things, must have it in its capacity to be both side and diameter. Now let there be added to the side a diameter and to the diameter two sides, for as often as the square on the diameter is taken once, so often is the square on the side taken twice. The diameter will therefore become the greater and the side will become the less. Now in the case of the first side and diameter the square on the unit diameter will be less by a unit than twice the square on the unit side; for units are equal, and 1 is less by a unit than twice 1. Let us add to the side a diameter, that is, to the unit let us add a unit; therefore the [second] side will be two units. To the diameter let us now add two sides, that is, to the unit let us add two units; the [second] diameter will therefore be three units. Now the square on the side of two units will be 4, while the square on the diameter of three units will be 9; and 9 is greater by a unit than twice the square on the side 2.

Again, let us add to the side 2 the diameter 3; the [third] side will be 5. To the diameter 3 let us add two sides, that is, twice 2; the third diameter will be 7. Now the square from the side 5 will be 25, while that from the diameter 7 will be 49; and 49 is less by a unit than twice 25. Again, add to the side 5 the diameter 7; the result will be 12. And to the

GREEK MATHEMATICS

προσθήης δις τὴν $\bar{\epsilon}$ πλευράν, ἔσται $\bar{\iota\zeta}$. καὶ τοῦ ἀπὸ τῆς $\bar{\iota\beta}$ τετραγώνου τὸ ἀπὸ τῆς $\bar{\iota\zeta}$ μονάδι πλέον ἢ διπλάσιον. καὶ κατὰ τὸ ἐξῆς τῆς προσθήκης ὁμοίως γιγνομένης, ἔσται τὸ ἀνάλογον ἐναλλάξ· ποτὲ μὲν μονάδι ἔλαττον, ποτὲ δὲ μονάδι πλέον ἢ διπλάσιον τὸ ἀπὸ τῆς διαμέτρου τετράγωνον τοῦ ἀπὸ τῆς πλευρᾶς· καὶ ῥηταὶ αἱ τοιαῦται καὶ πλευραὶ καὶ διάμετροι.

Procl. in Plat. Remp., ed. Kroll ii. 27. 11-22

Προετίθεσαν δὲ οἱ Πυθαγόρειοι τούτου τοιόνδε

^a In algebraical notation, a pair of *side-* and *diameter-* numbers, a_n, d_n are such that

$$d_n^2 - 2a_n^2 = \pm 1,$$

and the law for the formation of any pair of such numbers from the preceding pair is

$$\begin{aligned} d_n &= 2a_{n-1} + d_{n-1} \\ a_n &= a_{n-1} + d_{n-1}. \end{aligned}$$

The general proof of the property of these numbers is not given by Theon (doubtless as being well known). It can be exhibited algebraically as follows:

$$\begin{aligned} d_n^2 - 2a_n^2 &= (2a_{n-1} + d_{n-1})^2 - 2(a_{n-1} + d_{n-1})^2 \\ &= 2a_{n-1}^2 - d_{n-1}^2 \\ &= -(d_{n-1}^2 - 2a_{n-1}^2) \\ &= +(d_{n-2}^2 - 2a_{n-2}^2), \end{aligned}$$

by similar reasoning, and so on. Starting with $a_1 = 1, d_1 = 1$ as the first pair of side and diameter numbers, we have

$$d_1^2 - 2a_1^2 = -1$$

and therefore by the above equation we have

$$\begin{aligned} d_2^2 - 2a_2^2 &= +1, \\ d_3^2 - 2a_3^2 &= -1, \end{aligned}$$

and so on, the positive and negative signs alternating. The

PYTHAGOREAN ARITHMETIC

diameter 7 add twice the side 5 ; the result will be 17. And the square of 17 is greater by a unit than twice the square of 12. Proceeding in this way in order, there will be the same alternating proportion ; the square on the diameter will be now greater by a unit, now less by a unit, than twice the square on the side ; and such sides and diameters are both rational.^a

Proclus, *Commentary on Plato's Republic*, ed. Kroll
ii. 27. 11-22

The Pythagoreans proposed this elegant theorem values of the first few pairs in the series are, as Theon correctly indicates,

$$(1, 1), (2, 3), (5, 7), (12, 17),$$

the last giving, for example, the equation

$$17^2 - 2 \cdot 12^2 = 289 - 288 = +1.$$

It is clear that the successive side- and diameter-numbers are rational approximations to the sides and hypotenuses of increasing isosceles right-angled triangles (hence the name), and therefore that the successive pairs give closer approximations to $\sqrt{2}$, namely

$$1, \frac{3}{2}, \frac{7}{5}, \frac{17}{12}, \text{ etc.,}$$

and this suggests one reason why the early Greek mathematicians were so interested in them.

The series was clearly known before Plato's time, for in the famous passage about the geometrical number (*Republic* 546 c) he distinguishes between the *rational* and the *irrational* "diameter of five." In a square of side 5, the diagonal or diameter is $\sqrt{50}$, and this is the "irrational diameter of five"; the "rational diameter" was the integral approximation $\sqrt{50} - 1 = 7$, which we have seen above to be the third diameter number.

In fact, since the publication of Kroll's edition of Proclus's commentary, the belief that these approximations are Pythagorean has been fully confirmed, as the next passage will show.

GREEK MATHEMATICS

θεώρημα γλαφυρὸν περὶ τῶν διαμέτρων καὶ πλευρῶν, ὅτι ἡ μὲν διάμετρος προσλαβοῦσα τὴν πλευράν, ἧς ἔστιν διάμετρος, γίνεται πλευρά, ἡ δὲ πλευρὰ ἐαυτῇ συντεθείσα καὶ προσλαβοῦσα τὴν διάμετρον τὴν ἐαυτῆς γίνεται διάμετρος. καὶ τοῦτο δεικνυται διὰ τῶν ἐν τῷ δευτέρῳ Στοιχείων γραμμικῶς ἀπ' ἐκείνου. ἐὰν εὐθεῖα τμηθῇ δίχα, προσλάβῃ δὲ εὐθεῖαν, τὸ ἀπὸ τῆς ὅλης σὺν τῇ προσκειμένη καὶ τὸ ἀπὸ ταύτης μόνης τετράγωνα διπλάσια τοῦ τε ἀπὸ τῆς ἡμισείας καὶ τοῦ ἀπὸ τῆς συγκεκλιμένης ἐκ τῆς ἡμισείας καὶ τῆς προσληφθείσης.

(ii.) *The " Bloom " of Thymaridas*

Iambl. in Nicom. Arith. Introd., ed. Pistelli 62. 18-63. 2

Ἐντεῦθεν καὶ ἡ ἔφοδος τοῦ Θυμαριδείου ἐπ-

^a This is Euclid ii. 10, which asserts that if AG is bisected at B

$$\text{A} \quad \text{B} \quad \text{Γ} \quad \text{Δ}$$

and produced to Δ , then

$$A\Delta^2 + \Delta\Gamma^2 = 2AB^2 + 2B\Delta^2.$$

If $AB = x$, $\Gamma\Delta = y$, this gives

$$(2x + y)^2 + y^2 = 2x^2 + 2(x + y)^2$$

or

$$(2x + y)^2 - 2(x + y)^2 = 2x^2 - y^2.$$

Therefore, if (x, y) are a pair of numbers satisfying one of the equations $2x^2 - y^2 = \pm 1$,

then $(x + y)$, $(2x + y)$ are another pair of numbers satisfying the other equation.

Proclus is not quoting exactly the Euclidean enunciation, for which see Euclid, ed. Heiberg-Menge i. 146. 15-22.

^b Thymaridas was apparently an early Pythagorean, not

PYTHAGOREAN ARITHMETIC

about the diameters and sides, that when the diameter receives the side of which it is diameter it becomes a side, while the side, added to itself and receiving its diameter, becomes a diameter. And this is proved graphically in the second book of the *Elements* by him [*sc.* Euclid]. If a straight line be bisected and a straight line be added to it, the square on the whole line including the added straight line and the square on the latter by itself are together double of the square on the half and of the square on the straight line made up of the half and the added straight line.^a

(ii.) *The "Bloom" of Thymaridas*^b

Iamblichus, *On Nicomachus's Introduction to Arithmetic*,
ed. Pistelli 62. 18-63. 2

The method of the "bloom" of Thymaridas was

later than the time of Plato, who lived at Paros. The name *ἐπάνθημα* (*flower* or *bloom*) given to his method shows that it must have been widely known in antiquity, though the term is not confined to this particular proposition. It is presumably used to give a sense of distinction, much as we say "flower of the army." The Greek is unfortunately most obscure, but the meaning was successfully extracted by Nesselman (*Die Algebra der Griechen*, pp. 232-236), who is followed by Gow (*History of Greek Mathematics*, p. 97), Cantor (*Vorlesungen* i³. 158-159), Loria (*Le scienze esatte nell' antica Grecia*, pp. 807-809), and Heath (*H.G.M.*, i. 94-96, *Diophantus of Alexandria*, 2nd ed., pp. 114-116). The "bloom" is a rule for solving n simultaneous equations connecting n unknown quantities, and states in effect:

- (1) if $x + x_1 + x_2 = S$,
 while $x + x_1 = s_1$, $x + x_2 = s_2$,
 then $x = s_1 + s_2 - S$;

GREEK MATHEMATICS

ανθήματος ἐλήφθη. ὠρισμένων γὰρ ἢ ἀορίστων μερισσμένων ὠρισμένον τι καὶ ἑνὸς οὐτινοσοῦν τοῖς λοιποῖς καθ' ἕκαστον συντεθέντος, τὸ ἐκ πάντων ἀθροισθὲν πλῆθος ἐπὶ μὲν τριῶν μετὰ τὴν ἐξ ἀρχῆς ὀρισθεῖσαν ποσότητα ὅλον τῷ συγκριθέντι προσγίμει τ' ἀφ' οὗ τὸ λείπον καθ' ἕκαστον τῶν λοιπῶν ἀφαιρεθήσεται, ἐπὶ δὲ τεσσάρων τὸ ἥμισυ καὶ ἐπὶ πέντε τὸ τρίτον καὶ ἐπὶ ἑξ τὸ τέταρτον καὶ αἰεὶ ἀκολουθῶς, δυνάδος κἀνταῦθα διαφορᾶς ἐπιφαινομένης πρὸς τε τὴν ποσότητα τῶν μεριζομένων καὶ πρὸς τὴν τοῦ μορίου κλήσιν.

(2) if $x + x_1 + x_2 + x_3 = S,$

while $x + x_1 = s_1, x + x_2 = s_2, x + x_3 = s_3,$

then $x = \frac{s_1 + s_2 + s_3 - S}{2},$

(3) while generally, if $x + x_1 + x_2 + \dots + x_{n-1} = S,$

while $x + x_1 = s_1, x + x_2 = s_2 \dots x + x_{n-1} = s_{n-1},$

then $x = \frac{s_1 + s_2 + \dots + s_{n-1} - S}{n-2}.$

Iamblichus goes on to show how other equations can be

PYTHAGOREAN ARITHMETIC

thence taken.^a When any determined or undefined quantities amount to a given sum, and the sum of one of them *plus* every other [in pairs] is given, the sum of these pairs minus the first given sum is, if there be three quantities, equal to the quantity which was added to all the rest [in the pairs]; if there be four quantities, one-half is so equal; if there be five quantities, one-third; if there be six quantities, one-fourth, and so on continually, there being always a difference of 2 between the number of quantities to be divided and the denomination of the part.

reduced to this form, so that the rule "does not leave us in the lurch" (οὐ παρέλκει) in these cases.

One of the most interesting features in this passage is the distinction between the *ὀρισμένον*, or known quantity, and the *ἀόριστον*, or unknown. This anticipates the phrase *πλήθος μονάδων ἀόριστον*, "an undefined number of units," by which Diophantus was later to describe his unknown quantity. Indeed, Thymaridas was already bordering on that indeterminate analysis which Diophantus was so brilliantly to develop; he has passed beyond the realm of strict arithmetic.

^a This passage immediately follows the section describing how gnomons of polygonal numbers are formed; see pp. 86-89 n. a, where it is shown that if n is the number of sides in the polygon, the successive gnomonic numbers differ by $n - 2$.

IV. PROCLUS'S SUMMARY

IV. PROCLUS'S SUMMARY

Procl. in *Eucl.* i., ed. Friedlein 64. 16-70. 18

Ἐπεὶ δὲ χρὴ τὰς ἀρχὰς καὶ τῶν τεχνῶν καὶ τῶν ἐπιστημῶν πρὸς τὴν παροῦσαν περίοδον σκοπεῖν, λέγομεν, ὅτι παρ' Αἰγυπτίοις μὲν εὐρήσθαι πρῶτον ἢ γεωμετρία παρὰ τῶν πολλῶν ἰστόρηται, ἐκ τῆς τῶν χωρίων ἀναμετρήσεως λαβοῦσα τὴν γένεσιν. ἀναγκαία γὰρ ἦν ἐκείνοις αὕτη διὰ τὴν ἀνοδὸν τοῦ Νείλου τοὺς προσήκοντας ὅρους ἐκάστοις ἀφανί-

^a The course of Greek geometry from the earliest days to the time of Euclid is reviewed in the few pages from Proclus's *Commentary on Euclid*, Book i., which are here reproduced. This "Summary" of Proclus has often been called the "Eudemian summary," on the assumption that it is extracted from the lost *History of Geometry* by Eudemus, the pupil of Aristotle. But the latter part dealing with Euclid cannot have been written by Eudemus, who preceded Euclid, nor is there any stylistic reason for attributing the earlier and later portions to different hands. Heath (*The Thirteen Books of Euclid's Elements*, i., pp. 37, 38, and *H.G.M.* i. 119, 120) gives arguments for believing that the author cannot have been Proclus himself, and suggests that the body of the summary was taken by Proclus from a compendium by some writer later than Eudemus, though the earlier portion was based, directly or indirectly, on Eudemus's *History*. The summary was written primarily for an understanding of the way in which the elements of geometry had come into being. The more advanced discoveries are therefore omitted or mentioned only in passing. Proclus himself lived from A.D. 410 to 485. On the death of Syrianus he became head of the

IV. PROCLUS'S SUMMARY ^a

Proclus, *On Euclid* i., ed. Friedlein 64. 16-70. 18

SINCE it behoves us to examine the beginnings both of the arts and of the sciences with reference to the present cycle [of the universe], we say that according to most accounts geometry was first discovered among the Egyptians,^b taking its origin from the measurement of areas. For they found it necessary by reason of the rising of the Nile, which wiped out

Neo-Platonic school at Athens, and his *Commentary on Euclid*, Book i., seems to be a revised edition of his lectures to beginners in mathematics (Heath, *The Thirteen Books of Euclid's Elements*, i., p. 31). This commentary is one of the two main sources for the history of Greek geometry, the other being the *Collection* of Pappus.

^b The Egyptian origin of geometry is taught by Herodotus, ii. 109, where it is asserted that Sesostris (Ramses II, c. 1300 B.C.) divided the land among the Egyptians in equal rectangular plots, on which an annual tax was levied; when therefore the river swept away a portion of a plot, the owner applied for a reduction of tax, and surveyors had to be sent down to report. In this he saw the origin of geometry, and this story may be the source of Proclus's account, as also of the similar accounts in Heron, *Geometrica* 2, ed. Heiberg 176. 1-13, Diodorus Siculus i. 69, 81 and Strabo xvii. c. 3. Aristotle also finds the origin of mathematics among the Egyptians, but in the existence of a leisured class of priests, not in a practical need (*Metaphysica* A 1, 981 b 23). The subject is fully dealt with in *H.G.M.* i. 121, 122, and an account of Egyptian geometry is given in succeeding pages.

GREEK MATHEMATICS

ζοντος. καὶ θλιμαστόν οὐδέν ἀπὸ τῆς χρείας ἄρξασθαι τὴν εὕρεσιν καὶ ταύτης καὶ τῶν ἄλλων ἐπιστημῶν, ἐπειδὴ πᾶν τὸ ἐν γενέσει φερόμενον ἀπὸ τοῦ ἀτελοῦς εἰς τὸ τέλειον πρόεισιν. ἀπὸ αἰσθήσεως οὖν εἰς λογισμόν καὶ ἀπὸ τούτου ἐπὶ νοῦν ἢ μετάβασις γέειοτο ἂν εἰκότως. ὥσπερ οὖν παρὰ τοῖς Φοίνιξιν διὰ τὰς ἐμπορείας καὶ τὰ συναλλάγματα τὴν ἀρχὴν ἔλαβεν ἢ τῶν ἀριθμῶν ἀκριβῆς γνῶσις, οὕτω δὴ καὶ παρ' Αἰγυπτίοις ἢ γεωμετρία διὰ τὴν εἰρημένην αἰτίαν εὔρηται.

Θαλῆς δὲ πρῶτον εἰς Αἴγυπτον ἔλθων μετήγαγεν εἰς τὴν Ἑλλάδα τὴν θεωρίαν ταύτην καὶ πολλὰ μὲν αὐτὸς εὔρεν, πολλῶν δὲ τὰς ἀρχὰς τοῖς μετ' αὐτὸν ὑφηγήσατο, τοῖς μὲν καθολικώτερον ἐπιβάλλων, τοῖς δὲ αἰσθητικώτερον. μετὰ δὲ τοῦτον Ἀμέριστος¹ ὁ Στησιχόρου τοῦ ποιητοῦ ἀδελφός, ὃς ἐφαψάμενος τῆς περὶ γεωμετρίαν σπουδῆς μνη-

¹ Μάμερκος Friedlein, following a correction in the oldest ms.

^a Thales (c. 624–547 B.C.), one of the “Seven Wise Men” of ancient Greece, is universally acknowledged as the founder of Greek geometry, astronomy and philosophy. His greatest fame in antiquity rested on his prediction of the total eclipse of the sun of May 28, 585 B.C., which led to the cessation of hostilities between the Medes and Lydians and a lasting

PROCLUS'S SUMMARY

everybody's proper boundaries. Nor is there anything surprising in that the discovery both of this and of the other sciences should have its origin in a practical need, since everything which is in process of becoming progresses from the imperfect to the perfect. Thus the transition from perception to reasoning and from reasoning to understanding is natural. Just as exact knowledge of numbers received its origin among the Phoenicians by reason of trade and contracts, even so geometry was discovered among the Egyptians for the aforesaid reason.

Thales^a was the first to go to Egypt and bring back to Greece this study; he himself discovered many propositions, and disclosed the underlying principles of many others to his successors, in some cases his method being more general, in others more empirical. After him Ameristus,^b the brother of the poet Stesichorus, is mentioned as having touched the study

peace (Herodotus i. 74); what Thales probably did was to predict the *year* in which the eclipse would take place, an achievement by no means beyond the astronomical powers of the age. Thales was noted for his political sense. He urged the separate states of Ionia, threatened by the encroachment of the Lydians, to form a federation with a capital at Teos; and his successful dissuasion of his fellow-Milesians from accepting the overtures of Croesus, king of the Lydians, may have had an influence on the favourable terms later granted to Miletus by Cyrus, king of the Persians, though the main reason for this preferential treatment was probably commercial. In philosophy Thales taught that the all is water. For his mathematical discoveries, see *infra*, pp. 164-169.

^b The name is uncertain. Friedlein, in suggesting Mamercus, observes that Suidas gives a brother of Stesichorus as Mamertinus, which could easily arise out of Mamercus. Another reading is Mamertius. Nothing more is known about him. Stesichorus, the lyric poet, flourished c. 611 B.C.

GREEK MATHEMATICS

μονεύεται, καὶ Ἰππίας ὁ Ἡλείος ἱστόρησεν ὡς ἐπὶ γεωμετρίᾳ δόξαν αὐτοῦ λαβόντος. ἐπὶ δὲ τούτοις Πυθαγόρας τὴν περὶ αὐτὴν φιλοσοφίαν εἰς σχῆμα παιδείας ἐλευθέρου μετέστησεν, ἄνωθεν τὰς ἀρχὰς αὐτῆς ἐπισκοπούμενος καὶ αὐλῶς καὶ νοερῶς τὰ θεωρήματα διερευνώμενος, ὃς δὴ καὶ τὴν τῶν ἀνὰ λόγον¹ πραγματείαν καὶ τὴν τῶν κοσμικῶν σχημάτων σύστασιν ἀνεῦρεν. μετὰ δὲ τοῦτον Ἀναξαγόρας ὁ Κλαζομένιος πολλῶν ἐφήσατο τῶν κατὰ γεωμετρίαν καὶ Οἰνοπίδης ὁ Χίος, ὀλίγω νεώτερος ὢν Ἀναξαγόρου, ὧν καὶ ὁ Πλάτων ἐν τοῖς ἀντερασταῖς ἐμνημόμευσεν ὡς ἐπὶ τοῖς μαθήμασι δόξαν λαβόντων.

¹ τῶν ἀνὰ λόγον coni. Diels ; τῶν ἀλόγων Friedlein.

^a The well-known Sophist, born about 460 B.C., whose various accomplishments are described in Plato's *Hippias Minor*. He claimed to have gone once to the Olympic Games with everything that he wore made by himself, as well as all kinds of works in prose and verse of his own composition. His system of mnemonics enabled him to remember any string of fifty names which he had heard once. The unmathematical Spartans, however, could not appreciate his genius, and from them he could get no fees. His chief mathematical discovery was the curve known as the quadratrix, which could be used for trisecting an angle or squaring the circle (see *infra*, pp. 336-347).

^b The life of Pythagoras is shrouded in mystery. He was probably born in Samos about 582 B.C. and migrated about 529 B.C. to Crotona, the Dorian colony in southern Italy, where a semi-religious brotherhood sprang up round him. This brotherhood was subjected to severe persecution in the fifth century B.C., and the Pythagoreans then took their

PROCLUS'S SUMMARY

of geometry, and Hippias of Elis ^a spoke of him as having acquired a reputation for geometry. After these Pythagoras ^b transformed this study into the form of a liberal education, examining its principles from the beginning and tracking down the theorems immaterially and intellectually; he it was who discovered the theory of proportionals ^c and the construction of the cosmic figures. After him Anaxagoras of Clazomenae ^d touched many questions affecting geometry, and so did Oenopides of Chios, ^e being a little younger than Anaxagoras, both of whom Plato mentioned in the *Rivals* ^f as having acquired a reputation for mathematics.

doctrines into Greece proper. Apart from important mathematical discoveries, noticed in a separate chapter, the Pythagoreans discovered the numerical ratios of the notes in the octave, and in astronomy conceived of the earth as a globe moving with the other planets about a central luminary.

^c Friedlein's reading is τῶν ἀλόγων, "irrationals," but there is grave difficulty in believing that Pythagoras could have developed a theory of irrationals; in fact, a Pythagorean is said to have been drowned at sea for his impiety in disclosing the existence of irrationals. There is an alternative reading τῶν ἀναλόγων, and the true reading could easily be τῶν ἀναλογίων, or τῶν ἀνὰ λόγον, "proportionals."

^d c. 500-428 B.C. Clazomenae was a town near Smyrna. All we know about the mathematics of Anaxagoras is that he wrote on the squaring of the circle while in prison (*infra*, p. 308) and may have written a book on perspective (Vitruvius, *De architectura* vii. praef. 11).

^e Oenopides was primarily an astronomer, and Eudemus is believed to have credited him with the discovery of the obliquity of the ecliptic and the period of the Great Year (Theon of Smyrna, ed. Hiller 198. 14-16). In mathematics Proclus attributed to him the discovery of Eucl. i. 12 and i. 23.

^f Plat. *Erastae* 132 A, B. Socrates finds two lads in the school of Dionysius disputing about Anaxagoras or Oenopides; they seemed to be drawing circles and indicating certain inclinations by placing their hands at an angle.

GREEK MATHEMATICS

Ἐφ' οἷς Ἴπποκράτης ὁ Χίος ὁ τὸν τοῦ μηνίσκου τετραγωνισμὸν εὐρών, καὶ Θεόδωρος ὁ Κυρηναῖος ἐγένοντο περὶ γεωμετρίαν ἐπιφανεῖς. πρῶτος γὰρ ὁ Ἴπποκράτης τῶν μνημονευομένων καὶ στοιχεῖα συνέγραψεν. Πλάτων δ' ἐπὶ τούτοις γενόμενος μεγίστην ἐποίησεν ἐπίδοσιν τὰ τε ἄλλα μαθήματα καὶ τὴν γεωμετρίαν λαβεῖν διὰ τὴν περὶ αὐτὰ σπουδὴν, ὅς που δηλὸς ἐστὶ καὶ τὰ συγγράμματα τοῖς μαθηματικοῖς λόγοις καταπυκνώσας καὶ πανταχοῦ τὸ περὶ αὐτὰ θαῦμα τῶν φιλοσοφίας ἀντεχομένων ἐπεγείρων. ἐν δὲ τούτῳ τῷ χρόνῳ καὶ Λεωδάμας ὁ Θάσιος ἦν καὶ Ἀρχύτας ὁ Ταραντῖνος καὶ Θεαίτητος ὁ Ἀθηναῖος, παρ' ὧν ἐπηυξήθη τὰ θεωρήματα καὶ προήλθεν εἰς ἐπιστημονικωτέραν σύστασιν.

Λεωδάμαντος δὲ νεώτερος ὁ Νεοκλείδης καὶ ὁ τούτου μαθητὴς Λέων, οἱ πολλὰ προσευπόρησαν τοῖς πρὸ αὐτῶν, ὥστε τὸν Λέοντα καὶ τὰ στοιχεῖα συνθεῖναι τῷ τε πλήθει καὶ τῇ χρεῖα τῶν δεικνυμένων ἐπιμελέστερον, καὶ διορισμοὺς εὐρεῖν, πότε δυνατόν ἐστὶ τὸ ζητούμενον πρόβλημα καὶ πότε ἀδύνατον. Εὐδοξος δὲ ὁ Κνίδιος, Λέοντος μὲν ὀλίγῳ νεώτερος, ἑταῖρος δὲ τῶν περὶ Πλάτωνα

^a Hippocrates was in Athens from about 450 to 430 B.C. For his mathematical achievements, see *infra*, pp. 234-253.

^b Our chief knowledge of Theodorus comes from the *Theaetetus* of Plato, whose mathematical teacher he is said to have been (Diog. Laert. ii. 103); see *infra*, pp. 380-383.

^c Proclus (*in Eucl.* i., ed. Friedlein 72 *et seq.*) explains that the *elements* in geometry are leading theorems having to those which follow the relation of an all-pervading principle; he compares them with the letters of the alphabet in relation

PROCLUS'S SUMMARY

After them Hippocrates of Chios,^a who discovered the quadrature of the lune, and Theodorus of Cyrene^b became distinguished in geometry. For Hippocrates is the first of those mentioned as having compiled *elements*.^c Plato,^d who came after them, made the other branches of mathematics as well as geometry take a very great step forward by his zeal for them; and it is obvious how he filled his writings with mathematical arguments and everywhere stirred up admiration for mathematics in those who took up philosophy. At this time also lived Leodamas of Thasos^e and Archytas of Taras^f and Theaetetus of Athens,^g by whom the theorems were increased and an advance was made towards a more scientific grouping.

Younger than Leodamas were Neoclides and his pupil Leon, who added many things to those known before them, so that Leon was able to make a collection of the *elements* in which he was more careful in respect both of the number and of the utility of the things proved; he also discovered *diorismi*, showing when the problem investigated can be solved and when not.^h Eudoxus of Cnidos, a little younger than Leon and an associate of Plato's school, was the first

to language; and they have, indeed, the same name in Greek.

^a See *infra*, pp. 386-405.

^e All we know about him is that Plato is said to have explained or communicated to him the method of analysis (Diog. Laert. iii. 24, Procl. *in Eucl.* i., ed. Friedlein 211. 19-23).

^f For Archytas, see *supra*, p. 4 n. a.

^g See *infra*, pp. 378-383.

^h We have no further knowledge of Neoclides and Leon. A good example of a *diorismos* is given in Plato, *Meno* 86 E—87 B (*infra*, pp. 394-397), which incidentally shows that Leon was not the first in this field.

GREEK MATHEMATICS

γενόμενος, πρῶτος τῶν καθόλου καλουμένων θεωρημάτων τὸ πλήθος ἠϋΐησεν καὶ ταῖς τρισὶν ἀναλογίαις ἄλλας τρεῖς προσέθηκεν καὶ τὰ περὶ τὴν τομὴν ἀρχὴν λαβόντα παρὰ Πλάτωνος εἰς πλήθος προήγαγεν καὶ ταῖς ἀναλύσεσιν ἐπ' αὐτῶν χρησάμενος. Ἀμύκλας δὲ ὁ Ἡρακλεώτης, εἰς τῶν Πλάτωνος ἐταίρων καὶ Μέναιχμος ἀκροατὴς ὢν Εὐδόξου καὶ Πλάτωνι δὲ συγγεγονῶς καὶ ὁ ἀδελφὸς αὐτοῦ Δεινόστρατος ἔτι τελεωτέραν ἐποίησαν τὴν ὅλην γεωμετρίαν. Θεῦδιος δὲ ὁ Μάγνης ἐν τε τοῖς μαθήμασιν ἔδοξεν εἶναι διαφέρων καὶ κατὰ τὴν ἄλλην φιλοσοφίαν· καὶ γὰρ τὰ στοιχεῖα καλῶς συνέταξεν καὶ πολλὰ τῶν μερικῶν¹ καθολικώτερα ἐποίησεν. καὶ μέντοι καὶ ὁ Κυζικηνὸς Ἀθήναιος κατὰ τοὺς αὐτοὺς γεγονῶς χρόνους καὶ ἐν τοῖς ἄλλοις μὲν μαθήμασι, μάλιστα δὲ κατὰ γεωμετρίαν ἐπιφανὴς ἐγένετο. διῆγον οὖν οὗτοι μετ' ἀλλήλων ἐν Ἀκαδημία κοινὰς ποιούμενοι τὰς ζητήσεις. Ἐρμότιμος δὲ ὁ Κολοφώνιος τὰ ὑπ' Εὐδόξου προηυπορημένα καὶ Θεαιτήτου προήγαγεν ἐπὶ πλεόν

¹ ὀρικῶν Friedlein.

^a For Eudoxus, one of the great mathematicians of all time, see *infra*, pp. 408-415. He lived c. 408-355 B.C. What the "so-called general theorems" may be is uncertain; Heath (*H.G.M.* i. 323) suggests theorems which are "true of everything falling under the conception of magnitude, as are the definitions and theorems forming part of Eudoxus's own theory of proportion." The three means which Eudoxus is said to have added to those already known are the three subcontrary means (*supra*, pp. 114-121). Iamblichus (*in Nicom.*, 101. 1-5) also attributes them to Eudoxus, but in other places (113. 16-18, 116. 1-4) he assigns them to Archytas and Hippiasus. It is disputed whether the "section" to which Eudoxus devoted his attention means sections of solids

PROCLUS'S SUMMARY

to increase the number of the so-called general theorems ; to the three proportions he added another three, and increased the number of theorems about the section, which had their origin with Plato, applying the method of analysis to them.^a Amyclas of Heraclea,^b one of the friends of Plato, and Menaechmus,^c a pupil of Eudoxus who had associated with Plato, and his brother Dinostratus^d made the whole of geometry still more perfect. Theudius^e of Magnesia seemed to excel both in mathematics and in the rest of philosophy ; for he made an admirable arrangement of *elements* and made many particular propositions more general. Again, Athenaeus^e of Cyzicus, who lived about those times, became famous in other branches of mathematics but mostly in geometry. They spent their time together in the Academy, conducting their investigations in common. Hermotimus^e of Colophon advanced farther the investigations begun by Eudoxus and Theaetetus ; he

by planes, which was the older view and that favoured by Tannery (*La géométrie grecque*, p. 76), or the "golden section" (division of a line in extreme and mean ratio, Eucl. ii. 11), a view put forward by Bretschneider in 1870 (*Die Geometrie und die Geometer vor Eukleides*, pp. 167-169). For discussions of this interesting question see Loria, *Le scienze esatte nell' antica Grecia*, pp. 139-142, Heath, *H.G.M.* i. 324-325.

^b The correct spelling appears to be Amyntas, though Diogenes Laertius (iii. 46) speaks of Amyclas of Heraclea as a pupil of Plato and in another place (ix. 40) says that a certain Pythagorean Amyclas dissuaded Plato from burning the works of Democritus. Heraclea was in Pontus.

^c He discovered the conic sections, see *infra*, p. 283 n. a.

^d He applied the quadratrix (probably discovered by Hippias) to the squaring of the circle.

^e No more is known of Theudius, Athenaeus or Hermotimus.

GREEK MATHEMATICS

καὶ τῶν στοιχείων πολλὰ ἀνεῦρε καὶ τῶν τόπων τινὰ συνέγραψεν. Φίλιππος δὲ ὁ Μεδμαῖος,¹ Πλάτωνος ὦν μαθητῆς καὶ ὑπ' ἐκείνου προτραπείς εἰς τὰ μαθήματα, καὶ τὰς ζητήσεις ἐποιεῖτο κατὰ τὰς Πλάτωνος ὑφηγήσεις καὶ ταῦτα προὔβαλλεν ἑαυτῷ, ὅσα ᾤετο τῇ Πλάτωνος φιλοσοφίᾳ συντελεῖν.

Οἱ μὲν οὖν τὰς ἱστορίας ἀναγράψαντες μέχρι τούτου προάγουσι τὴν τῆς ἐπιστήμης ταύτης τελείωσιν. οὐ πολὺ δὲ τούτων νεώτερός ἐστιν Εὐκλείδης ὁ τὰ στοιχεῖα συναγαγὼν καὶ πολλὰ μὲν τῶν Εὐδόξου συντάξας, πολλὰ δὲ τῶν Θεαιτήτου τελεωσάμενος, ἔτι δὲ τὰ μαλακώτερον δεικνύμενα τοῖς ἔμπροσθεν εἰς ἀνελέγκτους ἀποδείξεις ἀναγαγών. γέγονε δὲ οὗτος ὁ ἀνὴρ ἐπὶ τοῦ πρώτου Πτολεμαίου· καὶ γὰρ ὁ Ἀρχιμήδης ἐπιβαλὼν καὶ τῷ πρώτῳ μνημονεύει τοῦ Εὐκλείδου, καὶ μέντοι καὶ φασιν ὅτι Πτολεμαῖος ἤρετό ποτε αὐτόν, εἴ τίς ἐστιν περὶ γεωμετρίαν ὁδὸς συντομωτέρα τῆς στοιχειώσεως· ὁ δὲ ἀπεκρίνατο, μὴ εἶναι βασιλικὴν ἀτραπὸν ἐπὶ γεωμετρίαν· νεώτερος μὲν οὖν ἐστι τῶν περὶ Πλάτωνα, πρεσβύτερος δὲ Ἐρατοσθένους καὶ

¹ Merdaios Friedlein.

^a Almost certainly the same as Philippus of Opus, who is said to have revised and published the *Laws* of Plato and (wrongly) to have written the *Epinomis*. Suidas notes a number of astronomical and mathematical works by him.

^b Not much more is known about the life of Euclid than is contained in this passage (see Heath, *The Thirteen Books of Euclid's Elements*, vol. i., pp. 1-6 and *H.G.M.* i. 354-357). The summary of Euclid's achievement in the *Elements* is a very fair one, agreeing with the considered judgement of Heath (*H.G.M.* i. 217): "There is therefore probably little

PROCLUS'S SUMMARY

discovered many propositions in the *elements* and compiled some portion of the theory of loci. Philippus of Medma,^a a disciple of Plato and by him diverted to mathematics, not only made his investigations according to Plato's directions but set himself to do such things as he thought would fit in with the philosophy of Plato.

Those who have compiled histories carry the development of this science up to this point. Not much younger than these is Euclid, who put together the *elements*, arranging in order many of Eudoxus's theorems, perfecting many of Theaetetus's, and also bringing to irrefutable demonstration the things which had been only loosely proved by his predecessors. This man lived in the time of the first Ptolemy; for Archimedes, who came immediately after the first Ptolemy, makes mention of Euclid; and further they say that Ptolemy once asked him if there was in geometry a way shorter than that of the *elements*; he replied that there was no royal road to geometry.^b He is therefore younger than the pupils of Plato, but

in the whole compass of the *Elements* of Euclid, except the new theory of proportion due to Eudoxus and its consequences, which was not in substance included in the recognized content of geometry and arithmetic by Plato's time, although the form and arrangement of the subject-matter and the method employed in particular cases were different from what we find in Euclid" (*cf. H.G.M.* i. 357). As Plato died in 347 B.C., and Archimedes was born in 287 B.C., Euclid must have flourished about 300 B.C.; Ptolemy I reigned from 306 to 283 B.C. Had not the confusion been common in the Middle Ages, it would scarcely be necessary to point out that this Euclid is to be distinguished from Euclid of Megara, the philosopher, who lived about 400 B.C. A story about there being no royal road to geometry is also told of Menaechmus and Alexander (Stobaeus, *Ecl.* ii. 31, ed. Wachsmuth 115).

GREEK MATHEMATICS

Αρχιμήδους. οὔτοι γὰρ σύγχρονοι ἀλλήλοις, ὡς πού φησιν Ἐρατοσθένης. καὶ τῇ προαιρέσει δὲ Πλατωνικός ἐστι καὶ τῇ φιλοσοφίᾳ ταύτῃ οἰκείος, ὅθεν δὴ καὶ τῆς συμπάσης Στοιχειώσεως τέλος προεστήσατο τὴν τῶν καλουμένων Πλατωνικῶν σχημάτων σύστασιν. πολλὰ μὲν οὖν καὶ ἄλλα τοῦ ἀνδρὸς τούτου μαθηματικὰ συγγράμματα θαυμαστῆς ἀκριβείας καὶ ἐπιστημονικῆς θεωρίας μεστά. τοιαῦτα γὰρ καὶ τὰ Ὀπτικά καὶ τὰ Κατοπτρικά, τοιαῦται δὲ καὶ αἱ κατὰ μουσικὴν στοιχειώσεις, ἔτι δὲ τὸ Περὶ διαιρέσεων βιβλίον. διαφερόντως δ' ἄν τις αὐτὸν ἀγασθεῖη κατὰ τὴν Γεωμετρικὴν στοιχειώσιν τῆς τάξεως ἔνεκα καὶ τῆς ἐκλογῆς τῶν πρὸς τὰ στοιχεῖα πεπονημένων θεωρημάτων τε καὶ προβλημάτων. καὶ γὰρ οὐχ ὅσα ἐνεχώρει λέγειν ἀλλ' ὅσα στοιχειοῦν ἠδύνατο παρείληφεν, ἔτι δὲ τοὺς τῶν συλλογισμῶν παντοίους τρόπους, τοὺς μὲν

^a Eratosthenes was born about 284 B.C. His ability in many branches of knowledge, but failure to achieve the highest place in any, won for him the nicknames "Beta" and "Pentathlos." He became tutor to Philopator, son of Ptolemy Euergetes (see *infra*, pp. 256-257) and librarian at Alexandria. He wrote a book *Platonicus* and another *On Means* (both lost). For his *sieve* for finding successive prime numbers, see *supra*, pp. 100-103 and for his solution of the problem of doubling the cube, *infra*, pp. 290-297. His greatest achievement was his measurement of the circumference of the earth to a surprising degree of exactitude (see Heath, *H.G.M.* i. 106-108, *Greek Astronomy*, pp. 109-112).

^b It is true that the final book of the *Elements*, as written by Euclid, dealt with the construction of the cosmic, or Platonic, figures, but the whole work was certainly not designed with a view to their construction. Euclid, however, may quite well have been a Platonist.

^c Euclid's *Optics* survives and is available in the Teubner text in two recensions, one probably Euclid's own, the other

PROCLUS'S SUMMARY

older than Eratosthenes and Archimedes. For these men were contemporaries, as Eratosthenes^a somewhere says. In his aim he was a Platonist, being in sympathy with this philosophy, whence it comes that he made the end of the whole *Elements* the construction of the so-called Platonic figures.^b There are many other mathematical writings by this man, wonderful in their accuracy and replete with scientific investigations. Such are the *Optics* and *Catoptrics*, and the *Elements of Music*, and again the book *On Divisions*.^c He deserves admiration pre-eminently in the compilation of his *Elements of Geometry* on account of the order and of the selection both of the theorems and of the problems made with a view to the elements. For he included not everything which he could have said, but only such things as he could set down as elements. And he used all the various forms of syllogisms, some getting their plausibility from the

by Theon of Alexandria. It is possible that Proclus has attributed to Euclid a treatise on *Catoptrics* (*Mirrors*) which was really Theon's; a treatise by Euclid on this subject is not otherwise known. Two musical treatises attributed to Euclid are extant, the *Sectio Canonis* (Κατατομή κανόνος) and the *Introductio Harmonica* (Εἰσαγωγή ἁρμονική); the latter, however, is definitely by Cleonides, a pupil of Aristoxenus, and it is not certain that the former is Euclid's own. The book *On Divisions (of Figures)* has survived in an Arabic text discovered by Woepcke at Paris and published in 1851; see R. C. Archibald, *Euclid's Book on Division of Figures with a restoration based on Woepcke's text and the Practica Geometriae of Leonardo Pisano* (Cambridge 1915). A Latin translation (probably by Gherard of Cremona, 1114-1187) from the Arabic was known in the Middle Ages, but the Arabic cannot have been a direct translation from Euclid's Greek. The general character of the treatise is indicated by Procl. in *Eucl.* i., ed. Friedlein 144. 22-26, as the division of figures into like and unlike figures.

GREEK MATHEMATICS

ἀπὸ τῶν αἰτίων λαμβάνοντας τὴν πίστιν, τοὺς δὲ ἀπὸ τεκμηρίων ὠρμημένους, πάντας δὲ ἀνελέγκτους καὶ ἀκριβεῖς καὶ πρὸς ἐπιστήμην οἰκείους, πρὸς δὲ τούτοις τὰς μεθόδους ἀπάσας τὰς διαλεκτικάς, τὴν μὲν διαιρετικὴν ἐν ταῖς εὐρέσεσι τῶν εἰδῶν, τὴν δὲ ὀριστικὴν ἐν τοῖς οὐσιώδεσι λόγοις, τὴν δὲ ἀποδεικτικὴν ἐν τοῖς ἀπὸ ἀρχῶν εἰς τὰ ζητούμενα μεταβάσει, τὴν δὲ ἀναλυτικὴν ἐν ταῖς ἀπὸ τῶν ζητουμένων ἐπὶ τὰς ἀρχὰς ἀναστροφαῖς. καὶ μὴν καὶ τὰ ποικίλα τῶν ἀντιστροφῶν εἶδη τῶν τε ἀπλουστέρων καὶ τῶν συνθετωτέρων ἱκανῶς ἔστιν ἐν τῇ πραγματείᾳ ταύτῃ διηκριβωμένα θεωρεῖν, καὶ τίνα μὲν ὅλα ὅλοις ἀντιστρέφειν δύναται, τίνα δὲ ὅλα μέρεσι καὶ ἀνάπαλιν, τίνα δὲ ὡς μέρη μέρεσιν. ἔτι δὲ λέγομεν τὴν συνέχειαν τῶν εὐρέσεων, τὴν οἰκονομίαν καὶ τὴν τάξιν τῶν τε προηγουμένων καὶ τῶν ἐπομένων, τὴν δύναμιν, μεθ' ἧς ἕκαστα παραδίδωσιν. ἢ καὶ τὸ τυχόν προσθεῖς ἢ ἀφελὼν οὐκ ἐπιστήμης λανθάνεις ἀποπεσῶν καὶ εἰς τὸ ἐναντίον ψεῦδος καὶ τὴν ἄγνοιαν ὑπενεχθεῖς; ἐπειδὴ δὲ πολλὰ φαντάζεται μὲν ὡς τῆς ἀληθείας ἀντεχόμενα καὶ ταῖς ἐπιστημονικαῖς ἀρχαῖς ἀκολουθοῦντα, φέρεται δὲ εἰς τὴν ἀπὸ τῶν ἀρχῶν πλάνην καὶ τοὺς

* Lit. "causes," but αἴτιον clearly means the same here as ἀρχή, as often in Aristotle, cf. *Met.* Δ 1, 1013 a 16, ἰσαχῶς δὲ καὶ τὰ αἴτια λέγεται πάντα γὰρ τὰ αἴτια ἀρχαί.

^b Geometrical conversion is to be distinguished from logical conversion, as described by Aristotle, *Cat.* xii. 6 and elsewhere. An analysis of the conversion of geometrical propositions is given by Proclus (*in Eucl.* i., ed. Friedlein, 252. 5 *et seq.*). In the leading form of conversion (ἢ προηγουμένη ἀντιστροφή, also called conversion *par excellence*, ἢ κυρίως ἀντιστροφή) the conversion is simple, the hypo-

PROCLUS'S SUMMARY

first principles,^a some setting out from demonstrative proofs, all being irrefutable and accurate and in harmony with science. In addition to these he used all the dialectical methods, the *divisional* in the discovery of figures, the *definitive* in the existential arguments, the *demonstrative* in the passages from first principles to the things sought, and the *analytic* in the converse process from the things sought to the first principles. And the various species of conversions,^b both of the simpler (propositions) and of the more complex, are in this treatise accurately set forth and skilfully investigated, what wholes can be converted with wholes, what wholes with parts and conversely, and what as parts with parts. Again, mention must be made of the continuity of the proofs, the disposition and arrangement of the things which precede and those which follow, and the power with which he treats each detail. Have you, adding or subtracting accidentally, fallen away unawares from science, carried into the opposite error and into ignorance? Since many things seem to conform with the truth and to follow from scientific principles, but lead away from the principles into error and

thesis and conclusion of one theorem becoming the conclusion and hypothesis of the converse theorem. The other form of conversion is more complex, being that where several hypotheses are combined into a single enunciation so as to lead to a single conclusion. In the converse proposition the conclusion of the original proposition is combined with the hypotheses of the original proposition, less one, so as to lead to the omitted hypothesis as the new conclusion. An example of the first species of conversion is Euclid i. 6, which is the converse of Euclid i. 5, and Heath's notes thereon are most valuable (*The Thirteen Books of Euclid's Elements*, vol. i. pp. 256-257); an example of partial conversion is given by Euclid i. 8, which is a converse to i. 4.

GREEK MATHEMATICS

ἐπιπολαιότερους ἕξαπατᾶ, μεθόδους παραδέδωκεν καὶ τῆς τούτων διορατικῆς φρονήσεως, ὡς ἔχοντες γυμνάζειν μὲν δυνησόμεθα τοὺς ἀρχομένους τῆς θεωρίας ταύτης πρὸς τὴν εὕρεσιν τῶν παραλογισμῶν, ἀνεξαπύτητοι δὲ διαμένειν. καὶ τοῦτο δὴ τὸ σύγγραμμα, δι' οὗ τὴν παρασκευὴν ἡμῖν ταύτην ἐντίθησι, Ψευδαρίων ἐπέγραψεν, τρόπους τε αὐτῶν ποικίλους ἐν τάξει διαριθμησάμενος καὶ καθ' ἕκαστον γυμνάσας ἡμῶν τὴν διάνοιαν παντοίοις θεωρήμασι καὶ τῷ ψεύδει τὸ ἀληθὲς παραθεῖς καὶ τῇ πείρᾳ τὸν ἔλεγχον τῆς ἀπάτης συναρμόσας. τοῦτο μὲν οὖν τὸ βιβλίον καθαρτικόν ἐστι καὶ γυμναστικόν, ἣ δὲ Στοιχείωσις αὐτῆς τῆς ἐπιστημονικῆς θεωρίας τῶν ἐν γεωμετρίας πραγμάτων ἀνελέγκτον ἔχει καὶ τελείαν ὑφήγησιν.

PROCLUS'S SUMMARY

deceive the more superficial, he has handed down methods for the clear-sighted understanding of these matters also, and with these methods in our possession we can train beginners in the discovery of paralogisms and avoid being misled. The treatise in which he gave this machinery to us he entitled [the book] of *Pseudaria*,^a enumerating in order their various kinds, exercising our intelligence in each case by theorems of all sorts, setting the true side by side with the false, and combining the refutation of the error with practical illustration. This book is therefore purgative and disciplinary, while the *Elements* contains an irrefutable and complete guide to the actual scientific investigation of geometrical matters.

^a This book is lost. It clearly belonged to elementary geometry.

V. THALES

V. THALES

The circle is bisected by its diameter

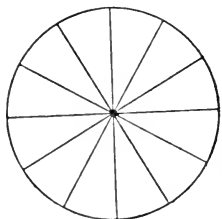
Procl. in Eucl. i., ed. Friedlein 157. 10-13

Τὸ μὲν οὖν διχοτομεῖσθαι τὸν κύκλον ὑπὸ τῆς διαμέτρου πρῶτον Θαλῆν ἐκείνους ἀποδείξαι φασιν, αἰτία δὲ τῆς διχοτομίας ἢ τῆς εὐθείας ἀπαρέγκλιτος διὰ τοῦ κέντρου χώρησις.

The angles at the base of an isosceles triangle are equal

Ibid. 250. 22-251. 2

Λέγεται γὰρ δὴ πρῶτος ἐκείνους ἐπιστῆσαι καὶ εἰπεῖν, ὡς ἄρα παντὸς ἰσοσκελοῦς αἱ πρὸς τῇ βάσει γωνίαι ἴσαι εἰσίν, ἀρχαϊκώτερον δὲ τὰς ἴσας ὁμοίας προσειρηκέναι.



* The word "demonstrate" (ἀποδείξαι) must not be taken too literally. Even Euclid did not demonstrate this property of the circle, but stated it as the 17th definition of his first book. Thales probably was the first to point out this property. Cantor (*Gesch. d. Math.* i³, pp. 109, 140) and Heath (*H.G.M.* i. 131) suggest that his attention may have been drawn to it by figures of circles divided into equal sectors by a number of diameters. Such figures are found on Egyptian monuments

V. THALES

The circle is bisected by its diameter

Proclus, *on Euclid* i., ed. Friedlein 157. 10-13

THEY say that Thales was the first to demonstrate^a that the circle is bisected by the diameter, the cause of the bisection being the unimpeded passage of the straight line through the centre.

The angles at the base of an isosceles triangle are equal

Ibid. 250. 22-251. 2

[Thales] is said to have been the first to have known and to have enunciated [the theorem] that the angles at the base of any isosceles triangle are equal, though in the more archaic manner he described the equal angles as similar.^b

and vessels brought by Asiatic tributary kings in the time of the eighteenth dynasty.

^b This theorem is Eucl. i. 5, the famous *pons asinorum*. Heath notes (*H.G.M.* i. 131): "It has been suggested that the use of the word 'similar' to describe the equal angles of an isosceles triangle indicates that Thales did not yet conceive of an angle as a magnitude, but as a *figure* having a certain *shape*, a view which would agree closely with the idea of the Egyptian *se-qet*, 'that which makes the nature,' in the sense of determining a similar or the same inclination in the faces of pyramids."

GREEK MATHEMATICS

The vertical and opposite angles are equal

Ibid. 299. 1-5

Τοῦτο τοίνυν τὸ θεώρημα δείκνυσιν, ὅτι δύο εὐθειῶν ἀλλήλας τεμνουσῶν αἱ κατὰ κορυφὴν γωνίαι ἴσαι εἰσίν, εὐρημένον μὲν, ὡς φησιν Εὐδῆμος, ὑπὸ Θαλοῦ πρώτου, τῆς δὲ ἐπιστημονικῆς ἀποδείξεως ἡξιωμένου παρὰ τῷ Στοιχειωτῇ.

Equality of Triangles

Ibid. 352. 14-18

Εὐδῆμος δὲ ἐν ταῖς γεωμετρικαῖς ἱστορίαις εἰς Θαλῆν τοῦτο ἀνάγει τὸ θεώρημα. τὴν γὰρ τῶν ἐν θαλάττῃ πλοίων ἀπόστασιν δι' οὗ τρόπου φασὶν αὐτὸν δεικνύναι τούτῳ προσχρησθαί φησιν ἀναγκαῖον.

The angle in a semicircle is a right-angle

Diog. Laert. i. 24-25

Παρά τε Αἰγυπτίων γεωμετρῆιν μαθόντα φησὶ Παμφίλη πρῶτον καταγράψαι κύκλου τὸ τρίγωνον

^a It is Eucl. i. 15.

^b The method by which Thales used the theorem referred to, Eucl. i. 26, to find the distance of a ship from the shore, has given rise to many conjectures. The most attractive is that of Heath (*The Thirteen Elements of Euclid's Elements*, i., p. 305, *H.G.M.* i. 133). He supposes that the observer had a rough instrument made of a straight stick and a cross-piece fastened to it so as to be capable of turning about the

THALES

The vertical and opposite angles are equal

Ibid. 299. 1-5

This theorem, that when two straight lines cut one another the vertical and opposite angles are equal, was first discovered, as Eudemus says, by Thales, though the scientific demonstration was improved by the writer of the *Elements*.^a

Equality of Triangles

Ibid. 352. 14-18

Eudemus in his *History of Geometry* attributes this theorem to Thales. For he says that the method by which Thales showed how to find the distance of ships at sea necessarily involves this method.^b

The angle in a semicircle is a right-angle

Diogenes Laertius i. 24-25

Pamphila says that, having learnt geometry from the Egyptians, he was the first to inscribe in a circle

fastening in such a manner so that it could form any angle with the stick and would remain where it was put. The observer, standing on the top of a tower or some other eminence on the shore, would fix the stick in the upright position and direct the cross-piece towards the ship. Leaving the cross-piece at this angle, he would turn the stick round, keeping it vertical, until the cross-piece pointed to some object on the land, which would be noted. The distance between the foot of the tower and this object would, by Eucl. i. 26, be equal to the distance of the ship. Apparently this method is found in many practical geometries during the first century of printing.

GREEK MATHEMATICS

ὀρθογώνιον, καὶ θῦσαι βοῦν. οἱ δὲ Πυθαγόραν
φασίν, ὧν ἔστιν Ἀπολλόδωρος ὁ λογιστικός.

^a Pamphila was a female writer who lived in the reign of Nero and won much repute by her historical commonplace book (*Συμμίκτων ἱστορικῶν ὑπομνημάτων λόγοι*). She may have been right in ascribing to Thales the discovery that the angle in a semicircle is a right angle, but the passage bristles with difficulties. The reference to the sacrifice of an ox is suspiciously like the better-attested story that Pythagoras sacrificed oxen when he discovered a certain theorem. This story is told in a distich by Apollodorus reproduced below (p. 176). In reproducing that distich Plutarch says it is uncertain whether the theorem was that about the square on the hypotenuse of a right-angled triangle or that about the application of areas; he does not mention the theorem about the angle in a semicircle. Diogenes Laertius probably made a mistake in bringing in Apollodorus; the reference to the sacrifice of an ox made him think of Apollodorus's distich

THALES

a right-angled triangle, whereupon he sacrificed an ox. Others say it was Pythagoras, among them being Apollodorus the calculator.^a

about Pythagoras, forgetting that they referred to a different proposition.

There are also difficulties on the way of believing that Thales could have discovered the theorem that the angle in a semicircle is a right angle. Euclid (iii. 31) proves this theorem by means of i. 32, that the sum of the angles of any triangle is two right-angles. Now Eudemus, as will be found below, pp. 176-179, attributed to the Pythagoreans the discovery of the theorem that in any triangle the sum of the angles is equal to two right-angles. The authority of Eudemus compels us to believe that Thales did not know this theorem. Could he have proved that the angle in a semicircle is a right angle without previously knowing that the sum of the angles of any triangle is two right-angles? Heath (*H.G.M.* i. 136-137) shows how he could have done so; and so Pamphila, for all her late date, may have preserved a correct tradition.

VI. PYTHAGOREAN GEOMETRY

VI. PYTHAGOREAN GEOMETRY

(a) GENERAL

Apollon. *Mirab.* 6 ; Diels, *Vors.* i⁵. 98. 29-31

Πυθαγόρας Μνησάρχου υἱὸς τὸ μὲν πρῶτον διεπονεῖτο περὶ τὰ μαθήματα καὶ τοὺς ἀριθμούς, ὕστερον δέ ποτε καὶ τῆς Φερεκύδου τερατοποιίας οὐκ ἀπέστη.

Aristot. *Met.* A 5, 985 b 23-26

Ἐν δὲ τούτοις καὶ πρὸ τούτων οἱ καλούμενοι Πυθαγόρειοι τῶν μαθημάτων ἀψάμενοι πρῶτοι ταῦτά τε προήγαγον, καὶ ἐντραφέντες ἐν αὐτοῖς τὰς τούτων ἀρχὰς τῶν ὄντων ἀρχὰς ᾤθησαν εἶναι πάντων.

Diog. Laert. viii. 24-25

Φησὶ δ' ὁ Ἀλέξανδρος ἐν ταῖς τῶν φιλοσόφων διαδοχαῖς καὶ ταῦτα εὐρηκέναι ἐν Πυθαγορικοῖς ὑπομνήμασι. ἀρχὴν μὲν ἀπάντων μονάδα· ἐκ δὲ τῆς μονάδος ἀόριστον δυάδα ὡς ἂν ὕλην τῇ μονάδι αἰτίῳ ὄντι ὑποστήναι· ἐκ δὲ τῆς μονάδος καὶ τῆς ἀορίστου δυάδος τοὺς ἀριθμούς· ἐκ δὲ τῶν ἀριθμῶν τὰ σημεῖα· ἐκ δὲ τούτων τὰς γραμμάς, ἐξ ὧν τὰ

VI. PYTHAGOREAN GEOMETRY

(a) GENERAL

Apollonius Paradoxographus, *On Marvels* 6; Diels, *Vors.*
i⁵. 98. 29-31 ^a

PYTHAGORAS, the son of Mnesarchus, first worked at mathematics and numbers, and later at one time did not hold himself aloof from the wonder-working of Pherecydes.

Aristotle, *Metaphysics* A 5, 985 b 23-26

In the time of these men [Leucippus and Democritus] and before them the so-called Pythagoreans applied themselves to mathematics and were the first to advance that science; and because they had been brought up in it they thought that its principles must be the principles of all existing things.

Diogenes Laertius viii. 24-25

Alexander in *The Successions of Philosophers* says that he found in the Pythagorean memoirs these beliefs also. The principle of all things is the monad; arising from the monad, the undetermined dyad acts as matter to the monad, which is cause; from the monad and the undetermined dyad arise numbers; from numbers, points; from these, lines, out of which

^a Apollonius is quoting Aristotle's book *On the Pythagoreans*, now lost.

GREEK MATHEMATICS

ἐπίπεδα σχήματα· ἐκ δὲ τῶν ἐπιπέδων τὰ στερεὰ σχήματα· ἐκ δὲ τούτων τὰ αἰσθητὰ σώματα, ὧν καὶ τὰ στοιχεῖα εἶναι τέτταρα, πῦρ, ὕδωρ, γῆν, ἀέρα· μεταβάλλειν δὲ καὶ τρέπεσθαι δι' ὄλων, καὶ γίνεσθαι ἐξ αὐτῶν κόσμον ἔμψυχο·, νοερόν, σφαιροειδῆ, μέσσην περιέχοντα τὴν γῆν καὶ αὐτὴν σφαιροειδῆ καὶ περιοικουμένην.

Diog. Laert. viii. 11-12

Τοῦτον καὶ γεωμετρίαν ἐπὶ πέρας ἀγαγεῖν, Μοίριδος πρώτου εὐρόντος τὰς ἀρχὰς τῶν στοιχείων αὐτῆς, ὡς φησιν Ἀντικλείδης ἐν δευτέρῳ Περὶ Ἀλεξάνδρου. μάλιστα δὲ σχολάσαι τὸν Πυθαγόραν περὶ τὸ ἀριθμητικὸν εἶδος αὐτῆς τὸν τε κανόνα τὸν ἐκ μίας χορδῆς εὐρεῖν. οὐκ ἠμέλησε δ' οὐδ' ἰατρικῆς. φησὶ δ' Ἀπολλόδωρος ὁ λογιστικὸς ἐκατόμβην θῦσαι αὐτόν, εὐρόντα ὅτι τοῦ ὀρθογωνίου τριγώνου ἢ ὑποτείνουσα πλευρὰ ἴσον δύναται ταῖς περιεχούσαις. καὶ ἔστιν ἐπίγραμμα οὕτως ἔχον·

ἦνίκα Πυθαγόρης τὸ περικλεῆς εὔρετο γράμμα,
κεῖν' ἔφ' ὅτῳ κλεινὴν ἤγαγε βουθυσίην.

Procl. in Eucl. i., ed. Friedlein 84. 13-23

“Ὅσα δὲ πραγματειωδεστέραν ἔχει θεωρίαν καὶ συντελεῖ πρὸς τὴν ὅλην φιλοσοφίαν, τούτων προηγουμένην ποιησόμεθα τὴν ὑπόμνησιν, ζηλοῦντες τοὺς Πυθαγορείους, οἷς πρόχειρον ἦν καὶ τοῦτο σύμβολον “σχᾶμα καὶ βᾶμα, ἀλλ' οὐ σχᾶμα καὶ τριῶβολον” ἐνδεικνυμένων, ὡς ἄρα δεῖ τὴν γεωμετρίαν ἐκείνην μεταδιώκειν, ἢ καθ' ἕκαστον

PYTHAGOREAN GEOMETRY

arise plane figures ; from planes, solid figures ; from these, sensible bodies, whose elements are four—fire, water, earth, air ; these elements interchange and turn into one another completely, and out of them arises a world which is animate, intelligent, spherical, and having as its centre the earth, which also is spherical and is inhabited round about.

Diogenes Laertius viii. 11-12

He [Pythagoras] it was who brought geometry to perfection, after Moeris had first discovered the beginnings of the elements of that science, as Anticleides says in the second book of his *History of Alexander*. He adds that Pythagoras specially applied himself to the arithmetical aspect of geometry and he discovered the musical intervals on the monochord ; nor did he neglect even medicine. Apollodorus the calculator says that he sacrificed a hecatomb on finding that the square on the hypotenuse of the right-angled triangle is equal to the squares on the sides containing the right angle. And there is an epigram as follows :

As when Pythagoras the famous figure found,
For which a sacrifice renowned he brought.

Proclus, *on Euclid* i., ed. Friedlein 84. 13-23

Whatsoever offers a more profitable field of research and contributes to the whole of philosophy, we shall make the starting-point of further inquiry, therein imitating the Pythagoreans, among whom there was prevalent this motto, " A figure and a platform, not a figure and sixpence," by which they implied that the geometry deserving study is that which, at each

GREEK MATHEMATICS

θεώρημα βῆμα τίθησιν εἰς ἄνοδον καὶ ἀπαίρει τὴν ψυχὴν εἰς ὕψος, ἀλλ' οὐκ ἐν τοῖς αἰσθητοῖς καταβαίνειν ἀφίησιν καὶ τὴν σύννοικον τοῖς θνητοῖς χρεῖαν ἀποπληροῦν καὶ ταύτης στοχαζομένην τῆς ἐντεῦθεν περιαγωγῆς καταμελεῖν.

Plut. *Non posse suav. vivi sec. Epic.* 11, 1094 B

Καὶ Πυθαγόρας ἐπὶ τῷ διαγράμματι βουὴν ἔθυσεν, ὡς φησιν Ἀπολλόδωρος·

ἦνίκα Πυθαγόρας τὸ περικλεῆς εὔρετο γράμμα
κεῖν' ἐφ' ὅτῳ λαμπρὴν ἤγετο βουθυσίην.

εἴτε περὶ τῆς ὑποτείνουσας ὡς ἴσον δύναται ταῖς περιεχούσαις τὴν ὀρθήν, εἴτε πρόβλημα περὶ τοῦ χωρίου τῆς παραβολῆς.

Plut. *Quaest. Conv.* viii. 2. 4, 720 A

Ἔστι γὰρ ἐν τοῖς γεωμετρικωτάτοις θεωρήμασι, μᾶλλον δὲ προβλήμασι, τὸ δυεῖν εἰδῶν δοθέντων ἄλλο τρίτον παραβάλλειν τῷ μὲν ἴσον τῷ δ' ὅμοιον· ἐφ' ᾧ καὶ φασιν ἐξευρεθέντι θῦσαι τὸν Πυθαγόραν. πολὺ γὰρ ἀμέλει γλαφυρότερον τοῦτο καὶ μουσικώτερον ἐκείνου τοῦ θεωρήματος, ὃ τὴν ὑποτείνουσαν ἀπέδειξε ταῖς περὶ τὴν ὀρθήν ἴσον δυναμένην.

(b) SUM OF THE ANGLES OF A TRIANGLE

Procl. in *Eucl.* i., ed. Friedlein 379. 2-16

Εὐδήμος δὲ ὁ περιπατητικὸς εἰς τοὺς Πυθαγορείους ἀναπέμπει τὴν τοῦδε τοῦ θεωρήματος εὔρεσιν, ὅτι τρίγωνον ἅπαν δυσὶν ὀρθαῖς ἴσας ἔχει

PYTHAGOREAN GEOMETRY

theorem, sets up a platform for further ascent and lifts the soul on high, instead of allowing it to descend among sensible objects and so fulfil the common needs of mortal men and in this lower aim neglect conversion to things above.

Plutarch, *The Epicurean Life* 11, 1094 B

Pythagoras sacrificed an ox in virtue of his proposition, as Apollodorus says—

As when Pythagoras the famous figure found
For which the noble sacrifice he brought ^a—

whether it was the theorem that the square on the hypotenuse is equal to the squares on the sides containing the right angle, or the problem about the application of the area.

Plutarch, *Convivial Questions* viii. 2. 4, 720 A

Among the most geometrical theorems, or rather problems, is this—given two figures, to apply a third equal to the one and similar to the other; it was in virtue of this discovery they say Pythagoras sacrificed. This is unquestionably more subtle and elegant than the theorem which he proved that the square on the hypotenuse is equal to the squares on the sides about the right angle.

(b) SUM OF THE ANGLES OF A TRIANGLE

Proclus, on *Euclid* i., ed. Friedlein 379. 2-16

Eudemus the Peripatetic ascribes to the Pythagoreans the discovery of this theorem, that any triangle has its internal angles equal to two right

^a See *supra*, p. 168 n. a, and p. 174.

GREEK MATHEMATICS

τὰς ἐντὸς γωνίας. καὶ δεικνύναι φησὶν αὐτοὺς οὕτως τὸ προκείμενον. ἔστω τρίγωνον τὸ $AB\Gamma$, καὶ ἤχθω διὰ τοῦ A τῇ $B\Gamma$ παράλληλος ἡ ΔE . ἐπεὶ οὖν παράλληλοί εἰσιν αἱ $B\Gamma$, ΔE , καὶ αἱ ἐναλλάξ ἴσαι εἰσίν, ἴση ἄρα ἡ μὲν ὑπὸ ΔAB τῇ ὑπὸ $AB\Gamma$, ἡ δὲ ὑπὸ EAG τῇ ὑπὸ AGB . κοινὴ προσκείσθω ἡ $BA\Gamma$. αἱ ἄρα ὑπὸ ΔAB , $BA\Gamma$, $\Gamma A E$, τουτέστιν αἱ ὑπὸ ΔAB , BAE , τουτέστιν αἱ δύο ὀρθαὶ ἴσαι εἰσὶ ταῖς τοῦ $AB\Gamma$ τριγώνου τρισὶ γωνίαις. αἱ ἄρα τρεῖς τοῦ τριγώνου δύσιν ὀρθαῖς εἰσιν ἴσαι.

(c) "PYTHAGORAS'S THEOREM"

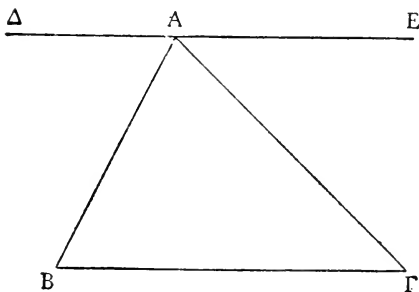
Eucl. *Elem.* i. 47

Ἐν τοῖς ὀρθογωνίοις τριγώνοις τὸ ἀπὸ τῆς τῆν ὀρθῆν γωνίαν ὑποτείνουσης πλευρᾶς τετράγωνον ἴσον ἐστὶ τοῖς ἀπὸ τῶν τῆν ὀρθῆν γωνίαν περιεχουσῶν πλευρῶν τετραγώνοις.

Ἐστω τρίγωνον ὀρθογώνιον τὸ $AB\Gamma$ ὀρθῆν ἔχον τῆν ὑπὸ $BA\Gamma$ γωνίαν· λέγω ὅτι τὸ ἀπὸ τῆς $B\Gamma$ τετράγωνον ἴσον ἐστὶ τοῖς ἀπὸ τῶν BA , $A\Gamma$ τετραγώνοις.

PYTHAGOREAN GEOMETRY

angles. He says they proved the theorem in question



after this fashion. Let $AB\Gamma$ be a triangle, and through A let ΔE be drawn parallel to $B\Gamma$. Now since $B\Gamma, \Delta E$ are parallel, and the alternate angles are equal, the angle ΔAB is equal to the angle $AB\Gamma$, and $E A \Gamma$ is equal to $A \Gamma B$. Let $B A \Gamma$ be added to both. Then the angles $\Delta AB, B A \Gamma, \Gamma A E$, that is, the angles $\Delta AB, B A E$, that is, two right angles, are equal to the three angles of the triangle. Therefore the three angles of the triangle are equal to two right angles.

(c) "PYTHAGORAS'S THEOREM"

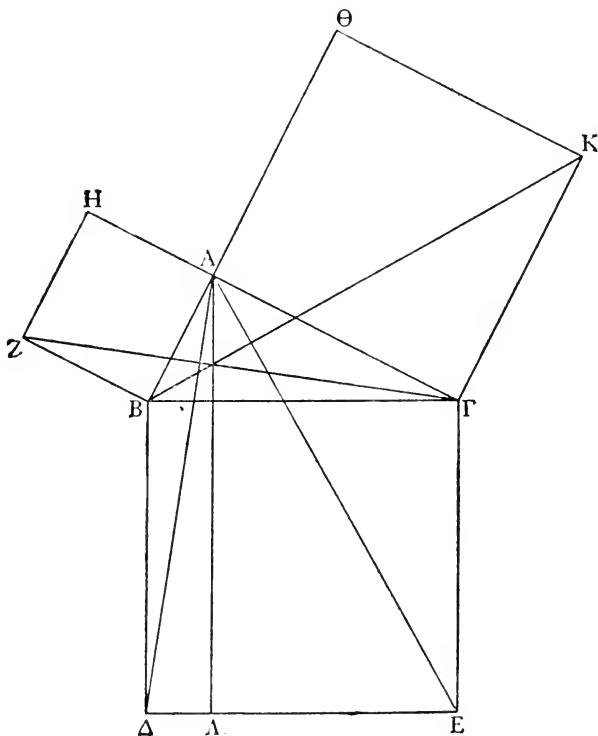
Euclid, *Elements* i. 47

In right-angled triangles the square on the side subtending the right angle is equal to the squares on the sides containing the right angle.

Let $AB\Gamma$ be a right-angled triangle having the angle $B A \Gamma$ right; I say that the square on $B\Gamma$ is equal to the squares on $BA, A\Gamma$.

GREEK MATHEMATICS

Ἀναγεγράφθω γὰρ ἀπὸ μὲν τῆς ΒΓ τετράγωνον τὸ ΒΔΕΓ, ἀπὸ δὲ τῶν ΒΑ, ΑΓ τὰ ΗΒ, ΘΓ, καὶ διὰ τοῦ Α ὁποτέρᾳ τῶν ΒΔ, ΓΕ παράλληλος ἤχθω ἢ ΑΛ· καὶ ἐπεζεύχθωσαν αἱ ΑΔ, ΖΓ. καὶ ἐπεὶ

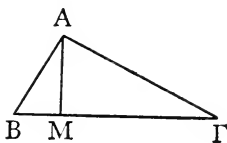


PYTHAGOREAN GEOMETRY

For let there be described on $B\Gamma$ the square $B\Delta E\Gamma$, and on BA , $A\Gamma$ the squares HB , $\Theta\Gamma$ [Eucl. i. 46], and through A let AA be drawn parallel to either $B\Delta$ or ΓE , and let $A\Delta$, $Z\Gamma$ be joined.^a Then, since each of

^a In this famous "windmill" figure, the lines AA , BK , ΓZ meet in a point. Euclid has no need to mention this fact, but it was proved by Heron; see *infra*, p. 185 n. b.

If AA , the perpendicular from A , meets $B\Gamma$ in M , as in the detached portion of the figure here reproduced, the triangles MBA , MAG are similar to the triangle $AB\Gamma$ and to one another. It follows from Eucl. *Elem.* vi. 4 and 17 (which do not depend on i. 47) that



$$BA^2 = BM \cdot B\Gamma,$$

and $A\Gamma^2 = \Gamma M \cdot B\Gamma.$

Therefore $BA^2 + A\Gamma^2 = B\Gamma (BM + \Gamma M)$
 $= B\Gamma^2.$

The theory of proportion developed in Euclid's sixth book therefore offers a simple method of proving "Pythagoras's Theorem." This proof, moreover, is of the same type as Eucl. *Elem.* i. 47 inasmuch as it is based on the equality of the square on $B\Gamma$ to the sum of two rectangles. This has suggested that Pythagoras proved the theorem by means of his inadequate theory of proportion, which applied only to commensurable magnitudes. When the incommensurable was discovered, it became necessary to find a new proof independent of proportions. Euclid therefore recast Pythagoras's invalidated proof in the form here given so as to get it into the first book in accordance with his general plan of the *Elements*.

For other methods by which the theorem can be proved, the complete evidence bearing on its reputed discovery by Pythagoras, and the history of the theorem in Egypt, Babylonia, and India, see Heath, *The Thirteen Books of Euclid's Elements*, i., pp. 351-366, *A Manual of Greek Mathematics*, pp. 95-100.

ὀρθή ἐστὶν ἑκατέρα τῶν ὑπὸ ΒΑΓ, ΒΑΗ γωνιῶν, πρὸς δὴ τινὶ εὐθείᾳ τῇ ΒΑ καὶ τῷ πρὸς αὐτῇ σημείῳ τῷ Α δύο εὐθεῖαι αἱ ΑΓ, ΑΗ μὴ ἐπὶ τὰ αὐτὰ μέρη κείμεναι τὰς ἐφεξῆς γωνίας δυσὶν ὀρθαῖς ἴσας ποιοῦσιν· ἐπ' εὐθείας ἄρα ἐστὶν ἡ ΓΑ τῇ ΑΗ. διὰ τὰ αὐτὰ δὴ καὶ ἡ ΒΑ τῇ ΑΘ ἐστὶν ἐπ' εὐθείας. καὶ ἐπεὶ ἴση ἐστὶν ἡ ὑπὸ ΔΒΓ γωνία τῇ ὑπὸ ΖΒΑ· ὀρθή γὰρ ἑκατέρα· κοινὴ προσκείσθω ἡ ὑπὸ ΑΒΓ· ὅλη ἄρα ἡ ὑπὸ ΔΒΑ ὅλη τῇ ὑπὸ ΖΒΓ ἐστὶν ἴση. καὶ ἐπεὶ ἴση ἐστὶν ἡ μὲν ΔΒ τῇ ΒΓ, ἡ δὲ ΖΒ τῇ ΒΑ, δύο δὴ αἱ ΔΒ, ΒΑ δύο ταῖς ΖΒ, ΒΓ ἴσαι εἰσὶν ἑκατέρα ἑκατέρα· καὶ γωνία ἡ ὑπὸ ΔΒΑ γωνία τῇ ὑπὸ ΖΒΓ ἴση· βάσις ἄρα ἡ ΑΔ βάσει τῇ ΖΓ [ἐστὶν] ἴση, καὶ τὸ ΑΒΔ τρίγωνον τῷ ΖΒΓ τριγώνῳ ἐστὶν ἴσον· καὶ [ἐστι] τοῦ μὲν ΑΒΔ τριγώνου διπλάσιον τὸ ΒΑ παραλληλόγραμμον· βάσιν τε γὰρ τὴν αὐτὴν ἔχουσι τὴν ΒΔ καὶ ἐν ταῖς αὐταῖς εἰσι παραλλήλοις ταῖς ΒΔ, ΑΛ· τοῦ δὲ ΖΒΓ τριγώνου διπλάσιον τὸ ΗΒ τετραγώνον· βάσιν τε γὰρ πάλιν τὴν αὐτὴν ἔχουσι τὴν ΖΒ καὶ ἐν ταῖς αὐταῖς εἰσι παραλλήλοις ταῖς ΖΒ, ΗΓ. [τὰ δὲ τῶν ἴσων διπλάσια ἴσα ἀλλήλοις ἐστίν·]¹ ἴσον ἄρα ἐστὶ καὶ τὸ ΒΑ παραλληλόγραμμον τῷ ΗΒ τετραγώνῳ. ὁμοίως δὴ ἐπιζευγνυμένων τῶν ΑΕ, ΒΚ δειχθήσεται καὶ τὸ ΓΑ παραλληλόγραμμον ἴσον τῷ ΘΓ τετραγώνῳ· ὅλον ἄρα τὸ ΒΔΕΓ τετραγώνον δυσὶ τοῖς ΗΒ, ΘΓ τετραγώνοις ἴσον ἐστίν. καὶ ἐστὶ τὸ μὲν ΒΔΕΓ τετραγώνον ἀπὸ τῆς ΒΓ ἀναγραφέν, τὰ δὲ ΗΒ, ΘΓ ἀπὸ τῶν ΒΑ, ΑΓ. τὸ ἄρα ἀπὸ τῆς ΒΓ πλευρᾶς τετραγώνον ἴσον ἐστὶ τοῖς ἀπὸ τῶν ΒΑ, ΑΓ πλευρῶν τετραγώνοις.

Ἐν ἄρα τοῖς ὀρθογωνίοις τριγώνοις τὸ ἀπὸ τῆς

PYTHAGOREAN GEOMETRY

the angles $B\hat{A}\Gamma$, $B\hat{A}H$ is right, it follows that with a straight line BA and at the point A on it, two straight lines $A\Gamma$, AH , not lying on the same side, make the adjacent angles equal to two right angles; therefore ΓA is in a straight line with AH [Eucl. i. 14]. For the same reasons BA is also in a straight line with $A\Theta$. And since the angle $\Delta B\hat{\Gamma}$ is equal to the angle $ZB\hat{A}$, for each is right, let the angle $A B\hat{\Gamma}$ be added to each; the whole angle $\Delta B\hat{A}$ is therefore equal to the whole angle $ZB\hat{\Gamma}$. And since ΔB is equal to $B\Gamma$, and ZB to BA , the two [sides] ΔB , BA are equal to the two [sides] $B\Gamma$, ZB respectively; and the angle $\Delta B\hat{A}$ is equal to the angle $ZB\hat{\Gamma}$. The base $A\Delta$ is therefore equal to the base $Z\Gamma$, and the triangle $AB\Delta$ is equal to the triangle $ZB\Gamma$ [Eucl. i. 4]. Now the parallelogram BA is double the triangle $AB\Delta$, for they have the same base $B\Delta$ and are in the same parallels $B\Delta$, $A\Lambda$ [Eucl. i. 41]. And the square HB is double the triangle $ZB\Gamma$, for they have the same base ZB and are in the same parallels ZB , $H\Gamma$. Therefore the parallelogram BA is equal to the square HB . Similarly, if AE , BK are joined, it can also be proved that the parallelogram ΓA is equal to the square $\Theta\Gamma$. Therefore the whole square $B\Delta E\Gamma$ is equal to the two squares HB , $\Theta\Gamma$. And the square $B\Delta E\Gamma$ is described on $B\Gamma$, while the squares HB , $\Theta\Gamma$ are described on BA , $A\Gamma$. Therefore the square on the side $B\Gamma$ is equal to the squares on the sides BA , $A\Gamma$.

Therefore in right-angled triangles the square on

¹ om. Heiberg. The words are equivalent to Common Notion 5, which must also be an interpolation as it is covered by Common Notion 2, *καὶ ἐὰν ἴσοις ἴσα προστεθῆ, τὰ ὅλα ἐστὶν ἴσα*, "if equals are added to equals the wholes are equal."

GREEK MATHEMATICS

τὴν ὀρθὴν γωνίαν ὑποτεينوῦσης πλευρᾶς τετράγωνον ἴσον ἐστὶ τοῖς ἀπὸ τῶν τῆν ὀρθὴν [γωνίαν] περιεχουσῶν πλευρῶν τετραγώνοις· ὅπερ ἔδει δεῖξαι.

Procl. in *Eucl.* i., ed. Friedlein 426. 6-14

Τῶν μὲν ἱστορεῖν τὰ ἀρχαῖα βουλομένων ἀκούοντας τὸ θεώρημα τοῦτο εἰς Πυθαγόραν ἀναπεμπόντων ἐστὶν εὐρεῖν καὶ βουθύτην λεγόντων αὐτὸν ἐπὶ τῇ εὐρέσει. ἐγὼ δὲ θαυμάζω μὲν καὶ τοὺς πρώτους ἐπιστάνας τῇ τοῦδε τοῦ θεωρήματος ἀληθείᾳ, μειζόνως δὲ ἄγαμαι τὸν Στοιχειωτὴν, οὐ μόνον ὅτι δι' ἀποδείξεως ἐναργεστάτης τοῦτο κατεδήσατο, ἀλλ' ὅτι καὶ τὸ καθολικώτερον αὐτοῦ τοῖς ἀνελέγκτοις λόγοις τῆς ἐπιστήμης ἐπίεσεν ἐν τῷ ἕκτῳ βιβλίῳ.

Ibid. 429. 9-15

Τῆς δὲ τοῦ Στοιχειωτοῦ ἀποδείξεως οὔσης φανερᾶς οὐδὲν ἡγοῦμαι δεῖν προσθεῖναι περιττόν, ἀλλὰ ἀρκεῖσθαι τοῖς γεγραμμένοις, ἐπεὶ καὶ ὅσοι προσέθεσάν τι πλεόν, ὡς οἱ περὶ Ἡρώνα καὶ Πάππον, ἠναγκάσθησαν προσλαβεῖν τι τῶν ἐν τῷ ἕκτῳ δεδειγμένων, οὐδενὸς ἔνεκα πραγματειῶδους.

^a *Eucl.* vi. 31. *In right-angled triangles the figure on the side subtending the right angle is equal to the similar and similarly described figures on the sides containing the right angle.*

^b By οἱ περὶ Ἡρώνα καὶ Πάππον Proclus doubtless means, in accordance with his practice elsewhere, Heron and Pappus themselves. Pappus, in *Coll.* iv. 1, ed. Hultsch 176-178, 184

PYTHAGOREAN GEOMETRY

the side subtending the right angle is equal to the squares on the sides containing the right angle; which was to be proved.

Proclus, *on Euclid* i., ed. Friedlein 426. 6-14

If we listen to those who wish to relate ancient history, we find some of them attributing this theorem to Pythagoras and saying that he sacrificed an ox upon the discovery. For my part, while I admire those who first became acquainted with the truth of this theorem, I marvel more at the writer of the *Elements*, not only because he established it by a most lucid demonstration, but because he insisted on the more general theorem by the irrefutable arguments of science in the sixth book.^a

Ibid. 429. 9-15

The proof by the writer of the *Elements* being clear, I think that it is unnecessary to add anything further, and that we may be content with what has been written, since, in fact, those who have added anything more, such as Heron and Pappus, were compelled to make use of what is proved in the sixth book, with no real object.^b

generalized "Pythagoras's Theorem" by proving that if *any* triangle is taken (not necessarily right-angled), and *any* parallelograms are described on two of the sides, their sum is equal to a third parallelogram. Proclus's words can, however, hardly refer to this elegant theorem. Heron is known from the Arabic commentary of an-Nairizī on Euclid's *Elements* (ed. Besthorn-Heiberg 175-185) to have proved that in Euclid's figure AA, BK, ΓZ meet in a point. Heron used three lemmas proved on the principles of Book i. alone, but they would more easily be proved from Book vi. It is quite likely that Proclus refers to this proof.

GREEK MATHEMATICS

(d) THE APPLICATION OF AREAS

One of the greatest of Pythagorean discoveries was the method known as the application of areas, which became a powerful engine in the hands of successive Greek geometers. The geometer is said to *apply* (*παραβάλλειν*) an area to a given straight line when a rectangle or parallelogram equal to the area is constructed on that straight line exactly; the area is said to *fall short* or *be deficient* (*ἐλλείπειν*) when the rectangle or parallelogram is constructed on a portion of the straight line; and to *exceed* (*ὑπερβάλλειν*) when the rectangle or parallelogram is constructed on the straight line produced. The method is developed in the following propositions of Euclid's *Elements*: i. 44, 45; ii. 5, 6, 11; vi. 27, 28, 29. These proposi-

Procl. in *Euc.* i., ed. Friedlein 419. 15-420. 12

*Ἔστι μὲν ἀρχαῖα, φασὶν οἱ περὶ τὸν Εὐδῆμον, καὶ τῆς τῶν Πυθαγορείων μούσης εὐρήματα ταῦτα, ἧ τε παραβολὴ τῶν χωρίων καὶ ἡ ὑπερβολὴ καὶ ἡ ἔλλειψις. ἀπὸ δὲ τούτων καὶ οἱ νεώτεροι τὰ ὀνόματα λαβόντες μετήγαγον αὐτὰ καὶ ἐπὶ τὰς κωνικὰς λεγομένας γραμμάς, καὶ τούτων τὴν μὲν παραβολήν, τὴν δὲ ὑπερβολὴν καλέσαντες, τὴν δὲ

186

PYTHAGOREAN GEOMETRY

tions are equivalent to the solution of quadratic equations, not only in particular cases but in the most general form. The application of areas (*παραβολή τῶν χωρίων*) is therefore a vital part of the "geometrical algebra" of the Greeks, who dealt in figures as familiarly as we do in symbols. This method is the foundation of Euclid's theory of irrationals and Apollonius's treatment of the conic sections. The subject will be introduced by Proclus's comment on Eucl. i. 44, and then the relevant propositions of Euclid will be given, with their equivalents in modern algebraical notation. Though the precise form of the later propositions cannot be due to Pythagoras, depending as they do on a theory of proportion invented by Eudoxus, there can be no doubt, as Eudemus said, that the method goes back to the Pythagorean school, and most probably to the master himself.

Proclus, *on Euclid i.*, ed. Friedlein 419. 15-420. 12

These things are ancient, says Eudemus, being discoveries of the Muse of the Pythagoreans, I mean the application of areas, their exceeding and their falling short. From these men the more recent geometers took the names that they gave to the so-called conic lines, calling one of these the *parabola*, one the *hyperbola* and one

GREEK MATHEMATICS

ἔλλειψιν, ἐκείνων τῶν παλαιῶν καὶ θείων ἀνδρῶν ἐν ἐπιπέδῳ καταγραφῇ χωρίων πρὸς εὐθείαν ὠρισμένην τὰ ὑπὸ τούτων σημαινόμενα τῶν ὀνομάτων ὀρώντων. ὅταν γὰρ εὐθείας ἐκκειμένης τὸ δοθὲν χωρίον πάσῃ τῇ εὐθείᾳ συμπαρατείησ, τότε παραβάλλειν ἐκείνο τὸ χωρίον φασίν, ὅταν μείζον δὲ ποιήσῃς τοῦ χωρίου τὸ μῆκος αὐτῆς τῆς εὐθείας, τότε ὑπερβάλλειν, ὅταν δὲ ἔλασσον, ὡς τοῦ χωρίου γραφέντος εἶναί τι τῆς εὐθείας ἐκτός, τότε ἐλλείπειν. καὶ οὕτως ἐν τῷ ἕκτῳ βιβλίῳ καὶ τῆς ὑπερβολῆς ὁ Εὐκλείδης μνημονεύει καὶ τῆς ἐλλείψεως, ἐνταῦθα δὲ τῆς παραβολῆς ἐδεήθη τῷ δοθέντι τριγώνῳ παρὰ τὴν δοθείσαν εὐθείαν ἴσον ἐθέλων παραβαλεῖν [παραλληλόγραμμον], ἵνα μὴ μόνον σύστασιν ἔχωμεν παραλληλογράμμου τῷ δοθέντι τριγώνῳ ἴσον, ἀλλὰ καὶ παρ' εὐθείαν ὠρισμένην παραβολήν.

Eucl. *Elem.* i. 44

Παρὰ τὴν δοθείσαν εὐθείαν τῷ δοθέντι τριγώνῳ ἴσον παραλληλόγραμμον παραβαλεῖν ἐν τῇ δοθείσῃ γωνίᾳ εὐθυγράμμῳ.

Ἔστω ἡ μὲν δοθείσα εὐθεῖα ἡ ΑΒ, τὸ δὲ δοθὲν τρίγωνον τὸ Γ, ἡ δὲ δοθείσα γωνία εὐθύγραμμος ἡ Δ· δεῖ δὴ παρὰ τὴν δοθείσαν εὐθείαν τὴν ΑΒ τῷ δοθέντι τριγώνῳ τῷ Γ ἴσον παραλληλόγραμμον παραβαλεῖν ἐν ἴσῃ τῇ Δ γωνίᾳ.

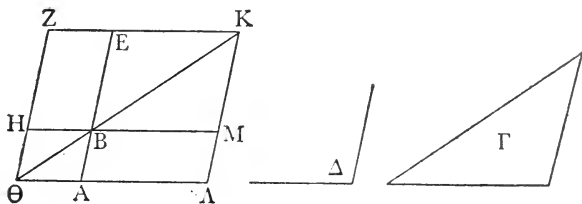
PYTHAGOREAN GEOMETRY

the *ellipse*, inasmuch as those god-like men of old saw the things signified by these names in the construction, in a plane, of areas upon a finite straight line. For when a straight line is set out and you lay the given area exactly alongside the whole of the straight line, they say that you apply that area; but when you make the length of the area greater than the straight line, then it is said to exceed, and when you make it less, so that when the area is drawn a portion of the straight line extends beyond it, it is said to fall short. In the sixth book Euclid speaks in this way both of exceeding and of falling short, but here he needed only the application, as he sought to apply to the given straight line an area equal to the given triangle, in order that we might have not only the construction of a parallelogram equal to the given triangle, but also its application to a finite straight line.

Euclid, *Elements* i. 44

To a given straight line to apply in a given rectilinear angle a parallelogram equal to a given triangle.

Let AB be the given straight line, Γ the given triangle and Δ the given rectilinear angle; then it is required to apply to the given straight line AB , in an angle equal to the angle Δ , a parallelogram equal to the given triangle Γ .



GREEK MATHEMATICS

Συνεστάτω τῷ Γ τριγώνῳ ἴσον παραλληλό-
 γραμμον τὸ $BEZH$ ἐν γωνία τῇ ὑπὸ EBH , ἣ ἐστὶν
 ἴση τῇ Δ · καὶ κείσθω ὥστε ἐπ' εὐθείας εἶναι τὴν
 BE τῇ AB , καὶ διήχθω ἡ ZH ἐπὶ τὸ Θ , καὶ διὰ
 τοῦ A ὁποτέρᾳ τῶν BH , EZ παράλληλος ἤχθω ἡ
 $A\Theta$, καὶ ἐπέξεύχθω ἡ ΘB . καὶ ἐπεὶ εἰς παραλλή-
 λους τὰς $A\Theta$, EZ εὐθεῖα ἐνέπεσεν ἡ ΘZ , αἱ ἄρα
 ὑπὸ $A\Theta Z$, ΘZE γωνίαι δυσὶν ὀρθαῖς εἰσὶν ἴσαι. αἱ
 ἄρα ὑπὸ $B\Theta H$, HZE δύο ὀρθῶν ἐλάσσονές εἰσιν·
 αἱ δὲ ἀπὸ ἐλασσόνων ἢ δύο ὀρθῶν εἰς ἄπειρον
 ἐκβαλλόμεναι συμπίπτουσιν· αἱ ΘB , ZE ἄρα
 ἐκβαλλόμεναι συμπεσοῦνται. ἐκβεβλήσθωσαν καὶ
 συμπιπτέτωσαν κατὰ τὸ K , καὶ διὰ τοῦ K σημείου
 ὁποτέρᾳ τῶν EA , $Z\Theta$ παράλληλος ἤχθω ἡ KL , καὶ
 ἐκβεβλήσθωσαν αἱ ΘA , HB ἐπὶ τὰ Λ , M σημεία.
 παραλληλόγραμμον ἄρα ἐστὶ τὸ ΘAKZ , διάμετρος
 δὲ αὐτοῦ ἡ ΘK , περὶ δὲ τὴν ΘK παραλληλόγραμμα
 μὲν τὰ AH , ME , τὰ δὲ λεγόμενα παραπληρώματα
 τὰ AB , BZ · ἴσον ἄρα ἐστὶ τὸ AB τῷ BZ . ἀλλὰ
 τὸ BZ τῷ Γ τριγώνῳ ἐστὶν ἴσον· καὶ τὸ AB ἄρα
 τῷ Γ ἐστὶν ἴσον. καὶ ἐπεὶ ἴση ἐστὶν ἡ ὑπὸ HBE
 γωνία τῇ ὑπὸ ABM , ἀλλὰ ἡ ὑπὸ HBE τῇ Δ ἐστὶν
 ἴση, καὶ ἡ ὑπὸ ABM ἄρα τῇ Δ γωνία ἐστὶν ἴση.

Παρὰ τὴν δοθείσαν ἄρα εὐθείαν τὴν AB τῷ
 δοθέντι τριγώνῳ τῷ Γ ἴσον παραλληλόγραμμον
 παραβέβληται τὸ AB ἐν γωνία τῇ ὑπὸ ABM , ἣ
 ἐστὶν ἴση τῇ Δ · ὅπερ ἔδει ποιῆσαι.

* Since any rectilinear figure can be divided into triangles, this proposition can be used to solve Euclid's next problem (i. 45), which is: τῷ δοθέντι εὐθυγράμμῳ ἴσον παραλληλό-

PYTHAGOREAN GEOMETRY

Let the parallelogram BEZH be constructed, equal to the triangle Γ , in the angle EBH which is equal to Δ [i. 42]; and let it be placed so that BE is in a straight line with AB, and let ZH be produced to Θ , and through A let A Θ be drawn parallel to either BH or EZ [i. 31], and let ΘB be joined. Then, since the straight line ΘZ falls upon the parallels A Θ , EZ, the angles A ΘZ , ΘZE are equal to two right angles [i. 29]. Therefore the angles B ΘH , HZE are less than two right angles. Now the straight lines produced indefinitely from angles less than two right angles will meet. Therefore ΘB , ZE, if produced, will meet. Let them be produced and let them meet at K, and through the point K let KA be drawn parallel to either EA or Z Θ [i. 31], and let ΘA , HB be produced to the points Λ , M. Then $\Theta \Lambda K Z$ is a parallelogram, ΘK is its diameter, and AH, ME are parallelograms, ΛB , BZ the so-called complements, about ΘK . Therefore ΛB is equal to BZ [i. 43]. But BZ is equal to the triangle Γ , and therefore ΛB is equal to Γ [Common Notion 1]. And since the angle HBE is equal to the angle ABM [i. 15], while the angle HBE is equal to Δ , therefore the angle ABM is also equal to Δ .

Therefore the parallelogram ΛB , equal to the given triangle Γ , has been applied to the given straight line AB in the angle ABM which is equal to Δ ; which was to be done.^a

γραμμῶν συστήσασθαι ἐν τῇ δοθείσῃ γωνίᾳ εὐθυγράμμῳ (to construct, in a given rectilinear angle, a parallelogram equal to a given rectilinear figure). The method is obvious and will not here be repeated. Proclus (*in Eucl.* i., ed. Friedlein 422. 24–423. 5, cited *infra*, p. 316) observes that it was in consequence of this problem that ancient geometers were led to investigate the squaring of the circle.

GREEK MATHEMATICS

Eucl. *Elem.* ii. 5

Ἐὰν εὐθεία γραμμὴ τμηθῆ εἰς ἴσα καὶ ἄνισα, τὸ ὑπὸ τῶν ἀνίσων τῆς ὅλης τμημάτων περιεχόμενον ὀρθογώνιον μετὰ τοῦ ἀπὸ τῆς μεταξὺ τῶν τομῶν τετραγώνου ἴσον ἐστὶ τῷ ἀπὸ τῆς ἡμισείας τετραγώνῳ.

Εὐθεία γάρ τις ἢ AB τετμήσθω εἰς μὲν ἴσα κατὰ τὸ Γ , εἰς δὲ ἄνισα κατὰ τὸ Δ . λέγω, ὅτι τὸ ὑπὸ τῶν $A\Delta$, ΔB περιεχόμενον ὀρθογώνιον μετὰ τοῦ ἀπὸ τῆς $\Gamma\Delta$ τετραγώνου ἴσον ἐστὶ τῷ ἀπὸ τῆς ΓB τετραγώνῳ.

Ἀναγεγράφθω γὰρ ἀπὸ τῆς ΓB τετράγωνον τὸ ΓEZB , καὶ ἐπέξεύχθω ἢ BE , καὶ διὰ μὲν τοῦ Δ ὁποτέρᾳ τῶν ΓE , BZ παράλληλος ἦχθω ἢ ΔH , διὰ δὲ τοῦ Θ ὁποτέρᾳ τῶν AB , EZ παράλληλος πάλιν ἦχθω ἢ KM , καὶ πάλιν διὰ τοῦ Λ ὁποτέρᾳ τῶν $\Gamma\Lambda$, BM παράλληλος ἦχθω ἢ AK . καὶ ἐπεὶ ἴσον ἐστὶ τὸ $\Gamma\Theta$ παραπλήρωμα τῷ ΘZ παραπληρώματι, κοινὸν προσκείσθω τὸ ΔM . ὅλον ἄρα τὸ ΓM ὅλω τῷ ΔZ ἴσον ἐστίν. ἀλλὰ τὸ ΓM τῷ AL ἴσον ἐστίν, ἐπεὶ καὶ ἢ AG τῇ ΓB ἐστὶν ἴση· καὶ τὸ AL ἄρα τῷ ΔZ ἴσον ἐστίν. κοινὸν προσκείσθω τὸ $\Gamma\Theta$. ὅλον ἄρα τὸ $A\Theta$ τῷ $MN\Xi$ γνώμονι ἴσον ἐστίν. ἀλλὰ τὸ $A\Theta$ τὸ ὑπὸ τῶν $A\Delta$, ΔB ἐστίν· ἴση γὰρ ἢ

^a Lit. "between the sections."

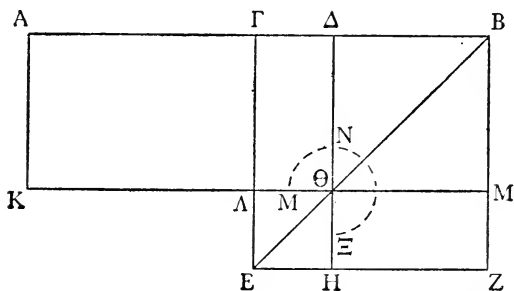
^b The gnomon is indicated in the figure of the mss. by the three points M , N , Ξ and a dotted curve; there are thus in the figure two points M which should not be confused. In the next proposition a similar gnomon is described as $N\Xi O$, and perhaps this is what Euclid here wrote.

PYTHAGOREAN GEOMETRY

Euclid, *Elements* ii. 5

If a straight line be cut into equal and unequal segments, the rectangle contained by the unequal segments of the whole together with the square on the line between the points of section^a is equal to the square on the half.

For let a straight line AB be cut into equal segments at Γ , and into unequal segments at Δ ; I say



that the rectangle contained by $A\Delta$, ΔB with the square on $\Gamma\Delta$ is equal to the square on ΓB .

For let the square ΓEZB be described on ΓB [i. 46] and let BE be joined, and through Δ let ΔH be drawn parallel to either ΓE or BZ , and through Θ let KM again be drawn parallel to either AB or EZ , and again through A let AK be drawn parallel to either $\Gamma\Lambda$ or BM [i. 31]. Then, since the complement $\Gamma\Theta$ is equal to the complement ΘZ [i. 43], let ΔM be added to each; therefore the whole ΓM is equal to the whole ΔZ . But ΓM is equal to $A\Lambda$, since $A\Gamma$ is also equal to ΓB [i. 36]; and therefore $A\Lambda$ is equal to ΔZ . Let $\Gamma\Theta$ be added to each; therefore the whole $A\Theta$ is equal to the gnomon $MN\Xi$.^b But $A\Theta$ is the rect-

GREEK MATHEMATICS

$\Delta\Theta$ τῆ ΔB · καὶ ὁ $MNΞ$ ἄρα γνώμων ἴσος ἐστὶ τῶ ὑπὸ $\Lambda\Delta$, ΔB . κοινὸν προσκείσθω τὸ ΛH , ὃ ἐστὶν ἴσον τῶ ἀπὸ τῆς $\Gamma\Delta$ · ὁ ἄρα $MNΞ$ γνώμων καὶ τὸ ΛH ἴσα ἐστὶ τῶ ὑπὸ τῶν $\Lambda\Delta$, ΔB περιεχομένῳ ὀρθογωνίῳ καὶ τῶ ἀπὸ τῆς $\Gamma\Delta$ τετραγώνῳ. ἀλλὰ ὁ $MNΞ$ γνώμων καὶ τὸ ΛH ὅλον ἐστὶ τὸ $\Gamma E Z B$ τετράγωνον, ὃ ἐστὶν ἀπὸ τῆς ΓB · τὸ ἄρα ὑπὸ τῶν $\Lambda\Delta$, ΔB περιεχόμενον ὀρθογώνιον μετὰ τοῦ ἀπὸ τῆς $\Gamma\Delta$ τετραγώνου ἴσον ἐστὶ τῶ ἀπὸ τῆς ΓB τετραγώνῳ.

Ἐὰν ἄρα κτλ.

^a If the unequal segments are p, q , then this theorem is equivalent to the algebraical proposition

$$pq + \left(\frac{p+q}{2} - q\right)^2 = \left(\frac{p+q}{2}\right)^2$$

or

$$\left(\frac{p+q}{2}\right)^2 - \left(\frac{p-q}{2}\right)^2 = pq.$$

This gives a ready means of obtaining the two rules, respectively attributed to the Pythagoreans and Plato (see *supra*, pp. 90-95) for finding integral square numbers which are the sum of two other integral square numbers. Putting $p = n^2$, $q = 1$, we have

$$\left(\frac{n^2+1}{2}\right)^2 - \left(\frac{n^2-1}{2}\right)^2 = n^2.$$

In order that the first two squares may be integers, n must be odd. This is the Pythagorean rule.

Putting $p = 2n^2$, $q = 2$,
 we have $(n^2+1)^2 - (n^2-1)^2 = 4n^2$.

This is Plato's rule, starting from an even number $2n$.

The theorem can be made to yield a result of even greater interest, namely, the geometrical solution of the quadratic equation

$$ax - x^2 = b^2,$$

as is shown by Heath (*The Thirteen Books of Euclid's Elements*, 194).

PYTHAGOREAN GEOMETRY

angle $\Lambda\Delta$, ΔB ; for $\Delta\Theta$ is equal to ΔB ; and therefore the gnomon $MN\Xi$ is equal to the rectangle $\Lambda\Delta$, ΔB . Let ΛH , which is equal to the square on $\Gamma\Delta$, be added to each; therefore the gnomon $MN\Xi$ and ΛH are equal to the rectangle contained by $\Lambda\Delta$, ΔB and the square on $\Gamma\Delta$. But the gnomon $MN\Xi$ and ΛH are the whole square ΓEZB , which is described on ΓB ; therefore the rectangle contained by $\Lambda\Delta$, ΔB together with the square on $\Gamma\Delta$ is equal to the square on ΓB .

Therefore, etc.^a

ments, vol. i. p. 384, and *H.G.M.* i. 151, 152), following Simson; see also Loria, *Le scienze esatte nell' antica Grecia*, pp. 42-45.

If $AB = a$, $\Delta B = x$,

then the theorem shows that

$(a - x) \cdot x = \text{the rectangle } A\Theta = \text{the gnomon } MN\Xi$.

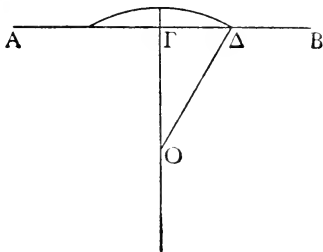
If the area of the gnomon is given ($= b^2$), then we have

$$ax - x^2 = b^2.$$

To solve this equation geometrically is to find the point Δ , and in Pythagorean language this is to apply to a given straight line (a) a rectangle which shall be equal to a given square (b^2) and shall fall short by a square figure, that is, to construct the rectangle $A\Theta$ or the gnomon $MN\Xi$.

Draw ΓO perpendicular to AB and equal to b .

With centre O and radius equal to ΓB ($= \frac{1}{2}a$) describe a circle. Provided that b is greater than $\frac{1}{2}a$, this circle will cut AB in two points. One of these is the required point Δ , $\Delta B = x$, and the rectangle $A\Theta$ can be constructed.

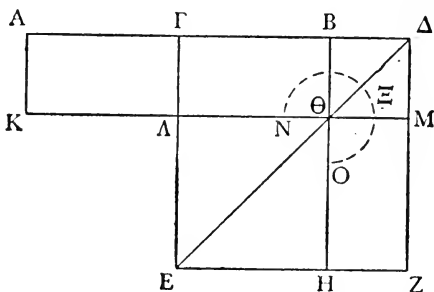


GREEK MATHEMATICS

Eucl. *Elem.* ii. 6

Ἐὰν εὐθεία γραμμὴ τμηθῆ διχα, προστεθῆ δέ τις αὐτῇ εὐθεία ἐπ' εὐθείας, τὸ ὑπὸ τῆς ὅλης σὺν τῇ προσκειμένῃ καὶ τῆς προσκειμένης περιεχόμενον ὀρθογώνιον μετὰ τοῦ ἀπὸ τῆς ἡμισείας τετραγώνου ἴσον ἐστὶ τῷ ἀπὸ τῆς συγκειμένης ἕκ τε τῆς ἡμισείας καὶ τῆς προσκειμένης τετραγώνῳ.

Εὐθεία γάρ τις ἢ AB τετμήσθω διχα κατὰ τὸ Γ σημεῖον, προσκείσθω δέ τις αὐτῇ εὐθεία ἐπ' εὐθείας ἢ ΒΔ· λέγω, ὅτι τὸ ὑπὸ τῶν ΑΔ, ΔΒ περιεχόμενον



ὀρθογώνιον μετὰ τοῦ ἀπὸ τῆς ΓΒ τετραγώνου ἴσον ἐστὶ τῷ ἀπὸ τῆς ΓΔ τετραγώνῳ.

For by the proposition (ii. 5) just proved,

$$\begin{aligned} \text{A}\Delta \cdot \Delta\text{B} + \Gamma\Delta^2 &= \text{GB}^2 \\ &= \text{O}\Delta^2 \\ &= \text{O}\Gamma^2 + \Gamma\Delta^2 \quad (\text{i. 47}) \end{aligned}$$

or $\therefore \text{A}\Delta \cdot \Delta\text{B} = \text{O}\Gamma^2$
 $(a-x)x = b^2.$

The two points in which the circle cuts AB give two real solutions of the equation, which are coincident when $b = \frac{1}{2}a$ and the circle touches AB.

There is no direct evidence that the Pythagoreans, or

PYTHAGOREAN GEOMETRY

Euclid, *Elements* ii. 6

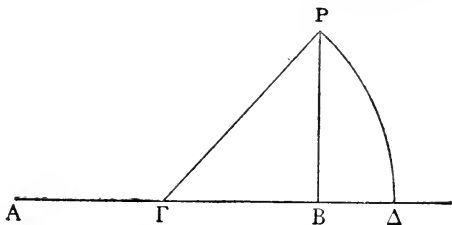
If a straight line be bisected, and a straight line be added to it in a straight line, the rectangle contained by the whole with the added straight line and the added straight line, together with the square on the half, is equal to the square on the straight line made up of the half and the added straight line.

For let a straight line AB be bisected at the point Γ , and let a straight line B Δ be added to it in a straight line; I say that the rectangle contained by A Δ , Δ B with the square on Γ B is equal to the square on $\Gamma\Delta$.^a

Euclid for that matter, used this proposition to solve geometrically the quadratic equation $ax - x^2 = b^2$. But, as will be shown below, the Pythagoreans must have solved a similar equation corresponding to ii. 11, and it may fairly safely be assumed that they solved the equations $ax - x^2 = b^2$ corresponding to ii. 5 and the equations $ax + x^2 = b^2$ and $x^2 - ax = b^2$ corresponding to ii. 6.

^a The proof is on the lines of that in the preceding proposition, the rectangle AM being shown equal to the gnomon N Ξ O, and can easily be supplied by the reader. If AB = a, B Δ = x, and the gnomon N Ξ O have a given value (= b^2), then
 or $(a + x) \cdot x = b^2$
 $ax + x^2 = b^2$.

To solve this equation geometrically is to apply to a given



straight line (a) a rectangle equal to a given square (b^2) and exceeding by a square figure, in short, to find the point Δ .

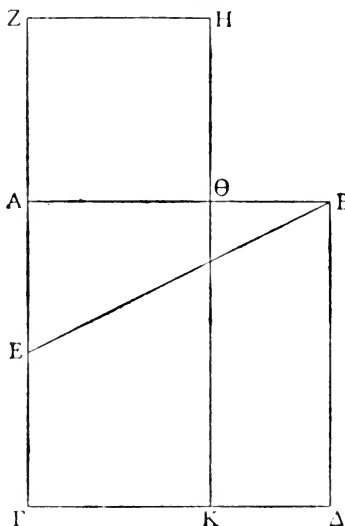
Continued on pp. 198-199.]

GREEK MATHEMATICS

Eucl. *Elem.* ii. 11

Τὴν δοθεῖσαν εὐθεῖαν τεμεῖν ὥστε τὸ ὑπὸ τῆς ὅλης καὶ τοῦ ἑτέρου τῶν τμημάτων περιεχόμενον ὀρθογώνιον ἴσον εἶναι τῷ ἀπὸ τοῦ λοιποῦ τμήματος τετραγώνῳ.

Ἐστω ἡ δοθεῖσα εὐθεῖα ἡ AB . δεῖ δὴ τὴν AB τεμεῖν ὥστε τὸ ὑπὸ τῆς ὅλης καὶ τοῦ ἑτέρου τῶν



τμημάτων περιεχόμενον ὀρθογώνιον ἴσον εἶναι τῷ ἀπὸ τοῦ λοιποῦ τμήματος τετραγώνῳ.

Continued from p. 197.]

Simson first showed how to do this. Let BP be drawn perpendicular to AB and equal to b . With centre Γ and

PYTHAGOREAN GEOMETRY

Euclid, *Elements* ii. 11

To cut the given straight line so that the rectangle contained by the whole and one of the segments is equal to the square on the remaining segment.

Let AB be the given straight line ; then it is required to cut AB so that the rectangle contained by the whole and one of the segments is equal to the square on the remaining segment.

radius GP let a circle be drawn cutting AB produced in Δ. Then Δ is the required point.

For by the proposition (ii. 6) just proved,

$$\begin{array}{rcl}
 \Lambda\Delta \cdot \Delta B + \Gamma B^2 & = & \Gamma\Delta^2 \\
 & = & \Gamma P^2, \\
 & = & \Gamma B^2 + BP^2 \\
 \therefore \Lambda\Delta \cdot \Delta B & = & BP^2 \\
 \text{i.e. } ax + x^2 & = & b^2.
 \end{array}$$

Because the circle cuts AB produced in two points there are two real solutions, and as the circle always cuts AB produced there is always a real solution. This bears out the algebraical proof that the equation

$$ax + x^2 = b^2$$

always has two real roots, which are equal when $b = \frac{1}{2}a$.

When we come to deal with Hippocrates' quadrature of lunes we shall come across the problem: To find x , when x is given by the equation

$$\sqrt{\frac{2}{3}}ax + x^2 = a^2.$$

This could have been solved theoretically by the above methods, and the solution was certainly not beyond the powers of Hippocrates. It seems more probable, however, from the wording of Eudemus's account, that he used an approximate mechanical solution for his purpose.

This same construction can be used to give a geometrical solution of the equation $x^2 - ax = b^2$. In the figure it has only to be supposed that $AB = a$ and $\Lambda\Delta$ (instead of $B\Delta$) = x . Then the theorem tells us that $x(x - a) = \text{the gnomon} = b^2$.

GREEK MATHEMATICS

Ἀναγεγράφθω γὰρ ἀπὸ τῆς AB τετράγωνον τὸ ABΔΓ, καὶ τετμήσθω ἢ ΑΓ δίχα κατὰ τὸ Ε σημεῖον, καὶ ἐπεζεύχθω ἢ ΒΕ, καὶ διήχθω ἢ ΓΑ ἐπὶ τὸ Ζ, καὶ κείσθω τῇ ΒΕ ἴση ἢ ΕΖ, καὶ ἀναγεγράφθω ἀπὸ τῆς ΑΖ τετράγωνον τὸ ΖΘ, καὶ διήχθω ἢ ΗΘ ἐπὶ τὸ Κ· λέγω, ὅτι ἢ ΑΒ τέτμηται κατὰ τὸ Θ, ὥστε τὸ ὑπὸ τῶν ΑΒ, ΒΘ περιεχόμενον ὀρθογώνιον ἴσον ποιεῖν τῷ ἀπὸ τῆς ΑΘ τετραγώνῳ.

Ἐπεὶ γὰρ εὐθεῖα ἢ ΑΓ τέτμηται δίχα κατὰ τὸ Ε, πρόσκειται δὲ αὐτῇ ἢ ΖΑ, τὸ ἄρα ὑπὸ τῶν ΓΖ, ΖΑ περιεχόμενον ὀρθογώνιον μετὰ τοῦ ἀπὸ τῆς ΑΕ τετραγώνου ἴσον ἐστὶ τῷ ἀπὸ τῆς ΕΖ τετραγώνῳ. ἴση δὲ ἢ ΕΖ τῇ ΕΒ· τὸ ἄρα ὑπὸ τῶν ΓΖ, ΖΑ μετὰ τοῦ ἀπὸ τῆς ΑΕ ἴσον ἐστὶ τῷ ἀπὸ ΕΒ. ἀλλὰ τῷ ἀπὸ ΕΒ ἴσα ἐστὶ τὰ ἀπὸ τῶν ΒΑ, ΑΕ· ὀρθὴ γὰρ ἢ πρὸς τῷ Α γωνία· τὸ ἄρα ὑπὸ τῶν ΓΖ, ΖΑ μετὰ τοῦ ἀπὸ τῆς ΑΕ ἴσον ἐστὶ τοῖς ἀπὸ τῶν ΒΑ, ΑΕ. κοινὸν ἀφηρήσθω τὸ ἀπὸ τῆς ΑΕ· λοιπὸν ἄρα τὸ ὑπὸ τῶν ΓΖ, ΖΑ περιεχόμενον ὀρθογώνιον ἴσον ἐστὶ τῷ ἀπὸ τῆς ΑΒ τετραγώνῳ. καὶ ἐστὶ τὸ μὲν ὑπὸ τῶν ΓΖ, ΖΑ τὸ ΖΚ· ἴση γὰρ ἢ ΑΖ τῇ ΖΗ· τὸ δὲ ἀπὸ τῆς ΑΒ τὸ ΑΔ· τὸ ἄρα ΖΚ ἴσον ἐστὶ τῷ ΑΔ. κοινὸν ἀφηρήσθω τὸ ΑΚ· λοιπὸν ἄρα τὸ ΖΘ τῷ ΘΔ ἴσον ἐστίν. καὶ ἐστὶ τὸ μὲν ΘΔ τὸ ὑπὸ τῶν ΑΒ, ΒΘ· ἴση γὰρ ἢ ΑΒ τῇ ΒΔ· τὸ δὲ ΖΘ τὸ ἀπὸ τῆς ΑΘ· τὸ ἄρα ὑπὸ τῶν ΑΒ, ΒΘ περιεχόμενον ὀρθογώνιον ἴσον ἐστὶ τῷ ἀπὸ ΘΑ τετραγώνῳ.

Ἡ ἄρα κτλ.

* If $AB = a$, $AΘ = x$, then AB has been so cut at $Θ$ that

$$a(a - x) = x^2$$

$$x^2 + ax = a^2.$$

or

PYTHAGOREAN GEOMETRY

Let the square $AB\Delta\Gamma$ be described on AB , and let $A\Gamma$ be bisected at the point E , and let BE be joined, and let ΓA be produced to Z , and let EZ be made equal to BE , and let the square $Z\Theta$ be described on AZ , and let $H\Theta$ be produced to K ; I say that AB has been so cut at Θ as to make the rectangle contained by AB , $B\Theta$ equal to the square on $A\Theta$.

For, since the straight line $A\Gamma$ has been bisected at E , and ZA is added to it, therefore the rectangle contained by ΓZ , ZA together with the square on AE is equal to the square on EZ [ii. 6]. But EZ is equal to EB ; therefore the rectangle contained by ΓZ , ZA together with the square on AE is equal to the square on EB . But the squares on BA , AE are equal to the square on EB , for the angle at A is right [i. 47]; therefore the rectangle contained by ΓZ , ZA together with the square on AE is equal to the squares on BA , AE . Let the square on AE be taken away from each; therefore the rectangle contained by ΓZ , ZA which remains is equal to the square on AB . Now the rectangle ΓZ , ZA is ZK , for AZ is equal to ZH ; and the square on AB is $A\Delta$; therefore ZK is equal to $A\Delta$. Let AK be taken away from each; therefore the remainder $Z\Theta$ is equal to $\Theta\Delta$. Now $\Theta\Delta$ is the rectangle AB , $B\Theta$, for AB is equal to $B\Delta$; and $Z\Theta$ is the square on $A\Theta$; therefore the rectangle contained by AB , $B\Theta$ is equal to the square on $A\Theta$.

Therefore, etc.^a

In other words, the proposition gives a geometrical solution of the equation

$$x^2 + ax = a^2$$

for it enables us to find $A\Theta$ or x .

This equation is a particular case of the more general proposition

$$x^2 + ax = b^2$$

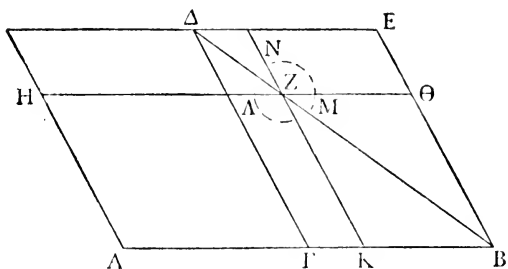
which, as was explained in the note on p. 197 n. *a*, can be solved

GREEK MATHEMATICS

Eucl. *Elem.* vi. 27

Πάντων τῶν παρὰ τὴν αὐτὴν εὐθείαν παραβαλλομένων παραλληλογράμμων καὶ ἔλλειπόντων εἶδει παραλληλογράμμοις ὁμοίοις τε καὶ ὁμοίως κειμένοις τῷ ἀπὸ τῆς ἡμισείας ἀναγραφομένῳ μέγιστόν ἐστι τὸ ἀπὸ τῆς ἡμισείας παραβαλλόμενον ὁμοιον ὄν τῷ ἔλλείματι.

Ἔστω εὐθεῖα ἡ AB καὶ τετμήσθω δίχα κατὰ



by a method based on ii. 6. There is good reason to believe, as will be shown below, pp. 222-225, that the Pythagoreans knew how to construct a regular pentagon $ABCDE$, and it is probable that this theorem was used in the construction, as can be shown if CE is allowed to cut AD in F .

For the Pythagoreans, knowing that the sum of the angles of any triangle is two right angles, would immediately have deduced that the sum of the internal angles of a regular pentagon is six right angles, and that each of the internal angles is therefore $\frac{2}{5}$ ths of a right angle. It easily follows that the angles CAD , ADC , DCA are respectively $\frac{2}{5}$ ths, $\frac{3}{5}$ ths and $\frac{3}{5}$ ths of a right angle, while the angles FCD , CDF , DFC are also respectively $\frac{2}{5}$ ths, $\frac{3}{5}$ ths and $\frac{3}{5}$ ths of a right angle. From this it follows that the triangles ACD , CDF are similar, while $AF = FC = CD$.

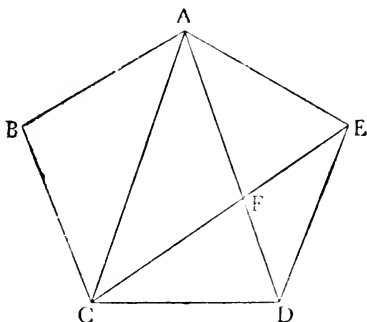
PYTHAGOREAN GEOMETRY

Euclid, *Elements* vi. 27

Of all the parallelograms applied to the same straight line and deficient by parallelogrammic figures similar and similarly situated to that described on the half of the straight line, that parallelogram is greatest which is applied to the half of the straight line and is similar to the defect.^a

Let AB be a straight line and let it be bisected

Therefore	$AC : CD = CD : DF$
or	$AD : AF = AF : FD$
or	$AD \cdot FD = AF^2$.



The point F can therefore be found according to the method of ii. 6, and the pentagon constructed, starting from AD.

^a This proposition gives the conditions under which it is possible to solve the next proposition, and so full consideration will be left to the note on p. 210. It is the first example we have met of a *διορισμός*. It will be remembered that according to Proclus Leon discovered *διορισμοί* (see *supra*, p. 150).

GREEK MATHEMATICS

τὸ Γ, καὶ παραβεβλήσθω παρὰ τὴν ΑΒ εὐθείαν τὸ ΑΔ παραλληλόγραμμον ἑλλείπον εἶδει παραλληλογράμμῳ τῷ ΔΒ ἀναγραφέντι ἀπὸ τῆς ἡμισείας τῆς ΑΒ, τουτέστι τῆς ΓΒ· λέγω, ὅτι πάντων τῶν παρὰ τὴν ΑΒ παραβαλλομένων παραλληλογράμμων καὶ ἑλλειπόντων εἶδεσι ὁμοίοις τε καὶ ὁμοίως κειμένοις τῷ ΔΒ μέγιστόν ἐστι τὸ ΑΔ. παραβεβλήσθω γὰρ παρὰ τὴν ΑΒ εὐθείαν τὸ ΑΖ παραλληλόγραμμον ἑλλείπον εἶδει παραλληλογράμμῳ τῷ ΖΒ ὁμοίῳ τε καὶ ὁμοίως κειμένῳ τῷ ΔΒ· λέγω, ὅτι μείζον ἐστι τὸ ΑΔ τοῦ ΑΖ.

Ἐπεὶ γὰρ ὁμοίον ἐστὶ τὸ ΔΒ παραλληλόγραμμον τῷ ΖΒ παραλληλογράμμῳ, περὶ τὴν αὐτὴν εἰσι διάμετρον. ἤχθω αὐτῶν διάμετρος ἡ ΔΒ, καὶ καταγεγράψθω τὸ σχῆμα.

Ἐπεὶ οὖν ἴσον ἐστὶ τὸ ΓΖ τῷ ΖΕ, κοινὸν δὲ τὸ ΖΒ, ὅλον ἄρα τὸ ΓΘ ὅλῳ τῷ ΚΕ ἐστὶν ἴσον. ἀλλὰ τὸ ΓΘ τῷ ΓΗ ἐστὶν ἴσον, ἐπεὶ καὶ ἡ ΑΓ τῇ ΓΒ. καὶ τὸ ΗΓ ἄρα τῷ ΕΚ ἐστὶν ἴσον. κοινὸν προσκείσθω τὸ ΓΖ· ὅλον ἄρα τὸ ΑΖ τῷ ΛΜΝ γνώμονι ἐστὶν ἴσον· ὥστε τὸ ΔΒ παραλληλόγραμμον, τουτέστι τὸ ΑΔ, τοῦ ΑΖ παραλληλογράμμου μείζον ἐστὶν.

Πάντων ἄρα τῶν παρὰ τὴν αὐτὴν εὐθείαν παραβαλλομένων παραλληλογράμμων καὶ ἑλλειπόντων εἶδεσι παραλληλογράμμοις ὁμοίοις τε καὶ ὁμοίως κειμένοις τῷ ἀπὸ τῆς ἡμισείας ἀναγραφομένῳ μέγιστόν ἐστι τὸ ἀπὸ τῆς ἡμισείας παραβληθέν· ὅπερ ἔδει δεῖξαι.

Eucl. *Elem.* vi. 28

Παρὰ τὴν δοθείσαν εὐθείαν τῷ δοθέντι εὐθυ-
204

PYTHAGOREAN GEOMETRY

at Γ , and let there be applied to the straight line AB the parallelogram $A\Delta$ deficient by the parallelogrammic figure ΔB described on the half of AB , that is, ΓB . I say that, of all the parallelograms applied to AB and deficient by figures similar and similarly situated to ΔB , $A\Delta$ is the greatest. For let there be applied to the straight line AB the parallelogram AZ deficient by the parallelogrammic figure ZB similar and similarly situated to ΔB . I say that $A\Delta$ is greater than AZ .

For since the parallelogram ΔB is similar to the parallelogram ZB , they are about the same diameter. Let their diameter ΔB be drawn and let the figure be described.

Then, since ΓZ is equal to ZE , and ZB is common, the whole $\Gamma\Theta$ is equal to the whole KE . But $\Gamma\Theta$ is equal to ΓH , since $A\Gamma$ is equal to ΓB . And therefore $H\Gamma$ is equal to EK . Let ΓZ be added to each. Then the whole AZ is equal to the gnomon ΔMN , so that the parallelogram ΔB , that is, $A\Delta$, is greater than the parallelogram AZ .

Therefore of all the parallelograms applied to this straight line and deficient by parallelogrammic figures similar and similarly situated to that described on the half of the straight line the greatest is that applied from the half; which was to be proved.

Euclid, *Elements* vi. 28

To the given straight line to apply a parallelogram

GREEK MATHEMATICS

γράφω ἴσον παραλληλόγραμμον παραβαλεῖν ἔλλειπον εἶδει παραλληλογράμμω ὁμοίω τῷ δοθέντι· δεῖ δὲ τὸ διδόμενον εὐθύγραμμον [ὧ δεῖ ἴσον παραβαλεῖν]¹ μὴ μείζον εἶναι τοῦ ἀπὸ τῆς ἡμισείας ἀναγραφομένου ὁμοίου τῷ ἔλλειματι [τοῦ τε ἀπὸ τῆς ἡμισείας καὶ ὧ δεῖ ὅμοιον ἔλλείπειν].¹

Ἔστω ἡ μὲν δοθεῖσα εὐθεῖα ἡ AB , τὸ δὲ δοθὲν εὐθύγραμμον, ὧ δεῖ ἴσον παρὰ τὴν AB παραβαλεῖν τὸ Γ μὴ μείζον [ὄν] τοῦ ἀπὸ τῆς ἡμισείας τῆς AB ἀναγραφομένου ὁμοίου τῷ ἔλλειμματι, ὧ δὲ δεῖ ὅμοιον ἔλλείπειν, τὸ Δ · δεῖ δὴ παρὰ τὴν δοθείσαν εὐθεῖαν τὴν AB τῷ δοθέντι εὐθυγράμμω τῷ Γ ἴσον παραλληλόγραμμον παραβαλεῖν ἔλλειπον εἶδει παραλληλογράμμω ὁμοίω ὄντι τῷ Δ .

Τετμήσθω ἡ AB δίχα κατὰ τὸ E σημεῖον, καὶ ἀναγεγράφθω ἀπὸ τῆς EB τῷ Δ ὅμοιον καὶ ὁμοίως κείμενον τὸ $EBZH$, καὶ συμπεπληρώσθω τὸ AH παραλληλόγραμμον.

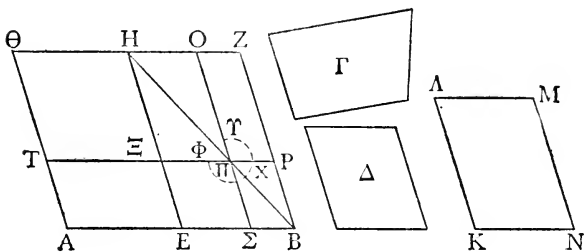
Εἰ μὲν οὖν ἴσον ἐστὶ τὸ AH τῷ Γ , γεγονὸς ἂν εἶη τὸ ἐπιταχθέν· παραβέβληται γὰρ παρὰ τὴν δοθείσαν εὐθεῖαν τὴν AB τῷ δοθέντι εὐθυγράμμω τῷ Γ ἴσον παραλληλόγραμμον τὸ AH ἔλλειπον εἶδει παραλληλογράμμω τῷ HB ὁμοίω ὄντι τῷ Δ . εἰ δὲ οὐ,

¹ The bracketed words are interpolations by Theon in his recension of the *Elements* (Heiberg).

PYTHAGOREAN GEOMETRY

equal to the given rectilinear figure and deficient by a parallelogrammic figure similar to the given one ; thus the given rectilinear figure must be not greater than the [parallelogram] described on the half [of the straight line] and similar to the defect.

Let AB be the given straight line, Γ the given rectilinear figure, to which the figure to be applied



to AB is required to be equal, being not greater than the [parallelogram] described on the half [of the straight line] and similar to the defect, and Δ the [parallelogram] to which the defect is required to be similar ; then it is required to apply to the given straight line AB a parallelogram equal to the given rectilinear figure Γ and deficient by a parallelogrammic form similar to Δ .

Let AB be bisected at the point E , and on E let $EBZH$ be described similar and similarly situated to Δ [vi. 18], and let the parallelogram AH be completed.

If then AH is equal to Γ , that which was enjoined will have been done ; for there has been applied to the given straight line AB a parallelogram AH equal to the given rectilinear figure Γ and deficient by a parallelogrammic figure HB similar to Δ . But if not,

GREEK MATHEMATICS

μείζον ἔστω τὸ ΘΕ τοῦ Γ. ἴσον δὲ τὸ ΘΕ τῷ ΗΒ· μείζον ἄρα καὶ τὸ ΗΒ τοῦ Γ. ᾧ δὴ μείζον ἔστι τὸ ΗΒ τοῦ Γ, ταύτῃ τῇ ὑπεροχῇ ἴσον, τῷ δὲ Δ ὁμοιον καὶ ὁμοίως κείμενον τὸ αὐτὸ συνεστάτω τὸ ΚΑΜΝ. ἀλλὰ τὸ Δ τῷ ΗΒ [ἔστιν] ὁμοιον· καὶ τὸ ΚΜ ἄρα τῷ ΗΒ ἔστιν ὁμοιον. ἔστω οὖν ὁμόλογος ἡ μὲν ΚΑ τῇ ΗΕ, ἡ δὲ ΛΜ τῇ ΗΖ. καὶ ἐπεὶ ἴσον ἔστι τὸ ΗΒ τοῖς Γ, ΚΜ, μείζον ἄρα ἔστι τὸ ΗΒ τοῦ ΚΜ· μείζων ἄρα ἔστι καὶ ἡ μὲν ΗΕ τῆς ΚΑ, ἡ δὲ ΗΖ τῆς ΛΜ. κείσθω τῇ μὲν ΚΑ ἴση ἡ ΗΞ, τῇ δὲ ΛΜ ἴση ἡ ΗΟ, καὶ συμπεπληρώσθω τὸ ΞΗΟΠ παραλληλόγραμμον· ἴσον ἄρα καὶ ὁμοιόν ἔστι [τὸ ΗΠ] τῷ ΚΜ [ἀλλὰ τὸ ΚΜ τῷ ΗΒ ὁμοιόν ἔστιν]. καὶ τὸ ΗΠ ἄρα τῷ ΗΒ ὁμοιόν ἔστιν· περὶ τὴν αὐτὴν ἄρα διάμετρόν ἔστι τὸ ΗΠ τῷ ΗΒ. ἔστω αὐτῶν διάμετρος ἡ ΗΠΒ, καὶ καταγεγράφθω τὸ σχῆμα.

Ἐπεὶ οὖν ἴσον ἔστι τὸ ΒΗ τοῖς Γ, ΚΜ, ὧν τὸ ΗΠ τῷ ΚΜ ἔστιν ἴσον, λοιπὸς ἄρα ὁ ὙΧΦ γνώμων λοιπῷ τῷ Γ ἴσος ἔστιν. καὶ ἐπεὶ ἴσον ἔστι τὸ ΟΡ τῷ ΞΣ, κοινὸν προσκείσθω τὸ ΠΒ· ὅλον ἄρα τὸ ΟΒ ὅλω τῷ ΞΒ ἴσον ἔστιν. ἀλλὰ τὸ ΞΒ τῷ ΤΕ ἔστιν ἴσον, ἐπεὶ καὶ πλευρὰ ἡ ΑΕ πλευρὰ τῇ ΕΒ ἔστιν ἴση· καὶ τὸ ΤΕ ἄρα τῷ ΟΒ ἔστιν ἴσον. κοινὸν προσκείσθω τὸ ΞΣ· ὅλον ἄρα τὸ ΤΣ ὅλω τῷ ΦΧΥ γνώμονί ἔστιν ἴσον. ἀλλ' ὁ ΦΧΥ γνώμων τῷ Γ ἐδείχθη ἴσος· καὶ τὸ ΤΣ ἄρα τῷ Γ ἔστιν ἴσον.

Παρὰ τὴν δοθεῖσαν ἄρα εὐθείαν τὴν ΑΒ τῷ δοθέντι εὐθυγράμμῳ τῷ Γ ἴσον παραλληλόγραμμον παραβέβληται τὸ ΣΤ ἐλλείπον εἶδει παραλληλογράμμῳ τῷ ΠΒ ὁμοίῳ ὄντι τῷ Δ [ἐπειδὴ-

PYTHAGOREAN GEOMETRY

let ΘE be greater than Γ . Now ΘE is equal to HB and therefore HB is greater than Γ . Let $K\Lambda MN$ be constructed at once equal to the excess by which HB is greater than Γ and similar and similarly situated to Δ [vi. 25]. But Δ is similar to HB ; therefore KM is also similar to HB [vi. 21]. Let $K\Lambda$ correspond to HE , ΛM to HZ . Now, since HB is equal to $\Gamma + KM$, HB is therefore greater than KM . Therefore HE is greater than $K\Lambda$, and HZ than ΛM . Let $H\Xi$ be made equal to $K\Lambda$, and HO equal to ΛM , and let the parallelogram $\Xi H O \Pi$ be completed. Therefore it is equal and similar to KM . Therefore $H\Pi$ is also similar to HB . Therefore $H\Pi$ is about the same diameter as HB [vi. 26]. Let $H\Pi B$ be their diameter, and let the figure be described.

Then since BH is equal to $\Gamma + KM$, and in these $H\Pi$ is equal to KM , therefore the remainder, the gnomon $YX\Phi$, is equal to Γ . And since OP is equal to $\Xi\Sigma$, let ΠB be added to each. Therefore the whole of OB is equal to the whole of ΞB . But ΞB is equal to TE , since the side AE is also equal to the side EB [i. 36]. Therefore TE is also equal to OB . Let $\Xi\Sigma$ be added to both. Therefore the whole of $T\Sigma$ is equal to the whole of the gnomon ΦXY . But the gnomon ΦXY was proved equal to Γ . Therefore $T\Sigma$ is also equal to Γ .

Therefore to the given straight line AB there has been applied the parallelogram ΣT equal to the given rectilinear figure Γ and deficient by a parallelo-

GREEK MATHEMATICS

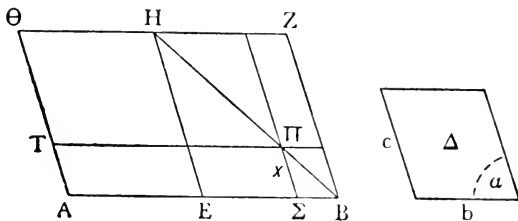
περ τὸ ΠΒ τῷ ΗΗ ὁμοίον ἐστίν]· ὅπερ ἔδει ποιῆσαι.

Eucl. *Elem.* vi. 29

Παρά τὴν δοθεῖσαν εὐθείαν τῷ δοθέντι εὐθυγράμμῳ ἴσον παραλληλόγραμμον παραβαλεῖν ὑπερβάλλον εἶδει παραλληλογράμμῳ ὁμοίῳ τῷ δοθέντι.

"Ἐστω ἡ μὲν δοθεῖσα εὐθεῖα ἡ ΑΒ, τὸ δὲ δοθὲν εὐθύγραμμον, ᾧ δεῖ ἴσον παρὰ τὴν ΑΒ παραβαλεῖν,

^a If $AB = a$, $\Sigma H = x$, while the sides of the given parallelogram Δ are in the ratio $b : c$, and the angle of Δ is α , then $\Sigma B = \frac{b}{c}x$, and



$$\begin{aligned} (\text{the parallelogram } T\Sigma) &= (\text{the parallelogram } TB) \\ &\quad - (\text{the parallelogram } \Pi B) \\ &= ax \sin \alpha - \frac{b}{c}x \cdot x \sin \alpha. \end{aligned}$$

If the area of the given rectilinear figure Γ is S , the proposition tells us that

$$ax \sin \alpha - \frac{b}{c}x^2 \sin \alpha = S.$$

To construct the parallelogram $T\Sigma$ is therefore equivalent to solving geometrically the equation

$$ax - \frac{b}{c}x^2 = \frac{S}{\sin \alpha}.$$

Heath (*The Thirteen Books of Euclid's Elements*, vol. vi

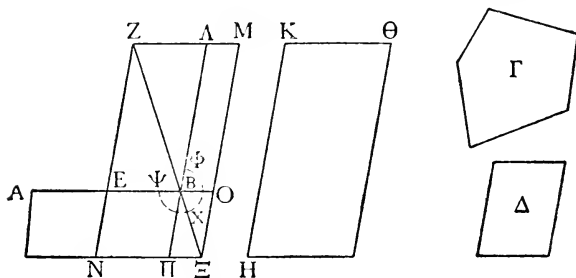
PYTHAGOREAN GEOMETRY

grammic form IIB similar to Δ ; which was to be done.^a

Euclid, *Elements* vi. 29

To the given straight line to apply a parallelogram equal to the given rectilinear figure and exceeding by a parallelogrammic figure similar to the given one.

Let AB be the given straight line, Γ the given



rectilinear figure to which the figure to be applied to

pp. 263-264), shows how the geometrical method is precisely equivalent to the algebraical method of completing the square on the left-hand side, and he demonstrates how the *two* solutions can be obtained geometrically, though Euclid, consistently with his practice, gives one only.

For a real solution it is necessary, as every schoolboy knows, that

$$\frac{S}{\sin a} > \frac{c}{b} \cdot \frac{a^2}{4}$$

$$\text{i.e. } S > \left(\frac{c}{b} \cdot \frac{a}{2}\right) (\sin a) \left(\frac{a}{2}\right)$$

$$\text{i.e. } S > HE \sin a \cdot EB$$

$$\text{i.e. } S > \text{parallelogram HB.}$$

This is precisely the result obtained in vi. 27.

GREEK MATHEMATICS

τὸ Γ, ᾧ δὲ δεῖ ὅμοιον ὑπερβάλλειν, τὸ Δ· δεῖ δὴ παρὰ τὴν ΑΒ εὐθείαν τῷ Γ εὐθυγράμμῳ ἴσον παραλληλόγραμμον παραβαλεῖν ὑπερβάλλον εἶδει παραλληλογράμμῳ ὁμοίῳ τῷ Δ.

Τετμήσθω ἡ ΑΒ δίχα κατὰ τὸ Ε, καὶ ἀναγεγράφθω ἀπὸ τῆς ΕΒ τῷ Δ ὅμοιον καὶ ὁμοίως κείμενον παραλληλόγραμμον τὸ ΒΖ, καὶ συναμφοτέροις μὲν τοῖς ΒΖ, Γ ἴσον, τῷ δὲ Δ ὅμοιον καὶ ὁμοίως κείμενον τὸ αὐτὸ συνεστάτω τὸ ΗΘ. ὁμόλογος δὲ ἔστω ἡ μὲν ΚΘ τῇ ΖΛ, ἡ δὲ ΚΗ τῇ ΖΕ. καὶ ἐπεὶ μείζον ἔστι τὸ ΗΘ τοῦ ΖΒ, μείζων ἄρα ἔστι καὶ ἡ μὲν ΚΘ τῆς ΖΛ, ἡ δὲ ΚΗ τῆς ΖΕ. ἐκβεβλήσθωσαν αἱ ΖΛ, ΖΕ, καὶ τῇ μὲν ΚΘ ἴση ἔστω ἡ ΖΑΜ, τῇ δὲ ΚΗ ἴση ἡ ΖΕΝ, καὶ συμπληρώσθω τὸ ΜΝ· τὸ ΜΝ ἄρα τῷ ΗΘ ἴσον τέ ἔστι καὶ ὅμοιον. ἀλλὰ τὸ ΗΘ τῷ ΕΛ ἔστιν ὅμοιον· καὶ τὸ ΜΝ ἄρα τῷ ΕΛ ὁμοίον ἔστιν· περὶ τὴν αὐτὴν ἄρα διάμετρον ἔστι τὸ ΕΛ τῷ ΜΝ. ἤχθω αὐτῶν διάμετρος ἡ ΖΞ, καὶ καταγεγράφθω τὸ σχῆμα.

Ἐπεὶ ἴσον ἔστι τὸ ΗΘ τοῖς ΕΛ, Γ, ἀλλὰ τὸ ΗΘ τῷ ΜΝ ἴσον ἔστιν, καὶ τὸ ΜΝ ἄρα τοῖς ΕΛ, Γ ἴσον ἔστιν. κοινὸν ἀφήρησθω τὸ ΕΛ· λοιπὸς ἄρα ὁ ΨΧΦ γνώμων τῷ Γ ἔστιν ἴσος. καὶ ἐπεὶ ἴση ἔστιν ἡ ΑΕ τῇ ΕΒ, ἴσον ἔστι καὶ τὸ ΑΝ τῷ ΝΒ, τουτέστι τῷ ΛΟ. κοινὸν προσκείσθω τὸ ΕΞ· ὅλον ἄρα τὸ ΑΞ ἴσον ἔστι τῷ ΦΧΨ γνώμονι. ἀλλὰ ὁ ΦΧΨ γνώμων τῷ Γ ἴσος ἔστιν· καὶ τὸ ΑΞ ἄρα τῷ Γ ἴσον ἔστιν.

Παρὰ τὴν δοθείσαν ἄρα εὐθείαν τὴν ΑΒ τῷ δοθέντι εὐθυγράμμῳ τῷ Γ ἴσον παραλληλόγραμμον παραβέβληται τὸ ΑΞ ὑπερβάλλον εἶδει παραλληλο-

PYTHAGOREAN GEOMETRY

AB is required to be equal, and Δ that to which the excess is required to be similar ; then it is required to apply to the straight line AB a parallelogram equal to the rectilinear figure Γ and exceeding by a parallelogrammic figure similar to Δ .

Let AB be bisected at E, and let there be described on EB the parallelogram BZ similar and similarly situated to Δ , and let $H\Theta$ be constructed at once equal to the sum of BZ, Γ and similar and similarly situated to Δ . Let $K\Theta$ correspond to $Z\Lambda$ and KH to ZE. Now since $H\Theta$ is greater than ZB, $K\Theta$ is therefore greater than $Z\Lambda$, and KH than ZE. Let $Z\Lambda$, ZE be produced, and let $Z\Lambda M$ be equal to $K\Theta$, and ZEN equal to KH, and let MN be completed ; therefore MN is both equal to $H\Theta$ and similar. But $H\Theta$ is similar to $E\Lambda$; therefore MN is similar to $E\Lambda$ [vi. 21] ; and therefore EA is about the same diameter with MN [vi. 26]. Let their diameter $Z\Xi$ be drawn, and let the figure be described.

Since $H\Theta$ is equal to $E\Lambda + \Gamma$, while $H\Theta$ is equal to MN, therefore MN is also equal to $E\Lambda + \Gamma$. Let $E\Lambda$ be taken away from each ; therefore the remainder, the gnomon $\Psi X\Phi$, is equal to Γ . And since AE is equal to EB, AN is also equal to NB [i. 36], that is, to ΛO [i. 43]. Let $E\Xi$ be added to each ; therefore the whole of $A\Xi$ is equal to the gnomon $\Phi X\Psi$. But the gnomon $\Phi X\Psi$ is equal to Γ ; therefore $A\Xi$ is also equal to Γ .

Therefore to the given straight line AB there has been applied a parallelogram $A\Xi$ equal to the given rectilinear figure Γ and exceeding by a parallelo-

GREEK MATHEMATICS

γράμμω τῷ ΠΟ ὁμοίω ὄντι τῷ Δ, ἐπεὶ καὶ τῷ ΕΛ ἔστιν ὁμοιον τὸ ΟΠ· ὅπερ ἔδει ποιῆσαι.

(e) THE IRRATIONAL

Schol. i. in Eucl. *Elem.* x., Eucl. ed. Heiberg
v. 415. 7-417. 14

Ἦλθον δὲ τὴν ἀρχὴν ἐπὶ τὴν τῆς συμμετρίας ζήτησιν οἱ Πυθαγόρειοι πρῶτοι αὐτὴν ἐξευρόντες ἐκ τῆς τῶν ἀριθμῶν κατανοήσεως. κοινῷ γὰρ ἀπάντων ὄντος μέτρου τῆς μονάδος καὶ ἐπὶ τῶν μεγεθῶν κοινὸν μέτρον εὔρειν οὐκ ἠδυνήθησαν. αἴτιον δὲ τὸ πάντα μὲν καὶ ὅποιοι οὖν ἀριθμὸν καθ' ὅποιασοῦν τομὰς διαιρούμενον μόνιον τι καταλιμπάνειν ἐλάχιστον καὶ τομῆς ἀνεπίδεκτον, πᾶν δὲ μέγεθος ἐπ' ἄπειρον διαιρούμενον μὴ καταλιμπάνειν μόνιον, ὃ διὰ τὸ εἶναι ἐλάχιστον τομῆν οὐκ ἐπιδέξεται, ἀλλὰ καὶ ἐκεῖνο ἐπ' ἄπειρον τεμνόμενον ποιεῖν ἄπειρα μέρη, ὧν ἕκαστον ἐπ' ἄπειρον τμηθήσεται, καὶ ἀπλῶς τὸ μὲν μέγεθος κατὰ μὲν τὸ μερίζεσθαι μετέχειν τῆς τοῦ ἀπείρου ἀρχῆς, κατὰ δὲ τὴν ὁλότητα τῆς τοῦ πέρατος, τὸν δὲ ἀριθμὸν κατὰ μὲν τὸ μερίζεσθαι τῆς τοῦ πέρατος,

^a If the angle of Δ is α and its sides are in the ratio $b : c$, while $AB = a$ and $OΞ = x$, then

$$\begin{aligned} (\text{parallelogram } \Lambda\Xi) &= (\text{parallelogram } \Lambda\Gamma) + (\text{parallelo-} \\ &\quad \text{gram } \Gamma\Xi) \\ &= ax \sin \alpha + \frac{b}{c} \cdot x \sin \alpha. \end{aligned}$$

PYTHAGOREAN GEOMETRY

grammic form IIO similar to Δ , since OII is similar to EA ; which was to be done.^a

(e) THE IRRATIONAL ^b

Euclid, *Elements* x., Scholium i., Eucl. ed. Heiberg
v. 415. 7-417. 14

The Pythagoreans were the first to make inquiry into commensurability, having first discovered it as a result of their observation of numbers; for though the unit is a common measure of all numbers they could not find a common measure of all magnitudes. The reason is that all numbers, of whatsoever kind, howsoever they be divided leave some least part which will not suffer further division; but all magnitudes are divisible *ad infinitum* and do not leave some part which, being the least possible, will not admit of further division, but that remainder can be divided *ad infinitum* so as to give an infinite number of parts, of which each can be divided *ad infinitum*; and, in sum, magnitude partakes in division of the principle of the infinite, but in its entirety of the principle of the finite, while number in division partakes of the

But by the proposition, if S is the area of Γ
(parallelogram $A\Xi$) = S ,

$$\therefore ax + \frac{b}{c}x^2 = \frac{S}{\sin \alpha}.$$

To construct the parallelogram $A\Xi$ is therefore equivalent to solving geometrically this quadratic equation. There is always a real solution, and so no *διορισμός* is necessary as in the case of the preceding proposition. Heath (*The Thirteen Books of Euclid's Elements*, vol. ii. pp. 266-267) again shows how the procedure is equivalent to the algebraic method of completing the square. Euclid's solution corresponds to the root with the positive sign.

^b For further notices see *supra*, pp. 110-111, p. 149 n. c.

GREEK MATHEMATICS

κατὰ δὲ τὴν ὁλότητα τῆς τοῦ ἀπείρου . . . τῶν γὰρ Πυθαγορείων λόγος τὸν πρῶτον τὴν περὶ τούτων θεωρίαν εἰς τοῦμφανὲς ἔξαγαγόντα ναυαγίῳ περιπεσεῖν.

(f) THE FIVE REGULAR SOLIDS

Phil. ap. Stob. *Ecl.* 1, proem. 3, ed. Wachsmuth 18. 5;
Diels, *Vors.* i⁵. 412. 15-413. 2

Καὶ τὰ μὲν τᾶς σφαίρας σώματα πέντε ἐντί, τὰ ἐν τᾷ σφαίρα πῦρ <καὶ> ὕδωρ καὶ γᾶ καὶ ἀήρ, καὶ ὁ τᾶς σφαίρας ὀλκάς,¹ πέμπτον.

Aët. *Plac.* ii. 6. 5; Diels, *Vors.* i⁵. 403. 8-12

Πυθαγόρας πέντε σχημάτων ὄντων στερεῶν, ἅπερ καλεῖται καὶ μαθηματικά, ἐκ μὲν τοῦ κύβου φησὶ γεγονέναι τὴν γῆν, ἐκ δὲ τῆς πυραμίδος τὸ πῦρ, ἐκ δὲ τοῦ ὀκταέδρου τὸν ἀέρα, ἐκ δὲ τοῦ εἰκοσαέδρου τὸ ὕδωρ, ἐκ δὲ τοῦ δωδεκαέδρου τὴν τοῦ παντὸς σφαῖραν.

¹ ὀλκάς: ὀλκός coniecit Wilamowitz.

* A regular solid is one having all its faces equal polygons and all its solid angles equal. The term is usually restricted to those regular solids in which the centre is singly enclosed. There are five, and only five, such figures—the pyramid, cube, octahedron, dodecahedron and icosahedron. They can all be inscribed in a sphere. Owing to the use made of them in Plato's *Timaeus* for the construction of the universe they were often called by the Greeks the *cosmic* or *Platonic* figures. As noted above (p. 148), Proclus attributes the construction of the cosmic figures to Pythagoras, but Suidas (*infra*, p. 378) says Theaetetus was the first to write on them. The theoretical construction of the regular solids and the calculation of their sides in terms of the radius of the circumscribed sphere occupies Book xiii. of Euclid's *Elements*. It

PYTHAGOREAN GEOMETRY

finite, but in its entirety of the infinite. . . . There is a legend that the first of the Pythagoreans who made public the investigation of these matters perished in a shipwreck.

(f) THE FIVE REGULAR SOLIDS ^a

Philolaus, cited by Stobaeus, *Extracts* 1, proem. 3, ed. Wachsmuth 18. 5 ; Diels, *Vors.* i⁵. 412. 15-413. 2

There are five bodies pertaining to the sphere—the fire, water, earth and air in the sphere, and the vessel of the sphere itself as the fifth.^b

Aëtius, *Placita* ii. 6. 5 ; Diels, *Vors.* i⁵. 403. 8-12

Pythagoras, seeing that there are five solid figures, which are also called the mathematical figures, says that the earth arose from the cube, fire from the pyramid, air from the octahedron, water from the icosahedron, and the sphere of the universe from the dodecahedron.^c

calls for mathematical knowledge which the Pythagoreans did not possess ; but there is no reason why the Pythagoreans should not have constructed them practically in the manner of Plato by putting together triangles, squares or pentagons. The passages here given almost compel that conclusion.

The subject is fully treated in *Die fünf Platonischen Körper*, by Eva Sachs (*Philologische Untersuchungen*, 21es Heft, 1917). Archimedes, according to Pappus, *Coll.* v., ed. Hultsch 352-358, discovered thirteen semi-regular solids, whose faces are all regular polygons, but not all of the same kind.

^b In place of *ὄγκας* Wilamowitz suggests *ὄγκός*, which is derived from *ἐλκω* and could be translated "envelope." This fragment, it will be noted, does not identify the regular solids with the elements in the sphere, but it is consistent with that identification, for which the earliest definite evidence is Plato's *Timaeus*.

^c Aëtius's authority is probably Theophrastus.

GREEK MATHEMATICS

Plat. *Tim.* 53 c-55 c

Πρῶτον μὲν δὴ πῦρ καὶ γῆ καὶ ὕδωρ καὶ ἀήρ ὅτι σώματά ἐστι, δῆλόν που καὶ παντί. τὸ δὲ τοῦ σώματος εἶδος πᾶν καὶ βάθος ἔχει. τὸ δὲ βάθος αὐτῶν πᾶσα ἀνάγκη τὴν ἐπίπεδον περιειληφέναι φύσιν. ἢ δὲ ὀρθὴ τῆς ἐπιπέδου βάσεως ἐκ τριγώνων συνέστηκε. τὰ δὲ τρίγωνα πάντα ἐκ δυοῖν ἄρχεται τριγώνου, μίαν μὲν ὀρθὴν ἔχοντος ἑκατέρου γωνίαν, τὰς δὲ ὀξείας· ὧν τὸ μὲν ἕτερον ἑκατέρωθεν ἔχει μέρος γωνίας ὀρθῆς πλευραῖς ἴσαις διηρημένης, τὸ δὲ ἕτερον ἀνίσοις ἄνισα μέρη νενεμημένης. . . .

Τοῖν δὴ δυοῖν τριγώνου τὸ μὲν ἰσοσκελὲς μίαν εἴληχε φύσιν, τὸ δὲ πρόμηκες ἀπεράντους. προαιρετέον οὖν αὐτῶν ἀπείρων τὸ κάλλιστον, εἰ μέλλομεν ἄρξασθαι κατὰ τρόπον. ἂν οὖν τις ἔχη κάλλιον ἐκλεξάμενος εἰπεῖν εἰς τὴν τούτων σύστασιν, ἐκεῖνος οὐκ ἐχθρὸς ὧν ἀλλὰ φίλος κρατεῖ· τιθέμεθα δ' οὖν τῶν πολλῶν τριγώνων κάλλιστον εἶναι, ὑπερβάντες τὰλλα, ἐξ οὗ τὸ ἰσόπλευρον τρίγωνον ἐκ τρίτου συνέστηκεν. . . .

Οἶον δὲ ἕκαστον αὐτῶν γέγονεν εἶδος καὶ ἐξ ὅσων συμπεσόντων ἀριθμῶν, λέγειν ἂν ἐπόμενον εἶη. ἄρξει δὴ τό τε πρῶτον εἶδος καὶ σμικρότατον συνιστάμενον· στοιχείον δ' αὐτοῦ τὸ τὴν ὑποτείνουσαν τῆς ἐλάττους πλευρᾶς διπλασίαν ἔχον μήκει· σύνδυο δὲ τοιούτων κατὰ διάμετρον συντιθεμένων καὶ τρεῖς τούτου γενομένου, τὰς διαμέτρους

^a This passage is put into the mouth of Timaeus of Locri, a Pythagorean leader, and in it Plato is generally held to be reproducing Pythagorean ideas.

^b *i.e.*, the rectangular isosceles triangle and the rectangular scalene triangle.

PYTHAGOREAN GEOMETRY

Plato, *Timaeus* 53 c-55 c ^a

In the first place, then, it is clear to everyone, I think, that fire and earth and water and air are bodies. Now in every case the form of a body has depth. Further, it is absolutely necessary that depth should be bounded by a plane surface; and the rectilinear plane is composed of triangles. Now all triangles have their origin in two triangles, each having one right angle and the others acute; and one of these triangles has on each side half a right angle marked off by equal sides, while the other has the right angle divided into unequal parts by unequal sides.^b . . .

Of the two triangles, the isosceles has one nature only, but the scalene has an infinite number; and of these infinite natures the fairest must be chosen, if we would make a suitable beginning. If, then, anyone can claim that he has a fairer one for the construction of these bodies, he is no foe but shall prevail as a friend; but we shall pass over all the rest and lay down as the fairest of the many triangles that from which the equilateral triangle arises as a third when two are conjoined. . . .^c

In the next place we have to describe the form in which each kind has come into existence and from what numbers it is compounded. A beginning must be made with that kind which is primary and has the smallest components, and its element is the triangle whose hypotenuse is twice as long as the lesser side. When a pair of these triangles are joined diagonally and this is done three times, by drawing the hypo-

^c *i.e.*, the "fairest" of rectangular scalene triangles is half of an equilateral triangle, the sides being in the proportion 1, $\sqrt{3}$, 2.

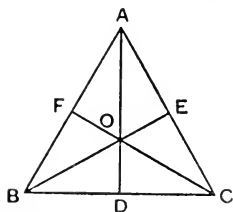
GREEK MATHEMATICS

καὶ τὰς βραχείας πλευρὰς εἰς ταῦτόν ὡς κέντρον ἐρείσαντων, ἐν ἰσόπλευρον τρίγωνον ἕξ ἕξ τὸν ἀριθμὸν ὄντων γέγονεν.

Τρίγωνα δὲ ἰσόπλευρα συνιστάμενα τέτταρα κατὰ σύντριες ἐπιπέδους γωνίας μίαν στερεὰν γωνίαν ποιεῖ, τῆς ἀμβλυτάτης τῶν ἐπιπέδων γωνιῶν ἐφεξῆς γεγωνυῖαν· τοιούτων δὲ ἀποτελεσθεισῶν τεττάρων πρῶτον εἶδος στερεόν, ὅλου περιφεροῦς διανεμητικὸν εἰς ἴσα μέρη καὶ ὅμοια, συνίσταται. δεύτερον δὲ ἐκ μὲν τῶν αὐτῶν τριγῶνων, κατὰ δὲ ἰσόπλευρα τρίγωνα ὀκτῶ συστάντων, μίαν ἀπεργασαμένων στερεὰν γωνίαν ἐκ τεττάρων ἐπιπέδων· καὶ γενομένων ἕξ τοιούτων τὸ δεύτερον αὐτῶν σῶμα οὕτως ἔσχε τέλος. τὸ δὲ τρίτον ἐκ δις ἐξήκοντα τῶν στοιχείων συμπαγόντων, στερεῶν δὲ γωνιῶν δώδεκα, ὑπὸ πέντε ἐπιπέδων τριγῶνων ἰσοπλεύρων περιεχομένης ἐκάστης, εἴκοσι βάσεις ἔχον ἰσοπλεύρους τριγῶνους γέγονεν.

Καὶ τὸ μὲν ἕτερον ἀπήλλακτο τῶν στοιχείων

^a As in the accompanying diagram, the triangles AOF, COD, AOE, BOD, COE, BOF are joined together so as to form the equilateral triangle ABC. As Plato has already observed, an equilateral triangle can also be made out of two such triangles.



A. E. Taylor (*A Commentary on Plato's Timaeus*, pp. 374-375), first pointed out the correct meaning of κατὰ διάμετρον, "diagonally." Previously, following Boeckh, editors had supposed that

it meant "so that their hypotenuses coincide," e.g., triangle AOF is placed κατὰ διάμετρον with triangle AOE; Plato almost certainly meant that triangles AOF, COD are κατὰ διάμετρον.

PYTHAGOREAN GEOMETRY

tenuses and shorter sides to a common centre, from those triangles, six in number, there is produced one equilateral triangle.^a

Now when four equilateral triangles are put together so that the three plane angles meet in a point, they make one solid angle, which comes next in order to the most obtuse of the plane angles ^b; and when four such angles are formed, the first solid figure ^c is constructed, dividing the whole of the circumscribed sphere into equal and similar parts. The second solid ^d is formed from the same triangles, but is constructed out of eight equilateral triangles, which make one solid angle from four planes; when six such solid angles have been produced, the second body is in turn completed. The third solid ^e is made up of twice sixty of the elemental triangles and of twelve solid angles, each solid angle being comprised by five plane equilateral triangles, and the manner of its formation gives it twenty equilateral triangular bases.

Now the first of the elemental triangles was dropped

^b The three plane angles together make two right angles, which is "the most obtuse of the plane angles."

^c *i.e.*, the regular tetrahedron or pyramid, which has four faces, each an equilateral triangle, and four solid angles, each formed by three of the equilateral triangles; Plato later makes it the element of fire.

^d *i.e.*, the regular octahedron, which has eight faces, each an equilateral triangle, and six solid angles, each formed by four of the equilateral triangles; Plato later makes it the element of air.

^e *i.e.*, the icosahedron, which has twenty faces, each an equilateral triangle (and is therefore made up of 120 elemental rectangular scalene triangles, inasmuch as six such triangles are put together to form one equilateral triangle), and twelve solid angles, each formed by five of the equilateral triangles; Plato later made it the element of water.

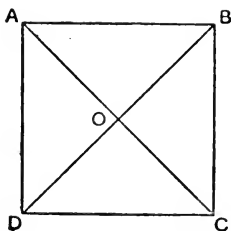
GREEK MATHEMATICS

ταῦτα γεννήσαν, τὸ δὲ ἰσοσκελὲς τρίγωνον ἐγέννα τὴν τοῦ τετάρτου φύσιν, κατὰ τέτταρα συνιστάμενον, εἰς τὸ κέντρον τὰς ὀρθὰς γωνίας συνάγον, ἐν ἰσόπλευρον τετράγωνον ἀπεργασάμενον· ἕξ δὲ τοιαῦτα συμπαγέντα γωνίας ὀκτῶ στερεὰς ἀπετέλεσε, κατὰ τρεῖς ἐπιπέδους ὀρθὰς συναρμοθείσης ἐκάστης· τὸ δὲ σχῆμα τοῦ συστάντος σώματος γέγονε κυβικόν, ἕξ ἐπιπέδους τετραγώνους ἰσοπλεύρους βάσεις ἔχον· ἔτι δὲ οὔσης συστάσεως μιᾶς πέμπτης, ἐπὶ τὸ πᾶν ὁ θεὸς αὐτῇ κατεχρήσατο ἐκείνο διαζωγραφῶν.

Iambl. *De Vita Pythag.* 18. 88, ed. Deubner 52. 2-8

Περὶ δ' Ἰππάσου μάλιστα, ὡς ἦν μὲν τῶν Πυθαγορείων, διὰ δὲ τὸ ἐξενεγκεῖν καὶ γράφασθαι πρῶτως σφαῖραν τὴν ἐκ τῶν δώδεκα πενταγώνων ἀπώλετο κατὰ θάλατταν ὡς ἀσεβήσας, δόξαν δὲ λάβοι ὡς εὐρών, εἶναι δὲ πάντα ἐκείνου τοῦ ἀνδρός·

- As in the accompanying figure, the four isosceles scalene triangles AOB, DOC, BOC, DOA placed about the common vertex O form the square ABCD. The fourth figure is the cube, which has six faces, each a square (and is therefore made up of twenty-four of the elemental rectangular isosceles triangles), and eight solid angles, each formed by three of the squares; Plato later makes it the element of earth.



^b *i.e.*, the regular dodecahedron. This requires, however,

PYTHAGOREAN GEOMETRY

when it had produced these three solids, the nature of the fourth being produced by the isosceles triangle. When four such triangles are joined together, with their right angles drawn towards the centre, they form one equilateral quadrangle ^a; and six such quadrangles, put together, made eight solid angles, each composed of three plane right angles; and the shape of the body thus constructed was cubic, having six plane equilateral quadrangular bases. As there still remained one compound figure, the fifth, ^b God used it for the whole, broidering it with designs. ^c

Iamblichus, *On the Pythagorean Life* 18. 88,
ed. Deubner 52. 2-8

It is related of Hippasus that he was a Pythagorean, and that, owing to his being the first to publish and describe the sphere from the twelve pentagons, he perished at sea for his impiety, but he received credit for the discovery, though really it all belonged to

a new element, the regular pentagon. It has twelve faces, each a regular pentagon, and twenty solid angles, each formed by three pentagons. The following passages give evidence that the Pythagoreans may have known the properties of the dodecahedron and pentagon. A number of objects of dodecahedral form have survived from pre-Pythagorean days.

^c This has often been held, following Plutarch, to refer to the twelve signs of the Zodiac, but A. E. Taylor (*A Commentary on Plato's Timaeus*, p. 377) rightly points out that the dodecagon, not the dodecahedron, would be the appropriate symbol for the Zodiac. He finds a clue to the meaning in *Timaeus Locrus* 98 ε, where it is pointed out that of the five regular solids inscribable in the same sphere the dodecahedron has the maximum volume and "comes nearest" to the sphere. Burnet finds the real allusion to the mapping of the apparently spherical heavens into twelve pentagonal regions.

GREEK MATHEMATICS

προσαγορεύουσι γὰρ οὕτω τὸν Πυθαγόραν καὶ οὐ
καλοῦσιν ὀνόματι.

Luc. *Pro Lapsu inter Salut.* 5, ed. Jacobitz i. 330. 11-14

Καὶ τό γε τριπλοῦν αὐτοῖς τρίγωνον, τὸ δι'
ἀλλήλων, τὸ πεντάγραμμον, ᾧ συμβόλω πρὸς τοὺς
ὁμοδόξους ἐχρῶντο, ὑγίεια πρὸς αὐτῶν ὀνομάζετο.

* Iamblichus tells the same story, almost word for word, in *De communi Mathematica Scientia* c. 25 (ed. Festa 77. 18-24); the only substantial difference is the substitution of the word ἐξαγώνων for πενταγώνων, which is a slip. The story recalls the passage given above (p. 216) about the Pythagorean who perished at sea for revealing the irrational. He may very well have been the same person as Hippasus, for the irrational would quickly come to light in a study of the regular solids.

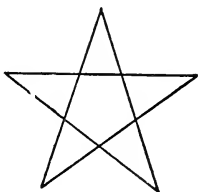
PYTHAGOREAN GEOMETRY

HIM (for in this way they refer to Pythagoras, and they do not call him by his name).^a

Lucian, *On Slips in Greetings* 5, ed. Jacobitz i. 330. 11-14

The triple interlaced triangle, the pentagram, which they (the Pythagoreans) used as a password among members of the same school, was called by them Health.^b

^b Cf. the scholium to Aristophanes, *Clouds* 609. The pentagram is the star-pentagon, as in the adjoining diagram. The fact that this was a familiar symbol among them lends some plausibility to the belief that they know how to construct the dodecahedron out of twelve pentagons.



VII. DEMOCRITUS

VII. DEMOCRITUS

Plut. *De Comm. Notit.* 39. 3, 1079 E

Ἔτι τοίνυν ὄρα τίνα τρόπον ἀπήντησε Δημοκρίτῳ, διαποροῦντι φυσικῶς καὶ ἐπιτυχῶς, εἰ κῶνος τέμνοιτο παρὰ τὴν βάσιν ἐπιπέδῳ, τί χρὴ διανοεῖσθαι τὰς τῶν τμημάτων ἐπιφανείας, ἴσας ἢ ἀνίσους γινομένας; ἄνισοι μὲν γὰρ οὔσαι τὸν κῶνον ἀνώμαλον παρέξουσι, πολλὰς ἀποχαράξεις λαμβάνοντα βαθμοειδεῖς καὶ τραχύτητας· ἴσων δ' οὐσῶν, ἴσα τμήματα ἔσται, καὶ φανεῖται τὸ τοῦ κυλίνδρου πεπονθῶς ὁ κῶνος, ἐξ ἴσων συγκείμενος καὶ οὐκ ἀνίσων κύκλων, ὅπερ ἐστὶν ἀτοπώτατον.

Archim. *Meth.*, Archim. ed. Heiberg ii. 430. 1-9

Διόπερ καὶ τῶν θεωρημάτων τούτων, ὧν Εὐδόξος ἐξηύρηκεν πρῶτος τὴν ἀπόδειξιν, περὶ τοῦ κῶνου καὶ τῆς πυραμίδος, ὅτι τρίτον μέρος ὁ μὲν κῶνος

* Plutarch tells this on the authority of Chrysippus. Democritus came from Abdera. He was born about the same time as Socrates, and lived to a great age. Plato ignored him in his dialogues, and is said to have wished to burn all his works. The two passages here given contain all that is definitely known of his mathematics, but we are informed that he wrote a book *On the Contact of a Circle and a Sphere*; another on *Geometry*; a third entitled *Geometrica*; a fourth on *Numbers*; a fifth *On Irrational Lines and Solids*; and a sixth called *Ἐκπετάσματα*, which would deal with the

VII. DEMOCRITUS

Plutarch, *On the Common Notions* 39. 3, 1079 E

CONSIDER further in what manner it occurred to Democritus,^a in his happy inquiries in natural science, to ask if a cone were cut by a plane parallel to the base,^b what must we think of the surfaces forming the sections, whether they are equal or unequal? For, if they are unequal, they will make the cone irregular, as having many indentations, like steps, and unevennesses; but if they are equal, the sections will be equal, and the cone will appear to have the property of the cylinder, and to be made up of equal, not unequal, circles, which is very absurd.^c

Archimedes, *Method*, Archim. ed. Heiberg
ii. 430. 1-9

This is a reason why, in the case of those theorems concerning the cone and pyramid of which Eudoxus first discovered the proof, the theorems that the cone projection of the armillary sphere on a plane. As his mathematical abilities were obviously great, it is unfortunate that our information is so meagre.

^b A plane indefinitely near to the base is clearly indicated by what follows.

^c This bold inquiry first brought the conception of the indefinitely small into Greek mathematics. The story harmonizes with Archimedes' statement that Democritus gave expressions for the volume of the cone and pyramid.

GREEK MATHEMATICS

τοῦ κυλίνδρου, ἢ δὲ πυραμὶς τοῦ πρίσματος, τῶν
βάσιν ἔχόντων τὴν αὐτὴν καὶ ὕψος ἴσον, οὐ μικρὰν
ἀπονείμαι ἂν τις Δημοκρίτῳ μερίδα πρώτῳ τὴν
ἀπόφασιν τὴν περὶ τοῦ εἰρημένου σχήματος χωρὶς
ἀποδείξεως ἀποφηναμένῳ.

DEMOCRITUS

is a third part of the cylinder, and the pyramid of the prism, having the same base and equal height, no small share of the credit should be given to Democritus, who was the first to make the assertion with regard to the said figure,^o though without proof.

- So the Greek. Perhaps "type of figure."

THE HISTORY OF THE UNITED STATES OF AMERICA

FROM 1776 TO 1876

BY

W. W. HUNT

AND

W. W. HUNT

W. W. HUNT

W. W. HUNT

W. W. HUNT

VIII. HIPPOCRATES OF CHIOS

VIII. HIPPOCRATES OF CHIOS

(a) GENERAL

Philop. *in Phys.* A 2 (Aristot. 185 a 16), ed. Vitelli
31. 3-9

Ἴπποκράτης Χίος τις ὦν ἔμπορος, ληστρικῇ νηὶ περιπεσὼν καὶ πάντα ἀπολέσας, ἦλθεν Ἀθήναζε γραψόμενος τοὺς ληστάς, καὶ πολὺν παραμένων ἐν Ἀθήναις διὰ τὴν γραφὴν χρόνον, ἐφοίτησεν εἰς φιλοσόφους, καὶ εἰς τοσοῦτον ἕξεως γεωμετρικῆς ἦλθεν, ὡς ἐπιχειρῆσαι εὐρεῖν τὸν κύκλου τετραγωνισμόν. καὶ αὐτὸν μὲν οὐχ εὔρε, τετραγωνίσας δὲ τὸν μηνίσκου ᾤήθη ψευδῶς ἐκ τούτου καὶ τὸν κύκλον τετραγωνίζειν· ἐκ γὰρ τοῦ τετραγωνισμοῦ τοῦ μηνίσκου καὶ τὸν τοῦ κύκλου τετραγωνισμόν ᾤήθη συλλογίζεσθαι.

(b) QUADRATURE OF LUNES

Simpl. *in Phys.* A 2 (Aristot. 185 a 14), ed. Diels
60. 22-68. 32

Ὁ μέντοι Εὐδῆμος ἐν τῇ Γεωμετρικῇ ἱστορίᾳ οὐκ ἐπὶ τετραγωνικῆς πλευρᾶς δεῖξαί φησι τὸν Ἴπποκράτην τὸν τοῦ μηνίσκου τετραγωνισμόν,
234

VIII. HIPPOCRATES OF CHIOS

(a) GENERAL

Philoponus, *Commentary on Aristotle's Physics A 2*
(185 a 16), ed. Vitelli 31. 3-9

HIPPOCRATES of Chios was a merchant who fell in with a pirate ship and lost all his possessions. He came to Athens to prosecute the pirates and, staying a long time in Athens by reason of the indictment, consorted with philosophers, and reached such proficiency in geometry that he tried to effect the quadrature of the circle. He did not discover this, but having squared the lune he falsely thought from this that he could square the circle also. For he thought that from the quadrature of the lune the quadrature of the circle also could be calculated.^a

(b) QUADRATURE OF LUNES

Simplicius, *Commentary on Aristotle's Physics A 2*
(185 a 14), ed. Diels 60. 22-68. 32

Eudemus, however, in his *History of Geometry* says that Hippocrates did not demonstrate the quadrature

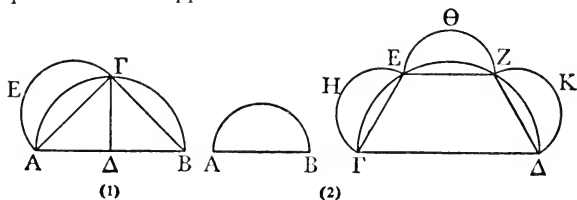
* A lune (meniscus) is the figure included between two intersecting arcs of circles. It is unlikely that Hippocrates himself thought he had squared the circle, but for a discussion of this point see *infra*, p. 310 n. b.

GREEK MATHEMATICS

ἀλλὰ καθόλου, ὡς ἂν τις εἴποι. εἰ γὰρ πᾶς μηνίσκος τὴν ἐκτὸς περιφέρειαν ἢ ἴσην ἔχει ἡμικυκλίου ἢ μείζονα ἢ ἐλάττονα, τετραγωνίζει δὲ ὁ Ἱπποκράτης καὶ τὸν ἴσην ἡμικυκλίου ἔχοντα καὶ τὸν μείζονα καὶ τὸν ἐλάττονα, καθόλου ἂν εἶη δεδειχῶς ὡς δοκεῖ. ἐκθήσομαι δὲ τὰ ὑπὸ τοῦ Εὐδήμου κατὰ λέξιν λεγόμενα ὀλίγα τινὰ προστιθεὶς (εἰς)¹ σαφήνειαν ἀπὸ τῆς τῶν Εὐκλείδου Στοιχείων ἀναμνήσεως διὰ τὸν ὑπομνηματικὸν τρόπον τοῦ Εὐδήμου κατὰ τὸ ἀρχαϊκὸν ἔθος συντόμους ἐκθεμένου τὰς ἀποδόσεις. λέγει δὲ ᾧδε ἐν τῷ δευτέρῳ βιβλίῳ τῆς Γεωμετρικῆς ἱστορίας.

¹ εἰς add. Usener.

^a As Alexander asserted. Alexander, as quoted by Simplicius in *Phys.* (ed. Diels 56. 1-57. 24), attributes two quadratures to Hippocrates.



In the first, AB is the diameter of a circle, $A\Gamma$, ΓB are sides of a square inscribed in it, and $A\epsilon\Gamma$ is a semicircle described on $A\Gamma$. Alexander shows that

$$\text{lune } A\epsilon\Gamma = \text{triangle } A\Gamma\Delta.$$

In the second, AB is the diameter of semicircle and on $\Gamma\Delta$, equal to twice AB , a semicircle is described. $\Gamma\epsilon$, ϵZ , $Z\Delta$ are sides of a regular hexagon, and $\Gamma\eta\epsilon$, $\epsilon\theta Z$, $Z\kappa\Delta$ are semicircles described on $\Gamma\epsilon$, ϵZ , $Z\Delta$. Alexander shows that

HIPPOCRATES OF CHIOS

of the lune on the side of a square ^a but generally, as one might say. For every lune has an outer circumference equal to a semicircle or greater or less, and if Hippocrates squared the lune having an outer circumference equal to a semicircle and greater and less, the quadrature would appear to be proved generally. I shall set out what Eudemus wrote word for word, adding only for the sake of clearness a few things taken from Euclid's *Elements* on account of the summary style of Eudemus, who set out his proofs in abridged form in conformity with the ancient practice. He writes thus in the second book of the *History of Geometry*.^b

lune ΓHE + lune EΘZ + lune ZKΔ + semicircle AB =
trapezium ΓEZΔ.

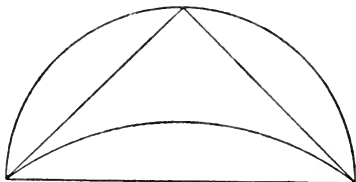
The proofs are easy. Alexander goes on to say that if the rectilinear figure equal to the three lunes ("for a rectilinear figure was proved equal to a lune") is subtracted, the circle will be squared. The fallacy is obvious and Hippocrates could hardly have committed it. This throws some doubt on the whole of Alexander's account, and Simplicius himself observes that Eudemus's account is to be preferred as he was "nearer to the times" of Hippocrates.

^b It is not always easy to distinguish what Eudemus wrote and what Simplicius has added. The task was first attempted by Allman (*Hermathena* iv., pp. 180-228; *Greek Geometry from Thales to Euclid*, pp. 64-75). Diels, in his edition of Simplicius published in 1882, with the help of Usener, printed in spaced type what they attributed to Eudemus. In 1883 Tannery (*Mémoires scientifiques* i., pp. 339-370) edited what he thought the Eudemian passages. Heiberg (*Philologus* xliii., pp. 336-344) gave his views in 1884. Rudio discussed the question exhaustively in 1907 (*Der Bericht des Simplicius über die Quadraturen des Antiphon und Hippokrates*), but unfortunately his judgement is not always trustworthy. Heath (*H.G.M.* i. 183-200) has an excellent analysis. In the following pages I have given only such passages as can safely be attributed to Eudemus and omitted the rest.

GREEK MATHEMATICS

“ Καὶ οἱ τῶν μηνίσκων δὲ τετραγωνισμοὶ δόξαντες εἶναι τῶν οὐκ ἐπιπολαίων διαγραμμάτων διὰ τὴν οἰκειότητα τὴν πρὸς τὸν κύκλον ὑφ’ Ἰπποκράτους ἐγράφησάν τε πρῶτον καὶ κατὰ τρόπον ἔδοξαν ἀποδοθῆναι· διόπερ ἐπὶ πλέον ἀψώμεθά τε καὶ διέλθωμεν. ἀρχὴν μὲν οὖν ἐποιήσατο καὶ πρῶτον ἔθετο τῶν πρὸς αὐτοὺς χρησίμων, ὅτι τὸν αὐτὸν λόγον ἔχει τὰ τε ὅμοια τῶν κύκλων τμήματα πρὸς ἄλληλα καὶ αἱ βάσεις αὐτῶν δυνάμει. τοῦτο δὲ ἐδείκνυεν ἐκ τοῦ τὰς διαμέτρους δεῖξαι τὸν αὐτὸν λόγον ἐχούσας δυνάμει τοῖς κύκλοις.

“ Δειχθέντος δὲ αὐτῷ τούτου πρῶτον μὲν ἔγραφε μηνίσκου τὴν ἐκτὸς περιφέρειαν ἔχοντος ἡμικυκλίου



τίνα τρόπον γένοιτο ἂν τετραγωνισμός. ἀπεδίδου δὲ τοῦτο περὶ τρίγωνον ὀρθογώνιον τε καὶ ἰσοσκελὲς ἡμικύκλιον περιγράψας καὶ περὶ τὴν βάσιν τμήμα κύκλου τοῖς ὑπὸ τῶν ἐπιζευχθεισῶν ἀφαιρουμένοις ὅμοιον. ὄντος δὲ τοῦ περὶ τὴν βάσιν τμήματος ἴσου τοῖς περὶ τὰς ἐτέρας ἀμφοτέροις, καὶ κοινῷ προστεθέντος τοῦ μέρους τοῦ τριγώνου τοῦ ὑπὲρ τὸ τμήμα τὸ περὶ τὴν βάσιν, ἴσος ἔσται ὁ μηνίσκος τῷ τριγώνῳ. ἴσος οὖν ὁ μηνίσκος τῷ τριγώνῳ δειχθεὶς τετραγωνίζοιτο ἂν. οὕτως μὲν
238

HIPPOCRATES OF CHIOS

“ The quadratures of lunes, which seemed to belong to an uncommon class of propositions by reason of the close relationship to the circle, were first investigated by Hippocrates, and seemed to be set out in correct form; therefore we shall deal with them at length and go through them. He made his starting-point, and set out as the first of the theorems useful to his purpose, that similar segments of circles have the same ratios as the squares on their bases.^a And this he proved by showing that the squares on the diameters have the same ratios as the circles.^b

“ Having first shown this he described in what way it was possible to square a lune whose outer circumference was a semicircle. He did this by circumscribing about a right-angled isosceles triangle a semicircle and about the base a segment of a circle similar to those cut off by the sides.^c Since the segment about the base is equal to the sum of those about the sides, it follows that when the part of the triangle above the segment about the base is added to both the lune will be equal to the triangle. Therefore the lune, having been proved equal to the triangle, can be squared. In this way, taking

^a Lit. “ as the bases in square.”

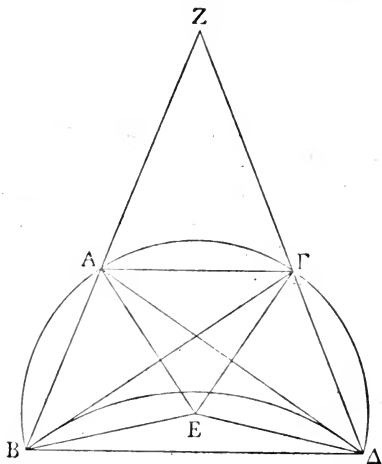
^b This is Eucl. xii. 2 (see *infra*, pp. 458-465). Euclid proves it by a method of exhaustion, based on a lemma or its equivalent which, on the evidence of Archimedes himself, can safely be attributed to Eudoxus. We are not told how Hippocrates effected the proof.

^c As Simplicius notes, this is the problem of Eucl. iii. 33 and involves the knowledge that similar segments contain equal angles.

GREEK MATHEMATICS

οὖν ἡμικυκλίου τὴν ἔξω τοῦ μηνίσκου περιφέρειαν ὑποθέμενος ἔτετραγώνισεν ὁ Ἰπποκράτης τὸν μηνίσκον εὐκόλως.

“Εἶτα ἐφεξῆς μείζονα ἡμικυκλίου ὑποτίθεται συστησάμενος τραπέζιον τὰς μὲν τρεῖς ἔχον πλευρὰς



ἴσας ἀλλήλαις, τὴν δὲ μίαν τὴν μείζω τῶν παραλλήλων τριπλασίαν ἐκείνων ἐκάστης δυνάμει, καὶ τότε τραπέζιον περιλαβὼν κύκλω καὶ περὶ τὴν μεγίστην αὐτοῦ πλευρὰν ὅμοιον τμήμα περιγράψας τοῖς ὑπὸ τῶν ἴσων τριῶν ἀποτεμνομένοις ἀπὸ τοῦ κύκλου. ὅτι δὲ μείζον ἐστὶν ἡμικυκλίου τὸ λεχθὲν τμήμα, δῆλον ἀχθείσης ἐν τῷ τραπέζιῳ διαμέτρου. ἀνάγκη γὰρ ταύτην ὑπὸ δύο πλευρὰς ὑποτείνουσιν τοῦ τραπέζιου τῆς ὑπολοίπου μιᾶς μείζονα ἢ δι-

HIPPOCRATES OF CHIOS

a semicircle as the outer circumference of the lune, Hippocrates readily squared the lune.

“Next in order he assumes [an outer circumference] greater than a semicircle [obtained by] constructing a trapezium having three sides equal to one another while one, the greater of the parallel sides, is such that the square on it is three times the square on each of those sides, and then comprehending the trapezium in a circle and circumscribing about ^a its greatest side a segment similar to those cut off from the circle by the three equal sides.^b That the said segment ^c is greater than a semicircle is clear if a diagonal is drawn in the trapezium. For this diagonal, subtending two sides of the trapezium, must be such that the square on it is greater than double the square on

^a *i.e.* “describing on.”

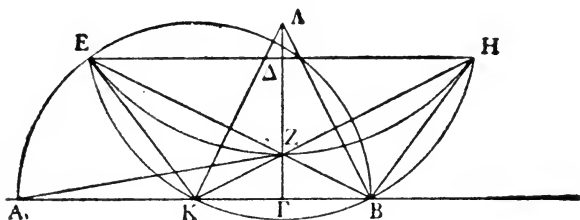
^b Simplicius here inserts a proof that a circle can be described about the trapezium.

^c *i.e.*, the segment bounded by the outer circumference. Eudemus is going to show that the angle in it is acute and therefore the segment is greater than a semicircle.

GREEK MATHEMATICS

πλασίαν εἶναι δυνάμει. ἡ ἄρα ΒΓ μείζον ἢ διπλάσιον δύναται ἐκατέρας τῶν ΒΑ, ΑΓ, ὥστε καὶ τῆς ΓΔ. καὶ τὴν μεγίστην ἄρα τῶν τοῦ τραπεζίου πλευρῶν τὴν ΒΔ ἀναγκαῖον ἔλαττον δύνασθαι τῆς τε διαμέτρου καὶ τῶν ἐτέρων πλευρῶν ἐκείνης, ὑφ' ἣν ὑποτείνει μετὰ τῆς διαμέτρου ἡ λεχθεῖσα. αἱ γὰρ ΒΓ, ΓΔ μείζον ἢ τριπλάσιον δύναται τῆς ΓΔ, ἡ δὲ ΒΔ τριπλάσιον. ὀξεῖα ἄρα ἐστὶν ἡ ἐπὶ τῆς μείζονος τοῦ τραπεζίου πλευρᾶς βεβηκυῖα γωνία. μείζον ἄρα ἡμικυκλίου ἐστὶ τὸ τμήμα ἐν ᾧ ἐστίν. ὅπερ ἐστὶν ἡ ἔξω περιφέρεια τοῦ μηνίσκου.

“Εἰ δὲ ἐλάττων ἡμικυκλίου εἴη, προγράψας τοιόνδε τι ὁ Ἰπποκράτης τοῦτο κατεσκεύασεν”



ἔστω κύκλος οὗ διάμετρος ἐφ' ἣ [ἡ]¹ ΑΒ, κέντρον δὲ αὐτοῦ ἐφ' ᾧ Κ· καὶ ἡ μὲν ἐφ' ἣ ΓΔ δίχα τε καὶ πρὸς ὀρθὰς τεμνέτω τὴν ἐφ' ἣ ΒΚ· ἡ δὲ ἐφ' ἣ ΕΖ κείσθω ταύτης μεταξὺ καὶ τῆς περιφερείας ἐπὶ τὸ Β νεύουσα τῶν ἐκ τοῦ κέντρου ἡμιολία οὔσα

¹ ἡ om. Diels.

* A proof is supplied in the text, probably by Simplicius though Diels attributes it to Eudemus. The proof is that, since ΒΔ is parallel to ΑΓ but greater than it, ΔΓ and ΒΑ produced will meet in Ζ. Then ΖΑΓ is an isosceles triangle,

HIPPOCRATES OF CHIOS

one of the remaining sides. Therefore the square on $B\Gamma$ is greater than double the square on either BA , $A\Gamma$, and therefore also on $\Gamma\Delta$.^a Therefore the square on $B\Delta$, the greatest of the sides of the trapezium, must be less than the sum of the squares on the diagonal and that one of the other sides which is subtended by the said [greatest] side together with the diagonal.^b For the squares on $B\Gamma$, $\Gamma\Delta$ are greater than three times, and the square on $B\Delta$ is equal to three times, the square on $\Gamma\Delta$. Therefore the angle standing on the greatest side of the trapezium ^c is acute. Therefore the segment in which it is is greater than a semicircle. And this segment is the outer circumference of the lune.^d

“ If [the outer circumference] were less than a semicircle, Hippocrates solved ^e this also, using the following preliminary construction. Let there be a circle with diameter AB and centre K . Let $\Gamma\Delta$ bisect BK at right angles ; and let the straight line EZ be placed between this and the circumference verging towards B so that the square on it is one-and-a-half so that the angle $ZA\Gamma$ is acute, and therefore the angle BAT is obtuse.

^b *i.e.* $B\Delta^2 < B\Gamma^2 + \Gamma\Delta^2$.

^c *i.e.* the angle $B\Gamma\Delta$.

^d Simplicius notes that Eudemus has omitted the actual squaring of the lune, presumably as being obvious. Since

$$B\Delta^2 = 3BA^2$$

(segment on $B\Delta$) = 3 (segment on BA)

= sum of segments on BA , $A\Gamma$, $\Gamma\Delta$.

Adding to each side of the equation the portion of the trapezium included by the sides BA , $A\Gamma$ and $\Gamma\Delta$ and the circumference of the segment on $B\Delta$, we get

trapezium $AB\Delta\Gamma$ = lune bounded by the two circumferences

and so the lune is “squared.”

^e Lit. “constructed.”

GREEK MATHEMATICS

δυνάμει. ἡ δὲ ἐφ' ἧ ΕΗ ἤχθω παρὰ τὴν ἐφ' ἧ ΑΒ, καὶ ἀπὸ τοῦ Κ ἐπεζεύχθωσαν ἐπὶ τὰ Ε, Ζ. συμπίπτέτω δὲ ἐκβαλλομένη ἡ ἐπὶ τὸ Ζ ἐπιζευχθεῖσα τῇ ἐφ' ἧ ΕΗ κατὰ τὸ Η καὶ πάλιν ἀπὸ τοῦ Β ἐπὶ τὰ Ζ, Η ἐπεζεύχθωσαν. φανερόν δὴ ὅτι ἡ μὲν ἐφ' ἧ ΕΖ ἐκβαλλομένη ἐπὶ τὸ Β πεσειται (ὑπόκειται γὰρ ἡ ΕΖ ἐπὶ τὸ Β νεύουσα), ἡ δὲ ἐφ' ἧ ΒΗ ἴση ἔσται τῇ ἐφ' ἧ ΕΚ.

“ Τούτων οὖν οὕτως ἐχόντων τὸ τραπέζιον φημι ἐφ' οὗ ΕΚΒΗ περιλήψεται κύκλος.

“ Περιγεγράφθω¹ δὴ περὶ τὸ ΕΖΗ τρίγωνον τμήμα κύκλου, δῆλον ὅτι ἐκάτερον τῶν ΕΖ, ΖΗ ὅμοιον ἐκάστῳ τῶν ΕΚ, ΚΒ, ΒΗ τμημάτων.

“ Τούτων οὕτως ἐχόντων ὁ γενόμενος μηνίσκος οὗ ἐκτὸς περιφέρεια ἡ ΕΚΒΗ ἴσος ἔσται τῷ εὐθυγράμμῳ τῷ συγκειμένῳ ἐκ τῶν τριῶν τριγώνων τῶν ΒΖΗ, ΒΖΚ, ΕΚΖ. τὰ γὰρ ἀπὸ τῶν εὐθειῶν ἐφ' αἷς ΕΖ, ΖΗ ἀφαιρούμενα ἐντὸς τοῦ μηνίσκου ἀπὸ τοῦ εὐθυγράμμου τμήματα ἴσα ἔστι τοῖς ἐκτὸς

¹ Περιγεγράφθω . . . τμημάτων. In the text of Simplicius this sentence precedes the one above and Simplicius's comments thereon. It is here restored to the place which it must have occupied in Eudemus's *History*.

• This is the first example we have had to record of the type of construction known to the Greeks as *νεύσεις*, *inclinations* or *vergings*. The general problem is to place a straight line so as to *verge towards* (pass through) a given point and so that a given length is intercepted on it by other lines. In this case the problem amounts to finding a length x such that, if Z be taken on $\Gamma\Delta$ so that $BZ = x$ and BZ be produced to

HIPPOCRATES OF CHIOS

times the square on one of the radii.^a Let EH be drawn parallel to AB, and from K let [straight lines] be drawn joining E and Z. Let the straight line [KZ] joined to Z and produced meet EH at H, and again let [straight lines] be drawn from B joining Z and H. It is then manifest that EZ produced will pass through B—for by hypothesis EZ verges towards B—and BH will be equal to EK.

“This being so, I say that the trapezium EKBH can be comprehended in a circle.

“Next let a segment of a circle be circumscribed about the triangle EZH; then clearly each of the segments on EZ, ZH will be similar to the segments on EK, KB, BH.

“This being so, the lune so formed, whose outer circumference is EKBH, will be equal to the rectilinear figure composed of the three triangles BZH, BZK, EKZ. For the segments cut off from the rectilinear figure, inside the lune, by the straight lines EZ, ZH are (together) equal to the segments outside

meet the circumference in E, then $EZ^2 = \frac{2}{3}AK^2$, or $EZ = \sqrt{\frac{2}{3}}AK$. If this is done, $EB \cdot BZ = AB \cdot BT = AK^2$

or $(x + \sqrt{\frac{2}{3}}a) \cdot x = a^2$, where $AK = a$.

In other words, the problem amounts to solving the quadratic equation

$$x^2 + \sqrt{\frac{2}{3}}ax = a^2.$$

This would be recognized by the Greeks as the problem of “applying to a straight line of length $\sqrt{\frac{2}{3}} \cdot a$, a rectangle exceeding by a square figure and equal in area to a^2 ,” and could have been solved theoretically by the Pythagorean method preserved in Eucl. ii. 6. Was this the method used by Hippocrates? Though it may have been, the authorities prefer to believe he used mechanical means (*H.G.M.* i. 196, Rudio, *loc cit.*, p. 59, Zeuthen, *Geschichte d. Math.*, p. 80). He could have marked on a ruler a length equal to $\sqrt{\frac{2}{3}}AK$ and moved it about until it was in the required position.

GREEK MATHEMATICS

τοῦ εὐθύγραμμου τμήμασιν ἀφαιρουμένοις ὑπὸ τῶν EK, KB, BH. ἐκάτερον γὰρ τῶν ἐντὸς ἡμιόλιόν ἐστιν ἐκάστου τῶν ἐκτὸς. ἡμιολία γὰρ¹ ὑπόκειται ἢ EZ τῆς ἐκ τοῦ κέντρου, τουτέστι τῆς EK καὶ KB καὶ BH. εἰ οὖν ὁ μὲν μηνίσκος τὰ τρία τμήματά ἐστι καὶ τοῦ εὐθύγραμμου τὸ παρὰ τὰ δύο τμήματα, τὸ δὲ εὐθύγραμμον μετὰ τῶν δύο τμημάτων ἐστὶ χωρὶς τῶν τριῶν, ἐστὶ δὲ τὰ δύο τμήματα τοῖς τρισὶν ἴσα, ἴσος ἂν εἶη ὁ μηνίσκος τῷ εὐθύγραμμῳ.

“Ὅτι δὲ οὗτος ὁ μηνίσκος ἐλάττονα ἡμικυκλίου τὴν ἐκτὸς ἔχει περιφέρειαν, δείκνυσι διὰ τοῦ τὴν EKH γωνίαν ἐν τῷ ἐκτὸς οὔσαν τμήματι ἀμβλεῖαν εἶναι. ὅτι δε ἀμβλεῖά ἐστὶν ἢ ὑπὸ EKH γωνία, δείκνυσιν οὕτως· ἐπεὶ² ἢ μὲν ἐφ’ ἢ EZ ἡμιολία ἐστὶ τῶν ἐκ τοῦ κέντρου δυνάμει, ἢ δὲ ἐφ’ ἢ KB μείζων τῆς ἐφ’ ἢ BZ ἢ διπλασία δυνάμει, φανερόν ὅτι καὶ ἢ ἐφ’ ἢ KE ἔσται τῆς ἐφ’ ἢ KZ ἄρα μείζων ἢ διπλασία δυνάμει. ἢ δὲ ἐφ’ ἢ EZ μείζων ἐστὶ δυνάμει τῶν ἐφ’ αἷς EK, KZ. ἀμβλεῖα ἄρα ἐστὶν ἢ πρὸς τῷ K γωνία, ἐλάττον ἄρα ἡμικυκλίου τὸ τμήμα ἐν ᾧ ἐστὶν.

“Οὕτως μὲν οὖν ὁ Ἱπποκράτης πάντα μηνίσκον ἐτετραγώνισεν, εἶπερ καὶ τὸν ἡμικυκλίου καὶ τὸν

¹ δυνάμει must be understood after ἡμιολία γὰρ, as Bretschneider first pointed out, but Diels and Rudio think that Simplicius probably omitted it as obvious, here and in his own comments.

² ἐπεὶ . . . ἐστὶν. Eudemus purports to give the proof in Hippocrates' own words. Unfortunately Simplicius's version is too confused to be worth reproducing. The proof is here given as reconstructed by Rudio. That it is substantially the proof given by Hippocrates is clear.

HIPPOCRATES OF CHIOS

the rectilinear figure cut off by EK, KB, BH. For each of the inner segments is one-and-a-half times each of the outer, because, by hypothesis, the square on EZ is one-and-a-half times the square on the radius, that is, the square on EK or KB or BH. Inasmuch then as the lune is made up of the three segments and the rectilinear figure *less* the two segments—the rectilinear figure including the two segments but not the three—while the sum of the two segments is equal to the sum of the three, it follows that the lune is equal to the rectilinear figure.

“That this lune has its outer circumference less than a semicircle, he proves by means of the angle EKH in the outer segment being obtuse. And that the angle EKH is obtuse, he proves thus.

Since
$$EZ^2 = \frac{3}{2} EK^2$$

and ^a
$$KB^2 > 2BZ^2,$$

it is manifest that $EK^2 > 2KZ^2$.

Therefore
$$EZ^2 > EK^2 + KZ^2.$$

The angle at K is therefore obtuse, so that the segment in which it is is less than a semicircle.

“Thus Hippocrates squared every lune, seeing that [he squared] not only the lune which has for its outer circumference a semicircle, but also the lune in which

^a This is assumed. Heath (*H.G.M.* i. 195) supplies the following proof:

By hypothesis, $EZ^2 = \frac{3}{2}KB^2$.

Also, since A, E, Z, Γ are concyclic,

or
$$\begin{aligned} EB \cdot BZ &= AB \cdot B\Gamma = KB^2 \\ EZ \cdot ZB + BZ^2 &= KB^2 = \frac{2}{3}EZ^2. \end{aligned}$$

It follows that $EZ > ZB$ and that $KB^2 > 2BZ^2$.

GREEK MATHEMATICS

μείζονα ἡμικυκλίου καὶ τὸν ἐλάττονα ἔχοντα τὴν ἐκτὸς περιφέρειαν.

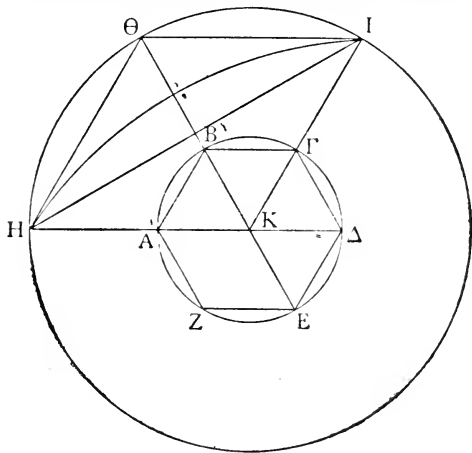
“ Ἄλλὰ μνήσκον ἅμα καὶ κύκλον ἐτετραγώνισεν οὕτως· ἔστωσαν περὶ κέντρον ἐφ’ οὗ Κ δύο κύκλοι, ἡ δὲ τοῦ ἐκτὸς διάμετρος ἐξαπλασία δυνάμει τῆς τοῦ ἐντὸς καὶ ἐξαγώνου ἐγγραφέντος εἰς τὸν ἐντὸς κύκλον τοῦ ἐφ’ οὗ ΑΒΓΔΕΖ αἵ τε ἐφ’ ὧν ΚΑ, ΚΒ, ΚΓ ἐκ τοῦ κέντρου ἐπιζευχθεῖσαι ἐκβεβλήσθωσαν ἕως τῆς τοῦ ἐκτὸς κύκλου περιφέρειας καὶ αἱ ἐφ’ ὧν ΗΘ, ΘΙ, (ΗΙ)¹ ἐπεζεύχθωσαν καὶ δῆλον ὅτι καὶ αἱ ΗΘ, ΘΙ ἐξαγώνου εἰσὶ πλευραὶ τοῦ εἰς τὸν μείζονα κύκλον ἐγγραφομένου. καὶ περὶ τὴν ἐφ’ ἧ ΗΙ τμήμα ὁμοιον τῷ ἀφαιρουμένῳ ὑπὸ τῆς ἐφ’ ἧ ΗΘ περιγεγράφθω, ἐπεὶ οὖν τὴν μὲν ἐφ’ ἧ ΗΙ τριπλασίαν ἀνάγκη εἶναι δυνάμει τῆς ἐφ’ ἧ ΘΗ τοῦ ἐξαγώνου πλευρᾶς (ἡ γὰρ ὑπὸ δύο τοῦ ἐξαγώνου πλευρᾶς ὑποτείνουσα μετὰ ἄλλης μιᾶς ὀρθὴν περι-

¹ ΗΙ add. Usener.

HIPPOCRATES OF CHIOS

the outer circumference is greater, and that in which it is less, than a semicircle.

“ But he also squared a lune and a circle together in the following manner. Let there be two circles



with K as centre, such that the square on the diameter of the outer is six times the square on the diameter of the inner. Let a [regular] hexagon ABΓΔEZ be inscribed in the inner circle, and let KA, KB, KΓ be joined from the centre and produced as far as the circumference of the outer circle, and let HΘ, ΘI, HI be joined. Then it is clear that HΘ, ΘI are sides of a [regular] hexagon inscribed in the outer circle. About HI let a segment be circumscribed similar to the segment cut off by HΘ. Since then $HI^2 = 3\Theta H^2$ (for the square on the line subtended by two sides of the hexagon, together with the square on one other

GREEK MATHEMATICS

έχουσα γωνίαν τὴν ἐν ἡμικυκλίῳ ἴσον δύναται τῇ διαμέτρῳ, ἢ δὲ διάμετρος τετραπλάσιον δύναται τῆς τοῦ ἑξαγώνου ἴσης οὔσης τῇ ἐκ τοῦ κέντρου διὰ τὸ τὰ μήκει διπλάσια εἶναι δυνάμει τετραπλάσια), ἢ δὲ ΘH ἑξαπλασία τῆς ἐφ' ἣ AB , δηλὸν ὅτι τὸ τμήμα τὸ περὶ τὴν ἐφ' ἣ HI περιγραφὴν ἴσον εἶναι συμβαίνει τοῖς τε ἀπὸ τοῦ ἐκτὸς κύκλου ὑπὸ τῶν ἐφ' αἷς $\text{H}\Theta$, ΘI ἀφαιρουμένοις καὶ τοῖς ἀπὸ τοῦ ἐντὸς ὑπὸ τῶν τοῦ ἑξαγώνου πλευρῶν ἀπασῶν. ἢ γὰρ HI τῆς $\text{H}\Theta$ τριπλάσιον δύναται, ἴσον δὲ τῇ $\text{H}\Theta$ δύναται ἢ ΘI , δύναται δὲ ἑκάτερα τούτων ἴσον καὶ αἱ ἐξ πλευραὶ τοῦ ἐντὸς ἑξαγώνου, διότι καὶ ἡ διάμετρος τοῦ ἐκτὸς κύκλου ἑξαπλάσιον ὑπόκειται δύνασθαι τῆς τοῦ ἐντὸς, ὥστε ὁ μὲν μηνίσκος ἐφ' οὗ $\text{H}\Theta\text{I}$ τοῦ τριγώνου ἐλάττων ἂν εἶη ἐφ' οὗ τὰ αὐτὰ γράμματα τοῖς ὑπὸ τῶν τοῦ ἑξαγώνου πλευρῶν ἀφαιρουμένοις τμήμασιν ἀπὸ τοῦ ἐντὸς κύκλου. τὸ γὰρ ἐπὶ τῆς HI τμήμα ἴσον ἦν τοῖς τε $\text{H}\Theta$, ΘI τμήμασι καὶ τοῖς ὑπὸ τοῦ ἑξαγώνου ἀφαιρουμένοις. τὰ οὖν $\text{H}\Theta$, ΘI τμήματα ἐλάττω ἐστὶ τοῦ περὶ τὴν HI (τμήματος τοῖς)¹ τμήμασι [καὶ]² τοῖς ὑπὸ τοῦ ἑξαγώνου ἀφαιρουμένοις. κοινῶ οὖν προστεθέντος τοῦ ὑπὲρ τὸ τμήμα τὸ περὶ τὴν HI μέρους τοῦ τριγώνου, ἐκ μὲν τούτου καὶ τοῦ περὶ τὴν HI τμήματος τὸ τρίγωνον ἔσται, ἐκ δὲ τοῦ αὐτοῦ καὶ τῶν $\text{H}\Theta$, ΘI τμημάτων ὁ μηνίσκος. ἔσται οὖν ἐλάττων ὁ μηνίσκος τοῦ τριγώνου τοῖς ὑπὸ τοῦ ἑξαγώνου ἀφαιρουμένοις τμήμασιν. ὁ ἄρα

¹ τμήματος τοῖς add. Bretschneider.

² καὶ om. Bretschneider.

• If HA be a side of the hexagon, then IA is a diameter and the angle IHA is right. Therefore $\text{HI}^2 + \text{HA}^2 = \text{IA}^2$,

HIPPOCRATES OF CHIOS

side, is equal, since they form a right angle in the semicircle, to the square on the diameter, and the square on the diameter is four times the side of the hexagon, the diameter being twice the side in length and so four times as great in square ^a), and $\Theta H^2 = 6 AB^2$, it is manifest that the segment circumscribed about HI is equal to the segments cut off from the outer circle by HΘ, ΘI, together with the segments cut off from the inner circle by all the sides of the hexagon.^b For $HI^2 = 3 H\Theta^2$, and $\Theta I^2 = H\Theta^2$, while ΘI^2 and $H\Theta^2$ are each equal to the sum of the squares on the six sides of the inner hexagonal, since, by hypothesis, the diameter of the outer circle is six times that of the inner. Therefore the lune HΘI is smaller than the triangle HΘI by the segments taken away from the inner circle by the sides of the hexagon. For the segment on HI is equal to the sum of the segments on HΘ, ΘI and those taken away by the hexagon. Therefore the segments [on] HΘ, ΘI are less than the segment about HI by the segments taken away by the hexagon. If to both sides there is added the part of the triangle which is above the segment about HI,^c out of this and the segment about HI will be formed the triangle, while out of the latter and the segments [on] HΘ, ΘI will be formed the lune. Therefore the lune will be less than the triangle by the segments taken away by the hexagon. For the lune and the

and so $HI^2 + \Theta H^2 = IA^2 = 4\Theta H^2$ (since $IA = 2\Theta H$). Consequently $HI^2 = 3\Theta H^2$.

^b For (segment on HI) = 3 (segment on HΘ)
 = 2 (segment on HΘ) + 6 (segment on AB)
 = (segments on HΘ, ΘI) + (all segments of inner circle).

^c i.e., the figure bounded by HΘ, ΘI and the arc IH.

GREEK MATHEMATICS

μηρίσκος καὶ τὰ ὑπὸ τοῦ ἑξαγώνου ἀφαιρούμενα τμήματα ἴσα ἔστιν τῷ τριγώνῳ. καὶ κοινοῦ προστεθέντος τοῦ ἑξαγώνου τὸ τρίγωνον τοῦτο καὶ τὸ ἑξάγωνον ἴσα ἔστι τῷ τε μηρίσκῳ τῷ λεχθέντι καὶ τῷ κύκλῳ τῷ ἐντός. εἰ οὖν τὰ εἰρημένα εὐθύγραμμα δυνατὸν τετραγωνισθῆναι, καὶ τὸν κύκλον ἄρα μετὰ τοῦ μηρίσκου.”

(c) TWO MEAN PROPORTIONALS

Procl. in *Eucl.* i., ed. Friedlein 212. 24-213. 11

Ἡ δὲ ἀπαγωγή μετάβασίς ἐστὶν ἀπ’ ἄλλου προβλήματος ἢ θεωρήματος ἐπ’ ἄλλο, οὗ γνωσθέντος ἢ πορισθέντος καὶ τὸ προκείμενον ἔσται καταφανές, οἷον ὥσπερ καὶ τοῦ διπλασιασμοῦ τοῦ κύβου ζητηθέντος μετέθεσαν τὴν ζήτησιν εἰς ἄλλο, ᾧ τοῦτο ἔπεται, τὴν εὔρεσιν τῶν δύο μέσων, καὶ τὸ λοιπὸν ἐζήτουν, πῶς ἂν δύο δοθεισῶν εὐθειῶν δύο μέσαι ἀνάλογον εὔρεθειεν. πρῶτον δέ φασι τῶν ἀπορουμένων διαγραμμάτων τὴν ἀπαγωγὴν ποιήσασθαι Ἰπποκράτην τὸν Χίον, ὃς καὶ μηρίσκον ἐτετραγώνισε καὶ ἄλλα πολλὰ κατὰ γεωμετρίαν εὔρεν εὐφυῆς περὶ τὰ διαγράμματα εἶπερ τις ἄλλος γενόμενος.

* What Hippocrates showed was that if $\frac{a}{x} = \frac{x}{y} = \frac{y}{b}$, then

HIPPOCRATES OF CHIOS

segments taken away by the hexagon are equal to the triangle. When the hexagon is added to both sides, this triangle and the hexagon will be equal to the aforesaid lune and to the inner circle. If then the aforementioned rectilinear figures can be squared, so also can the circle with the lune."

(c) TWO MEAN PROPORTIONALS

Proclus, *on Euclid* i., ed. Friedlein 212. 24-213. 11

Reduction is a transition from one problem or theorem to another, whose solution or construction makes manifest also that which is propounded, as when those who sought to double the cube transferred the investigation to another [problem] which it follows, the discovery of the two means, and from that time forward inquired how between two given straight lines two mean proportionals could be found. They say the first to effect the reduction of the difficult constructions was Hippocrates of Chios, who also squared a lune and discovered many other things in geometry, being unrivalled in the cleverness of his constructions.^a

$\frac{a^3}{x^3} = \frac{a}{b}$, so that if $b = 2a$, a cube of side x is twice the size of a cube of side a . For a fuller discussion, see *infra*, p. 258 n. b. It has been supposed from this passage that Hippocrates discovered the method of geometrical reduction, but this is unlikely.



IX. SPECIAL PROBLEMS

IX. SPECIAL PROBLEMS

1. DUPLICATION OF THE CUBE

(a) GENERAL

Theon Smyr., ed. Hiller 2. 3-12

Ἐρατοσθένης μὲν γὰρ ἐν τῷ ἐπιγραφομένῳ Πλατωνικῷ φησιν ὅτι, Δηλίοις τοῦ θεοῦ χρήσαντος ἐπὶ ἀπαλλαγῇ λοιμοῦ βωμόν τοῦ ὄντος διπλασίονα κατασκευάσαι, πολλὴν ἀρχιτέκτοσιν ἐμπεσεῖν ἀπορίαν ζητοῦσιν ὅπως χρὴ στερεὸν στερεοῦ γενέσθαι διπλάσιον, ἀφικέσθαι τε πευσομένους περὶ τούτου Πλάτωνος. τὸν δὲ φάναι αὐτοῖς, ὡς ἄρα οὐ διπλασίον βωμοῦ ὁ θεὸς δεόμενος τοῦτο Δηλίοις ἐμαντεύσατο, προφέρων δὲ καὶ ὄνειδίζων τοῖς Ἑλλησιν ἀμελοῦσι μαθημάτων καὶ γεωμετρίας ὠλιγωρηκόσιν.

Eutoc. *Comm. in Archim. de Sphaera et Cyl.* ii., Archim. ed. Heiberg iii. 88. 4-90. 13

Βασιλεῖ Πτολεμαίῳ Ἐρατοσθένης χαίρειν.

Τῶν ἀρχαίων τινὰ τραγωδοποιῶν φασιν εἰσαγαγεῖν τὸν Μίνω τῷ Γλαύκῳ κατασκευάζοντα τάφον,

^a Wilamowitz (*Gött. Nachr.*, 1894) shows that the letter is a forgery, but there is no reason to doubt the story it relates, which is indeed amply confirmed; and the author must be thanked for having included in his letter a proof and an

256

IX. SPECIAL PROBLEMS

1. DUPLICATION OF THE CUBE

(a) GENERAL

Theon of Smyrna, ed. Hiller 2. 3-12

IN his work entitled *Platonicus* Eratosthenes says that, when the god announced to the Delians by oracle that to get rid of a plague they must construct an altar double of the existing one, their craftsmen fell into great perplexity in trying to find how a solid could be made double of another solid, and they went to ask Plato about it. He told them that the god had given this oracle, not because he wanted an altar of double the size, but because he wished, in setting this task before them, to reproach the Greeks for their neglect of mathematics and their contempt for geometry.

Eutocius, *Commentary on Archimedes' Sphere and Cylinder* ii., Archim. ed. Heiberg iii. 88. 4-90. 13

To King Ptolemy Eratosthenes sends greeting.^a

They say that one of the ancient tragic poets represented Minos as preparing a tomb for Glaucus, epigram, taken from a votive monument, which are the genuine work of Eratosthenes (*infra*, pp. 294-297). The monarch addressed is Ptolemy Euergetes, to whose son, Philopator, Eratosthenes was tutor.

GREEK MATHEMATICS

πυθόμενον δέ, ὅτι πανταχοῦ ἑκατόμπεδος εἶη, εἰπεῖν·

μικρόν γ' ἔλεξας βασιλικοῦ σηκὸν τάφου·
διπλάσιος ἔστω, τοῦ καλοῦ δὲ μὴ σφαλῆς
δίπλαζ' ἕκαστον κῶλον ἐν τάχει τάφου.

ἔδόκει δὲ διημαρτηκῆναι· τῶν γὰρ πλευρῶν διπλασιασθεισῶν τὸ μὲν ἐπίπεδον γίνεται τετραπλάσιον, τὸ δὲ στερεὸν ὀκταπλάσιον. ἐζητεῖτο δὲ καὶ παρὰ τοῖς γεωμέτραις, τίνα ἂν τις τρόπον τὸ δοθὲν στερεὸν διαμένον ἐν τῷ αὐτῷ σχήματι διπλασιάσειεν, καὶ ἔκαλεῖτο τὸ τοιοῦτον πρόβλημα κύβου διπλασιασμός· ὑποθέμενοι γὰρ κύβον ἐζήτουν τοῦτον διπλασιάσαι. πάντων δὲ διαπορούντων ἐπὶ πολὺν χρόνον πρῶτος Ἰπποκράτης ὁ Χίος ἐπενόησεν, ὅτι, ἐὰν εὔρεθῇ δύο εὐθειῶν γραμμῶν, ὧν ἡ μείζων τῆς ἐλάσσονός ἐστι διπλασία, δύο μέσας ἀνάλογον λαβεῖν ἐν συνεχείᾳ ἀναλογία, διπλασιασθήσεται ὁ κύβος, ὥστε τὸ ἀπόρημα αὐτῷ εἰς ἕτερον οὐκ ἔλασσον ἀπόρημα κατέστρεφεν. μετὰ χρόνον δὲ τινὰς φασιν Δηλίους ἐπιβαλλομένους κατὰ χρησμὸν διπλασιάσαι τινὰ τῶν βωμῶν ἐμπεσεῖν εἰς τὸ αὐτὸ ἀπόρημα, διαπεμψαμένους δὲ τοὺς παρὰ τῷ Πλάτωνι ἐν Ἀκαδημίᾳ γεωμέτραις ἀξιούν αὐτοῖς εὔρεῖν τὸ ζητούμενον. τῶν δὲ φιλοπόνως ἐπιδιδόντων ἑαυτοὺς καὶ ζητούντων δύο τῶν δοθεισῶν δύο μέσας

^a Valckenaer attributed these lines to Euripides, but Wilamowitz has shown that they cannot be from any play by Aeschylus, Sophocles or Euripides and must be the work of some minor poet.

^b For if x, y are mean proportionals between a, b ,

then
$$\frac{a}{x} = \frac{x}{y} = \frac{y}{b}.$$

SPECIAL PROBLEMS

and as declaring, when he learnt it was a hundred feet each way : " Small indeed is the tomb thou hast chosen for a royal burial. Let it be double, and thou shalt not miss that fair form if thou quickly doublest each side of the tomb." ^a He seems to have made a mistake. For when the sides are doubled, the surface becomes four times as great and the solid eight times. It became a subject of inquiry among geometers in what manner one might double the given solid, while it remained the same shape, and this problem was called the duplication of the cube ; for, given a cube, they sought to double it. When all were for a long time at a loss, Hippocrates of Chios first conceived that, if two mean proportionals could be found in continued proportion between two straight lines, of which the greater was double the lesser, the cube would be doubled, ^b so that the puzzle was by him turned into no less a puzzle. After a time, it is related, certain Delians, when attempting to double a certain altar in accordance with an oracle, fell into the same quandary, and sent over to ask the geometers who were with Plato in the Academy to find what they sought. When these men applied themselves diligently and sought to find two mean proportionals between two given straight lines,

Therefore
$$y = \frac{x^2}{a} = \frac{ab}{x}$$

and, eliminating y ,
$$x^3 = a^2b$$

so that
$$\frac{a^3}{x^3} = \frac{a}{b}.$$

This property is stated in Eucl. *Elem.* v. Def. 10.

If $b = 2a$, then x is the side of a cube double a cube of side a . Once this was discovered by Hippocrates, the problem was always so treated.

GREEK MATHEMATICS

λαβεῖν Ἀρχύτας μὲν ὁ Ταραντῖνος λέγεται διὰ τῶν ἡμικυλίνδρων εὐρηκέαι, Εὐδόξος δὲ διὰ τῶν καλουμένων καμπύλων γραμμῶν· συμβέβηκε δὲ πᾶσιν αὐτοῖς ἀποδεικτικῶς γεγραφέναι, χειρουργῆσαι δὲ καὶ εἰς χρεῖαν πεσεῖν μὴ δύνασθαι πλὴν ἐπὶ βραχύτι τὸν Μέναιχμον καὶ ταῦτα δυσχερῶς. ἐπινενόηται δέ τις ὑφ' ἡμῶν ὀργανικὴ λήψις ῥαδία, δι' ἧς εὐρήσομεν δύο τῶν δοθεισῶν οὐ μόνον δύο μέσας, ἀλλ' ὅσας ἂν τις ἐπιτάξῃ.

(b) SOLUTIONS GIVEN BY EUTOCIUS

Eutoc. Comm. in Archim. de Sphaera et Cyl. ii., Archim. ed. Heiberg iii. 54. 26-56. 12

Εἰς τὴν σύνθεσιν τοῦ α'

Τούτου ληφθέντος ἐπεὶ δι' ἀναλύσεως αὐτῷ προέβη τὰ τοῦ προβλήματος, ληξάσης τῆς ἀναλύσεως εἰς τὸ δεῖν δύο δοθεισῶν δύο μέσας ἀνάλογον προσευρεῖν ἐν συνεχείᾳ ἀναλογία φησὶν ἐν τῇ συνθέσει· “εὐρήσθωσαν.” τὴν δὲ εὔρεσιν τούτων ὑπ' αὐτοῦ μὲν γεγραμμένην οὐδὲ ὅλως εὐρίσκομεν, πολλῶν δὲ κλεινῶν ἀνδρῶν γραφαῖς ἐντετυχήκαμεν τὸ πρόβλημα τοῦτο ἐπαγγελλομέναις, ὧν τὴν Εὐδόξου τοῦ Κνιδίου παρητησάμεθα γραφὴν, ἐπειδὴ φησὶν μὲν ἐν προοιμίῳ διὰ καμπύλων γραμμῶν αὐτὴν εὐρηκέαι, ἐν δὲ τῇ ἀποδείξει πρὸς τῷ μὴ κεχρηῆσθαι καμπύλαις γραμμαῖς ἀλλὰ καὶ

• “Given a cone or cylinder, to find a sphere equal to the cone or cylinder” (Archim. ed. Heiberg i. 170-174).

• This is a great misfortune, as we may be sure Eudoxus would have treated the subject in his usual brilliant fashion.

SPECIAL PROBLEMS

Archytas of Taras is said to have found them by the half-cylinders, and Eudoxus by the so-called curved lines ; but it turned out that all their solutions were theoretical, and they could not give a practical construction and turn it to use, except to a certain small extent Menaechmus, and that with difficulty. An easy mechanical solution was, however, found by me, and by means of it I will find, not only two means to the given straight lines, but as many as may be enjoined.

(b) SOLUTIONS GIVEN BY EUTOCIUS

Eutocius, *Commentary on Archimedes' Sphere and Cylinder* ii., Archim. ed. Heiberg iii. 54. 26-56. 12

On the Synthesis of Prop. 1^a

With this assumption the problem became for him one of analysis, and when the analysis resolved itself into the discovery of two mean proportionals in continuous proportion between two given straight lines he says in the synthesis : " Let them be found." How they were found we nowhere find described by him, but we have come across writings of many famous men dealing with this problem. Among them is Eudoxus of Cnidos, but we have omitted his account,^b since he says in the preface that he made his discovery by means of curved lines, but in the demonstration itself not only did he not use curved

Tannery (*Mémoires scientifiques*, vol. i. pp. 53-61) suggests that Eudoxus's construction was a modified form of that by Archytas, for which see *infra*, pp. 284-289, the modification being virtually projection on the plane. Heath (*H.G.M.* i. 249-251) considers Tannery's suggestion ingenious and attractive, but too close an adaptation of Archytas's ideas to be the work or so original a mathematician as Eudoxus.

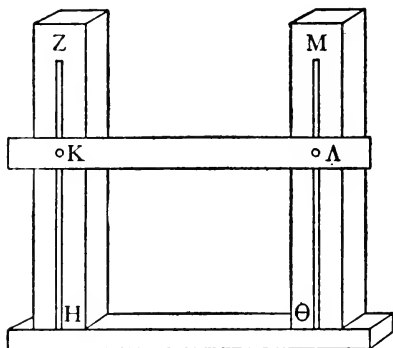
GREEK MATHEMATICS

διηρημένην ἀναλογίαν εὐρῶν ὡς συνεχεῖ χρήται ὅπερ ἦν ἄτοπον ὑπονοῆσαι, τί λέγω περὶ Εὐδόξου, ἀλλὰ περὶ τῶν καὶ μετρίως περὶ γεωμετρίαν ἀνεστραμμένων. ἵνα δὴ ἡ τῶν εἰς ἡμᾶς ἐληλυθότων ἀνδρῶν ἔννοια ἐμφανῆς γένηται, ὁ ἐκάστου τῆς εὐρέσεως τρόπος καὶ ἐνταῦθα γραφήσεται.

Ibid. 56. 13-58. 14

Ὡς Πλάτων

Δύο δοθεισῶν εὐθειῶν δύο μέσας ἀνάλογον εὐρεῖν ἐν συνεχεῖ ἀναλογία.



*Ἐστῶσαν αἱ δοθεῖσαι δύο εὐθεῖαι αἱ ΑΒΓ πρὸς

^a The complete list of solutions given by Eutocius is: Plato, Heron, Philon, Apollonius, Diocles, Pappus, Sporus, Menaechmus (two solutions), Archytas, Eratosthenes, Nicomedes.

^b It is virtually certain that this solution is wrongly attributed to Plato. Eutocius alone mentions it, and if it had been known to Eratosthenes he could hardly have failed to

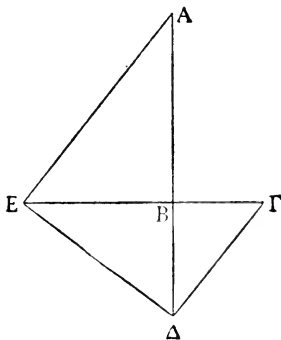
SPECIAL PROBLEMS

lines but he used as continuous a discrete proportion which he found. That would be a foolish thing to imagine, not only of Eudoxus, but of any one moderately versed in geometry. In order that the ideas of those men who have come down to us may be made manifest, the manner in which each made his discovery will be described here also.^a

Ibid. 56. 13-58. 14

(i.) *The Solution of Plato*^b

Given two straight lines, to find two mean proportionals in continuous proportion.



Let the two given straight lines be AB , $B\Gamma$, per-
cite it along with those of Archytas, Menaechmus and
Eudoxus. Furthermore, Plato told the Delians, according to
Plutarch's account, that Eudoxus or Helicon of Cyzicus
would solve the problem for them: he did not apparently
propose to tackle it himself. And Plutarch twice says that
Plato objected to mechanical solutions as destroying the
good of geometry, a statement which is consistent with his
known attitude towards mathematics.

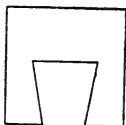
GREEK MATHEMATICS

ὀρθὰς ἀλλήλαις, ὧν δεῖ δύο μέσας ἀνάλογον εὐρεῖν. ἐκβεβλήσθωσαν ἐπ' εὐθείας ἐπὶ τὰ Δ, Ε, καὶ κατεσκευάσθω ὀρθὴ γωνία ἢ ὑπὸ ΖΗΘ, καὶ ἐν ἐνὶ σκέλει, οἷον τῷ ΖΗ, κινείσθω κανὼν ὁ ΚΛ ἐν σωλῆνί τινι ὄντι ἐν τῷ ΖΗ οὕτως, ὥστε παράλληλον αὐτὸν διαμένειν τῷ ΗΘ. ἔσται δὲ τοῦτο, εἰ καὶ ἕτερον κανόνιον νοηθῆ συμφυῆς τῷ ΘΗ, παράλληλον δὲ τῷ ΖΗ, ὡς τὸ ΘΜ. σωληνισθεισῶν γὰρ τῶν ἄνωθεν ἐπιφανειῶν τῶν ΖΗ, ΘΜ σωλῆσιν πελεκινοειδέσιν καὶ τύλων συμφυῶν γενομένων τῷ ΚΛ εἰς τοὺς εἰρημένους σωλῆνας ἔσται ἡ κίνησις τοῦ ΚΛ παράλληλος ἀεὶ τῷ ΗΘ. τούτων οὖν κατεσκευασμένων κείσθω τὸ ἐν σκέλος τῆς γωνίας τυχὸν τὸ ΗΘ ψαῦον τοῦ Γ, καὶ μεταφερέσθω ἢ τε γωνία καὶ ὁ ΚΛ κανὼν ἐπὶ τοσοῦτον, ἄχρις ἂν τὸ μὲν Η σημεῖον ἐπὶ τῆς ΒΔ εὐθείας ἢ τοῦ ΗΘ σκέλους ψαύοντος τοῦ Γ, ὁ δὲ ΚΛ κανὼν κατὰ μὲν τὸ Κ ψαύῃ τῆς ΒΕ εὐθείας, κατὰ δὲ τὸ λοιπὸν μέρος τοῦ Α, ὥστε εἶναι, ὡς ἔχει ἐπὶ τῆς καταγραφῆς, τὴν μὲν ὀρθὴν γωνίαν θέσιν ἔχουσιν ὡς τὴν ὑπὸ

SPECIAL PROBLEMS

pendicular to each other, between which it is required to find two mean proportionals. Let them be produced in a straight line to Δ , E , let the right-angle $ZH\Theta$ be constructed, and in one leg, say ZH , let the ruler $K\Lambda$ be moved in a kind of groove in ZH , in such a way that it remains parallel to $H\Theta$. This will come about if another ruler be conceived fixed to ΘH , but parallel to ZH , such as ΘM . If the upper surfaces of ZH , ΘM are grooved with axe-like grooves,^a and there are notches on $K\Lambda$ fitting into the aforementioned grooves, the motion of $K\Lambda$ will always be parallel to $H\Theta$. When this instrument is constructed, let one leg of the angle, say $H\Theta$, be placed so as to touch Γ , and let the angle and the ruler $K\Lambda$ be turned about until the point H falls upon the straight line $B\Delta$, while the leg $H\Theta$ touches Γ , and the ruler $K\Lambda$ touches the straight line BE at K , and in the other part touches A , so that it comes about, as in the figure, that the right angle takes up the position of the angle $\Gamma\Delta E$, while

- The grooves are presumably after the manner of the



accompanying diagram, or, as we should say, the notches and the grooves are *dove-tailed*.

GREEK MATHEMATICS

ΓΔΕ, τὸν δὲ ΚΛ κανόνα θέσιν ἔχειν, οἷαν ἔχει ἡ ΕΑ· τούτων γὰρ γεναμένων ἔσται τὸ προκείμενον. ὀρθῶν γὰρ οὐσῶν τῶν πρὸς τοῖς Δ, Ε ἔστιν, ὡς ἡ ΓΒ πρὸς ΒΔ, ἢ ΔΒ πρὸς ΒΕ καὶ ἡ ΕΒ πρὸς ΒΑ.

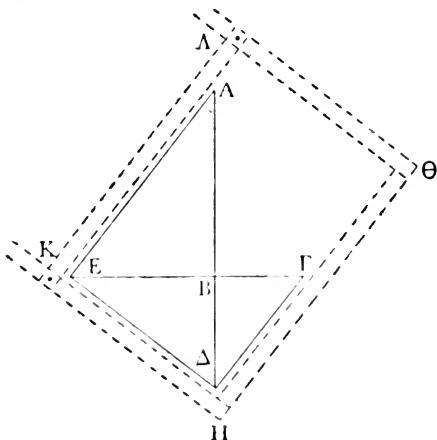
Ibid. 58. 15-16

Ὡς Ἡρων ἐν Μηχανικαῖς εἰσαγωγαῖς καὶ ἐν τοῖς
Βελοπουκοῖς

Papp. *Coll.* iii. 9. 26, ed. Hultsch 62. 26-64. 18; Heron,
Mech. i. 11, ed. Schmidt 268. 3-270. 15

Ἐστωσαν γὰρ αἱ δοθεῖσαι εὐθεῖαι αἱ ΑΒ, ΒΓ πρὸς ὀρθὰς ἀλλήλαις κείμεναι, ὧν δεῖ δύο μέσας ἀνάλογον εὔρεῖν.

° The account may become clearer from the accompanying diagram in which the instrument is indicated in its final



SPECIAL PROBLEMS

the ruler KA takes up the position EA .^a When this is done, what was enjoined will be brought about. For since the angles at Δ , E are right, $\Gamma B : B\Delta = \Delta B : BE = EB : BA$. [Eucl. vi. 8, coroll.]

Ibid. 58. 15-16

(ii.) *The Solution of Heron in his "Mechanics" and "Construction of Engines of War"*^b

Pappus, *Collection* iii. 9. 26, ed. Hultsch 62. 26-64. 18 ;
Heron, *Mechanics* i. 11, ed. Schmidt 268. 3-270. 15

Let the two given straight lines between which it is required to find two mean proportionals be AB , BF lying at right angles one to another.

position by dotted lines. $H\Theta$ is made to pass through Γ and the instrument is turned until the point H lies on AB produced. The ruler is then moved until its edge KA passes through A . If K does not then lie on ΓB produced, the instrument has to be manipulated again until all conditions are fulfilled: (1) $H\Theta$ passes through Γ ; (2) H lies on AB produced; (3) KA passes through A ; (4) K lies on ΓB produced. It may not be easy to do this, but it is possible.

^b Heron's own words have been most closely preserved by Pappus, whose version is here given in preference to Eutocius's, which includes some additions by the commentator. Schmidt also prefers Pappus's version in his edition of the Greek fragments of Heron's *Mechanics* in the Teubner edition of Heron's works (vol. ii., fasc. 1). The proof in the *Belopoeica* (edited by Wescher, *Poliorcétique des Grecs*, pp. 116-119) is extant. Philon of Byzantium and Apollonius gave substantially identical proofs.

GREEK MATHEMATICS

Συμπεπληρώσθω τὸ ΑΒΓΔ παραλληλόγραμμον, καὶ ἐκβεβλήσθωσαν αἱ ΔΓ, ΔΑ, καὶ ἐπέζεύχθωσαν αἱ ΔΒ, ΓΑ, καὶ παρακείσθω κανόνιον πρὸς τῷ Β σημείῳ καὶ κινείσθω τέμνον τὰς ΓΕ, ΑΖ, ἄχρις οὗ ἢ ἀπὸ τοῦ Η <ἀχθείσα>¹ ἐπὶ τὴν τῆς ΓΕ τομὴν ἴση γένηται τῇ ἀπὸ τοῦ Η ἐπὶ τὴν τῆς ΑΖ τομὴν. γεγονέτω, καὶ ἔστω ἡ μὲν τοῦ κανονίου θέσις ἡ ΕΒΖ, ἴσαι δὲ αἱ ΕΗ, ΗΖ. λέγω οὖν ὅτι αἱ ΑΖ, ΓΕ μέσαι ἀνάλογόν εἰσιν τῶν ΑΒ, ΒΓ.

Ἐπεὶ γὰρ ὀρθογώνιον ἔστιν τὸ ΑΒΓΔ παραλληλόγραμμον, αἱ τέσσαρες εὐθεῖαι αἱ ΔΗ, ΗΑ, ΗΒ, ΗΓ ἴσαι ἀλλήλαις εἰσίν. ἐπεὶ οὖν ἴση ἡ ΔΗ τῇ ΑΗ καὶ διῆκται ἡ ΗΖ, τὸ ἄρα ὑπὸ ΔΖΑ μετὰ τοῦ ἀπὸ ΑΗ ἴσον ἔστιν τῷ ἀπὸ ΗΖ. διὰ τὰ αὐτὰ δὴ καὶ τὸ ὑπὸ ΔΕΓ μετὰ τοῦ ἀπὸ ΓΗ ἴσον ἔστιν τῷ ἀπὸ ΗΕ. καὶ εἰσὶν ἴσαι αἱ ΗΕ,

¹ ἀχθείσα add. Hultsch.

^a The full proof requires ΗΘ to be drawn perpendicular to ΔΖ so that Θ bisects ΔΑ.

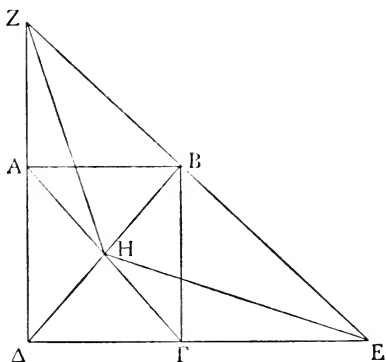
Then $\Delta Z \cdot ZA + A\Theta^2 = Z\Theta^2.$ [Eucl. ii. 6

Add ΗΘ² to each side.

Then $\Delta Z \cdot ZA + AH^2 = HZ^2.$ [Eucl. i. 47

SPECIAL PROBLEMS

Let the parallelogram $AB\Gamma\Delta$ be completed, and let $\Delta\Gamma$, ΔA be produced and let ΔB , ΓA be joined,



and let a ruler be placed at B and moved about until the sections ΓE , AZ cut off [from $\Delta\Gamma$, ΔA produced] are such that the straight line drawn from H to the section ΓE is equal to the straight line drawn from H to the section AZ . Let this be done, and let the position of the ruler be EBZ , so that EH , HZ are equal. I say that AZ , ΓE are mean proportionals between AB , $B\Gamma$.

For since the parallelogram $AB\Gamma\Delta$ is right-angled, the four straight lines ΔH , HA , HB , $H\Gamma$ are equal one to another. Since ΔH is equal to AH , and HZ has been drawn (from the vertex of the isosceles triangle $AH\Delta$ to the base), therefore ^a

$$\Delta Z \cdot ZA + AH^2 = HZ^2.$$

For the same reasons

$$\Delta E \cdot E\Gamma + \Gamma H^2 = HE^2.$$

But HE , HZ are equal.

GREEK MATHEMATICS

ΗΖ. ἴσον ἄρα καὶ τὸ ὑπὸ ΔΖΑ μετὰ τοῦ ἀπὸ ΑΗ τῶ ὑπὸ ΔΕΓ μετὰ τοῦ ἀπὸ ΓΗ. ὦν τὸ ἀπὸ ΓΗ ἴσον ἐστὶν τῶ ἀπὸ ΗΑ. λοιπὸν ἄρα τὸ ὑπὸ ΔΕΓ ἴσον ἐστὶν τῶ ὑπὸ ΔΖΑ. ὡς ἄρα ἡ ΕΔ πρὸς ΔΖ, ἡ ΖΑ πρὸς ΓΕ. ὡς δε ἡ ΕΔ πρὸς ΔΖ, ἡ τε ΒΑ πρὸς ΑΖ καὶ ἡ ΕΓ πρὸς ΓΒ, ὥστε ἔσται καὶ ὡς ἡ ΑΒ πρὸς ΑΖ, ἡ τε ΖΑ πρὸς ΓΕ καὶ ἡ ΓΕ πρὸς ΓΒ. τῶν ἄρα ΑΒ, ΒΓ μέσαι ἀνάλογόν εἰσιν αἱ ΑΖ, ΓΕ.]

Eutoc. *Comm. in Archim. De Sphaera et Cyl.* ii., Archim. ed. Heiberg iii. 66. 8-10. 5

Ὡς Διοκλῆς ἐν τῶ Περὶ πυρίων

Ἐν κύκλῳ ἤχθωσαν δύο διαμέτροι πρὸς ὀρθὰς αἱ ΑΒ, ΓΔ, καὶ δύο περιφέρειαι ἴσαι ἀπειλήφθωσαν ἐφ' ἐκάτερα τοῦ Β αἱ ΕΒ, ΒΖ, καὶ διὰ τοῦ Ζ παράλληλος τῇ ΑΒ ἤχθω ἡ ΖΗ, καὶ ἐπέζεύχθω ἡ ΔΕ. λέγω, ὅτι τῶν ΓΗ, ΗΘ δύο μέσαι ἀνάλογόν εἰσιν αἱ ΖΗ, ΗΔ.

Ἡχθω γὰρ διὰ τοῦ Ε τῇ ΑΒ παράλληλος ἡ

* Another fragment from the *Περὶ πυρίων* of Diocles is preserved by Eutocius (pp. 160 *et seq.*). It contains a solution by means of conics of the problem of dividing a sphere by a plane in such a way that the volumes of the resulting segments shall be in a given ratio, and refers both to Archi-

SPECIAL PROBLEMS

Therefore $\Delta Z \cdot ZA + AH^2 = \Delta E \cdot E\Gamma + \Gamma H^2.$

And $AH^2 = \Gamma H^2.$

Therefore $\Delta Z \cdot ZA = \Delta E \cdot E\Gamma.$

Therefore $E\Delta : \Delta Z = ZA : \Gamma E.$

But (by similar triangles)

$$E\Delta : \Delta Z = BA : AZ = E\Gamma : \Gamma B,$$

so that $AB : AZ = ZA : \Gamma E = \Gamma E : \Gamma B.$

Therefore $AZ, \Gamma E$ are mean proportionals between $AB, \Gamma B.$]

Eutocius, *Commentary on Archimedes' Sphere and Cylinder* ii., Archim. ed. Heiberg iii. 66. 8-70. 5

(iii.) *The Solution of Diocles in his Book* "On Burning Mirrors" ^a

In a circle let there be drawn two diameters $AB, \Gamma\Delta$ at right angles, and on either side of B let there be cut off two equal arcs EB, BZ , and through Z let ZH be drawn parallel to AB , and let ΔE be joined. I say that $ZH, H\Delta$ are two mean proportionals between $\Gamma H, H\Theta$.

For let EK be drawn through E parallel to AB ;

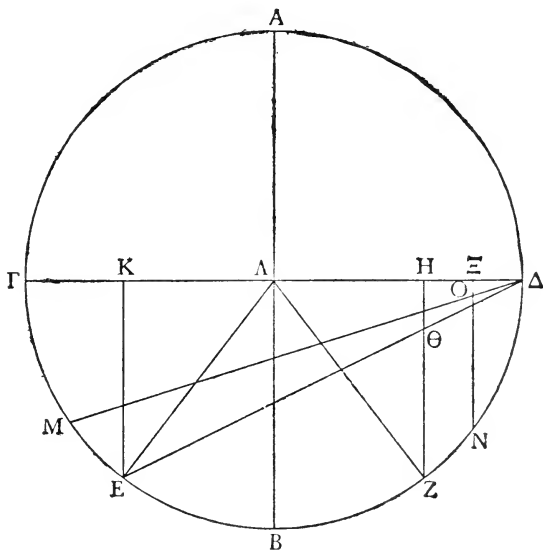
medes and to Apollonius. Diocles must therefore have flourished later than these geometers. It appears also, from allusions in Proclus's commentary on Eucl. i., that the curve known to Geminus as the cissoid was none other than the curve here described and used by Diocles for finding two mean proportionals, though the identification is not certain (see Loria, *Le scienze esatte nell' antica Grecia*, pp. 410-415, Heath, *H.G.M.* i. 264). In that case, Diocles preceded Geminus, who flourished about 70 B.C. It is probable therefore that Diocles lived towards the end of the second century or the beginning of the first century B.C.

GREEK MATHEMATICS

ΕΚ· ἴση ἄρα ἐστὶν ἡ μὲν ΕΚ τῇ ΖΗ, ἡ δὲ ΚΓ τῇ ΗΔ. ἔσται γὰρ τοῦτο δῆλον ἀπὸ τοῦ Λ ἐπὶ τὰ Ε, Ζ ἐπιζευχθεισῶν εὐθειῶν· ἴσαι γὰρ γίνονται αἱ ὑπὸ ΓΛΕ, ΖΛΔ, καὶ ὀρθαὶ αἱ πρὸς τοῖς Κ, Η· καὶ πάντα ἄρα πᾶσιν διὰ τὸ τὴν ΛΕ τῇ ΛΖ ἴσην εἶναι· καὶ λοιπὴ ἄρα ἡ ΓΚ τῇ ΗΔ ἴση ἐστίν· ἐπεὶ οὖν ἐστίν, ὡς ἡ ΔΚ πρὸς ΚΕ, ἡ ΔΗ πρὸς ΗΘ, ἀλλ' ὡς ἡ ΔΚ πρὸς ΚΕ, ἡ ΕΚ πρὸς ΚΓ· μέση γὰρ ἀνάλογον ἡ ΕΚ τῶν ΔΚ, ΚΓ· ὡς ἄρα ἡ ΔΚ πρὸς ΚΕ καὶ ἡ ΕΚ πρὸς ΚΓ, οὕτως ἡ ΔΗ

SPECIAL PROBLEMS

EK will therefore be equal to ZH, and KΓ to HΔ; this will be clear if straight lines are drawn joining



Λ to E, Z; for the angles ΓΛE, ZΛΔ are equal, and the angles at K, H are right; and therefore, since ΛE = ΛZ, all things will be equal to all; and therefore the remaining element ΓK is equal to HΔ. Now since

$$\Delta K : KE = \Delta H : H\Theta,$$

but

$$\Delta K : KE = EK : K\Gamma \quad (\text{for } EK \text{ is a mean proportional between } \Delta K, K\Gamma),$$

therefore

$$\Delta K : KE = EK : K\Gamma = \Delta H : H\Theta.$$

πρὸς ΗΘ. καὶ ἐστὶν ἴση ἢ μὲν ΔΚ τῇ ΓΗ, ἢ δὲ
 ΚΕ τῇ ΖΗ, ἢ δὲ ΚΓ τῇ ΗΔ· ὡς ἄρα ἢ ΓΗ πρὸς
 ΗΖ, ἢ ΖΗ πρὸς ΗΔ καὶ ἢ ΔΗ πρὸς ΗΘ. εἰ δὲ
 παρ' ἐκάτερα τοῦ Β ληφθῶσιν περιφέρειαι ἴσαι αἱ
 ΜΒ, ΒΝ, καὶ διὰ μὲν τοῦ Ν παράλληλος ἀχθῆ τῇ
 ΑΒ ἢ ΝΞ, ἐπιζευχθῆ δὲ ἢ ΔΜ, ἔσονται πάλιν τῶν
 ΓΞ, ΞΟ μέσαι ἀνάλογον αἱ ΝΞ, ΞΔ. πλειόνων
 οὖν οὕτως καὶ συνεχῶν παραλλήλων ἐκβληθεισῶν
 μεταξὺ τῶν Β, Δ καὶ ταῖς ἀπολαμβανομέναις
 ὑπ' αὐτῶν περιφερείαις πρὸς τῷ Β ἴσων τεθεισῶν
 ἀπὸ τοῦ Β ὡς ἐπὶ τὸ Γ καὶ ἐπὶ τὰ γενάμενα σημεῖα
 ἐπιζευχθεισῶν εὐθειῶν ἀπὸ τοῦ Δ, ὡς τῶν ὁμοίων
 ταῖς ΔΕ, ΔΜ, τμηθήσονται αἱ παράλληλοι αἱ
 μεταξὺ τῶν Β, Δ κατὰ τινα σημεῖα, ἐπὶ τῆς
 προκειμένης καταγραφῆς τὰ Ο, Θ, ἐφ' ᾧ κανόνος
 παραθέσει ἐπιζεύξαντες εὐθείας ἕξομεν καταγε-

SPECIAL PROBLEMS

And $\Delta K = \Gamma H, KE = ZH, K\Gamma = H\Delta$;

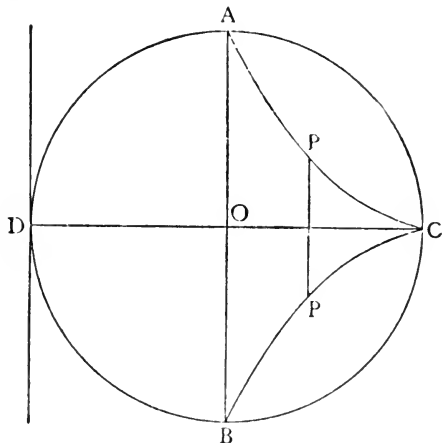
therefore $\Gamma H : HZ = ZH : H\Delta = \Delta H : H\Theta$.

If then on either side of B there be cut off equal arcs MB, BN, and NΞ be drawn through N parallel to AB, and ΔM be joined, NΞ, ΞΔ, will again be mean proportionals between ΓΞ, ΞO. If in this way more parallels are drawn continually between B, Δ, and arcs equal to the arcs cut off between them and B are marked off from B in the direction of Γ, and straight lines are drawn from Δ to the points so obtained, such as ΔE, ΔM, the parallels between B and Δ will be cut in certain points, such as O, Θ in the accompanying figure. Joining these points with straight lines by applying a ruler we shall describe in the

GREEK MATHEMATICS

γραμμένην ἐν τῷ κύκλῳ τινὰ γραμμὴν, ἐφ' ἧς εἰς ληφθῆ τυχὸν σημεῖον καὶ δι' αὐτοῦ παράλληλος ἀχθῆ τῇ AB , ἔσται ἡ ἀχθεῖσα καὶ ἡ ἀπολαμβανομένη ὑπ' αὐτῆς ἀπὸ τῆς διαμέτρου πρὸς τῷ Δ μέσαι ἀνάλογον τῆς τε ἀπολαμβανομένης ὑπ' αὐτῆς ἀπὸ τῆς διαμέτρου πρὸς τῷ Γ σημείῳ καὶ τοῦ μέρους αὐτῆς τοῦ ἀπὸ τοῦ ἐν τῇ γραμμῇ σημείου ἐπὶ τὴν $\Gamma\Delta$ διάμετρον.

Τούτων προκατεσκευασμένων ἔστωσαν αἱ δο-



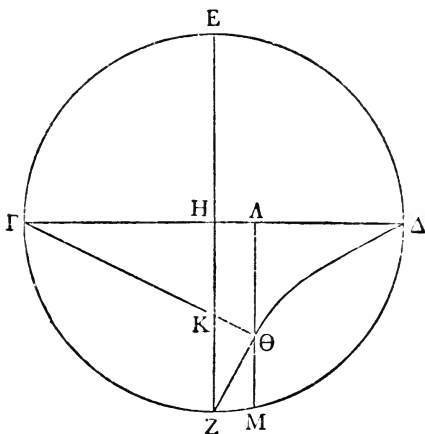
small straight lines, a typical Greek conception which has all the power of a theory of infinitesimals while avoiding its logical fallacies. The Greeks were never so modern as in this conception.

The curve described by Diocles has two branches, sym-

SPECIAL PROBLEMS

circle a certain curve,^a and if on this any point be taken at random, and through it a straight line be drawn parallel to ΛB , the line so drawn and the portion of the diameter cut off by it in the direction of Δ will be mean proportionals between the portion of the diameter cut off by it in the direction of the point Γ and the part of the parallel itself between the point on the curve and the diameter $\Gamma\Delta$.

With this preliminary construction, let the two



A
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B
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E
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N
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GREEK MATHEMATICS

θεῖσαι δύο εὐθεῖαι, ὧν δεῖ δύο μέσας ἀνάλογον εὐρεῖν, αἱ A, B , καὶ ἔστω κύκλος, ἐν ᾧ δύο διαμέτροι πρὸς ὀρθὰς ἀλλήλαις αἱ $\Gamma\Delta, EZ$, καὶ γεγράφθω ἐν αὐτῷ ἡ διὰ τῶν συνεχῶν σημείων γραμμὴ, ὡς προεῖρηται, ἡ $\Delta\Theta Z$, καὶ γεγονέτω, ὡς ἡ A πρὸς τὴν B , ἡ $\Gamma\eta$ πρὸς $\eta\kappa$, καὶ ἐπιζευχθεῖσα ἡ $\Gamma\kappa$ καὶ ἐκβληθεῖσα τεμνέτω τὴν γραμμὴν κατὰ τὸ Θ , καὶ διὰ τοῦ Θ τῇ EZ παράλληλος ἦχθω ἡ ΛM . διὰ ἄρα τὰ προγεγραμμένα τῶν $\Gamma\Lambda, \Lambda\Theta$ μέσαι ἀνάλογόν εἰσιν αἱ $M\Lambda, \Lambda\Delta$. καὶ ἐπεὶ ἔστιν, ὡς ἡ $\Gamma\Lambda$ πρὸς $\Lambda\Theta$, οὕτως ἡ $\Gamma\eta$ πρὸς $\eta\kappa$, ὡς δὲ ἡ $\Gamma\eta$ πρὸς $\eta\kappa$, οὕτως ἡ A πρὸς τὴν B , ἐὰν ἐν τῷ αὐτῷ λόγῳ ταῖς $\Gamma\Lambda, \Lambda M, \Lambda\Delta, \Lambda\Theta$ παρεμβάλωμεν μέσας τῶν A, B , ὡς τὰς N, Ξ , ἔσονται εἰλημμέναι τῶν A, B μέσαι ἀνάλογον αἱ N, Ξ . ὅπερ ἔδει εὐρεῖν.

Ibid. 78. 13-80. 24

Ὡς Μέναιχμος

Ἔστωσαν αἱ δοθεῖσαι δύο εὐθεῖαι αἱ A, E . δεῖ δὴ τῶν A, E δύο μέσας ἀνάλογον εὐρεῖν.

Γεγονέτω, καὶ ἔστωσαν αἱ B, Γ , καὶ ἐκκείσθω θέσει εὐθεῖα ἡ $\Delta\eta$ πεπερασμένη κατὰ τὸ Δ , καὶ πρὸς τῷ Δ τῇ Γ ἴση κείσθω ἡ ΔZ , καὶ ἦχθω πρὸς ὀρθὰς ἡ $Z\Theta$, καὶ τῇ B ἴση κείσθω ἡ $Z\Theta$. ἐπεὶ οὖν τρεῖς εὐθεῖαι ἀνάλογον αἱ A, B, Γ , τὸ ὑπὸ τῶν A, Γ ἴσον ἐστὶ τῷ ἀπὸ τῆς B . τὸ ἄρα ὑπὸ

metrical about the diameter CD in the accompanying figure, and proceeding to infinity. There is a cusp at C and the tangent to the circle at D is an asymptote. If OC is the axis of x , and OA the axis of y , while the radius of the circle is a , then by definition the Cartesian equation of the curve is

SPECIAL PROBLEMS

given straight lines, between which it is required to find two mean proportionals, be A, B , and let there be a circle in which $\Gamma\Delta, EZ$ are two diameters at right angles to each other, and let there be drawn in it through the successive points a curve $\Delta\Theta Z$, in the aforesaid manner, and let $A : B = \Gamma H : HK$, and let Γ, K be joined, and let the straight line joining them be produced so as to cut the line in Θ , and through Θ let ΛM be drawn parallel to EZ ; therefore by what has been written previously $M\Lambda, \Lambda\Delta$ are mean proportionals between $\Gamma\Lambda, \Lambda\Theta$. And since $\Gamma\Lambda : \Lambda\Theta = \Gamma H : HK$ and $\Gamma H : HK = A : B$, if between A, B we place means N, Ξ in the same ratio as $\Gamma\Lambda, \Lambda M, \Lambda\Delta, \Lambda\Theta$,^a then N, Ξ will be mean proportionals between A, B ; which was to be found.

Ibid. 78. 13-80. 24

(iv.) *The Solutions of Menaechmus*

Let the two given straight lines be A, E ; it is required to find two mean proportionals between A, E .

Assume it done, and let the means be B, Γ , and let there be placed in position a straight line ΔH , with an end point Δ , and at Δ let ΔZ be placed equal to Γ , and let $Z\Theta$ be drawn at right angles and let $Z\Theta$ be equal to B . Since the three straight lines A, B, Γ are in proportion, $A.\Gamma = B^2$; therefore the rectangle com-

$$\frac{a+x}{\sqrt{a^2-x^2}} = \frac{a-x}{y} \text{ or } y^2(a+x) = (a-x)^2.$$

The curve was called by the Greeks the *cissoïd* (*κισσοειδής γραμμή*) because the portion within the circle reminded them of a leaf of ivy (*κισσός*).

^a *i.e.*, if we take $\Gamma\Lambda : \Lambda M = A : N$, $\Lambda M : \Lambda\Delta = N : \Xi$ and $\Lambda\Delta : \Lambda\Theta = \Xi : B$.

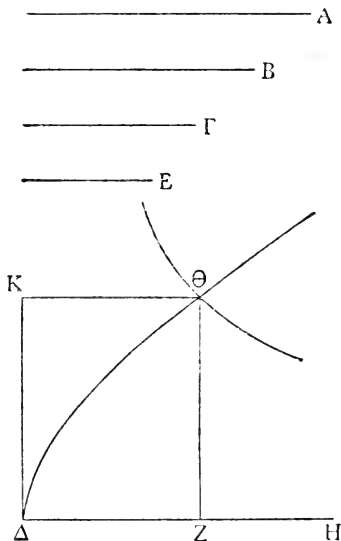
GREEK MATHEMATICS

δοθείσης τῆς A καὶ τῆς Γ , τουτέστι τῆς ΔZ , ἴσον ἐστὶ τῷ ἀπὸ τῆς B , τουτέστι τῷ ἀπὸ τῆς $Z\Theta$. ἐπὶ παραβολῆς ἄρα τὸ Θ διὰ τοῦ Δ γεγραμμένης. ἤχθωσαν παράλληλοι αἱ ΘK , ΔK . καὶ ἐπεὶ δοθὲν τὸ ὑπὸ B , Γ —ἴσον γάρ ἐστι τῷ ὑπὸ A , E —δοθὲν ἄρα καὶ τὸ ὑπὸ $K\Theta Z$. ἐπὶ ὑπερβολῆς ἄρα τὸ Θ ἐν ἀσυμπτώτοις ταῖς $K\Delta$, ΔZ . δοθὲν ἄρα τὸ Θ . ὥστε καὶ τὸ Z .

Συντεθήσεται δὴ οὕτως. ἔστωσαν αἱ μὲν δοθεῖσαι εὐθεῖαι αἱ A , E , ἣ δὲ τῇ θέσει ἡ ΔH πεπερασμένη κατὰ τὸ Δ , καὶ γεγράφθω διὰ τοῦ Δ

SPECIAL PROBLEMS

prehended by the given straight line A and the straight line Γ , that is, ΔZ , is equal to the square on



B , that is, to the square on $Z\theta$. Therefore θ is on a parabola drawn through Δ . Let the parallels θK , ΔK be drawn. Then since the rectangle $B \cdot \Gamma$ is given—for it is equal to the rectangle $A \cdot E$ —the rectangle $K\theta \cdot \theta Z$ is given. The point θ is therefore on a hyperbola with asymptotes $K\Delta$, ΔZ . Therefore θ is given; and so also is Z .

Let the synthesis be made in this manner. Let the given straight lines be A , E , let ΔH be a straight line given in position with an end point at Δ , and let

GREEK MATHEMATICS

παραβολή, ἣς ἄξων μὲν ἡ ΔΗ, ὀρθία δὲ τοῦ εἶδους
 πλευρὰ ἡ Α, αἱ δὲ καταγόμεναι ἐπὶ τὴν ΔΗ ἐν
 ὀρθῇ γωνίᾳ δυνάσθωσαν τὰ παρὰ τὴν Α παρα-
 κείμενα χωρία πλάτη ἔχοντα τὰς ἀπολαμβανο-
 μένας ὑπ' αὐτῶν πρὸς τῷ Δ σημείῳ. γεγράφθω
 καὶ ἔστω ἡ ΔΘ, καὶ ὀρθῇ ἡ ΔΚ, καὶ ἐν ἀσυμπτώτοις
 ταῖς ΚΔ, ΔΖ γεγράφθω ὑπερβολή, ἀφ' ἣς αἱ παρὰ
 τὰς ΚΔ, ΔΖ ἀχθείσαι ποιήσουσιν τὸ χωρίον ἴσον
 τῷ ὑπὸ Α, Ε· τεμεί δὴ τὴν παραβολὴν. τεμνέτω
 κατὰ τὸ Θ, καὶ κάθετοι ἤχθωσαν αἱ ΘΚ, ΘΖ.
 ἐπεὶ οὖν τὸ ἀπὸ ΖΘ ἴσον ἐστὶ τῷ ὑπὸ Α, ΔΖ,
 ἔστιν, ὡς ἡ Α πρὸς τὴν ΖΘ, ἡ ΘΖ πρὸς ΖΔ.
 πάλιν, ἐπεὶ τὸ ὑπὸ Α, Ε ἴσον ἐστὶ τῷ ὑπὸ ΘΖΔ,
 ἔστιν, ὡς ἡ Α πρὸς τὴν ΖΘ, ἡ ΖΔ πρὸς τὴν Ε.
 ἀλλ' ὡς ἡ Α πρὸς τὴν ΖΘ, ἡ ΖΘ πρὸς ΖΔ· καὶ
 ὡς ἄρα ἡ Α πρὸς τὴν ΖΘ, ἡ ΖΘ πρὸς ΖΔ καὶ ἡ
 ΖΔ πρὸς Ε. κείσθω τῇ μὲν ΘΖ ἴση ἡ Β, τῇ δὲ
 ΔΖ ἴση ἡ Γ. ἔστιν ἄρα, ὡς ἡ Α πρὸς τὴν Β, ἡ
 Β πρὸς τὴν Γ καὶ ἡ Γ πρὸς Ε. αἱ Α, Β, Γ, Ε
 ἄρα ἐξῆς ἀνάλογόν εἰσιν· ὅπερ ἔδει εὐρεῖν.

SPECIAL PROBLEMS

there be drawn through Δ a parabola whose axis is ΔH , and *latus rectum* A , and let the squares of the ordinates drawn at right angles to ΔH be equal to the areas applied to A having as their sides the straight lines cut off by them towards Δ . Let it be drawn, and let it be $\Delta\theta$, and let ΔK be perpendicular [to ΔH], and in the asymptotes $K\Delta$, ΔZ let there be drawn a hyperbola, such that the straight lines drawn parallel to $K\Delta$, ΔZ will make an area equal to the rectangle comprehended by A , E . It will then cut the parabola. Let it cut at θ , and let θK , θZ be drawn perpendicular. Since then

$$Z\theta^2 = A \cdot \Delta Z,$$

it follows that

$$A : Z\theta = \theta Z : Z\Delta.$$

Again, since $A \cdot E = \theta Z \cdot Z\Delta$,

it follows that

$$A : Z\theta = Z\Delta : E.$$

But $A : Z\theta = Z\theta : Z\Delta$.

Therefore $A : Z\theta = Z\theta : Z\Delta = Z\Delta : E$.

Let B be placed equal to θZ , and Γ equal to ΔZ . It follows that

$$A : B = B : \Gamma = \Gamma : E.$$

A , B , Γ , E are therefore in continuous proportion : which was to be found.^a

^a If a , x , y , b are in continuous proportion,

$$\frac{a}{x} = \frac{x}{y} = \frac{y}{b}, \text{ and } x^2 = ay, y^2 = bx, xy = ab.$$

Therefore x , y may be determined as the intersection of the parabola $y^2 = bx$ and the hyperbola $xy = ab$. This is the

GREEK MATHEMATICS

Ibid. 84. 12-88. 2

Ἡ Ἀρχύτου εὕρησις, ὡς Εὐδήμος ἱστορεῖ

Ἔστωσαν αἱ δοθεῖσαι δύο εὐθείαι αἱ ΑΔ, Γ·
δεῖ δὴ τῶν ΑΔ, Γ δύο μέσας ἀνάλογον εὑρεῖν.

Γεγράφθω περὶ τὴν μείζονα τὴν ΑΔ κύκλος
ὁ ΑΒΔΖ, καὶ τῇ Γ ἴση ἐνηρμόσθω ἡ ΑΒ καὶ ἐκβλη-
θεῖσα συμπιπτέτω τῇ ἀπὸ τοῦ Δ ἐφαπτομένη τοῦ
κύκλου κατὰ τὸ Π, παρὰ δὲ τὴν ΠΔΟ ἤχθω ἡ

analytical expression of the solution given above, where $E=a$ and $A=b$. Menaechmus gave a second solution, reproduced by Eutocius, determining x, y as the intersection of the parabolas $x^2 = ay, y^2 = bx$.

This is the earliest known use of conic sections in the history of Greek mathematics, and Menaechmus is accordingly credited with their discovery. But the names parabola and hyperbola were not used by him; they are due to Apollonius; Menaechmus would have called them, with Archimedes, sections of a right-angled and obtuse-angled cone.

From the equations given above it follows that

$$x^2 + y^2 - bx - ay = 0$$

is a circle passing through the points common to the parabolas

$$x^2 = ay, y^2 = bx.$$

It follows that x, y may be determined by the intersection of this circle with the hyperbola $xy = ab$.

This is, in effect, the proof given by Heron, Philon and Apollonius. For, in the figure on p. 269, if $\Delta Z, \Delta E$ are the co-ordinate axes, $AB = a, B\Gamma = b$, then $x^2 + y^2 - bx - ay = 0$ is the circle passing through A, B, Γ , and $xy = ab$ is the hyperbola having $\Delta Z, \Delta E$ as asymptotes and passing through B .

GREEK MATHEMATICS

ΒΕΖ, καὶ νενοήσθω ἡμικυλίνδριον ὀρθὸν ἐπὶ τοῦ
 ΑΒΔ ἡμικυκλίου, ἐπὶ δὲ τῆς ΑΔ ἡμικύκλιον ὀρθὸν
 ἐν τῷ τοῦ ἡμικυλινδρίου παραλληλογράμμῳ κεί-
 μενον· τοῦτο δὴ τὸ ἡμικύκλιον περιαγόμενον ὡς
 ἀπὸ τοῦ Δ ἐπὶ τὸ Β μένοντος τοῦ Α πέρατος τῆς
 διαμέτρου τεμεῖ τὴν κυλινδρικήν ἐπιφάνειαν ἐν
 τῇ περιαγωγῇ καὶ γράφει ἐν αὐτῇ γραμμὴν τινα.
 πάλιν δέ, ἐὰν τῆς ΑΔ μενούσης τὸ ΑΠΔ τρίγωνον
 περιενεχθῇ τὴν ἐναντίαν τῷ ἡμικυκλίῳ κίνησιν,
 κωνικὴν ποιήσει ἐπιφάνειαν τῇ ΑΠ εὐθείᾳ, ἣ δὴ
 περιαγομένη συμβαλεῖ τῇ κυλινδρικῇ γραμμῇ κατὰ
 τι σημεῖον· ἅμα δὲ καὶ τὸ Β περιγράφει ἡμικύκλιον
 ἐν τῇ τοῦ κώνου ἐπιφανείᾳ. ἐχέτω δὴ θέσιν κατὰ
 τὸν τόπον τῆς συμπτώσεως τῶν γραμμῶν τὸ μὲν
 κινούμενον ἡμικύκλιον ὡς τὴν τοῦ ΔΚΑ, τὸ δὲ
 ἀντιπεριαγόμενον τρίγωνον τὴν τοῦ ΔΛΑ, τὸ δὲ
 τῆς εἰρημένης συμπτώσεως σημεῖον ἔστω τὸ Κ,
 ἔστω δὲ καὶ διὰ τοῦ Β γραφόμενον ἡμικύκλιον τὸ
 ΒΜΖ, κοινὴ δὲ αὐτοῦ τομὴ καὶ τοῦ ΒΔΖΑ κύκλου
 ἔστω ἡ ΒΖ, καὶ ἀπὸ τοῦ Κ ἐπὶ τὸ τοῦ ΒΔΑ
 ἡμικυκλίου ἐπίπεδον κάθετος ἤχθω· πεσεῖται δὴ
 ἐπὶ τὴν τοῦ κύκλου περιφέρειαν διὰ τὸ ὀρθὸν
 ἐστάναι τὸν κύλινδρον. πιπτέτω καὶ ἔστω ἡ ΚΙ,
 καὶ ἡ ἀπὸ τοῦ Ι ἐπὶ τὸ Α ἐπιζευχθεῖσα συμβαλέτω
 τῇ ΒΖ κατὰ τὸ Θ, ἣ δὲ ΑΛ τῷ ΒΜΖ ἡμικυκλίῳ
 κατὰ τὸ Μ, ἐπεζεύχθωσαν δὲ καὶ αἱ ΚΔ, ΜΙ, ΜΘ.
 ἐπεὶ οὖν ἐκάτερον τῶν ΔΚΑ, ΒΜΖ ἡμικυκλίων
 ὀρθὸν ἐστὶ πρὸς τὸ ὑποκείμενον ἐπίπεδον, καὶ ἡ
 κοινὴ ἄρα αὐτῶν τομὴ ἡ ΜΘ πρὸς ὀρθάς ἐστὶ τῷ
 τοῦ κύκλου ἐπιπέδῳ· ὥστε καὶ πρὸς τὴν ΒΖ
 ὀρθή ἐστὶν ἡ ΜΘ. τὸ ἄρα ὑπὸ τῶν ΒΘΖ, του-

SPECIAL PROBLEMS

and let a right half-cylinder be conceived upon the semicircle $AB\Delta$, and on $A\Delta$ a right semicircle lying in the parallelogram of the half-cylinder. When this semicircle is moved about from Δ to B , the end point A of the diameter remaining fixed, it will cut the cylindrical surface in its motion and will describe in it a certain curve. Again, if $A\Delta$ be kept stationary and the triangle $A\Pi\Delta$ be moved about with an opposite motion to that of the semicircle, it will make a conic surface by means of the straight line $A\Pi$, which in its motion will meet the curve on the cylinder in a certain point; at the same time B will describe a semicircle on the surface of the cone. Corresponding to the point in which the curves meet let the moving semicircle take up a position $\Delta'KA$,^a and the triangle moved in the opposite direction a position $\Delta\Lambda A$; let the point of the aforesaid meeting be K , and let BMZ be the semicircle described through B , and let BZ be the section common to it and the circle $B\Delta ZA$, and let there be drawn from K a perpendicular upon the plane of the semicircle $B\Delta A$; it will fall upon the circumference of the circle because the cylinder is right. Let it fall, and let it be KI , and let the straight line joining I to A meet BZ in Θ ; let ΛA meet the semicircle BMZ in M , and let $K\Delta$, MI , $M\Theta$ be joined. Therefore since each of the semicircles $\Delta'KA$, BMZ is at right angles to the underlying plane, their common section $M\Theta$ is also at right angles to the plane of the circle; so that $M\Theta$ is also at right angles to BZ . Therefore the rectangle contained by

^a In the text and figure of the mss. the same letter is used to indicate the initial and final positions of Δ ; for convenience they are distinguished in the figure and translation as Δ , Δ' . It would make the figure easier to grasp if Λ could be written Π' (for Λ is the final position of Π).

GREEK MATHEMATICS

τέστι τὸ ὑπὸ ΑΘΙ, ἴσον ἐστὶ τῷ ἀπὸ ΜΘ· ὁμοιον ἄρα ἐστὶ τὸ ΛΜΙ τρίγωνον ἑκατέρω τῶν ΜΙΘ, ΜΑΘ, καὶ ὀρθὴ ἢ ὑπὸ ΙΜΑ. ἔστιν δὲ καὶ ἡ ὑπὸ ΔΚΑ ὀρθή. παράλληλοι ἄρα εἰσὶν αἱ ΚΔ, ΜΙ, καὶ ἔσται ἀνάλογον, ὡς ἡ ΔΑ πρὸς ΑΚ, τουτέστιν ἡ ΚΑ πρὸς ΑΙ, οὕτως ἡ ΙΑ πρὸς ΑΜ, διὰ τὴν ὁμοιότητα τῶν τριγώνων. τέσσαρες ἄρα αἱ ΔΑ, ΑΚ, ΑΙ, ΑΜ ἐξῆς ἀνάλογόν εἰσιν. καὶ ἐστὶν ἡ ΑΜ ἴση τῇ Γ, ἐπεὶ καὶ τῇ ΑΒ· δύο ἄρα δοθεισῶν τῶν ΑΔ, Γ δύο μέσαι ἀνάλογον ἠϋρηνται αἱ ΑΚ, ΑΙ.

^a The above solution is a remarkable achievement when it is remembered that Archytas flourished in the first half of the fourth century B.C., at which time Greek geometry was still in its infancy. It is quite easy, however, for us to represent the solution analytically. If $\Delta\Delta$ is taken as the axis of x , the perpendicular to $\Delta\Delta$ at A in the plane of the paper as the axis of y , and the perpendicular to these lines as the axis of z , and if $\Delta\Delta = a$, $\Gamma = b$, then the point K is determined as the intersection of the following three curves :

(1) The cylinder $x^2 + y^2 = ax$,

(2) the curve formed by the motion of the half-circle about A (a torc of inner diameter nil)

$$x^2 + y^2 + z^2 = a\sqrt{x^2 + y^2},$$

(3) the cone $x^2 + y^2 + z^2 = \frac{a^2}{b^2}x^2$.

SPECIAL PROBLEMS

$B\theta, \theta Z$, which is the same as the rectangle contained by $A\theta, \theta I$, is equal to the square on $M\theta$; therefore the triangle AMI is similar to each of the triangles $M\theta, MA\theta$, and the angle IMA is right. The angle $\Delta'KA$ is also right. Therefore $K\Delta', MI$ are parallel, and owing to the similarity of the triangles the following proportion holds :

$$\Delta'A : AK = KA : AI = IA : AM.$$

Therefore the four straight lines $\Delta A, AK, AI, AM$ are in continuous proportion. And AM is equal to Γ , since it is equal to AB ; therefore to the two given straight lines $A\Delta, \Gamma$, two mean proportionals, AK, AI , have been found.^a

Since K is the point of intersection,

$$AK = \sqrt{x^2 + y^2 + z^2}, \quad AI = \sqrt{x^2 + y^2}.$$

From (2) it follows directly that

$$AK^2 = a \cdot AI$$

i.e.,

$$\frac{a}{AK} = \frac{AK}{AI}.$$

From (1) and (3) it follows that

$$x^2 + y^2 + z^2 = \frac{(x^2 + y^2)^2}{b^2}$$

$$\therefore \sqrt{x^2 + y^2 + z^2} = \frac{x^2 + y^2}{b}$$

i.e.,

$$AK = \frac{AI^2}{b}$$

or

$$\frac{AK}{AI} = \frac{AI}{b}$$

$$\therefore \frac{a}{AK} = \frac{AK}{AI} = \frac{AI}{b},$$

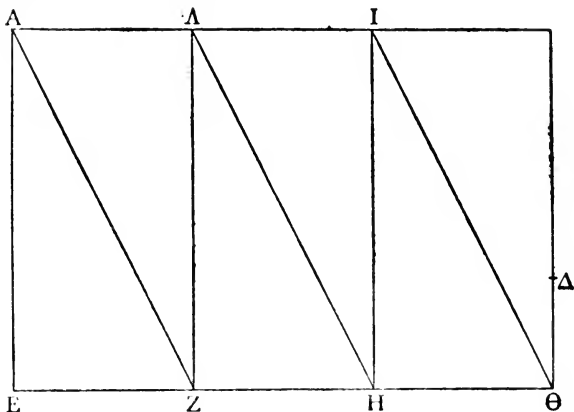
and AK, AI are mean proportionals between a and b .

GREEK MATHEMATICS

Ibid. 88. 3-96. 27

Ὡς Ἐρατοσθένης . . .

Δεδόσθωσαν δύο ἄνισοι εὐθείαι, ὧν δεῖ δύο μέσας ἀνάλογον εὑρεῖν ἐν συνεχεί ἀναλογία, αἱ ΑΕ, ΔΘ, καὶ κείσθω ἐπὶ τινος εὐθείας τῆς ΕΘ



πρὸς ὀρθὰς ἢ ΑΕ, καὶ ἐπὶ τῆς ΕΘ τρία συνεστάτω παραλληλόγραμμα ἐφεξῆς τὰ ΑΖ, ΖΙ, ΙΘ, καὶ ἤχθωσαν διάμετροι ἐν αὐτοῖς αἱ ΑΖ, ΛΗ, ΙΘ· ἔσονται δὴ αὐταὶ παράλληλοι. μένοντος δὴ τοῦ μέσου παραλληλογράμμου τοῦ ΖΙ συνωσθήτω τὸ μὲν ΑΖ ἐπάνω τοῦ μέσου, τὸ δὲ ΙΘ ὑποκάτω, καθάπερ ἐπὶ τοῦ δευτέρου σχήματος, ἕως οὗ γένηται τὰ Α, Β, Γ, Δ κατ' εὐθείαν, καὶ διήχθω διὰ τῶν Α, Β, Γ, Δ σημείων εὐθεῖα καὶ συμπιπέτω τῇ ΕΘ ἐκβληθείση κατὰ τὸ Κ· ἔσται δὴ, ὡς ἢ ΑΚ πρὸς ΚΒ, ἐν μὲν ταῖς ΑΕ, ΖΒ παραλλ-

SPECIAL PROBLEMS

Ibid. 88. 3-96. 27^a

(vi.) *The Solution of Eratosthenes . . .*

Let there be given two unequal straight lines AE, ΔΘ between which it is required to find two mean proportionals in continued proportion, and let AE be placed at right angles to the straight line EΘ, and upon EΘ let there be erected three successive parallelograms^b AZ, ZI, IΘ, and let the diagonals AZ, ΔH, IΘ be drawn therein; these will be parallel. While the middle parallelogram ZI remains stationary, let the other two approach each other, AZ above the middle one, IΘ below it, as in the second figure,^c until A, B, Γ, Δ lie along a straight line, and let a straight line be drawn through the points A, B, Γ, Δ, and let it meet EΘ produced in K; it will follow that in the parallels AE, ZB

$$AK : KB = EK : KZ$$

^a This is the letter falsely purporting to be by Eratosthenes of which the beginning has already been cited, *supra*, pp. 256-261. The extract here given (δεδόσθωσαν . . .) starts in Heiberg's text at 90. 30. Eratosthenes' solution is given, with variations, by Pappus, *Collection* iii. 7, ed. Hultsch 56. 18-58. 22.

^b Pappus says triangles in his account; it makes no difference.

^c See p. 294.

GREEK MATHEMATICS

λήλοις ἢ ΕΚ πρὸς ΚΖ, ἐν δὲ ταῖς ΑΖ, ΒΗ παραλλήλοις ἢ ΖΚ πρὸς ΚΗ. ὡς ἄρα ἢ ΑΚ πρὸς ΚΒ, ἢ ΕΚ πρὸς ΚΖ καὶ ἢ ΚΖ πρὸς ΚΗ. πάλιν, ἐπεὶ ἔστιν, ὡς ἢ ΒΚ πρὸς ΚΓ, ἐν μὲν ταῖς ΒΖ, ΓΗ παραλλήλοις ἢ ΖΚ πρὸς ΚΗ, ἐν δὲ ταῖς ΒΗ, ΓΘ παραλλήλοις ἢ ΗΚ πρὸς ΚΘ, ὡς ἄρα ἢ ΒΚ πρὸς ΚΓ, ἢ ΖΚ πρὸς ΚΗ καὶ ἢ ΗΚ πρὸς ΚΘ. ἀλλ' ὡς ἢ ΖΚ πρὸς ΚΗ, ἢ ΕΚ πρὸς ΚΖ· καὶ ὡς ἄρα ἢ ΕΚ πρὸς ΚΖ, ἢ ΖΚ πρὸς ΚΗ καὶ ἢ ΗΚ πρὸς ΚΘ. ἀλλ' ὡς ἢ ΕΚ πρὸς ΚΖ, ἢ ΑΕ πρὸς ΒΖ, ὡς δὲ ἢ ΖΚ πρὸς ΚΗ, ἢ ΒΖ πρὸς ΓΗ, ὡς δὲ ἢ ΗΚ πρὸς ΚΘ, ἢ ΓΗ πρὸς ΔΘ· καὶ ὡς ἄρα ἢ ΑΕ πρὸς ΒΖ, ἢ ΒΖ πρὸς ΓΗ καὶ ἢ ΓΗ πρὸς ΔΘ. ἠϋρηνται ἄρα τῶν ΑΕ, ΔΘ δύο μέσαι ἢ τε ΒΖ καὶ ἢ ΓΗ.

Ταῦτα οὖν ἐπὶ τῶν γεωμετρούμενων ἐπιφανειῶν ἀποδέδεικται· ἵνα δὲ καὶ ὀργανικῶς δυνώμεθα τὰς δύο μέσας λαμβάνειν, διαπήγνυται πλινθίον ξύλινον ἢ ἐλεφάντινον ἢ χαλκοῦν ἔχον τρεῖς πινακίσκους ἴσους ὡς λεπτοτάτους, ὧν ὁ μὲν μέσος ἐνήρμοσται, οἱ δὲ δύο ἐπωστοί εἰσιν ἐν χολέδραις, τοῖς δὲ μεγέθεσιν καὶ ταῖς συμμετρίαις ὡς ἕκαστοι ἑαυτοὺς πείθουσιν· τὰ μὲν γὰρ τῆς ἀποδείξεως ὡσαύτως συντελεῖται· πρὸς δὲ τὸ ἀκριβέστερον λαμβάνεσθαι τὰς γραμμὰς φιλοτεχνητέον, ἵνα ἐν τῷ συνάγεσθαι τοὺς πινακίσκους παράλληλα διαμένη πάντα καὶ ἄσχεστα καὶ ὁμαλῶς συναπτόμενα ἀλλήλοις.

Ἐν δὲ τῷ ἀναθήματι τὸ μὲν ὀργανικὸν χαλκοῦν ἔστιν καὶ καθήρμοσται ὑπ' αὐτὴν τὴν στεφάνην τῆς στήλης προσμεμολυβδοχοημένον, ὑπ' αὐτοῦ δὲ ἢ ἀπόδειξις συντομώτερον φραζομένη καὶ τὸ σχῆμα,

SPECIAL PROBLEMS

and in the parallels AZ, BH

$$AK : KB = ZK : KH.$$

Therefore $AK : KB = EK : KZ = KZ : KH.$

Again, since in the parallels BZ, ΓH

$$BK : KΓ = ZK : KH$$

and in the parallels BH, ΓΘ

$$BK : KΓ = HK : KΘ,$$

therefore $BK : KΓ = ZK : KH = HK : KΘ.$

But $ZK : KH = EK : KZ$, and therefore

$$EK : KZ = ZK : KH = HK : KΘ.$$

But $EK : KZ = AE : BZ$, $ZK : KH = BZ : ΓH$,
 $HK : KΘ = ΓH : ΔΘ.$

Therefore $AE : BZ = BZ : ΓH = ΓH : ΔΘ.$

Therefore between AE, ΔΘ two means, BZ, ΓH, have been found.

Such is the demonstration on geometrical surfaces; and in order that we may find the two means mechanically, a board of wood or ivory or bronze is pierced through, having on it three equal tablets, as smooth as possible, of which the midmost is fixed and the two outside run in grooves, their sizes and proportions being a matter of individual choice—for the proof is accomplished in the same manner; in order that the lines may be found with the greatest accuracy, the instrument must be skilfully made, so that when the tablets are moved everything remains parallel, smoothly fitting without a gap.

In the votive gift the instrument is of bronze and is fastened on with lead close under the crown of the pillar, and beneath it is a shortened form of the proof

SPECIAL PROBLEMS

and the figure, and along with this is an epigram. These also shall be written below for you, in order that you may have what is on the votive gift. Of the two figures, the second is that which is inscribed on the pillar.^a

“Between two given straight lines to find two means in continuous proportion. Let $AE, \Delta\theta$ be the given straight lines. Then I move the tables in the instrument until the points A, B, Γ, Δ are in the same straight line. Let this be pictured as in the second figure. Then $AK : KB$ is equal, in the parallels AE, BZ , to $EK : KZ$, and in the parallels AZ, BH to $ZK : KH$; therefore $EK : KZ = KZ : KH$. Now this is also the ratio $AE : BZ$ and $BZ : \Gamma H$. Similarly we shall show that $ZB : \Gamma H = \Gamma H : \Delta\theta$; $AE, BZ, \Gamma H, \Delta\theta$ are therefore proportional. Between the two given straight lines two means have therefore been found.

“If the given straight lines are not equal to $AE, \Delta\theta$, by making $AE, \Delta\theta$ proportional to them and taking the means between these and then going back to the original lines, we shall do what was enjoined. If it is required to find more means, we shall continually insert more tables in the instrument according to the number of means to be taken; and the proof is the same.

^a The short proof and epigram which follow are presumably the genuine work of Eratosthenes, being taken from the votive gift. The reference to the *second* figure cannot, however, be genuine as there was only one figure on the votive offering; perhaps $\delta\epsilon\acute{\upsilon}\tau\epsilon\rho\omicron\nu$ should be omitted.

GREEK MATHEMATICS

“ Εἰ κύβον ἐξ ὀλίγου διπλήσιον, ὦγαθε, τεύχειν
 φράζεαι ἢ στερεὴν πᾶσαν ἐς ἄλλο φύσιν
 εὖ μεταμορφῶσαι, τόδε τοι πάρα, κἂν σύ γε
 μάνδρην
 ἢ σιρὸν ἢ κοίλου φρεΐατος εὐρὸν κύτος
 τῆδ’ ἀναμετρήσαιο, μέσας ὅτε τέρμασιν ἄκροισ
 συνδρομάδας δισσωὼν ἐντὸς ἔλης κανόνων.
 μηδὲ σύ γ’ Ἀρχύτεω δυσμήχανα ἔργα κυλίνδρων
 μηδὲ Μεναιχμείους κωνοτομεῖν τριάδας
 διζήση, μηδ’ εἴ τι θεουδέος Εὐδόξοιο
 καμπύλοι ἐγ γραμμαῖς εἶδος ἀναγράφεται.
 τοῖσδε γὰρ ἐν πινάκεσσι μεσόγραφα μυρία τεύχους
 ρεῖά κεν ἐκ παύρου πυθμένος ἀρχόμενος.
 εὐαίων, Πτολεμαῖε, πατήρ ὅτι παιδὶ συνηβῶν
 πάνθ’, ὅσα καὶ Μούσαις καὶ βασιλεῦσι φίλα,
 αὐτὸς ἐδωρήσω· τὸ δ’ ἐς ὕστερον, οὐράνιε Ζεῦ,
 καὶ σκήπτρων ἐκ σῆς ἀντιάσειε χερὸς.
 καὶ τὰ μὲν ὡς τελείοιτο, λέγοι δέ τις ἄνθεμα λεύσ-
 σων
 τοῦ Κυρηναίου τοῦτ’ Ἐρατοσθένους.”

Ibid. 98. 1-7

Ὡς Νικομήδης ἐν τῷ Περὶ κογχοειδῶν γραμμῶν
 Γράφει δὲ καὶ Νικομήδης ἐν τῷ ἐπιγεγραμμένῳ
 πρὸς αὐτοῦ Περὶ κογχοειδῶν συγγράμματι ὄργάνου
 κατασκευὴν τὴν αὐτὴν ἀποπληροῦντος χρεῖαν, ἐφ’
 ᾧ καὶ μεγάλα μὲν σεμννόμενος φαίνεται ὁ ἀνὴρ,
 πολλὰ δὲ τοῖς Ἐρατοσθένους ἐπεγγελῶν εὐρήμασιν

^a Or “ with a small effort,” Heiberg.

^b Perhaps so called because there are three conic sections
 —of an acute-angled, right-angled and obtuse-angled cone

SPECIAL PROBLEMS

“ If, good friend, thou thinkest to produce from a small [cube] ^a one double thereof, or duly to change any solid figure into another nature, this is in thy power, and thou canst measure a byre or corn-pit or the broad basin of a hollow well by this method, when thou takest between two rulers means converging with their extreme ends. Do not seek to do the difficult business of the cylinders of Archytas, or to cut the cone in the triads ^b of Menaechmus, or to produce any such curved form in lines as is described by the divine Eudoxus. Indeed, on these tablets thou couldst easily find a thousand means, beginning from a small base. Happy art thou, O Ptolemy, a father who lives his son's life in all things, in that thou hast given him such things as are dear to the Muses and kings; and in the future, O heavenly Zeus, may he also receive the sceptre from thy hands. May this prayer be fulfilled, and may anyone seeing this votive offering say: This is the gift of Eratosthenes of Cyrene.”

Ibid. 98. 1-7

(vii.) *The Solution of Nicomedes in his Book*
“ *On Conchoidal Lines* ” ^c

Nicomedes also describes, in the book written by him *On Conchoids*, the construction of an instrument fulfilling the same purpose, upon which it appears he prided himself exceedingly, greatly deriding the (ellipse, parabola and hyperbola). If so, this proves that Menaechmus discovered the ellipse as well as the other two.

^c It follows from this extract that Nicomedes was later than Eratosthenes; and as Apollonius called a certain curve “sister of the *cochloid*” (*infra*, p. 334), he must have been younger than Apollonius. He was therefore born about 270 B.C.

GREEK MATHEMATICS

ὡς ἀμηχάνους τε ἄμα καὶ γεωμετρικῆς ἕξεως ἑστερημένοις.

Papp. *Coll.* iv. 26. 39–28. 43, ed. Hultsch 242. 13–250. 25

κς'. Εἰς τὸν διπλασιασμὸν τοῦ κύβου παράγεται τις ὑπὸ Νικομήδους γραμμὴ καὶ γένεσιν ἔχει τοιαύτην.

Ἐκκείσθω εὐθεῖα ἡ AB , καὶ αὐτῇ πρὸς ὀρθὰς ἡ $\Gamma\Delta Z$, καὶ εἰλήφθω τι σημεῖον ἐπὶ τῆς $\Gamma\Delta Z$ δοθὲν τὸ E , καὶ μένοντος τοῦ E σημείου ἐν ω ἔστιν τόπων ἡ $\Gamma\Delta EZ$ εὐθεῖα φερέσθω κατὰ τῆς AB εὐθείας ἔλκομένη διὰ τοῦ E σημείου οὕτως ὥστε διὰ παντὸς φέρεσθαι τὸ Δ ἐπὶ τῆς AB εὐθείας καὶ μὴ ἐκπίπτειν ἔλκομένης τῆς $\Gamma\Delta EZ$ διὰ τοῦ E . τοιαύτης δὴ κινήσεως γενομένης ἐφ' ἑκάτερα φανερόν ὅτι τὸ Γ σημεῖον γράψει γραμμὴν οἷα ἔστιν ἡ $\Lambda\Gamma M$, καὶ ἔστιν αὐτῆς τὸ σύμπτωμα τοιοῦτον. ὡς ἂν εὐθεῖα προσπίπτῃ τις ἀπὸ τοῦ E σημείου πρὸς τὴν γραμμὴν, τὴν ἀπολαμβανομένην μεταξὺ τῆς τε AB εὐθείας καὶ τῆς $\Lambda\Gamma M$ γραμμῆς ἴσην εἶναι τῇ $\Gamma\Delta$ εὐθείᾳ· μενούσης γὰρ τῆς AB καὶ μένοντος τοῦ E σημείου, ὅταν γένηται τὸ Δ ἐπὶ τὸ H , ἡ $\Gamma\Delta$ εὐθεῖα τῇ $H\Theta$ ἐφαρμόσει καὶ τὸ Γ σημεῖον ἐπὶ τὸ Θ (πεσεῖται)¹. ἴση ἄρα ἔστιν ἡ $\Gamma\Delta$ τῇ $H\Theta$. ὁμοίως καὶ ἐὰν ἕτερα τις

¹ πεσεῖται add. Hultsch.

^a Eutocius proceeds to describe Nicomedes' solution; we shall give an alternative account by Pappus.

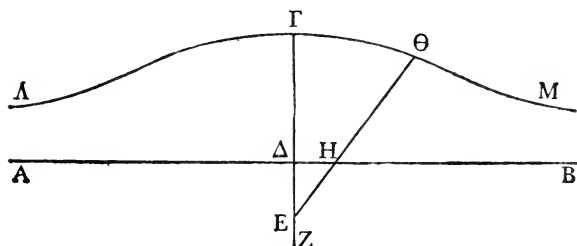
SPECIAL PROBLEMS

discoveries of Eratosthenes as impracticable and lacking in geometrical sense.^a

Pappus, *Collection* iv. 26. 39-28. 43, ed. Hultsch
242. 13-250. 25

26. For the duplication of the cube a certain line is drawn by Nicomedes and generated in this way.

Let there be a straight line AB , with $\Gamma\Delta Z$ at right angles to it, and on $\Gamma\Delta Z$ let there be taken a certain



given point E , and while the point E remains in the same position let the straight line $\Gamma\Delta EZ$ be drawn through the point E and moved about the straight line $A\Delta B$ in such a way that Δ always moves along the straight line AB and does not fall beyond it while $\Gamma\Delta EZ$ is drawn through E . The motion being after this fashion on either side, it is clear that the point Γ will describe a curve such as $\Lambda\Gamma M$, and its property is of this nature: when any straight line drawn from the point E falls upon the curve, the portion cut off between the straight line AB and the curve $\Lambda\Gamma M$ is equal to the straight line $\Gamma\Delta$; for AB is stationary and the point E fixed, and when Δ goes to H , the straight line $\Gamma\Delta$ will coincide with $H\Theta$ and the point Γ will fall upon Θ ; therefore $\Gamma\Delta$ is equal to $H\Theta$.

GREEK MATHEMATICS

ἀπὸ τοῦ Ε σημείου πρὸς τὴν γραμμὴν προσπέση, τὴν ἀποτεμνομένην ὑπὸ τῆς γραμμῆς καὶ τῆς ΑΒ εὐθείας ἴσην ποιήσει τῇ ΓΔ [ἐπειδὴ ταύτη ἴσαι εἰσὶν αἱ προσπίπτουσαι].¹ καλείσθω δέ, φησίν, ἡ μὲν ΑΒ εὐθεῖα κανὼν, τὸ δὲ σημεῖον πόλος, διάστημα δὲ ἡ ΓΔ, ἐπειδὴ ταύτη ἴσαι εἰσὶν αἱ προσπίπτουσαι πρὸς τὴν ΛΓΜ γραμμὴν, αὐτὴ δὲ ἡ ΛΓΜ γραμμὴ κοχλοειδῆς πρώτη (ἐπειδὴ καὶ ἡ δευτέρα καὶ ἡ τρίτη καὶ ἡ τετάρτη ἐκτίθεται εἰς ἄλλα θεωρήματα χρησιμεύουσαι).

κζ'. "Ὅτι δὲ ὀργανικῶς δύναται γράφεσθαι ἡ γραμμὴ καὶ ἐπ' ἔλαττον αἰεὶ συμπορεύεται τῷ κανόνι, τουτέστιν ὅτι πασῶν τῶν ἀπὸ τινων σημείων τῆς ΛΓΘ γραμμῆς ἐπὶ τὴν ΑΒ εὐθείαν καθέτων μεγίστη ἐστὶν ἡ ΓΔ κάθετος, αἰεὶ δὲ ἡ ἔγγιον τῆς ΓΔ ἀγομένη κάθετος τῆς ἀπώτερον μείζων ἐστίν, καὶ ὅτι, εἰς τὸν μεταξὺ τόπον τοῦ κανόνος καὶ τῆς κοχλοειδοῦς ἂν τις ἡ εὐθεῖα, ἐκβαλλομένη τμηθήσεται ὑπὸ τῆς κοχλοειδοῦς, αὐτὸς ἀπέδειξεν ὁ Νικομήδης, καὶ ἡμεῖς ἐν τῷ εἰς τὸ Ἀνάλημμα Διοδώρου, τρίχα τεμεῖν τὴν γωνίαν βουλόμενοι, κεκρήμεθα τῇ προειρημένη γραμμῇ.

¹ ἐπειδὴ . . . προσπίπτουσαι "ex proximis inepte huc translata" del. Hultsch.

^a Let a be the interval or constant intercept between the curve and the base, and b the distance from the pole to the base (ΕΔ). If Θ is any point on the curve, and $E\Theta = \tau$, $\angle \Gamma E\Theta = \phi$, then the fundamental equation of the curve is

$$\tau = b \sec \phi + a.$$

If a is measured *backwards* from the base towards the pole, then another conchoidal figure is obtained on the same side of the base as the pole, having for its fundamental equation

$$\tau = b \sec \phi - a.$$

This takes three forms according as a is greater than, 300

SPECIAL PROBLEMS

Similarly, if any other straight line drawn from the point E falls upon the curve, the portion cut off by the curve and the straight line AB will make a straight line equal to $\Gamma\Delta$. Now, says he, let the straight line AB be called the ruler, the point [E] the pole, $\Gamma\Delta$ the interval, since the straight lines falling upon the line $\Lambda\Gamma\text{M}$ are equal to it, and let the curve $\Lambda\Gamma\text{M}$ itself be called the first cochloidal line (since there are second and third and fourth cochloids which are useful for other theorems).^a

27. Nicomedes himself proved that the curve can be described mechanically, and that it continually approaches closer to the ruler—which is equivalent to saying that of all the perpendiculars drawn from points on the line $\Lambda\Gamma\Theta$ to the straight line AB the greatest is the perpendicular $\Gamma\Delta$, while the perpendicular drawn nearer to $\Gamma\Delta$ is always greater than the more remote; he also proved that any straight line in the space between the ruler and the cochloid will be cut, when produced, by the cochloid; and we used the aforesaid line in the commentary on the *Analemma*^b of Diodorus when we sought to trisect an angle.

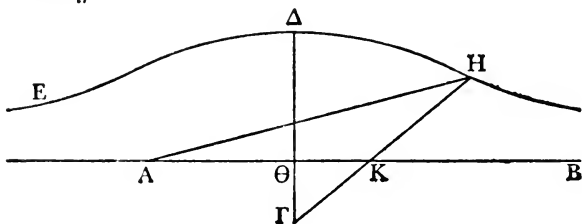
equal to, or less than b . These three forms are probably the "second, third and fourth cochloids," but we have no direct information. When a is greater than b , the curve has a loop at the pole; when a equals b , there is a cusp at the pole; when a is less than b , there is no double point.

The original name of the curve would appear to be the *cochloid* (*κοχλοειδής γραμμή*), as it is called by Pappus, from a supposed resemblance to a shell-fish (*κόχλος*). Later it was called the *conchoid* (*κογχοειδής γραμμή*), the "mussel-like" curve.

^b Diodorus of Alexandria lived in the time of Caesar and is commemorated in the *Anthology* (xiv. 139) as a maker of gnomons. Ptolemy also wrote an *Analemma*, whose object is a graphic representation on a plane of parts of the heavenly sphere.

GREEK MATHEMATICS

Διὰ δὴ τῶν εἰρημένων φανερόν ὡς δυνατόν ἐστὶν γωνίας δοθείσης ὡς τῆς ὑπὸ HAB καὶ σημείου ἔκτος αὐτῆς τοῦ Γ διάγειν τὴν GH καὶ ποιεῖν τὴν KH μεταξὺ τῆς γραμμῆς καὶ τῆς AB ἴσην τῇ δοθείσῃ.



Ἦχθω κάθετος ἀπὸ τοῦ Γ σημείου ἐπὶ τὴν AB ἢ $\Gamma\Theta$ καὶ ἐκβεβλήσθω, καὶ τῇ δοθείσῃ ἴση ἔστω ἢ $\Delta\Theta$, καὶ πύλω μὲν τῷ Γ , διαστήματι δὲ τῷ δοθέντι, τουτέστιν τῇ $\Delta\Theta$, κανόνι δὲ τῷ AB γεγράφθω κοχλοειδῆς γραμμὴ πρώτη ἢ $E\Delta H$. συμβάλλει ἄρα τῇ AH διὰ τὸ προλεχθέν. συμβαλλέτω κατὰ τὸ H , καὶ ἐπεζεύχθω ἢ GH . ἴση ἄρα καὶ ἢ KH τῇ δοθείσῃ.

κη'. Τινὲς δὲ τῆς χρήσεως ἔνεκα παρατιθέντες κανόνα τῷ Γ κινουσιν αὐτόν, ἕως ἂν ἐκ τῆς πείρας ἢ μεταξὺ ἀπολαμβανομένη τῆς AB εὐθείας καὶ τῆς $E\Delta H$ γραμμῆς ἴση γένηται τῇ δοθείσῃ· τούτου γὰρ ὄντος τὸ προκείμενον ἐξ ἀρχῆς δείκνυται (λέγω δὲ κύβος κύβου διπλάσιος εὑρίσκεται). πρότερον δὲ δύο δοθεισῶν εὐθειῶν δύο μέσαι κατὰ τὸ συνεχὲς ἀνάλογον λαμβάνονται, ὧν ὁ μὲν Νικομήδης τὴν κατασκευὴν ἐξέθετο μόνον, ἡμεῖς 302

SPECIAL PROBLEMS

Now by what has been said it is clear that if there is an angle, such as HAB , and a point Γ outside the angle, it is possible so to draw ΓH as to make KH between the line and AB equal to a given straight line.

Let $\Gamma\Theta$ be drawn from the point Γ perpendicular to AB and produced to Δ so that $\Delta\Theta$ is equal to the given straight line, and with Γ for pole, the given straight line, that is $\Delta\Theta$, for interval, and AB for ruler let the first cochloid $E\Delta H$ be drawn; then by what has been said above it will meet AH ; let it meet it in H , and let ΓH be joined; KH will therefore be equal to the given straight line.

28. Some people, following [a more convenient] usage, apply a ruler to Γ and move it until by trial the portion between the straight line AB and the line $E\Delta H$ becomes equal to the given straight line; and when this is done the problem which was posed at the outset is solved (I mean a cube which is double of a cube is found). But first two means in continuous proportion are taken between two given straight lines; Nicomedes explained only the construction necessary

GREEK MATHEMATICS

δὲ καὶ τὴν ἀπόδειξιν ἐφηρμόσαμεν τῇ κατασκευῇ
τὸν τρόπον τοῦτον.

Δεδόσθωσαν γὰρ δύο εὐθεῖαι αἱ ΓΛ, ΛΑ πρὸς
ὀρθὰς ἀλλήλαις, ὧν δεῖ δύο μέσας ἀνάλογον κατὰ
τὸ συνεχές εὐρεῖν, καὶ συμπεπληρώσθω τὸ ΑΒΓΛ
παραλληλόγραμμον, καὶ τετμήσθω δίχα ἑκατέρα
τῶν ΑΒ, ΒΓ τοῖς Δ, Ε σημείοις, καὶ ἐπιζευχθεῖσα

^a The proof is given by Eutocius with very few variations (pp. 104-106) and also in another place by Pappus himself (iii. 8, ed. Hultsch 58. 23-62. 13, with several differences). In iii. 8 the straight lines are called ΔΓ, ΔΑ, whereas here and in the passage from Eutocius the mss. have ΓΛ, ΛΑ. Wherever we have Λ here, it is reasonably certain that Pappus wrote Δ, and *vice versa*.

μὲν ἡ ΔΑ ἐκβεβλήσθω καὶ συμπιπέτω τῇ ΓΒ ἐκβληθείσῃ κατὰ τὸ Η, τῇ δὲ ΒΓ πρὸς ὀρθὰς ἡ ΕΖ, καὶ προσβεβλήσθω ἡ ΓΖ ἴση οὖσα τῇ ΑΔ, καὶ ἐπεζεύχθω ἡ ΖΗ καὶ αὐτῇ παράλληλος ἡ ΓΘ, καὶ γωνίας οὔσης τῆς ὑπὸ τῶν ΚΓΘ ἀπὸ δοθέντος τοῦ Ζ διήχθω ἡ ΖΘΚ ποιούσα ἴσην τὴν ΘΚ τῇ ΑΔ ἢ τῇ ΓΖ (τοῦτο γὰρ ὡς δυνατόν ἐδείχθη διὰ τῆς κοχλοειδοῦς γραμμῆς), καὶ ἐπιζευχθείσα ἡ ΚΛ ἐκβεβλήσθω καὶ συμπιπέτω τῇ ΑΒ ἐκβληθείσῃ κατὰ τὸ Μ· λέγω ὅτι ἐστὶν ὡς ἡ ΑΓ πρὸς ΚΓ, ἢ ΚΓ πρὸς ΜΑ, καὶ ἡ ΜΑ πρὸς τὴν ΑΔ.

Ἐπεὶ ἡ ΒΓ τέτμηται δίχα τῷ Ε καὶ πρόσκειται αὐτῇ ἡ ΚΓ, τὸ ἄρα ὑπὸ ΒΚΓ μετὰ τοῦ ἀπὸ ΓΕ ἴσον ἐστὶν τῷ ἀπὸ ΕΚ. κοινὸν προσκείσθω τὸ ἀπὸ ΕΖ· τὸ ἄρα ὑπὸ ΒΚΓ μετὰ τῶν ἀπὸ ΓΕΖ, τουτέστιν τοῦ ἀπὸ ΓΖ, ἴσον ἐστὶν τοῖς ἀπὸ ΚΕΖ, τουτέστιν τῷ ἀπὸ ΚΖ. καὶ ἐπεὶ ὡς ἡ ΜΑ πρὸς ΑΒ, ἢ ΜΛ πρὸς ΑΚ, ὡς δὲ ἡ ΜΛ πρὸς ΑΚ, οὕτως ἡ ΒΓ πρὸς ΓΚ, καὶ ὡς ἄρα ἡ ΜΑ πρὸς ΑΒ, οὕτως ἡ ΒΓ πρὸς ΓΚ. καὶ ἐστὶ τῆς μὲν ΑΒ ἡμίσεια ἡ ΑΔ, τῆς δὲ ΒΓ διπλῆ ἡ ΓΗ· ἐστὶ ἄρα καὶ ὡς ἡ ΜΑ πρὸς ΑΔ, οὕτως ἡ ΗΓ πρὸς ΚΓ. ἀλλ' ὡς ἡ ΗΓ πρὸς ΓΚ, οὕτως ἡ ΖΘ πρὸς ΘΚ διὰ τὰς παραλλήλους τὰς ΗΖ, ΓΘ· καὶ συνθέντι ἄρα ὡς ἡ ΜΔ πρὸς ΔΑ, ἢ ΖΚ πρὸς ΚΘ. ἴση δὲ ὑπόκειται καὶ ἡ ΑΔ τῇ ΘΚ, ἐπεὶ¹ καὶ τῇ ΓΖ ἴση ἐστὶν ἡ ΑΔ¹. ἴση ἄρα καὶ ἡ ΜΔ τῇ ΖΚ· ἴσον ἄρα καὶ τὸ ἀπὸ ΜΔ τῷ ἀπὸ ΖΚ. καὶ ἐστὶ τῷ μὲν ἀπὸ ΜΔ ἴσον τὸ ὑπὸ ΒΜΑ μετὰ τοῦ ἀπὸ ΔΑ, τῷ δὲ

¹ ἐπεὶ . . . ΑΔ. Hultsch thinks these words are interpolated; they appear in both other versions.

SPECIAL PROBLEMS

Δ , E respectively, and let ΔA be joined and produced, and let it meet ΓB produced in H, and let EZ be drawn at right angles to $B\Gamma$ in such a way that ΓZ is equal to $A\Delta$, and let ZH be joined and parallel to it let $\Gamma\Theta$ be drawn, and, since the angle $\text{K}\Gamma\Theta$ is given, from the given point Z let $Z\Theta K$ be so drawn as to make ΘK equal to $A\Delta$ or to ΓZ (that this is possible is proved by the cochloidal line), and let $K\Lambda$ be joined and produced, and let it meet AB produced in M; I say that $\Lambda\Gamma : K\Gamma = K\Gamma : MA = MA : A\Lambda$.

Since $B\Gamma$ is bisected at E and $K\Gamma$ lies in $B\Gamma$ produced, therefore

$$BK \cdot K\Gamma + \Gamma E^2 = EK^2. \quad [\text{Eucl. ii. 6}]$$

Let EZ^2 be added to both sides.

$$\text{Therefore } BK \cdot K\Gamma + \Gamma E^2 + EZ^2 = EK^2 + EZ^2,$$

$$\text{that is } BK \cdot K\Gamma + \Gamma Z^2 = KZ^2. \quad [\text{Eucl. i. 47}]$$

$$\text{And since } MA : AB = M\Lambda : \Lambda K$$

$$\text{and } M\Lambda : \Lambda K = B\Gamma : \Gamma K,$$

$$\text{therefore } MA : AB = B\Gamma : \Gamma K.$$

$$\text{And } A\Delta = \frac{1}{2}AB, \Gamma H = 2B\Gamma.$$

$$\text{Therefore } MA : A\Delta = H\Gamma : K\Gamma.$$

But on account of HZ , $\Gamma\Theta$ being parallels,

$$H\Gamma : \Gamma K = Z\Theta : \Theta K.$$

Therefore, compounding,

$$M\Delta : \Delta A = ZK : K\Theta.$$

But by hypothesis $A\Delta = \Theta K$, since $\Gamma Z = A\Delta$;

$$\text{therefore } M\Delta = ZK;$$

$$\text{therefore } M\Delta^2 = ZK^2.$$

$$\text{And } M\Delta^2 = BM \cdot MA + \Delta A^2 \quad [\text{Eucl. ii. 6}]$$

GREEK MATHEMATICS

ἀπὸ ΖΚ ἴσον ἐδείχθη τὸ ὑπὸ ΒΚΓ μετὰ τοῦ ἀπὸ ΖΓ, ὡν τὸ ἀπὸ ΑΔ ἴσον τῷ ἀπὸ ΓΖ (ἴση γὰρ ὑπόκειται ἡ ΑΔ τῇ ΓΖ). ἴσον ἄρα καὶ τὸ ὑπὸ ΒΜΑ τῷ ὑπὸ ΒΚΓ. ὡς ἄρα ἡ ΜΒ πρὸς ΒΚ, ἡ ΓΚ πρὸς ΜΑ. ἀλλ' ὡς ἡ ΒΜ πρὸς ΒΚ, ἡ ΛΓ πρὸς ΓΚ. ὡς ἄρα ἡ ΛΓ πρὸς ΓΚ, ἡ ΓΚ πρὸς ΑΜ. ἔστι δὲ καὶ ὡς ἡ ΜΒ πρὸς ΒΚ, ἡ ΜΑ πρὸς ΑΛ. καὶ ὡς ἄρα ἡ ΛΓ πρὸς ΓΚ, ἡ ΓΚ πρὸς ΑΜ, καὶ ἡ ΑΜ πρὸς ΑΛ.

2. SQUARING OF THE CIRCLE

(a) GENERAL

Plut. *De Exil.* 17, 607E, F

Ἀνθρώπου δ' οὐδεὶς ἀφαιρεῖται τόπος εὐδαιμονίαν, ὡσπερ οὐδ' ἀρετὴν οὐδὲ φρόνησιν. ἀλλ' Ἀναξαγόρας μὲν ἐν τῷ δεσμωτηρίῳ τὸν τοῦ κύκλου τετραγωνισμόν ἔγραφε.

Aristoph. *Aves* 1001-1005

ΜΕΤΩΝ. Προσθεῖς οὖν ἐγὼ
τὸν κανόν' ἄνωθεν τουτονὶ τὸν καμπύλον,
ἐνθεῖς διαβήτην—μανθάνεις; ΠΕΙΣΘΕΤΑΙΡΟΣ.
οὐ μανθάνω.
ΜΕΤΩΝ. Ὅρθῳ μετρήσω κανόνι προστιθείς, ἵνα
ὁ κύκλος γένηται σοι τετράγωνος.

^a This reference shows the popularity of the problem of squaring the circle in 414 B.C., when the *Birds* was first produced. Meton, who is here burlesqued, is the great astronomer who about eighteen years earlier had found that after any period of 6940 days (a little over nineteen solar

SPECIAL PROBLEMS

and it was proved that

$$ZK^2 = BK \cdot K\Gamma + Z\Gamma^2,$$

and here $\Gamma Z^2 = A\Delta^2$ (for by hypothesis $A\Delta = \Gamma Z$);

therefore $BM \cdot MA = BK \cdot K\Gamma$;

therefore $MB : BK = \Gamma K : MA$. [Eucl. vi. 16

But $BM : BK = \Lambda\Gamma : \Gamma K$;

therefore $\Lambda\Gamma : \Gamma K = \Gamma K : AM$.

And $MB : BK = MA : A\Lambda$;

and therefore $\Lambda\Gamma : \Gamma K = \Gamma K : AM = AM : A\Lambda$.

2. SQUARING OF THE CIRCLE

(a) GENERAL

Plutarch, *On Exile* 17, 607E, F

There is no place that can take away the happiness of a man, nor yet his virtue or wisdom. Anaxagoras, indeed, wrote on the squaring of the circle while in the prison.

Aristophanes, *Birds* 1001-1005^a

METON. So then applying here my flexible rod, and there my compass—you understand? **PEISTHETAÏROS.** I don't.

METON. With the straight rod I measure so that the circle may become a square for you.

years) the sun and moon occupy the same relative positions as at the beginning, and had just built a water-clock worked by water from a neighbouring spring on the Colonus in the Athenian Agora. Actually, Meton made no contribution to squaring the circle; all he seems to be represented as doing is to divide the circle into four quadrants by two diameters at right angles.

GREEK MATHEMATICS

(b) APPROXIMATION BY POLYGONS

(i.) *Antiphon*

Aristot. *Phys.* A 2, 185 a 14-17

Ἄμα δ' οὐδὲ λύειν ἅπαντα προσήκει, ἀλλ' ἢ ὅσα ἐκ τῶν ἀρχῶν τις ἐπιδεικνύς ψεύδεται, ὅσα δὲ μή, οὗ, οἷον τὸν τετραγωνισμόν τὸν μὲν διὰ τῶν τμημάτων γεωμετρικοῦ διαλύσαι, τὸν δὲ Ἀντιφῶντος οὐ γεωμετρικοῦ.

Them. in *Phys.* A 2 (Aristot. 185 a 14), ed. Schenkl
3. 30-4. 7

Ἐπεὶ καὶ τὰ ψευδογραφήματα ὅσα μὲν σῶζει τὰς γεωμετρικὰς ὑποθέσεις λυτέον τῷ γεωμέτρῳ, ὅσα δὲ μάχεται πρὸς ἐκείνας, παραιτητέον, οἷον

• Antiphon was an Athenian sophist contemporary with Socrates.

• The comments of Themistius, Philoponus and Simplicius on this passage are of great importance in the history of Greek geometry. All three agree (Simplicius with a reservation) that "the quadrature by means of segments" is to be ascribed to Hippocrates of Chios. Simplicius's reproduction of the passage in Eudemus's *History of Geometry* which tells us of certain areas squared by Hippocrates has already been given (*supra*, pp. 234-253). The four quadratures there given contain no fallacy. What then is the fallacy with which Aristotle and the commentators charge Hippocrates? It is most probably an alleged assumption by Hippocrates that because he had squared a particular lune in each of three kinds, he had squared all types of lunes; and, as he had also squared a figure consisting of a lune and a circle, that he had squared the circle. In fact, the last-mentioned lune was not of a kind which he had previously squared, and so he had not really squared the circle. But did Hippocrates think that he had squared the circle? There is no reason to suppose that he so thought, and it is extremely unlikely that a mathematician of his calibre

SPECIAL PROBLEMS

(b) APPROXIMATION BY POLYGONS

(i.) *Antiphon*^a

Aristotle, *Physics* A 2, 185 a 14-17

At the same time it is not convenient to refute everything, but only false demonstrations starting from the fundamental principles, and otherwise not; thus it is the business of the geometer to refute the quadrature by means of segments, but it is not the business of the geometer to refute that of Antiphon.^b

Themistius, *Commentary on Aristotle's Physics* A 2
(185 a 14), ed. Schenkl 3. 30-4. 7

For such false arguments as preserve the geometrical hypotheses are to be refuted by geometry, but such as conflict with them are to be left alone.

could be so deluded. Heiberg (*Philol.* xliii. 336-344) thinks that in the then state of logic he may have thought he had squared the circle. Björnbo (in Pauly-Wissowa, *Real-Encyclopädie*, xvi. 1787-1799) thinks he knew perfectly well what he had done, but used language calculated to give the impression that he had squared the circle. Both suggestions are highly improbable. Heath (*H.G.M.* i. 197) prefers to think that Hippocrates was trying to put what he had discovered in the most favourable light. Ross (*Aristotle's Physics*, p. 466) is of opinion that Hippocrates simply proved his quadratures of lunes and the sum of a lune and circle, no doubt in the hope of ultimately squaring the circle, but without any claim to have done so. This appears the best view. Aristotle has misunderstood what Hippocrates claimed to have done.

τμήματα means "segments," and is not properly used of "lunes," but mathematical terminology was fluid in Aristotle's time, and *τμήμα* may have been used to denote any portion cut out of a circle. In *De Caelo* ii. 8, 290 a 4, Aristotle uses it to denote a "sector."

GREEK MATHEMATICS

δύο τινές κύκλον ἐπιχειρήσαντες τετραγωνίζειν Ἴπποκράτης τε ὁ Χίος καὶ ὁ Ἀντιφῶν. τὸν μὲν οὖν Ἴπποκράτους λυτέον. τὰς γὰρ ἀρχὰς φυλάττων παραλογίζεται τῷ μόνον μὲν ἐκείνον τὸν μηνίσκον τετραγωνίσαι ὃς γράφεται περὶ τὴν τοῦ τετραγώνου πλευρὰν τοῦ εἰς τὸν κύκλον ἐγγραφομένου, πάντα¹ δὲ μηνίσκον οἷόν τε τετραγωνίζειν λαβεῖν εἰς¹ ἀπόδειξιν, πρὸς Ἀντιφῶντα δὲ οὐκέτ' ἂν ἔχοι λέγειν ὁ γεωμέτρης, ὃς ἐγγράφων τρίγωνον ἰσόπλευρον εἰς τὸν κύκλον καὶ ἐφ' ἐκάστης τῶν πλευρῶν ἕτερον ἰσοσκελὲς συνιστὰς πρὸς τῇ περιφερείᾳ τοῦ κύκλου καὶ τοῦτο ἐφεξῆς ποιῶν ὧστέ ποτε ἐφαρμόσειν τοῦ τελευταίου τριγώνου τὴν πλευρὰν εὐθείαν οὔσαν τῇ περιφερείᾳ.

Simpl. in *Phys.* A 2 (Aristot. 185 a 14), ed. Diels
54. 20-55. 24

Ὁ δὲ Ἀντιφῶν γράψας κύκλον ἐνέγραφέ τι χωρίον εἰς αὐτὸν πολύγωνον τῶν ἐγγράφεσθαι δυναμένων. ἔστω δὲ εἰ τύχοι τετράγωνον τὸ ἐγγεγραμμένον. . . . καὶ δῆλον ὅτι ἡ συναγωγή παρὰ τὰς γεωμετρικὰς ἀρχὰς γέγονεν οὐχ ὡς ὁ Ἀλέξανδρός φησιν, "ὅτι ὑποτίθεται μὲν ὁ γεωμέτρης τὸ τὸν κύκλον τῆς εὐθείας κατὰ σημείον ἄπτεσθαι ὡς ἀρχήν, ὁ δὲ Ἀντιφῶν ἀναιρεῖ τοῦτο." οὐ γὰρ ὑποτίθεται ὁ γεωμέτρης τοῦτο, ἀλλ' ἀποδείκνυσιν αὐτὸ ἐν τῷ τρίτῳ βιβλίῳ. ἄμεινον οὖν

¹ πάντα . . . εἰς: a lacuna in the text is satisfactorily filled, as Schenkl notes, if these words are supplied from Simplicius.

• Accounts differ about Antiphon's procedure, but it makes no difference to the result, which is to get a regular polygon approaching the circle as its limit. Themistius was
312

SPECIAL PROBLEMS

Examples are given by two men who tried to square the circle, Hippocrates of Chios and Antiphon. The attempt of Hippocrates is to be refuted. For, while preserving the principles, he commits a paralogism by squaring only that lune which is described about the side of the square inscribed in the circle, though including every lune that can be squared in the proof. But the geometer could have nothing to say against Antiphon, who inscribed an equilateral triangle in the circle,^a and on each of the sides set up another triangle, an isosceles triangle with its vertex on the circumference of the circle, and continued this process, thinking that at some time he would make the side of the last triangle, although a straight line, coincide with the circumference.

Simplicius, *Commentary on Aristotle's Physics A 2*
(185 a 14), ed. Diels 54. 20-55. 24

Antiphon described a circle and inscribed some one of the (regular) polygons that can be inscribed therein. Suppose, for example, that the inscribed polygon is a square. . . . It is clear that the breach with the principles of geometry comes about not, as Alexander says, "because the geometer lays down as a hypothesis that a circle touches a straight line in one point [only], while Antiphon violates this." For the geometer does not lay this down as a hypothesis, but it is proved in the third book of the *Elements*.^b It

the earliest of the commentators, and Heath considers his account "the authentic version." Philoponus makes Antiphon begin by inscribing a square, then an octagon and so on. Simplicius, as will be seen below, allows him to begin with any one of the regular polygons, but starts with the square as an example.

^b Eucl. *Elem.* iii. 16.

GREEK MATHEMATICS

λέγειν ἀρχὴν εἶναι τὸ ἀδύνατον εἶναι εὐθείαν ἐφαρμόσαι περιφερεία, ἀλλ' ἡ μὲν ἐκτὸς κατὰ ἓν σημεῖον ἐφάπεται τοῦ κύκλου, ἡ δὲ ἐντὸς κατὰ δύο μόνον καὶ οὐ πλείω, καὶ ἡ ἐπαφή κατὰ σημεῖον γίνεται. καὶ μέντοι τέμνων αἰεὶ τὸ μεταξὺ τῆς εὐθείας καὶ τῆς τοῦ κύκλου περιφερείας ἐπίπεδον οὐ δαπανήσει αὐτὸ οὐδὲ καταλήψεται ποτε τὴν τοῦ κύκλου περιφέρειαν, εἴπερ ἐπ' ἄπειρόν ἐστι διαιρετὸν τὸ ἐπίπεδον. εἰ δὲ καταλαμβάνει, ἀνήρηται τις ἀρχὴ γεωμετρικὴ ἢ λέγουσα ἐπ' ἄπειρον εἶναι τὰ μεγέθη διαιρετά. καὶ ταύτην καὶ ὁ Εὐδήμος τὴν ἀρχὴν ἀναιρεῖσθαι φησιν ὑπὸ τοῦ Ἀντιφῶντος.

(ii.) *Bryson*

Alex. Aphr. in *Soph. El.* 11 (Aristot. 171 b 7), ed. Wallies 90. 10-21

Ἄλλ' ὁ τοῦ Βρύσωνος τετραγωνισμὸς τοῦ κύκλου ἐριστικός ἐστι καὶ σοφιστικός, ὅτι οὐκ ἐκ τῶν οἰκείων ἀρχῶν τῆς γεωμετρίας ἀλλ' ἐκ τινῶν κοινοτέρων. τὸ γὰρ περιγράφειν ἐκτὸς τοῦ κύκλου

• Heath (*H.G.M.* i. 222-223) comments: "The objection to Antiphon's statement is really no more than verbal; Euclid uses exactly the same construction in xii. 2, only he expresses the conclusion in a different way, saying that, if the process be continued far enough, the small segments left over will be together less than any assigned area. Antiphon in effect said the same thing, which again we express by saying that the circle is the *limit* of such an inscribed polygon when the number of its sides is indefinitely increased. Antiphon therefore deserves an honourable place in the history of geometry as having originated the idea of *exhausting* an area by means of inscribed regular polygons

SPECIAL PROBLEMS

would be better therefore to say that the principle is that a straight line cannot coincide with the circumference, a straight line drawn from outside the circle touching it in one point only, a straight line drawn from inside cutting it in two points and not more, and tangential contact being in one point only. Now continual division of the space between the straight line and the circumference of the circle will never exhaust it nor ever reach the circumference of the circle, if the space is really divisible without limit. For if the circumference could be reached, the geometrical principle that magnitudes are divisible without limit would be violated. This was the principle which Eudemus says was violated by Antiphon.^a

(ii.) Bryson^b

Alexander, *Commentary on Aristotle's Sophistic Refutations* 11 (171 b 7), ed. Wallies 90. 10-21

But Bryson's quadrature of the circle is eristic and sophistical, because he proceeds not from principles peculiar to geometry but from wider principles. For to circumscribe a square about the circle and to

with an ever-increasing number of sides, an idea upon which Eudoxus founded his epoch-making *method of exhaustion*. The practical value of Antiphon's construction is illustrated by Archimedes' treatise on the *Measurement of a Circle* [reproduced below] . . . The same construction starting from a square was likewise the basis of Vieta's expression for $\frac{2}{\pi}$, namely,

$$\begin{aligned} \frac{2}{\pi} &= \cos \frac{\pi}{4} \cdot \cos \frac{\pi}{8} \cdot \cos \frac{\pi}{16} \cdot \dots \\ &= \sqrt{\frac{1}{2}} \cdot \sqrt{\frac{1}{2}(1 + \sqrt{\frac{1}{2}})} \cdot \sqrt{\frac{1}{2}(1 + \sqrt{\frac{1}{2}(1 + \sqrt{\frac{1}{2}})}}} \dots \end{aligned}$$

^b Bryson was a pupil either of Socrates or of Euclid of Megara.

GREEK MATHEMATICS

τετράγωνον καὶ ἐντὸς ἐγγράφειν ἕτερον καὶ μεταξὺ τῶν δύο τετραγώνων ἕτερον τετράγωνον, εἶτα λέγειν ὅτι ὁ μεταξὺ τῶν δύο τετραγώνων κύκλος, ὁμοίως δὲ καὶ τὸ μεταξὺ τῶν δύο τετραγώνων τετράγωνον τοῦ μὲν ἐκτὸς τετραγώνου ἐλάττονα εἶσι τοῦ δὲ ἐντὸς μείζονα, τὰ δὲ τῶν αὐτῶν μείζονα καὶ ἐλάττονα ἴσα ἐστίν, ἴσος ἄρα ὁ κύκλος καὶ τὸ τετράγωνον, ἕκ τινων κοινῶν ἀλλὰ καὶ ψευδῶν ἐστι, κοινῶν μὲν, ὅτι καὶ ἐπ' ἀριθμῶν καὶ χρόνων καὶ τόπων καὶ ἄλλων κοινῶν ἀρμόσοι ἄν, ψευδῶν δέ, ὅτι ὀκτώ καὶ ἐννέα τῶν δέκα καὶ ἐπτὰ ἐλάττονες καὶ μείζονές εἶσι καὶ ὅμως οὐκ εἰσὶν ἴσοι.

(iii.) *Archimedes*

Procl. in *Eucl.* i., ed. Kroll 422. 24-423. 5

Ἐκ τούτου δὲ οἶμαι τοῦ προβλήματος ἐπαχθέντες οἱ παλαιοὶ καὶ τὸν τοῦ κύκλου τετραγωνισμόν ἐζήτησαν. εἰ γὰρ παραλληλόγραμμον ἴσον εὑρίσκεται παντὶ εὐθυγράμμῳ, ζητήσεως ἄξιον, μὴ καὶ τὰ εὐθύγραμμα τοῖς περιφερογράμμοις ἴσα δεικνύναι δυνατόν. καὶ ὁ Ἀρχιμήδης ἔδειξεν, ὅτι πᾶς κύκλος ἴσος ἐστὶ τριγώνῳ ὀρθογωνίῳ, οὗ ἡ μὲν ἐκ κέντρου ἴση ἐστὶν μιᾷ τῶν περὶ τὴν ὀρθήν, ἡ δὲ περίμετρος τῆ βάσει.

Archim. *Dim. Circ.*, Archim. ed. Heiberg i. 232-242

α'

Πᾶς κύκλος ἴσος ἐστὶ τριγώνῳ ὀρθογωνίῳ, οὗ

^a Bryson marks a step beyond Antiphon because he conceived the circle as intermediate in area between an inscribed and an escribed polygon, an idea which was powerfully developed by Archimedes. The manner in which he took a square intermediate between the inscribed and escribed

SPECIAL PROBLEMS

inscribe another ^a within and between the two squares to take another square, and then to say that the circle is intermediate between the two squares, and similarly that the square between the two squares is less than the outside square but greater than the inside and that, since things which are greater and less than the same things are equal, therefore the circle and the square are equal, is to proceed from wider principles (than those of geometry) and false ones; wider, because the argument would apply to numbers and times and spaces and other entities, false, because eight and nine are respectively less and greater than ten and seven and nevertheless are not equal.

(iii.) *Archimedes*

Proclus, *On Euclid* i., ed. Kroll 422. 24-423. 5

I think it was in consequence of this problem ^b that the ancient geometers were led to investigate the squaring of the circle. For if a parallelogram is found equal to any rectilinear figure, it is worth inquiring whether it be not also possible to prove rectilinear figures equal to circular. Archimedes in fact proved that any circle is equal to a right-angled triangle wherein one of the sides about the right-angle is equal to the radius and the base to the perimeter.

Archimedes, *Measurement of a Circle*, Archim.
ed. Heiberg i. 232-242

Prop. 1

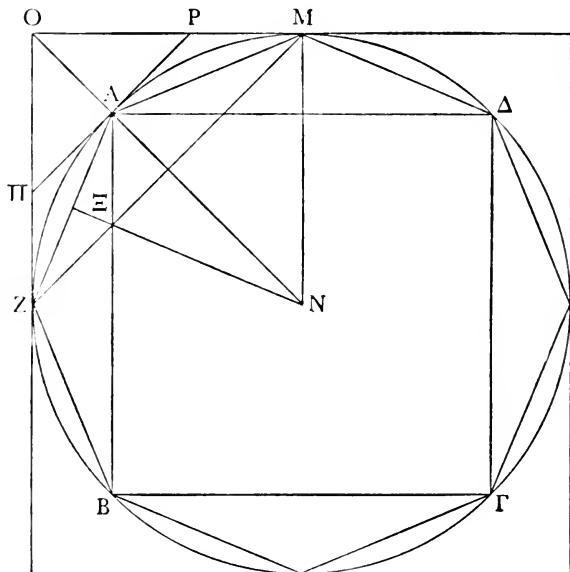
Any circle is equal to a right-angled triangle in which squares is unknown. Some have assumed that it was the arithmetic mean, others the geometric (see Heath, *H.G.M.* i. 223, 224).

^b Eucl. i. 45. "To construct, in a given rectilinear angle, a parallelogram equal to a given rectilinear figure."

GREEK MATHEMATICS

ἡ μὲν ἐκ τοῦ κέντρου ἴση μιᾷ τῶν περὶ τὴν ὀρθήν,
ἡ δὲ περίμετρος τῇ βάσει.

Ἐχέτω ὁ $ΑΒΓΔ$ κύκλος τριγώνω τῷ $Ε$, ὡς
ὑπόκειται· λέγω, ὅτι ἴσος ἐστίν.



Εἰ γὰρ δυνατόν, ἔστω μείζων ὁ κύκλος, καὶ
ἐγγεγράφθω τὸ $ΑΓ$ τετράγωνον, καὶ τετμήσθωσαν
αἱ περιφέρειαι δίχα, καὶ ἔστω τὰ τμήματα ἤδη
ἐλάσσονα τῆς ὑπεροχῆς, ἣ ὑπερέχει ὁ κύκλος τοῦ
τριγώνου· τὸ εὐθύγραμμον ἄρα ἔτι τοῦ τριγώνου
ἐστὶ μείζον. εἰλήφθω κέντρον τὸ N καὶ κάθετος

SPECIAL PROBLEMS

one of the sides about the right angle is equal to the radius, and the base is equal to the circumference.

Let the circle $AB\Gamma\Delta$ have to the triangle E the stated relation ; I say that it is equal.



For, if possible, let the circle be greater, and let the square $A\Gamma$ be inscribed, and let the arcs be divided into equal parts [and let BZ , ZA , AM , $M\Delta$, etc., be drawn],^a and let the segments be less than the excess by which the circle exceeds the triangle.^b The rectilinear figure is therefore greater than the triangle.

^a Heiberg's note is: "Tale aliquid Archimedes sine dubio addiderat: Omnino in toto hoc opusculo genus dicendi et exponendi brevitare tam negligenti laborat, ut manum excerptoris potius quam Archimedis agnoscas."

^b That this can be done is shown in Eucl. *Elem.* xii. 2, depending on x. 1. The latter theorem was probably discovered by Eudoxus, but is commonly known as the "Axiom of Archimedes" from his repeated use of it.

GREEK MATHEMATICS

ἢ ΝΞ· ἐλάσσων ἄρα ἢ ΝΞ τῆς τοῦ τριγώνου πλευρᾶς. ἔστιν δὲ καὶ ἡ περίμετρος τοῦ εὐθύγραμμου τῆς λοιπῆς ἐλάττων, ἐπεὶ καὶ τῆς τοῦ κύκλου περιμέτρου· ἔλαττον ἄρα τὸ εὐθύγραμμον τοῦ Ε τριγώνου· ὅπερ ἄτοπον.

Ἔστω δὲ ὁ κύκλος, εἰ δυνατόν, ἐλάσσων τοῦ Ε τριγώνου, καὶ περιγεγράφθω τὸ τετράγωνον, καὶ τετμήσθωσαν αἱ περιφέρειαι δίχα, καὶ ἤχθωσαν ἐφαπτόμεναι διὰ τῶν σημείων· ὀρθὴ ἄρα ἡ ὑπὸ ΟΑΡ. ἢ ΟΡ ἄρα τῆς ΜΡ ἐστὶν μείζων· ἢ γὰρ ΡΜ τῆ ΡΑ ἴση ἐστὶ· καὶ τὸ ΡΟΠ τρίγωνον ἄρα τοῦ ΟΖΑΜ σχήματος μείζον ἐστὶν ἢ τὸ ἥμισυ. λελειφθωσαν οἱ τῶ ΠΖΑ τομεῖ ὅμοιοι ἐλάσσους τῆς ὑπεροχῆς, ἣ ὑπερέχει τὸ Ε τοῦ ΑΒΓΔ κύκλου· ἔτι ἄρα τὸ περιγεγραμμένον εὐθύγραμμον τοῦ Ε ἐστὶν ἐλάσσων· ὅπερ ἄτοπον· ἐστὶν γὰρ μείζων, ὅτι ἢ μὲν ΝΑ ἴση ἐστὶ τῆ καθέτῳ τοῦ τριγώνου, ἢ δὲ περίμετρος μείζων ἐστὶ τῆς βάσεως τοῦ τριγώνου. ἴσος ἄρα ὁ κύκλος τῶ Ε τριγώνῳ.

γ'

Παντὸς κύκλου ἢ περίμετρος τῆς διαμέτρου τριπλασίῳν ἐστὶ καὶ ἔτι ὑπερέχει ἐλάσσονι μὲν ἢ ἐβδόμῳ μέρει τῆς διαμέτρου, μείζονι δὲ ἢ δέκα ἐβδομηκοστομόνοις.

^a *i.e.*, the space between the arc ΖΑ of the circle and the sides ΖΗ, ΗΑ of the escribed polygon. The name given to this figure, *τομεύς*, is more properly used of a *sector* of a circle, and Heiberg notes: "*τομεῖ* Archimedes non scripsit pro ἀποτμήματι." The process, it is not quite clearly stated

SPECIAL PROBLEMS

Let N be the centre, and $N\Xi$ perpendicular [to ZA]; $N\Xi$ is then less than the side of the triangle. But the perimeter of the rectilinear figure is also less than the other side, since it is less than the perimeter of the circle. The rectilinear figure is therefore less than the triangle E ; which is absurd.

Let the circle be, if possible, less than the triangle E , and let the square be circumscribed, and let the arcs be divided into equal parts, and through the points [of division] let tangents be drawn; the angle OAP is therefore right. Therefore OP is greater than MP ; for PM is equal to PA ; and the triangle $POII$ is greater than half the figure $OZAM$. Let the spaces left between the circle and the circumscribed polygon, such as the figure^a ΠZA , be less than the excess by which E exceeds the circle $AB\Gamma\Delta$. Therefore the circumscribed rectilinear figure is now less than E ; which is absurd; for it is greater, because NA is equal to the perpendicular of the triangle, while the perimeter is greater than the base of the triangle. The circle is therefore equal to the triangle E .

Prop. 3^b

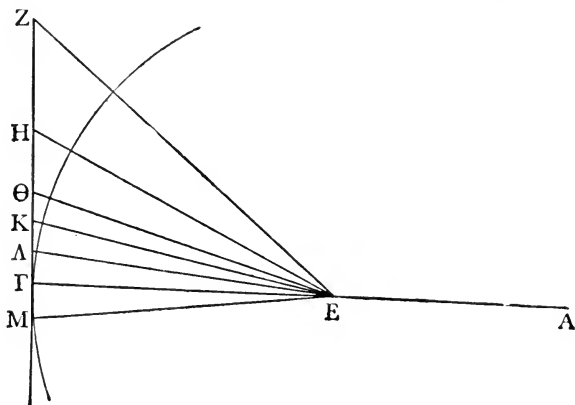
The circumference of any circle is greater than three times the diameter and exceeds it by a quantity less than the seventh part of the diameter but greater than ten seventy-first parts.

in the Greek, is to be *continued until* the escribed polygon is such that the spaces left between it and the circle are less than the excess of E over the circle. That this can be done follows from the "Axiom of Archimedes," Eucl. *Elem.* x. 1.

^b The order of the propositions in the manuscripts is manifestly wrong. Props. 2 and 3 must be interchanged.

GREEK MATHEMATICS

Ἐστω κύκλος καὶ διάμετρος ἡ ΑΓ καὶ κέντρον τὸ Ε καὶ ἡ ΓΛΖ ἐφαπτομένη καὶ ἡ ὑπὸ ΖΕΓ τρίτου ὀρθῆς· ἡ ΕΖ ἄρα πρὸς ΖΓ λόγον ἔχει, ὃν



$\overline{\tau\sigma}$ πρὸς $\overline{\rho\nu\gamma}$, ἡ δὲ ΕΓ πρὸς [τὴν] ΓΖ λόγον ἔχει, ὃν $\overline{\sigma\xi\epsilon}$ πρὸς $\overline{\rho\nu\gamma}$. τετμήσθω οὖν ἡ ὑπὸ ΖΕΓ δίχα τῇ ΕΗ· ἔστιν ἄρα, ὡς ἡ ΖΕ πρὸς ΕΓ, ἡ ΖΗ πρὸς ΗΓ [καὶ ἐναλλάξ καὶ συνθέντι]. ὡς ἄρα συναμφοτέρος ἡ ΖΕ, ΕΓ πρὸς ΖΓ, ἡ ΕΓ πρὸς ΓΗ· ὥστε ἡ ΓΕ πρὸς ΓΗ μείζονα λόγον ἔχει ἢ περ $\overline{\phi\omicron\alpha}$ πρὸς $\overline{\rho\nu\gamma}$. ἡ ΕΗ ἄρα πρὸς ΗΓ δυνάμει λόγον ἔχει, ὃν $\overline{M}^{\lambda\delta}$ πρὸς \overline{M}^{β} $\overline{\gamma\nu\theta}$. μήκει ἄρα, ὃν

^a As Eutocius explains in his commentary on this passage (Archim. ed. Heiberg iii. 234), if EZ is represented by 306 and ΓΖ by 153, then by Pythagoras's theorem $ΕΓ^2 = 306^2 - 153^2 = 70227$. Since $265^2 = 70225$, ΕΓ is therefore 265 322

SPECIAL PROBLEMS

Let there be a circle with diameter $A\Gamma$ and centre E , and let ΓAZ be a tangent and the angle $Z\Gamma E$ one-third of a right angle. Then

$$E\Gamma : \Gamma Z [= \sqrt{3} : 1] > 265 : 153^a \quad . \quad . \quad (1)$$

and $EZ : Z\Gamma [= 2 : 1] = 306 : 153 \quad . \quad . \quad (2)$

Now let $\angle Z\Gamma E$ be bisected by EH . It follows that

$$ZE : E\Gamma = ZH : H\Gamma \text{ [Eucl. vi. 3]}$$

so that $[ZE + E\Gamma : E\Gamma = ZH + H\Gamma : H\Gamma$
 $= Z\Gamma : H\Gamma, \text{ or}]$

$$ZE + E\Gamma : Z\Gamma = E\Gamma : H\Gamma.$$

Therefore $\Gamma E : \Gamma H [= E\Gamma + ZE : Z\Gamma$
 $> 265 + 306 : 153,$
by (1) and (2)]

$$> 571 : 153 \quad . \quad . \quad (3)$$

Hence $EH^2 : H\Gamma^2 [= E\Gamma^2 + \Gamma H^2 : H\Gamma^2$
 $> 571^2 + 153^2 : 153^2]$
 $> 349450 : 23409,$

and a "minute and imperceptible fraction" (*μόριον ἐλάχιστον καὶ ἀνεπαίσθητον*). As the sides of the triangle are in the ratio $1, \sqrt{3}, 2$, this is equivalent to saying that $\sqrt{3} > \frac{265}{153}$. In the second part of the proof Archimedes assumes that $\sqrt{3} < \frac{13861}{7956}$. The way in which he makes these assumptions, without explanation of any kind, shows that they were common in his day, and much ingenuity has been spent in devising processes by which they may have been reached. *v. Heath, The Works of Archimedes, lxxx-lxxxiv, xc-xcix.*

Eutocius fully explains the arithmetical working, where Archimedes merely sets down the results. In the translation the necessary working, where not given by Archimedes, is shown in square brackets. In the Greek text as we have it a few equalities are given where the argument requires inequalities. The translation reproduces what Archimedes must have written.

GREEK MATHEMATICS

$\overline{\phi\zeta\alpha}$ ἡ' πρὸς $\overline{\rho\nu\gamma}$. πάλιν δίχα ἢ ὑπὸ $\text{HE}\Gamma$ τῆ $\text{E}\Theta$. διὰ
 τὰ αὐτὰ ἄρα ἢ $\text{E}\Gamma$ πρὸς $\Gamma\Theta$ μείζονα λόγον ἔχει
 ἢ ὄν $\overline{\alpha\rho\xi\beta}$ ἡ' πρὸς $\overline{\rho\nu\gamma}$. ἢ ΘE ἄρα πρὸς $\Theta\Gamma$ μείζονα
 λόγον ἔχει ἢ ὄν $\overline{\alpha\rho\omicron\beta}$ ἡ' πρὸς $\overline{\rho\nu\gamma}$. ἔτι δίχα ἢ
 ὑπὸ $\Theta\text{E}\Gamma$ τῆ EK . ἢ $\text{E}\Gamma$ ἄρα πρὸς ΓK μείζονα
 λόγον ἔχει ἢ ὄν $\overline{\beta\tau\lambda\delta}$ δ' πρὸς $\overline{\rho\nu\gamma}$. ἢ EK ἄρα πρὸς

SPECIAL PROBLEMS

so that $EH : HG > 591\frac{1}{8} : 153 . . (4)$

Again, let $\angle HEG$ be bisected by $E\theta$; then by the same reasoning

so that
$$\begin{aligned} [HE : EG &= H\theta : \theta G \text{ [Eucl. vi. 3]} \\ HE + EG : EG &= H\theta + \theta G : \theta G \\ &= HG : G\theta, \end{aligned}$$

or $HE + EG : HG = EG : G\theta.$

Therefore] $EG : G\theta$ $[= GE + EH : HG$
 $> 571 + 591\frac{1}{8} : 153,$
by (3) and (4),]

$> 1162\frac{1}{8} : 153 . . (5)$

[Hence $\theta E^2 : G\theta^2 = EG^2 + G\theta^2 : G\theta^2$

$> 1162\frac{1}{8}^2 + 153^2 : 153^2$

$> 1350534\frac{3}{8} + 23409 :$
23409

$> 1373943\frac{3}{8} : 23409,]$

so that $\theta E : \theta G > 1172\frac{1}{8} : 153 . . (6)$

Again, let θEG be bisected by EK .

Then $[\theta E : EG = \theta K : KG . \text{ [Eucl. vi. 3]}$

so that $\theta E + EG : EG = \theta K + KG : KG$

$= \theta G : GK, \text{ or}]$

$EG : GK$ $[= EG + \theta E : \theta G$

$> 1162\frac{1}{8} + 1172\frac{1}{8} : 153,$

by (5) and (6),]

$> 2334\frac{1}{4} : 153 . . (7)$

[Hence $EK^2 : GK^2 = EG^2 + GK^2 : GK^2$

$> 2334\frac{1}{4}^2 + 153^2 : 153^2$

$> 5472132\frac{1}{16} : 23409,]$

GREEK MATHEMATICS

ΓΚ μείζονα ἢ ὄν $\overline{\beta\tau\lambda\theta}$ δ' πρὸς $\overline{\rho\nu\gamma}$. ἔτι δίχα ἢ ὑπὸ ΚΕΓ τῆ ΛΕ· ἢ ΕΓ ἄρα πρὸς ΛΓ μείζονα [μήκει] λόγον ἔχει ἢ περ τὰ $\overline{\delta\chi\omicron\gamma}$ <' πρὸς $\overline{\rho\nu\gamma}$. ἐπεὶ οὖν ἢ ὑπὸ ΖΕΓ τρίτου οὔσα ὀρθῆς τέτμηται τετράκις δίχα, ἢ ὑπὸ ΛΕΓ ὀρθῆς ἐστὶ μῆ'. κείσθω οὖν αὐτῇ ἴση πρὸς τῷ Ε ἢ ὑπὸ ΓΕΜ· ἢ ἄρα ὑπὸ ΛΕΜ ὀρθῆς ἐστὶ κδ'. καὶ ἢ ΛΜ ἄρα εὐθεῖα τοῦ περι τὸν κύκλον ἐστὶ πολυγώνου πλευρὰ πλευρὰς ἔχοντος $\overline{\zeta\sigma}$. ἐπεὶ οὖν ἢ ΕΓ πρὸς τὴν ΓΛ ἐδείχθη μείζονα λόγον ἔχουσα ἢ περ $\overline{\delta\chi\omicron\gamma}$ <' πρὸς $\overline{\rho\nu\gamma}$, ἀλλὰ τῆς μὲν ΕΓ διπλῆ ἢ ΑΓ, τῆς δὲ ΓΛ διπλασίων ἢ ΛΜ, καὶ ἢ ΑΓ ἄρα πρὸς τὴν τοῦ $\overline{\zeta\sigma}$ -γώνου περίμετρον μείζονα λόγον ἔχει ἢ περ $\overline{\delta\chi\omicron\gamma}$ <' πρὸς $\overline{\mu}$ $\overline{\delta\chi\pi\eta}$. καὶ ἐστὶν τριπλάσια, καὶ ὑπερέχουσιν $\overline{\chi\zeta\zeta}$ <', ἢ περ τῶν $\overline{\delta\chi\omicron\gamma}$ <' ἐλάττονα ἐστὶν ἢ τὸ ἑβδομον· ὥστε τὸ πολύγωνον τὸ περι τὸν κύκλον τῆς διαμέτρου ἐστὶ τριπλάσιον καὶ ἐλάττιον ἢ τῷ ἑβδόμῳ μέρει μείζον· ἢ τοῦ κύκλου ἄρα περίμετρος πολὺ μᾶλλον ἐλάσσων ἐστὶν ἢ τριπλασίων καὶ ἑβδόμῳ μέρει μείζων.

Ἔστω κύκλος καὶ διάμετρος ἢ ΑΓ, ἢ δὲ ὑπὸ ΒΑΓ τρίτου ὀρθῆς· ἢ ΑΒ ἄρα πρὸς ΒΓ ἐλάσσονα λόγον ἔχει ἢ ὄν $\overline{\alpha\tau\nu\alpha}$ πρὸς $\overline{\psi\pi}$ [ἢ δὲ ΑΓ πρὸς ΓΒ, ὄν $\overline{\alpha\phi\zeta}$ πρὸς $\overline{\psi\pi}$]. δίχα ἢ ὑπὸ ΒΑΓ τῆ ΑΗ. ἐπεὶ οὖν ἴση ἐστὶν ἢ ὑπὸ ΒΑΗ τῆ ὑπὸ ΗΓΒ, ἀλλὰ

SPECIAL PROBLEMS

so that $EK : \Gamma K > 2339\frac{1}{4} : 153 \quad \dots (8)$

Again, let $\angle KE\Gamma$ be bisected by ΛE .

Then $[KE : E\Gamma = K\Lambda : \Lambda\Gamma \quad [\text{Eucl. vi. 3}]$

so that $KE + E\Gamma : E\Gamma = K\Lambda + \Lambda\Gamma : \Lambda\Gamma$

$$= K\Gamma : \Lambda\Gamma, \text{ or}]$$

$$E\Gamma : \Lambda\Gamma \quad [= E\Gamma + KE : K\Gamma$$

$$> 2334\frac{1}{4} + 2339\frac{1}{4} : 153,$$

by (7) and (8),]

$$> 4673\frac{1}{2} : 153.$$

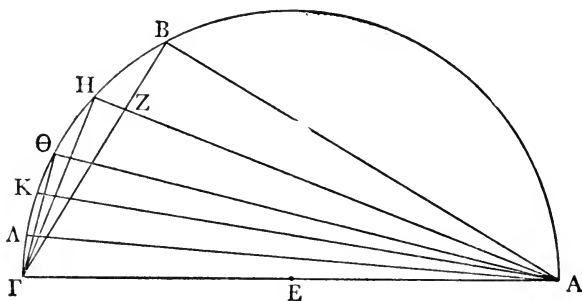
Now since $\angle ZEF$, which is the third part of a right angle, has been bisected four times, $\angle \Lambda E\Gamma$ is one forty-eighth of a right angle. Let $\angle \Gamma E M$ be placed at E equal to it. $\angle \Lambda E M$ is therefore one twenty-fourth of a right angle. And ΛM is therefore the side of a polygon escribed to the circle and having ninety-six sides. Since $E\Gamma : \Gamma\Lambda$ was proved to be greater than $4673\frac{1}{2} : 153$ and $\Lambda\Gamma = 2E\Gamma$, $\Lambda M = 2\Gamma\Lambda$, the ratio of $\Lambda\Gamma$ to the perimeter of the 96-sided polygon is greater than $[4673\frac{1}{2} : 96 \cdot 153, \text{ or}] 4673\frac{1}{2} : 14688$. And the ratio $[14688 : 4673\frac{1}{2}]$ is greater than 3, being in excess by $667\frac{1}{2}$, which is less than the seventh part of $4673\frac{1}{2}$; so that the [perimeter of the] escribed polygon is greater than three times the diameter by less than the seventh part; *a fortiori* therefore the circumference of the circle is less than $3\frac{1}{7}$ times the diameter.

Let there be a circle with diameter $\Lambda\Gamma$ and $\angle B\Lambda\Gamma$ one-third of a right angle. Then $AB : B\Gamma [= \sqrt{3} : 1] < 1351 : 780$.^a Let $B\Lambda\Gamma$ be bisected by AH . Now since $\angle BAH = \angle H\Gamma B$ and $\angle BAH = \angle H\Lambda\Gamma$, there-

^a See *supra*, p. 322 n. a.

GREEK MATHEMATICS

καὶ τῆ ὑπὸ ΗΑΓ, καὶ ἡ ὑπὸ ΗΓΒ τῆ ὑπὸ ΗΑΓ
 ἔστιν ἴση. καὶ κοινὴ ἡ ὑπὸ ΑΗΓ ὀρθή· καὶ τρίτη



ἄρα ἡ ὑπὸ ΗΖΓ τρίτη τῆ ὑπὸ ΑΓΗ ἴση. ἰσο-
 γώνιον ἄρα τὸ ΑΗΓ τῷ ΓΗΖ τριγώνω· ἔστιν
 ἄρα, ὡς ἡ ΑΗ πρὸς ΗΓ, ἡ ΓΗ πρὸς ΗΖ καὶ ἡ
 ΑΓ πρὸς ΖΓ. ἀλλ' ὡς ἡ ΑΓ πρὸς ΖΓ, [καὶ]
 συναμφοτέρος ἡ ΓΑΒ πρὸς ΒΓ· καὶ ὡς συναμ-
 φοτέρος ἄρα ἡ ΒΑΓ πρὸς ΒΓ, ἡ ΑΗ πρὸς ΗΓ.
 διὰ τοῦτο οὖν ἡ ΑΗ πρὸς [τὴν] ΗΓ ἐλάσσονα
 λόγον ἔχει ἢ περ $\overline{\beta\lambda\iota\alpha}$ πρὸς $\overline{\psi\pi}$, ἡ δὲ ΑΓ πρὸς τὴν
 ΓΗ ἐλάσσονα ἢ ὄν $\overline{\gamma\iota\gamma}$ \angle' δ' πρὸς $\overline{\psi\pi}$. δίχα ἡ ὑπὸ
 ΓΑΗ τῆ ΑΘ· ἡ ΑΘ ἄρα διὰ τὰ αὐτὰ πρὸς τὴν
 ΘΓ ἐλάσσονα λόγον ἔχει ἢ ὄν $\overline{\epsilon\lambda\kappa\delta}$ \angle' δ' πρὸς $\overline{\psi\pi}$
 ἢ ὄν $\overline{\alpha\omega\kappa\gamma}$ πρὸς $\overline{\sigma\mu}$ · ἑκατέρα γὰρ ἑκατέρας δ $\iota\gamma'$ ·
 ὥστε ἡ ΑΓ πρὸς τὴν ΓΘ ἢ ὄν $\overline{\alpha\omega\lambda\eta}$ θ $\iota\alpha'$ πρὸς

SPECIAL PROBLEMS

fore $\angle H\Gamma B = \angle H A \Gamma$. And the right angle $A H \Gamma$ is common. Therefore the third angle $H Z \Gamma$ is equal to the third angle $A \Gamma H$. The triangle $A H \Gamma$ is therefore equiangular with the triangle $\Gamma H Z$; therefore

$$A H : H \Gamma = \Gamma H : H Z = A \Gamma : \Gamma Z.$$

But $A \Gamma : \Gamma Z = \Gamma A + A B : B \Gamma$.

Therefore $B A + A \Gamma : B \Gamma = A H : H \Gamma$.

[But $B A : B \Gamma < 1351 : 780$, as stated above,
while $A \Gamma : B \Gamma = 2 : 1$
 $= 1560 : 780.$]

Therefore $A H : H \Gamma$ [$= 1351 + 1560 : 780$]
 $< 2911 : 780 \dots \dots (1a)$

Hence $A \Gamma^2 : \Gamma H^2 = A H^2 + H \Gamma^2 : \Gamma H^2$
 $< 2911^2 + 780^2 : 780^2$
 $< 9082321 : 608400,$

so that $A \Gamma : \Gamma H < 3013\frac{3}{4} : 780 \dots \dots (2a)$

Let $\angle \Gamma A H$ be bisected by $A \Theta$. By the same reasoning

$$\begin{aligned} A \Theta : \Theta \Gamma & [= A \Gamma + A H : \Gamma H \\ & < 3013\frac{3}{4} + 2911 : 780, \text{ by } (1a) \\ & \text{and } (2a),] \\ & < 5924\frac{3}{4} : 780 \\ & < \frac{4}{13} \cdot 5924\frac{3}{4} : \frac{4}{13} \cdot 780 \\ & < 1823 : 240 \dots \dots (3a) \end{aligned}$$

[Hence $A \Gamma^2 : \Gamma \Theta^2 = A \Theta^2 + \Gamma \Theta^2 : \Gamma \Theta^2$
 $< 1823^2 + 240^2 : 240^2$
 $< 3380929 : 57600.$]

Therefore $A \Gamma : \Gamma \Theta < 1838\frac{9}{11} : 240 \dots \dots (4a)$

GREEK MATHEMATICS

$\overline{\sigma\mu}$. ἔτι δίχα ἡ ὑπὸ ΘΑΓ τῆ ΚΑ· καὶ ἡ ΑΚ πρὸς τὴν ΚΓ ἐλάσσονα [ἄρα] λόγον ἔχει ἢ ὄν $\overline{\alpha\zeta}$ πρὸς $\overline{\xi\varsigma}$ · ἐκατέρα γὰρ ἐκατέρας $\overline{\iota\alpha}$ μ'. ἡ ΑΓ ἄρα πρὸς [τὴν] ΚΓ ἢ ὄν $\overline{\alpha\theta}$ ς' πρὸς $\overline{\xi\varsigma}$. ἔτι δίχα ἡ ὑπὸ ΚΑΓ τῆ ΛΑ· ἡ ΑΛ ἄρα πρὸς [τὴν] ΛΓ ἐλάσσονα λόγον ἔχει ἢ ὄν τὰ $\overline{\beta\iota\varsigma}$ ς' πρὸς $\overline{\xi\varsigma}$, ἡ δὲ ΑΓ πρὸς ΓΛ ἐλάσσονα ἢ τὰ $\overline{\beta\iota\zeta}$ δ' πρὸς $\overline{\xi\varsigma}$. ἀνάπαλιν ἄρα ἡ περίμετρος τοῦ πολυγώνου πρὸς τὴν διάμετρον μείζονα λόγον ἔχει ἢ περ $\overline{\varsigma\tau\lambda\varsigma}$ πρὸς $\overline{\beta\iota\zeta}$ δ', ἄπερ τῶν $\overline{\beta\iota\zeta}$ δ' μείζονά ἐστίν ἢ τριπλασίονα καὶ δέκα οα'. καὶ ἡ περίμετρος ἄρα τοῦ $\overline{\zeta\varsigma}$ -γώνου τοῦ ἐν τῷ κύκλῳ τῆς διαμέτρου τριπλασίων ἐστὶ καὶ μείζων ἢ $\overline{\iota}$ οα'. ὥστε καὶ ὁ κύκλος ἔτι μᾶλλον τριπλασίων ἐστὶ καὶ μείζων ἢ $\overline{\iota}$ οα'.

Ἡ ἄρα τοῦ κύκλου περίμετρος τῆς διαμέτρου

SPECIAL PROBLEMS

Further, let $\angle \Theta A \Gamma$ be bisected by KA .

$$\begin{aligned} \text{Then} \quad AK : K\Gamma & [= A\Gamma + A\Theta : \Gamma\Theta] \\ & < 1838\frac{9}{11} + 1823 : 24, \\ & \qquad \qquad \qquad \text{by (3a) and (4a),} \\ & < 3661\frac{9}{11} : 240] \\ & < \frac{11}{40} \cdot 3661\frac{9}{11} : \frac{11}{40} \cdot 240 \\ & < 1007 : 66 \quad \dots \dots \dots (5a) \end{aligned}$$

$$\begin{aligned} [\text{Hence} \quad A\Gamma^2 : K\Gamma^2 & = AK^2 + K\Gamma^2 : K\Gamma^2 \\ & < 1007^2 + 66^2 : 66^2 \\ & < 1018405 : 4356.] \end{aligned}$$

$$\text{Therefore} \quad A\Gamma : K\Gamma < 1009\frac{1}{8} : 66 \quad \dots \dots \dots (6a)$$

Further, let $\angle K A \Gamma$ be bisected by ΛA .

$$\begin{aligned} \text{Then} \quad A\Lambda : \Lambda\Gamma & [= \Gamma A + AK : \Gamma K] \\ & < 1009\frac{1}{8} + 1007 : 66, \text{ by (5a)} \\ & \qquad \qquad \qquad \text{and (6a),]} \\ & < 2016\frac{1}{8} : 66. \end{aligned}$$

$$\begin{aligned} [\text{Hence} \quad A\Gamma^2 : \Gamma\Lambda^2 & = A\Lambda^2 + \Lambda\Gamma^2 : \Gamma\Lambda^2 \\ & < 2016\frac{1}{8}^2 + 66^2 : 66^2 \\ & < 4069284\frac{1}{8} : 4356.] \end{aligned}$$

$$\begin{aligned} \text{Therefore} \quad A\Gamma : \Gamma\Lambda & < 2017\frac{1}{4} : 66, \\ \text{and } \textit{invertendo} & [\Gamma\Lambda : A\Gamma > 66 : 2017\frac{1}{4}. \end{aligned}$$

But $\Gamma\Lambda$ is the side of a polygon of 96 sides; and accordingly] the perimeter of the polygon bears to the diameter a ratio greater than $[96 \cdot 66 : 2017\frac{1}{4}]$, or $6336 : 2017\frac{1}{4}$, which is greater than $3\frac{1}{71}$. Therefore the perimeter of the 96-sided polygon is greater than $3\frac{1}{71}$ times the diameter, so that *a fortiori* the circle is greater than $3\frac{1}{71}$ times the diameter.

The perimeter of the circle is therefore more than

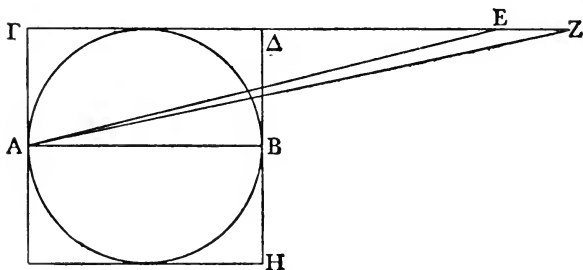
GREEK MATHEMATICS

τριπλασίων ἐστὶ καὶ ἐλάσσονι μὲν ἢ ἐβδόμῳ μέρει, μείζονι δὲ ἢ ἰσᾶ' μείζων.

β'

Ὁ κύκλος πρὸς τὸ ἀπὸ τῆς διαμέτρου τετράγωνον λόγον ἔχει, ὃν $\overline{\iota\alpha}$ πρὸς $\overline{\iota\delta}$.

Ἐστω κύκλος, οὗ διάμετρος ἡ AB , καὶ περιγεγράφθω τετράγωνον τὸ ΓH , καὶ τῆς $\Gamma\Delta$ διπλῆ ἡ ΔE , ἑβδομον δὲ ἡ EZ τῆς $\Gamma\Delta$. ἐπεὶ οὖν τὸ



$\Delta\Gamma E$ πρὸς τὸ $\Delta\Gamma\Delta$ λόγον ἔχει, ὃν $\overline{\kappa\alpha}$ πρὸς ζ , πρὸς δὲ τὸ $\Delta E Z$ τὸ $\Delta\Gamma\Delta$ λόγον ἔχει, ὃν ἑπτὰ πρὸς ἓν, τὸ $\Delta\Gamma Z$ πρὸς τὸ $\Delta\Gamma\Delta$ ἐστίν, ὡς $\overline{\kappa\beta}$ πρὸς ζ . ἀλλὰ τοῦ $\Delta\Gamma\Delta$ τετραπλασίον ἐστὶ τὸ ΓH τετράγωνον, τὸ δὲ $\Delta\Gamma\Delta Z$ τρίγωνον τῷ AB κύκλῳ ἴσον ἐστίν [ἐπεὶ ἡ μὲν $\Delta\Gamma$ κάθετος ἴση ἐστὶ τῇ ἐκ τοῦ κέντρου, ἡ δὲ βᾶσις τῆς διαμέτρου τριπλασίον καὶ τῷ ζ' ἔγγιστα ὑπερέχουσα δειχθήσεται]¹. ὁ κύκλος οὖν πρὸς τὸ ΓH τετράγωνον λόγον ἔχει, ὃ $\overline{\iota\alpha}$ πρὸς $\overline{\iota\delta}$.

SPECIAL PROBLEMS

three times the diameter, exceeding by a quantity less than the seventh part but greater than ten seventy-first parts.^a

Prop. 2

The circle bears to the square on the diameter the ratio 11 : 14.

Let there be a circle with diameter AB, and let the square ΓH be circumscribed, and let $\Delta E = 2\Gamma\Delta$, $EZ = \frac{1}{7}\Gamma\Delta$. Then, since $A\Gamma E : A\Gamma\Delta = 21 : 7$, while $A\Gamma\Delta : AEZ = 7 : 1$ [Euclid vi. 1], it follows that $A\Gamma Z : A\Gamma\Delta = 22 : 7$.^b But the square $\Gamma H = 4 A\Gamma\Delta$, while the triangle $A\Gamma\Delta Z$ is equal to the circle AB; therefore the circle bears to the square ΓH the ratio 11 : 14.

^a We know from Heron, *Metrica* i. 26 (ed. Schöne 66. 13-17), that Archimedes made a still closer approximation to π . The figures in the Greek text are unfortunately corrupt, but a plausible correction by Heiberg (*Nordisk Tidsskrift for Filologi*, 3^e Sér. xx. Fasc. 1-2) would give the approximation

$$3.141697 \dots > \pi > 3.141495 \dots$$

Ptolemy, *Syntaxis* vi. 7 (ed. Heiberg 513. 1-5), gives the value of π in sexagesimal fractions as $3 + \frac{8}{60} + \frac{30}{60^2}$ or $3.141\dot{6}$.

^b For *ἀνάπαλιν* $AEZ : A\Gamma\Delta = 1 : 7$, and $A\Gamma E : A\Gamma\Delta = 21 : 7$, and therefore *συνθέντι* $A\Gamma Z : A\Gamma\Delta = (AEZ + A\Gamma E) : A\Gamma\Delta = 22 : 7$. But the same result could be obtained immediately from Eucl. vi. 1.

¹ "Hic locus ἐπεὶ . . . δειχθήσεται mire confusus transcriptori tribuendus, qui eum addidit, postquam prop. 2 et 3 permutavit; neque enim Archimedes hanc propositionem ante prop. 3, qua nititur, posuit" (Heiberg).

GREEK MATHEMATICS

(c) SOLUTIONS BY HIGHER CURVES

(i.) *General*

Simpl. in *Cat.* 7, ed. Kalbfleisch 192. 15-25

Ἔστιν δὲ τετραγωνισμὸς κύκλου, ὅταν τῷ δοθέντι κύκλῳ ἴσον τετράγωνον συστησώμεθα. τοῦτο δὲ Ἀριστοτέλης μὲν, ὡς ἔοικεν, οὐπω ἐγνώκει, παρὰ δὲ τοῖς Πυθαγορείοις ηὔρησθαί φησιν Ἰάμβλιχος, “ὡς δῆλόν ἐστιν ἀπὸ τῶν Σέξτου τοῦ Πυθαγορείου ἀποδείξεων, ὃς ἄνωθεν κατὰ διαδοχὴν παρέλαβεν τὴν μέθοδον τῆς ἀποδείξεως. καὶ ὕστερον δέ, φησὶν, Ἀρχιμήδης διὰ τῆς Λυκομήδους¹ γραμμῆς καὶ Νικομήδης διὰ τῆς ἰδίως τετραγωνιζούσης καλουμένης καὶ Ἀπολλώνιος διὰ τινος γραμμῆς, ἣν αὐτὸς μὲν κοχλιοειδοῦς ἀδελφὴν προσγορεύει, ἣ αὐτὴ δὲ ἐστὶν τῇ Νικομήδους, καὶ Κάρπος δὲ διὰ τινος γραμμῆς, ἣ ἀπλῶς ἐκ διπλῆς κινήσεως καλεῖ, ἄλλοι τε πολλοὶ ποικίλως τὸ πρόβλημα κατεσκεύασαν,” ὡς Ἰάμβλιχος ἱστορεῖ.

¹ No meaning can be extracted from *Λυκομήδους*, which is an otherwise unknown word. The correct reading is probably *ἑλικοειδοῦς*, “spiral-shaped.”

SPECIAL PROBLEMS

(c) SOLUTIONS BY HIGHER CURVES

(i.) *General*

Simplicius, *Commentary on Aristotle's Categories* 7,
ed. Kalbfleisch 192. 15-25

The circle is squared when we construct a square equal to the given circle. Aristotle, it would appear, did not know how to do this, but Iamblichus says it was discovered by the Pythagoreans, "as is plain from the proofs of Sextus the Pythagorean,^a who received the method of the proof from early tradition. And later (he says), Archimedes effected it by means of the spiral-shaped curve,^b Nicomedes by means of the curve known by the special name *quadratrix*, Apollonius by means of a certain curve which he himself calls *sister of the cochloid*, but which is the same as Nicomedes' curve,^c Carpus by means of a certain curve which he simply calls that *arising from a double motion*,^d and many others constructed a solution of this problem in divers ways," as Iamblichus relates.

^a Sextus (more properly Sextius) lived in the reign of Augustus (or Tiberius) and there is no valid reason for believing the early Pythagoreans solved the problem.

^b Archimedes himself in his book *On Spirals*, which will be noticed when we come to him, merely uses the spiral to rectify the circle (Prop. 19). But the quadrature follows from *Measurement of a Circle*, Prop. 1.

^c Nothing further is known of Apollonius's "*sister of the cochloid*," but Heath (*H.G.M.* i. 232) points out that Apollonius wrote a treatise on the *cochlias*, or cylindrical helix, that the subtangent to this curve can be used to square the circular section of the cylinder, and that the name is sufficiently akin to justify Apollonius in speaking of it as the "*sister of the cochloid*."

^d Tannery thought this was the cycloid, but there is no evidence.

GREEK MATHEMATICS

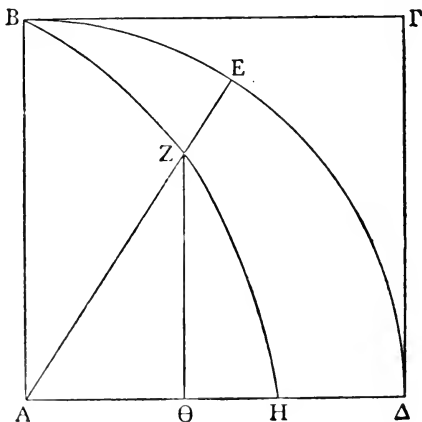
(ii.) *The Quadratrix*

Papp. *Coll.* iv. 30. 45-32. 50, ed. Hultsch 250. 33-258. 19

Construction of the Curve

λ'. Εἰς τὸν τετραγωνισμόν τοῦ κύκλου παρελήφθη τις ὑπὸ Δεινοστράτου καὶ Νικομήδους γραμμὴ καὶ τινῶν ἄλλων νεωτέρων ἀπὸ τοῦ περιὸς αὐτὴν συμπτώματος λαβοῦσα τοῦνομα· καλεῖται γὰρ ὑπ' αὐτῶν τετραγωνίζουσα καὶ γένεσιν ἔχει τοιαύτην.

Ἐκκείσθω τετράγωνον τὸ ΑΒΓΔ καὶ περιὸς κέντρον τὸ Α περιφέρεια γεγράφθω ἡ ΒΕΔ, καὶ



κινείσθω ἡ μὲν ΑΒ οὕτως ὥστε τὸ μὲν Α σημεῖον μένειν τὸ δὲ Β φέρεσθαι κατὰ τὴν ΒΕΔ περιφέρειαν, ἡ δὲ ΒΓ παράλληλος αἰεὶ διαμένουσα τῇ ΑΔ τῷ Β σημείῳ φερομένῳ¹ κατὰ τῆς ΒΑ συνακολουθείτω, καὶ ἐν ἴσῳ χρόνῳ ἡ τε ΑΒ κινουμένη

SPECIAL PROBLEMS

(ii.) *The Quadratrix*

Pappus, *Collection* iv. 30. 45-32. 50, ed. Hultsch
250. 33-258. 19

Construction of the Curve

30. For the squaring of the circle a certain line was used by Dinostratus and Nicomedes and certain other more recent geometers, and it takes its name from its special property; for it is called by them the quadratrix,^a and it is generated in this way.

Let $AB\Gamma\Delta$ be a square, and with centre A let the arc $BE\Delta$ be described, and let AB be so moved that the point A remains fixed while B is carried along the arc $BE\Delta$; furthermore let $B\Gamma$, while always remaining parallel to $A\Delta$, follow the point B in its motion along BA , and in equal times let AB , moving uni-

^a Heath (*H.G.M.* i. 225-226) shows that the quadratrix was discovered by Hippias and that he may himself have used it (though this is not absolutely certain) to rectify, and so to square, the circle.

¹ σημείον φέρον ἐν ϕ in the MSS. was corrected by Torelli.

GREEK MATHEMATICS

ὁμαλῶς τὴν ὑπὸ ΒΑΔ γωνίαν, τουτέστιν τὸ Β σημείον τὴν ΒΕΔ περιφέρειαν, διανύτω, καὶ ἡ ΒΓ τὴν ΒΑ εὐθείαν παροδενέτω, τουτέστιν τὸ Β σημείον κατὰ τῆς ΒΑ φερέσθω. συμβήσεται δῆλον τῇ ΑΔ εὐθείᾳ ἅμα ἐφαρμόζειν ἑκατέραν τὴν τε ΑΒ καὶ τὴν ΒΓ. τοιαύτης δὲ γινομένης κινήσεως τεμοῦσιν ἀλλήλας ἐν τῇ φορᾷ αἱ ΒΓ, ΒΑ εὐθεῖαι κατὰ τι σημείον αἰεὶ συμμεθιστάμενον αὐταῖς, ὑφ' οὗ σημείου γράφεται τις ἐν τῷ μεταξὺ τόπῳ τῶν τε ΒΑΔ εὐθειῶν καὶ τῆς ΒΕΔ περιφερείας γραμμὴ ἐπὶ τὰ αὐτὰ κοίλη, οἷα ἐστὶν ἡ ΒΖΗ, ἣ καὶ χρειώδης εἶναι δοκεῖ πρὸς τὸ τῷ δοθέντι κύκλῳ τετράγωνον ἴσον εὔρειν. τὸ δὲ ἀρχικὸν αὐτῆς σύμπτωμα τοιοῦτόν ἐστιν. ἥτις γὰρ ἂν διαχθῆ τυχούσα (πρὸς τὴν περιφέρειαν, ὡς ἡ ΑΖΕ, ἔσται ὡς ὅλη ἡ)¹ περιφέρεια πρὸς τὴν ΕΔ, ἡ ΒΑ εὐθεῖα πρὸς τὴν ΖΘ· τοῦτο γὰρ ἐκ τῆς γενέσεως τῆς γραμμῆς φανερόν ἐστιν.

Sporus's Criticisms

λα'. Δυσαρεστεῖται δὲ αὐτῇ ὁ Σπόρος εὐλόγως διὰ ταῦτα. πρῶτον μὲν γὰρ πρὸς ὃ δοκεῖ χρειώδης εἶναι πᾶγμα, τοῦτ' ἐν ὑποθέσει λαμβάνει. πῶς γὰρ δυνατόν, δύο σημείων ἀρξαμένων ἀπὸ τοῦ Β

¹ πρὸς τὴν . . . ὅλη ἡ add. Hultsch.

SPECIAL PROBLEMS

formly, pass through the angle $BA\Delta$ (that is, the point B pass along the arc $B\Delta$), and $B\Gamma$ pass by the straight line BA (that is, let the point B traverse the length of BA). Plainly then both AB and $B\Gamma$ will coincide simultaneously with the straight line $A\Delta$. While the motion is in progress the straight lines $B\Gamma$, BA will cut one another in their movement at a certain point which continually changes place with them, and by this point there is described in the space between the straight lines BA , $A\Delta$ and the arc $BE\Delta$ a concave curve, such as BZH , which appears to be serviceable for the discovery of a square equal to the given circle. Its principal property is this. If any straight line, such as AZE , be drawn to the circumference, the ratio of the whole arc to $E\Delta$ will be the same as the ratio of the straight line BA to $Z\Theta$; for this is clear from the manner in which the line was generated.^a

Sporus's Criticisms^b

31. With this Sporus is rightly displeased for these reasons. In the first place, the end for which the construction seems to be useful is assumed in the hypothesis. For how is it possible, with two points

^a If $AZ = \rho$, $\angle ZA\Delta = \phi$, $AB = a$, then the equation of the curve is

$$\frac{\frac{1}{2}\pi}{\phi} = \frac{a}{\rho \sin \phi}$$

or

$$\pi \rho \sin \phi = 2a\phi.$$

^b These acute criticisms of the quadratrix as a practical method of squaring the circle appear to be well founded. Sporus, who was not much older than Pappus himself, lived towards the end of the third century A.D. He compiled a work called *Κηρία* giving extracts on the quadrature of the circle and duplication of the cube.

GREEK MATHEMATICS

κινεῖσθαι, τὸ μὲν κατ' εὐθείας ἐπὶ τὸ Α, τὸ δὲ κατὰ περιφερείας ἐπὶ τὸ Δ ἐν ἴσῳ χρόνῳ συναποκαταστήσῃαι¹ μὴ πρότερον τὸν λόγον τῆς ΑΒ εὐθείας πρὸς τὴν ΒΕΔ περιφέρειαν ἐπιστάμενον; ἐν γὰρ τούτῳ τῷ λόγῳ καὶ τὰ τάχη τῶν κινήσεων ἀνάγκη εἶναι. ἐπεὶ πῶς οἶόν τε συναποκαταστήναι τάχεσιν ἀκρίτοις χρώμενα, πλὴν εἰ μὴ ἂν κατὰ τύχην ποτὲ συμβῆ; τοῦτο δὲ πῶς οὐκ ἄλογον; ἔπειτα δὲ τὸ πέρασ αὐτῆς ᾧ χρῶνται πρὸς τὸν τετραγωνισμόν τοῦ κύκλου, τουτέστιν καθ' ὃ τέμνει σημεῖον τὴν ΑΔ εὐθείαν, οὐχ εὐρίσκεται. νοεῖσθω δὲ ἐπὶ τῆς προκειμένης τὰ λεγόμενα καταγραφῆς· ὁπόταν γὰρ αἱ ΓΒ, ΒΑ φερόμεναι συναποκατασταθῶσιν, ἐφαρμόσουσιν τῇ ΑΔ καὶ τομὴν οὐκέτι ποιήσουσιν ἐν ἀλλήλαις· παύεται γὰρ ἡ τομὴ πρὸ τῆς ἐπὶ τὴν ΑΔ ἐφαρμογῆς ἢ περ τομὴ πέρασ αὐτῆς ἐγένετο τῆς γραμμῆς, καθ' ὃ τῇ ΑΔ εὐθείᾳ συνέπιπτεν. πλὴν εἰ μὴ λέγοι τις ἐπινοεῖσθαι προσεκβαλλομένην τὴν γραμμὴν, ὡς ὑποτιθέμεθα τὰς εὐθείας, ἕως τῆς ΑΔ. τοῦτο δ' οὐχ ἔπεται ταῖς ὑποκειμέναις ἀρχαῖς, ἀλλ' ὡς ἂν ληφθεῖη τὸ Η σημεῖον προειλημμένου τοῦ τῆς περιφερείας πρὸς τὴν εὐθείαν λόγου. χωρὶς δὲ τοῦ δοθῆναι τὸν λόγον τοῦτον οὐ χρὴ τῇ τῶν εὐρόντων ἀνδρῶν δόξῃ πιστεύοντασ παραδέχεσθαι τὴν γραμμὴν μηχανικωτέραν πῶσ οὔσαν [καὶ εἰσ πολλὰ προβλήματα χρησιμεύουσαν τοῖσ μηχανικοῖσ].² ἀλλὰ πρότερον παραδεκτέον ἐστὶ τὸ δι' αὐτῆσ δεικνύμενον πρόβλημα.

¹ συναποκαταστήναι coniecit Hultsch.

² καὶ . . . μηχανικοῖσ interpolatori tribuit Hultsch.

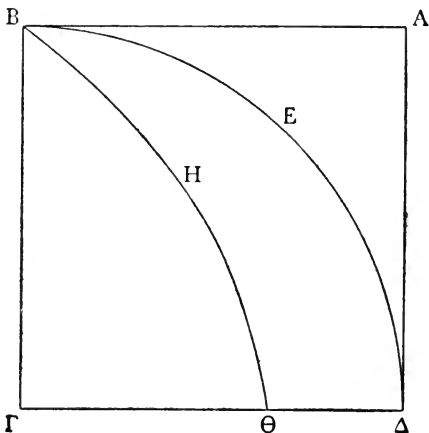
SPECIAL PROBLEMS

beginning to move from B, to make one of them move along a straight line to A and the other along a circumference to Δ in equal time unless first the ratio of the straight line AB to the circumference BE Δ is known? For it is necessary that the speeds of the moving points should be in this ratio. And how then could one, using unadjusted speeds, make the motions end together, unless this should sometimes happen by chance? But how could this fail to be irrational? Again, the extremity of the curve which they use for the squaring of the circle, that is, the point in which the curve cuts the straight line A Δ , is not found. Let the construction be conceived as aforesaid. When the straight lines ΓB , BA move so as to end their motion together, they will coincide with A Δ and will no longer cut each other. In fact, the intersection ceases before the coincidence with A Δ , yet it was this intersection which was the extremity of the curve where it met the straight line A Δ . Unless, indeed, anyone should say the curve is conceived as produced, in the same way that we produce straight lines, as far as A Δ . But this does not follow from the assumptions made; the point H can be found only by assuming the ratio of the circumference to the straight line. So unless this ratio is given, we must beware lest, in following the authority of those men who discovered the line, we admit its construction, which is more a matter of mechanics. But first let us deal with that problem which we have said can be proved by means of it.

GREEK MATHEMATICS

Application of Quadratrix to Squaring of Circle

Τετραγώνου γὰρ ὄντος τοῦ ΑΒΓΔ καὶ τῆς μὲν περὶ τὸ κέντρον τὸ Γ περιφερείας τῆς ΒΕΔ, τῆς



δὲ ΒΗΘ τετραγωνιζούσης γινομένης, ὡς προείρηται, δείκνυται, ὡς ἡ ΔΕΒ περιφέρεια πρὸς τὴν ΒΓ εὐθείαν, οὕτως ἡ ΒΓ πρὸς τὴν ΓΘ εὐθείαν. εἰ γὰρ μὴ ἔστιν, ἦτοι πρὸς μείζονα ἔσται τῆς ΓΘ ἢ πρὸς ἐλάσσονα.

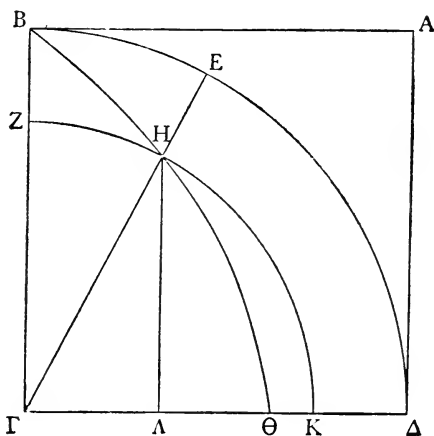
Ἔστω πρότερον, εἰ δυνατόν, πρὸς μείζονα τὴν ΓΚ, καὶ περὶ κέντρον τὸ Γ περιφέρεια ἡ ΖΗΚ γεγράφθω τέμνουσα τὴν γραμμὴν κατὰ τὸ Η, καὶ κάθετος ἡ ΗΛ, καὶ ἐπιζευχθεῖσα ἡ ΓΗ ἐκβεβλήσθω ἐπὶ τὸ Ε. ἐπεὶ οὖν ἔστιν ὡς ἡ ΔΕΒ περιφέρεια πρὸς τὴν ΒΓ εὐθείαν, οὕτως ἡ ΒΓ,

SPECIAL PROBLEMS

Application of Quadratrix to Squaring of Circle

If $AB\Gamma\Delta$ is a square and $BE\Delta$ the arc of a circle with centre Γ , while $BH\Theta$ is a quadratrix generated in the aforesaid manner, it is proved that the ratio of the arc ΔEB towards the straight line $B\Gamma$ is the same as that of $B\Gamma$ towards the straight line $\Gamma\Theta$. For if it is not, the ratio of the arc ΔEB towards the straight line $B\Gamma$ will be the same as that of $B\Gamma$ towards either a straight line greater than $\Gamma\Theta$ or a straight line less than $\Gamma\Theta$.

Let it be the former, if possible, towards a greater straight line ΓK , and with centre Γ let the arc ZHK be drawn cutting the curve at H , and let the perpendicular $H\Lambda$ be drawn, and let ΓH be joined and pro-

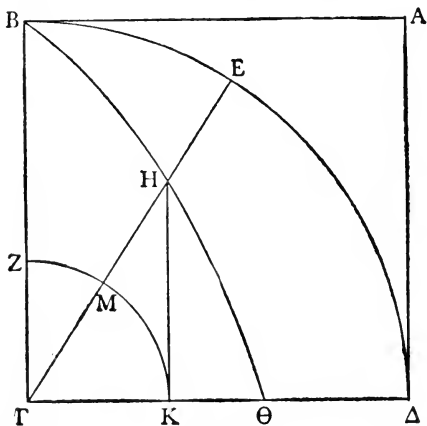


duced to E . Since therefore the ratio of the arc ΔEB towards the straight line $B\Gamma$ is the same as the

GREEK MATHEMATICS

τουτέστιν ἡ $\Gamma\Delta$, πρὸς τὴν $\Gamma\text{Κ}$, ὡς δὲ ἡ $\Gamma\Delta$ πρὸς τὴν $\Gamma\text{Κ}$, ἡ $\text{ΒΕ}\Delta$ περιφέρεια πρὸς τὴν $\text{ΖΗ}\text{Κ}$ περιφέρεια (ὡς γὰρ ἡ διάμετρος τοῦ κύκλου πρὸς τὴν διάμετρον, ἡ περιφέρεια τοῦ κύκλου πρὸς τὴν περιφέρεια), φανερόν ὅτι ἴση ἐστὶν ἡ $\text{ΖΗ}\text{Κ}$ περιφέρεια τῇ $\text{Β}\Gamma$ εὐθείᾳ. καὶ ἐπειδὴ διὰ τὸ σύμπτωμα τῆς γραμμῆς ἐστὶν ὡς ἡ $\text{ΒΕ}\Delta$ περιφέρεια πρὸς τὴν $\text{Ε}\Delta$, οὕτως ἡ $\text{Β}\Gamma$ πρὸς τὴν $\text{Η}\Lambda$, καὶ ὡς ἄρα ἡ $\text{ΖΗ}\text{Κ}$ πρὸς τὴν $\text{Η}\text{Κ}$ περιφέρεια, οὕτως ἡ $\text{Β}\Gamma$ εὐθεῖα πρὸς τὴν $\text{Η}\Lambda$. καὶ ἐδείχθη ἴση ἡ $\text{ΖΗ}\text{Κ}$ περιφέρεια τῇ $\text{Β}\Gamma$ εὐθείᾳ· ἴση ἄρα καὶ ἡ $\text{Η}\text{Κ}$ περιφέρεια τῇ $\text{Η}\Lambda$ εὐθείᾳ, ὅπερ ἄτοπον. οὐκ ἄρα ἐστὶν ὡς ἡ $\text{ΒΕ}\Delta$ περιφέρεια πρὸς τὴν $\text{Β}\Gamma$ εὐθεῖαν, οὕτως ἡ $\text{Β}\Gamma$ πρὸς μείζονα τῆς $\Gamma\Theta$.

λβ'. Λέγω δὲ ὅτι οὐδὲ πρὸς ἐλάσσονα. εἰ γὰρ



δυνατόν, ἔστω πρὸς τὴν $\text{Κ}\Gamma$, καὶ περὶ κέντρον τὸ

SPECIAL PROBLEMS

ratio of $B\Gamma$, that is $\Gamma\Delta$, towards ΓK , and the ratio of $\Gamma\Delta$ towards ΓK is the same as that of the arc $BE\Delta$ towards the arc ZHK (for the arcs of circles are in the same ratio as their diameters), it is clear that the arc ZHK is equal to the straight line $B\Gamma$. And since by the property of the curve the ratio of the arc $BE\Delta$ towards $E\Delta$ is the same as the ratio of $B\Gamma$ towards $H\Lambda$, therefore the ratio of ZHK towards the arc HK is the same as the ratio of the straight line $B\Gamma$ towards $H\Lambda$. And the arc ZHK was proved equal to the straight line $B\Gamma$; therefore the arc HK is also equal to the straight line $H\Lambda$, which is absurd. Therefore the ratio of the arc $BE\Delta$ towards the straight line $B\Gamma$ is not the same as the ratio of $B\Gamma$ towards a straight line greater than $\Gamma\Theta$.

32. I say that neither is it equal to the ratio of $B\Gamma$ towards a straight line less than $\Gamma\Theta$. For, if it is possible, let the ratio be towards $K\Gamma$, and with centre

GREEK MATHEMATICS

Γ περιφέρεια γεγράφθω ἢ ΖΜΚ, καὶ πρὸς ὀρθὰς τῇ ΓΔ ἢ ΚΗ τέμνουσα τὴν τετραγωνίζουσαν κατὰ τὸ Η, καὶ ἐπιζευχθεῖσα ἢ ΓΗ ἐκβεβλήσθω ἐπὶ τὸ Ε. ὁμοίως δὴ τοῖς προγεγραμμένοις δείξομεν καὶ τὴν ΖΜΚ περιφέρειαν τῇ ΒΓ εὐθείᾳ ἴσην, καὶ ὡς τὴν ΒΕΔ περιφέρειαν πρὸς τὴν ΕΔ, τουτέστιν ὡς τὴν ΖΜΚ πρὸς τὴν ΜΚ, οὕτως τὴν ΒΓ εὐθεῖαν πρὸς τὴν ΗΚ. ἐξ ὧν φανερόν ὅτι ἴση ἔσται ἢ ΜΚ περιφέρεια τῇ ΚΗ εὐθείᾳ, ὅπερ ἄτοπον. οὐκ ἄρα ἔσται ὡς ἢ ΒΕΔ περιφέρεια πρὸς τὴν ΒΓ εὐθεῖαν, οὕτως ἢ ΒΓ πρὸς ἐλάσσονα τῆς ΓΘ. ἐδείχθη δὲ ὅτι οὐδὲ πρὸς μείζονα· πρὸς αὐτὴν ἄρα τὴν ΓΘ.

Ἔστι δὲ καὶ τοῦτο φανερόν ὅτι ἢ τῶν ΘΓ, ΓΒ εὐθειῶν τρίτη ἀνάλογον λαμβανομένη εὐθεῖα ἴση ἔσται τῇ ΒΕΔ περιφερείᾳ, καὶ ἢ τετραπλασίων αὐτῆς τῇ τοῦ ὅλου κύκλου περιφερείᾳ. εὐρημένης δὲ τῇ τοῦ κύκλου περιφερείᾳ ἴσης εὐθείας πρόδηλον ὡς δὴ καὶ αὐτῷ τῷ κύκλῳ ῥάδιον ἴσον τετράγωνον συστήσασθαι· τὸ γὰρ ὑπὸ τῆς περιμέτρου τοῦ κύκλου καὶ τῆς ἐκ τοῦ κέντρου διπλάσιόν ἐστι τοῦ κύκλου, ὡς Ἀρχιμήδης ἀπέδειξεν.

3. TRISECTION OF AN ANGLE

(a) TYPES OF GEOMETRICAL PROBLEMS

Papp. *Coll.* iv. 36. 57-59, ed. Hultsch 270. 1-272. 14

λς'. Τὴν δοθεῖσαν γωνίαν εὐθύγραμμον εἰς τρία ἴσα τεμεῖν οἱ παλαιοὶ γεωμέτραι θελήσαντες ἠπόρησαν δι' αἰτίαν τοιαύτην. τρία γένη φαμέν εἶναι

SPECIAL PROBLEMS

Γ let the arc ZMK be described, and let KH at right angles to $\Gamma\Delta$ cut the quadratrix at H , and let ΓH be joined and produced to E . In similar manner to what has been written above, we shall prove also that the arc ZMK is equal to the straight line $B\Gamma$, and that the ratio of the arc $BE\Delta$ towards $E\Delta$, that is, the ratio of ZMK towards MK , is the same as that of the straight line $B\Gamma$ towards HK . From this it is clear that the arc MK is equal to the straight line KH , which is absurd. The ratio of the arc $BE\Delta$ towards the straight line $B\Gamma$ is therefore not the same as the ratio of $B\Gamma$ towards a straight line less than $\Gamma\Theta$. Moreover it was proved not the same as the ratio of $B\Gamma$ towards a straight line greater than $\Gamma\Theta$; therefore it is the same as the ratio of $B\Gamma$ towards $\Gamma\Theta$ itself.

This also is clear, that if a straight line is taken as a third proportional to the straight lines $\Theta\Gamma$, ΓB it will be equal to the arc $BE\Delta$, and four times this straight line will be equal to the circumference of the whole circle. A straight line equal to the circumference of the circle having been found, a square can easily be constructed equal to the circle itself. For the rectangle contained by the perimeter of the circle and the radius is double of the circle, as Archimedes demonstrated.^a

3. TRISECTION OF AN ANGLE

(a) TYPES OF GEOMETRICAL PROBLEMS

Pappus, *Collection* iv. 36. 57-59, ed. Hultsch 270. 1-272. 14

36. When the ancient geometers sought to divide a given rectilinear angle into three equal parts they were at a loss for this reason. We say that there

^a See *supra*, pp. 316-321.

GREEK MATHEMATICS

τῶν ἐν γεωμετρία προβλημάτων, καὶ τὰ μὲν αὐτῶν ἐπίπεδα καλεῖσθαι, τὰ δὲ στερεά, τὰ δὲ γραμμικά. τὰ μὲν οὖν δι' εὐθείας καὶ κύκλου περιφερείας δυνάμενα λύεσθαι λέγοντ' ἂν εἰκότως ἐπίπεδα· καὶ γὰρ αἱ γραμμαὶ δι' ὧν εὐρίσκεται τὰ τοιαῦτα προβλήματα τὴν γένεσιν ἔχουσιν ἐν ἐπιπέδῳ. ὅσα δὲ λύεται προβλήματα παραλαμβανομένης εἰς τὴν εὐρεσιν μιᾶς τῶν τοῦ κώνου τομῶν ἢ καὶ πλειόνων, στερεὰ ταῦτα κέκληται· πρὸς γὰρ τὴν κατασκευὴν χρῆσασθαι στερεῶν σχημάτων ἐπιφανείαις, λέγω δὲ ταῖς κωνικαῖς, ἀναγκαῖον. τρίτον δέ τι προβλημάτων ὑπολείπεται γένος τὸ καλούμενον γραμμικόν· γραμμαὶ γὰρ ἕτεραι παρὰ τὰς εἰρημένας εἰς τὴν κατασκευὴν λαμβάνονται ποικιλωτέραν ἔχουσαι τὴν γένεσιν καὶ βεβιασμένην μᾶλλον, ἐξ ἀτακτοτέρων ἐπιφανειῶν καὶ κινήσεων ἐπιπεπλεγμένων γεννῶμεναι. τοιαῦται δὲ εἰσιν αἱ τε ἐν τοῖς πρὸς ἐπιφανείαις καλουμένοις τόποις εὐρισκόμεναι γραμμαὶ ἕτεραί τε τούτων ποικιλώτεραι καὶ πολλαὶ τὸ πλῆθος ὑπὸ Δημητρίου τοῦ Ἀλεξανδρέως ἐν ταῖς Γραμμικαῖς ἐπιστάσεσι καὶ Φίλωνος τοῦ Τυανέως ἐξ ἐπιπλοκῆς πλεκτοειδῶν τε καὶ ἐτέρων παντοίων ἐπιφανειῶν εὐρισκόμεναι πολλὰ καὶ θαυμαστὰ συμπτώματα περὶ αὐτὰς ἔχουσαι. καὶ τινες αὐτῶν ὑπὸ τῶν νεωτέρων ἠξιώθησαν λόγου πλείονος, μία δὲ τις ἐξ αὐτῶν ἔστιν ἢ καὶ παράδοξος ὑπὸ τοῦ Μενελάου κληθεῖσα γραμμή. τοῦ δὲ αὐτοῦ γένους ἕτεραι ἑλικές εἰσιν

* Whether τοποὶ πρὸς ἐπιφανείαις are "loci which are surfaces" or "loci which lie on surfaces" (e.g., the cylindrical helix) is a moot point. Euclid wrote two books under the title.

SPECIAL PROBLEMS

are three kinds of problems in geometry, some being called *plane*, some *solid*, some *linear*. Those which can be solved by means of a straight line and a circumference of a circle are properly called plane; for the lines by which such problems are solved have their origin in a plane. Such problems, however, as are solved by using for their discovery one or more of the sections of the cone are called solid; for in the construction it is necessary to use surfaces of solid figures, I mean the conic surfaces. There remains a third kind of problem called linear; for other lines besides those mentioned are used for their construction, having a more complicated and less natural origin as they are generated from more irregular surfaces and intricate movements. Among such lines are those found in the so-called *surface-loci*,^a and many others more complicated than these were discovered by Demetrius of Alexandria in his *Linear Considerations* and Philon of Tyana^b as a result of interweaving plektoids and other surfaces of all kinds, and they exhibit many wonderful properties. Some of these curves were investigated more fully by more recent geometers, and among them in the line called *paradoxical* by Menelaus.^c Other lines of

^b Nothing further is known of these writers, unless Demetrius be the Cynic, mentioned by Diogenes Laertius, who lived about 300 B.C., or the philosopher who flourished in the time of Seneca.

^c Menelaus flourished c. A.D. 100 and his name is preserved in a famous theorem in spherical trigonometry. Tannery (*Mémoires scientifiques* ii. p. 17) has suggested that the curve called *paradoxical* was Viviani's curve of double curvature, defined as the intersection of a sphere with a cylinder touching it internally and having for its diameter the radius of the sphere. It is a particular case of Eudoxus's *hippopede* (see *infra*, p. 414), and the portion lying outside

GREEK MATHEMATICS

τετραγωνίζουσαί τε καὶ κοχλοειδεῖς καὶ κισσοειδεῖς. δοκεῖ δέ πως ἀμάρτημα τὸ τοιοῦτον οὐ μικρὸν εἶναι τοῖς γεωμέτραις, ὅταν ἐπίπεδον πρόβλημα διὰ τῶν κωνικῶν ἢ τῶν γραμμικῶν ὑπό τινος εὐρίσκηται, καὶ τὸ σύνολον ὅταν ἐξ ἀνοικείου λύηται γένους, οἷόν ἐστιν τὸ ἐν τῷ πέμπτῳ τῶν Ἀπολλωνίου Κωνικῶν ἐπὶ τῆς παραβολῆς πρόβλημα καὶ ἡ ἐν τῷ περὶ τῆς ἔλικος ὑπὸ Ἀρχιμήδους λαμβανομένη στερεοῦ νεῦσις ἐπὶ κύκλον· μηδενὶ

the curve of the surface of the hemisphere on which it lies is equal to the square on the diameter of the sphere; the fact that this area can be squared is thought to justify the name *paradoxical*. An Arabian tradition that Menelaus reproduced in his *Elements of Geometry* Archytas's solution of the problem of duplicating the cube (involving the intersection of a tore, cylinder and cone) lends a certain plausibility to the suggestion (v. Heath, *H.G.M.* ii. 261, Loria, *Le scienze esatte*, pp. 518-520).

^a Heath identifies this (*Apollonius of Perga* cxxvii-cxxix) as *Conics* v. 58, where Apollonius finds the feet of the normals to a parabola passing through a given point by constructing a rectangular hyperbola whose intersections with the parabola give the required points. The feet of the normals could be found in the case of the parabola (though not of the ellipse or hyperbola) by the intersection of the parabola with a certain *circle*.

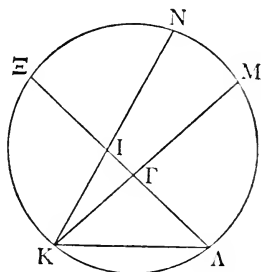
^b The assumption made by Archimedes (*Περὶ ἐλίκων* 8, 9) is to the following effect, the relevant portion of his figure being detached:

If $\Xi\Lambda$, KM are two chords of a circle, meeting at right angles at Γ , so that $\Xi\Gamma > \Gamma\Lambda$, then it is possible to draw another chord KN meeting $\Xi\Lambda$ in I such that $\text{IN} = \text{MI}$ (or, as Archimedes expresses the matter, *it is possible to place the straight line IN equal to MI and verging towards K*).

SPECIAL PROBLEMS

this kind are spirals and quadratics and cochloids and cissoids. It appears to be no small error for geometers when a plane problem is solved by conics or other curved lines, and in general when any problem is solved by an inappropriate kind, as in the problem concerning the parabola in the fifth book of the *Conics* of Apollonius ^a and the verging of a solid character with respect to a circle assumed by Archimedes in his book on the spiral ^b; for it is possible

In general, the line KN is determined by the intersection of a hyperbola and a parabola, as Pappus himself shows in



another place (iv. 52-53, ed. Hultsch 298-302). The particular case where $\Xi\Lambda$ is a diameter bisecting the chord KM in Γ can be solved by plane methods, namely, by the "application of areas"; the solution for the case where IN is to be made equal to $\sqrt{\frac{3}{2}}$ (radius of the circle) is assumed by Hippocrates in the fragment from Eudemus preserved by Simplicius (see *supra*, p. 244 n. a).

Archimedes gives no indication of the solution he had in mind, but all he requires for his purpose is its *possibility*; and its possibility can be demonstrated without any use of conics. For this reason Heath (*The Works of Archimedes* civ) thinks that Archimedes is to be excused from Pappus's censure that he had solved a plane problem by solid methods.

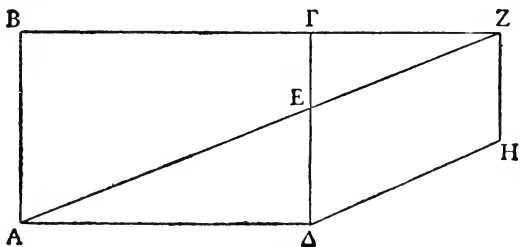
GREEK MATHEMATICS

γὰρ προσχρώμενον στερεῶ δυνατὸν εὑρεῖν τὸ ὑπ' αὐτοῦ γραφόμενον θεώρημα, λέγω δὴ τὸ τὴν περιφέρειαν τοῦ ἐν τῇ πρώτῃ περιφορᾷ κύκλου ἴσην ἀποδείξαι τῇ πρὸς ὀρθὰς ἀγομένη εὐθείᾳ τῇ ἐκ τῆς γενέσεως ἕως τῆς ἐφαπτομένης τῆς ἑλικος. τοιαύτης δὴ τῆς διαφορᾶς τῶν προβλημάτων ὑπαρχούσης οἱ πρότεροι γεωμέτραι τὸ προειρημένον ἐπὶ τῆς γωνίας πρόβλημα τῇ φύσει στερεὸν ὑπάρχον διὰ τῶν ἐπιπέδων ζητοῦντες οὐχ οἰοί τ' ἦσαν εὐρίσκειν· οὐδέπω γὰρ αἱ τοῦ κώνου τομαὶ συνήθεις ἦσαν αὐτοῖς, καὶ διὰ τοῦτο ἠπόρησαν· ὕστερον μέντοι διὰ τῶν κωνικῶν ἐτριχοτόμησαν τὴν γωνίαν εἰς τὴν εὔρεσιν χρησάμενοι τῇ ὑπογεγραμμένη νεύσει.

(b) SOLUTION BY MEANS OF A VERGING

Ibid. iv. 36. 60, ed. Hultsch 272. 15-274. 2

Παραλληλογράμμου δοθέντος ὀρθογωνίου τοῦ ΑΒΓΔ καὶ ἐκβληθείσης τῆς ΒΓ, δέον ἔστω διαγαγόντα τὴν ΑΕ ποιεῖν τὴν ΕΖ εὐθείαν ἴσην τῇ δοθείσῃ.



Γεγονέτω, καὶ ταῖς ΕΖ, ΕΔ παράλληλοι ἦχθωσαν

SPECIAL PROBLEMS

without using anything solid to find the theorem stated by him, I mean the theorem proving that the circumference of the circle in the first turn is equal to the straight line drawn at right angles to the initial line to meet the tangent to the spiral.^a Since problems differ in this way, the earlier geometers were not able to solve the aforementioned problem about the angle, when they sought to do so by means of planes, because it is by nature solid; for they were not yet familiar with the sections of the cone, and for this reason were at a loss. Later, however, they trisected the angle by means of the conics, using in the solution the verging described below.

(b) SOLUTION BY MEANS OF A VERGING

Ibid. iv. 36. 60, ed. Hultsch 272. 15-274. 2

Given a right-angled ^b parallelogram $AB\Gamma\Delta$, with BI' produced, let it be required to draw AE so as to make the straight line EZ equal to the given straight line.

Suppose it done, and let ΔH , HZ be drawn parallel

^a Archimedes' enunciation (*Περὶ ἐλίκων* 18) is: *Εἴ κα τῆς ἑλικῆς τῆς ἐν τῇ πρώτῃ περιφορᾷ γεγραμμένης εὐθεία γραμμὰ ἐπιφανῆ κατὰ τὸ πέρασ τῆς ἑλικῆς, ἀπὸ δὲ τοῦ σαμείου, ὃ ἐστὶν ἀρχὴ τῆς ἑλικῆς, ποτ' ὀρθὰς ἀχθῆ τις τῇ ἀρχῇ τῆς περιφορᾶς, ἀ ἀχθείσα συμπεσείται τῇ ἐπιφανούσῃ, καὶ ἀ μεταξὺ εὐθεία τῆς ἐπιφανούσας καὶ τῆς ἀρχῆς τῆς ἑλικῆς ἴσα ἐσσεύεται τῇ τοῦ πρώτου κύκλου περιφερείᾳ.*

^b It is not, in fact, necessary that the parallelogram should be right-angled.

SPECIAL PROBLEMS

to EZ , $E\Delta$. Since ZE is given and is equal to ΔH , therefore ΔH is also given. And Δ is given; therefore H is on the circumference of a circle given in position. And since the rectangle contained by $B\Gamma$, $\Gamma\Delta$ is given and is equal to the rectangle contained by BZ , $E\Delta$ [Eucl. i. 43], therefore the rectangle contained by BZ , $E\Delta$ is given, that is, the rectangle contained by BZ , ZH is given; therefore H lies on a hyperbola. But it is also on the circumference of a circle given in position; therefore H is given.^a

Ibid. iv. 38. 62, ed. Hultsch. 274. 18–276. 14

38. With this proved, the given rectilinear angle is trisected in the following manner.

First let $AB\Gamma$ be an acute angle, and from any point [of the straight line AB] let the perpendicular $A\Gamma$ be drawn, and let the parallelogram ΓZ be completed, and let ZA be produced to E , and inasmuch as ΓZ is a right-angled parallelogram let the straight line $E\Delta$ be placed between EA , $A\Gamma$ so as to verge towards B and be equal to twice AB —that this is possible has been proved above; I say that $EB\Gamma$ is a third part of the given angle $AB\Gamma$.

• The formal synthesis then follows as Pappus iv. 37.

GREEK MATHEMATICS

Τετμήσθω γὰρ ἡ ΕΔ δίχα τῷ Η, καὶ ἐπεζεύχθω ἡ ΑΗ· αἱ τρεῖς ἄρα αἱ ΔΗ, ΗΑ, ΗΕ ἴσαι εἰσίν· διπλῆ ἄρα ἡ ΔΕ τῆς ΑΗ. ἀλλὰ καὶ τῆς ΑΒ διπλῆ· ἴση ἄρα ἐστὶν ἡ ΒΑ τῇ ΑΗ, καὶ ἡ ὑπὸ ΑΒΔ γωνία τῇ ὑπὸ ΑΗΔ. ἡ δὲ ὑπὸ ΑΗΔ διπλασία τῆς ὑπὸ ΑΕΔ, τουτέστιν τῆς ὑπὸ ΔΒΓ· καὶ ἡ ὑπὸ ΑΒΔ ἄρα διπλῆ ἐστὶν τῆς ὑπὸ ΔΒΓ. καὶ ἐὰν τὴν ὑπὸ ΑΒΔ δίχα τέμωμεν, ἔσται ἡ ὑπὸ ΑΒΓ γωνία τρίχα τετμημένη.

(c) DIRECT SOLUTIONS BY MEANS OF CONICS

Ibid. iv. 43. 67-44. 68, ed. Hultsch 280. 20-284. 20

μγ'. Καὶ ἄλλως τῆς δοθείσης περιφερείας τὸ

^a We may easily show with Heath (*H.G.M.* i. 237-238) how the solution of the *νεῦσις* is equivalent to the solution of a cubic equation. If in the accompanying figure ZE, ZB are the axes of x, y respectively, and ZA = a , ZB = b , the point Θ giving E is determined as the intersection of the circle

$$(x - a)^2 + (y - b)^2 = 4(a^2 + b^2)$$

and the hyperbola $xy = ab$.

By eliminating x from these equations we may obtain

$$(y + b)(y^3 - 3by^2 - 3a^2y + a^2b) = 0.$$

One of the points of intersection of the circle and hyperbola is therefore given by $y = -b, x = -a$.

The other three are determined by the equation

$$y^3 - 3by^2 - 3a^2y + a^2b = 0.$$

SPECIAL PROBLEMS

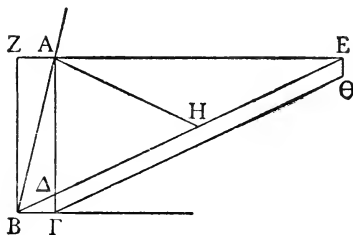
For let $E\Delta$ be bisected at H , and let AH be joined; the three straight lines ΔH , HA , HE are therefore equal; therefore ΔE is double of AH . But it is also double of AB ; therefore BA is equal to AH , and the angle $AB\Delta$ is equal to $AH\Delta$. Now $AH\Delta$ is double of $AE\Delta$, that is, of $\Delta B\Gamma$; and therefore $AB\Delta$ is double of $\Delta B\Gamma$. And if we bisect $AB\Delta$, the angle $AB\Gamma$ will be trisected.^a

(c) DIRECT SOLUTIONS BY MEANS OF CONICS

Ibid. iv. 43. 67-44. 68, ed. Hultsch 280. 20-284. 20

43. Another way of cutting off the third part of a

If $\angle AB\Gamma = \theta$, so that $\tan \theta = \frac{b}{a}$,
 and $\tau = \tan \Delta B\Gamma$, so that $y = a\tau$,
 then $a^3\tau^3 - 3ba^2\tau^2 - 3a^3\tau + a^2b = 0$



i.e. $a\tau^3 - 3b\tau^2 - 3a\tau + b = 0$
 whence $b(1 - 3\tau^2) = a(3\tau - \tau^3)$
 and $\tan \theta = \frac{b}{a} = \frac{3\tau - \tau^3}{1 - 3\tau^2}$.

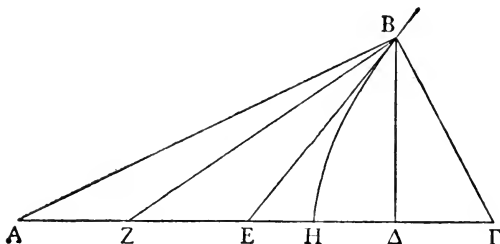
Accordingly, by a well-known theorem in trigonometry,

$$\tau = \tan \frac{1}{3}\theta,$$

and $\angle AB\Gamma$ is trisected by EB .

GREEK MATHEMATICS

τρίτον ἀφαιρεῖται μέρος, χωρὶς τῆς νεύσεως, διὰ στερεοῦ τόπου τοιούτου.



Θέσει ἡ διὰ τῶν Α, Γ, καὶ ἀπὸ δοθέντων ἐπ' αὐτῆς τῶν Α, Γ κεκλάσθω ἡ ΑΒΓ διπλασίαν ποιούσα τὴν ὑπὸ ΑΓΒ γωνίαν τῆς ὑπὸ ΓΑΒ· ὅτι τὸ Β πρὸς ὑπερβολῇ.

Ἦχθω καθέτος ἡ ΒΔ, καὶ τῇ ΓΔ ἴση ἀπειλήφθω ἡ ΔΕ· ἐπιζευχθεῖσα ἄρα ἡ ΒΕ ἴση ἔσται τῇ ΑΕ· κείσθω καὶ τῇ ΔΕ ἴση ἡ ΕΖ· τριπλασία ἄρα ἡ ΓΖ τῆς ΓΔ· ἔστω καὶ ἡ ΑΓ τῆς ΓΗ τριπλασία· ἔσται δὴ δοθὲν τὸ Η, καὶ λοιπὴ ἡ ΑΖ τῆς ΗΔ τριπλασία· καὶ ἐπεὶ τῶν ἀπὸ ΒΕ, ΕΖ ὑπεροχὴ ἔστιν τὸ ἀπὸ ΒΔ, ἔστιν δὲ καὶ τὸ ὑπὸ ΔΑ, ΑΖ τῶν αὐτῶν ὑπεροχὴ, ἔσται ἄρα τὸ ὑπὸ ΔΑΖ, τουτέστιν τὸ τρὶς ὑπὸ ΑΔΗ, ἴσον τῷ ἀπὸ ΒΔ· πρὸς ὑπερβολῇ ἄρα τὸ Β, ἧς πλαγία μὲν τοῦ πρὸς ἄξονι εἶδους ἡ

^a For by the equality of the triangles BEΔ, BΓΔ, we have $\angle BEΓ = \angle BΓE = 2\angle ΓΑΒ$ (*ex hypothesi*). But $\angle BEΓ = \angle ΓΑΒ + \angle ΑΒΕ$.

Therefore $\angle ΓΑΒ = \angle ΑΒΕ$, and so $BE = AE$.

^b *i.e.* since $ΓΗ = \frac{1}{3}ΑΓ$ and $ΓΔ = \frac{1}{3}ΓΖ$, by subtraction,

$$ΓΗ - ΓΔ = \frac{1}{3}(ΑΓ - ΓΖ), \text{ or } ΗΔ = \frac{1}{3}ΑΖ.$$

SPECIAL PROBLEMS

given arc is furnished, without the use of a verging, by this solid locus.

Let the straight line through A, Γ be given in position, and from the given points A, Γ upon it let $AB\Gamma$ be inflected, making the angle $A\Gamma B$ double of ΓAB ; I say that B lies on a hyperbola.

For let $B\Delta$ be drawn perpendicular [to $A\Gamma$] and let ΔE be cut off equal to $\Gamma\Delta$; when BE is joined it will therefore be equal to AE.^a And let EZ be placed equal to ΔE ; therefore $\Gamma Z = 3\Gamma\Delta$. Now let ΓH be placed equal to $\frac{1}{3}A\Gamma$; therefore the point H will be given, and the remainder^b AZ will equal $3H\Delta$.

Now since ^c $BE^2 - EZ^2 = B\Delta^2$,

and $BE^2 - EZ^2 = \Delta A \cdot AZ$,

therefore $\Delta A \cdot AZ = B\Delta^2$,

that is $3A\Delta \cdot \Delta H = B\Delta^2$;

therefore B lies on a hyperbola with transverse axis

^e The reasoning here is much abbreviated, and in full may be written as follows:

$$\begin{aligned} BE^2 - EZ^2 &= BE^2 - E\Delta^2 \quad (\text{since } EZ = E\Delta \text{ ex hypothesi}) \\ &= B\Delta^2 \quad (\text{Eucl. i. 47}) \end{aligned}$$

$$\begin{aligned} \text{Now } BE^2 - EZ^2 &= AE^2 - EZ^2 \quad (\text{since BE was proved equal to AE}) \\ &= \Delta A \cdot AZ \quad (\text{Eucl. ii. 6}) \end{aligned}$$

$$\therefore \Delta A \cdot AZ = B\Delta^2$$

$$\therefore 3A\Delta \cdot \Delta H = B\Delta^2 \quad (\text{since } AZ \text{ was proved equal to } 3H\Delta)$$

$$\begin{aligned} \therefore B\Delta^2 : A\Delta \cdot \Delta H &= 3 : 1 \\ &= \frac{3AH^2}{AH^2}; \end{aligned}$$

\therefore B lies on a hyperbola with transverse axis AH and conjugate axis $\sqrt{3}AH$.

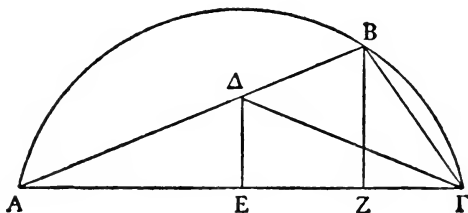
GREEK MATHEMATICS

ΑΗ, ἡ δὲ ὀρθία τριπλασία τῆς ΑΗ. καὶ φανερόν ὅτι τὸ Γ σημεῖον ἀπολαμβάνει πρὸς τῇ Η κορυφῇ τῆς τομῆς τὴν ΓΗ ἡμίσειαν τῆς πλαγίας τοῦ εἴδους πλευρᾶς τῆς ΑΗ.

Καὶ ἡ σύνθεσις φανερά· δεήσει γὰρ τὴν ΑΓ τεμεῖν ὥστε διπλασίαν εἶναι τὴν ΑΗ τῆς ΗΓ, καὶ περὶ ἄξονα τὸν ΑΗ γράψαι διὰ τοῦ Η ὑπερβολήν, ἣς ὀρθία τοῦ εἴδους πλευρὰ τριπλασία τῆς ΑΗ, καὶ δεικνύναι ποιούσαν αὐτὴν τὸν εἰρημένον διπλάσιον λόγον τῶν γωνιῶν. καὶ ὅτι τῆς δοθείσης κύκλου περιφερείας τὸ γ' ἀποτέμνει μέρος ἢ τοῦτον γραφομένη τὸν τρόπον ὑπερβολῇ συνιδεῖν ῥάδιον τῶν Α, Γ σημείων περάτων τῆς περιφερείας ὑποκειμένων.

μδ'. Ἐτέρως δὲ τὴν ἀνάλυσιν τοῦ τρίχα τεμεῖν τὴν γωνίαν ἢ περιφέρειαν ἐξέθεντό τινες ἄνευ τῆς νεύσεως. ἔστω δὲ ἐπὶ περιφερείας ὁ λόγος· οὐδὲν γὰρ διαφέρει γωνίαν ἢ περιφέρειαν τεμεῖν.

Γεγονέτω δὴ, καὶ τῆς ΑΒΓ περιφερείας τρίτον



ἀπειλήφθω μέρος ἢ ΒΓ, καὶ ἐπεζεύχθωσαν αἱ ΑΒ, ΒΓ, ΓΑ· διπλασίων ἄρα ἢ ὑπὸ ΑΓΒ τῆς ὑπὸ

SPECIAL PROBLEMS

AH and conjugate axis $\sqrt{3}AH$. And it is clear that the point Γ cuts off at the vertex H of the [conic] section a straight line ΓH which is one-half of the transverse axis AH.

And the synthesis is clear ; for it will be required so to cut $A\Gamma$ that AH is double of $H\Gamma$, and about AH as axis to describe through H a hyperbola with conjugate axis $\sqrt{3}AH$, and to prove that it makes the aforementioned double ratio of the angles. And that the hyperbola described in this manner cuts off the third part of the arc of the given circle is easily understood if the points A, Γ are the end points of the arc.^a

44. Some set out differently the analysis of the problem of trisecting an angle or arc without a verging. Let the ratio be upon an arc ; it makes no difference whether an angle or an arc is to be divided.

Let it be done, and let $B\Gamma$, the third part of the arc $AB\Gamma$, be cut off, and let AB, $B\Gamma$, ΓA be joined ; then

• For let O be the centre of a circle of which $A\Gamma$ is an arc. Let $A\Gamma$ be divided at H so that $AH = 2H\Gamma$. Let the hyperbola be constructed

which has AH for transverse axis and $\sqrt{3}AH$ for conjugate axis, and let this hyperbola cut the arc of the circle in B. Then by Pappus's proposition,

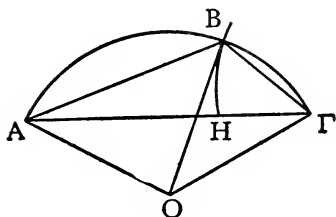
$$\angle B\Gamma A = 2\angle BA\Gamma.$$

Therefore their doubles are equal,

or

$$\angle BOA = 2\angle BO\Gamma,$$

and so OB trisects the angle $AO\Gamma$ and the arc AB.



GREEK MATHEMATICS

ΒΑΓ. τετμήσθω δίχα ἡ ὑπὸ ΑΓΒ τῆ ΓΔ, καὶ κάθεται αἱ ΔΕ, ΖΒ· ἴση ἄρα ἡ ΑΔ τῆ ΔΓ, ὥστε καὶ ἡ ΑΕ τῆ ΕΓ· δοθέν ἄρα τὸ Ε. ἐπεὶ οὖν ἐστὶν ὡς ἡ ΑΓ πρὸς ΓΒ, οὕτως ἡ ΑΔ πρὸς ΔΒ, τουτέστιν ἡ ΑΕ πρὸς ΕΖ, καὶ ἐναλλάξ ἄρα ἐστὶν ὡς ἡ ΓΑ πρὸς ΑΕ, ἡ ΒΓ πρὸς ΕΖ. διπλῆ δὲ ἡ ΓΑ τῆ ΑΕ· διπλῆ ἄρα καὶ ἡ ΒΓ τῆς ΕΖ· τετραπλάσιον ἄρα τὸ ἀπὸ ΒΓ, τουτέστιν τὰ ἀπὸ τῶν ΒΖΓ, τοῦ ἀπὸ τῆς ΕΖ. ἐπεὶ οὖν δύο δοθέντα ἐστὶν τὰ Ε, Γ, καὶ ὀρθὴ ἡ ΒΖ, καὶ λόγος ἐστὶν τοῦ ἀπὸ ΕΖ πρὸς τὰ ἀπὸ τῶν ΒΖΓ, τὸ Β ἄρα πρὸς ὑπερβολῆ. ἀλλὰ καὶ πρὸς θέσει περιφερεία· δοθέν ἄρα τὸ Β. καὶ ἡ σύνθεσις φανερά.

* The relation $BΓ = 2EZ$ tells us that B lies on a hyperbola with foci A, Γ, directrix BZ and eccentricity 2. Pappus proceeds to turn this into the axial form $EΖ^2 : BΖ^2 + ΖΓ^2 = 1 : 4$ which was more commonly used by the Greeks. In fact, there are only two other extant passages in which the focus-directrix property is used. One of them is also given by Pappus (vii., ed. Hultsch 1004-1014), who there proved

SPECIAL PROBLEMS

$\angle A\Gamma B = 2\angle B A \Gamma$. Let $\angle A\Gamma B$ be bisected by $\Gamma\Delta$, and let ΔE , ZB be drawn perpendicular; therefore $A\Delta$ is equal to $\Delta\Gamma$, so that $A E$ is also equal to $E\Gamma$; therefore E is given.

Now because $A\Gamma : \Gamma B = A\Delta : \Delta B$ [Eucl. vi. 5]
 $= A E : E Z$,

therefore alternately $\Gamma A : A E = B\Gamma : E Z$.

But $\Gamma A = 2A E$; and therefore $B\Gamma = 2E Z$; therefore $B\Gamma^2 = 4E Z^2$, that is, $B Z^2 + Z\Gamma^2 = 4E Z^2$. Now, since the two points E , Γ are given, and $B Z$ is drawn at right angles, and the ratio $E Z^2 : B Z^2 + Z\Gamma^2$ is given, B lies on a hyperbola. But it also lies on an arc given in position; therefore B is given. And the synthesis is clear.^a

generally that "if the distance of a point from a fixed point is in a given ratio to its distance from a fixed line, the locus of the point is a conic section which is an ellipse, a parabola or a hyperbola according as the given ratio is less than, equal to, or greater than, unity." The proof is among a number of lemmas to the *Surface Loci* of Euclid, so presumably the focus-directrix property was already well known when Euclid wrote.

X. ZENO OF ELEA

X. ZENO OF ELEA

Aristot. *Phys.* Z 9, 239 b 5-240 a 18

Ζήνων δὲ παραλογίζεται· εἰ γὰρ αἰεὶ, φησὶν, ἡρεμεῖ πᾶν ἢ κινεῖται¹ ὅταν ἢ κατὰ τὸ ἴσον, ἐστὶν δ' αἰεὶ τὸ φερόμενον ἐν τῷ νῦν, ἀκίνητον τὴν φερόμενην εἶναι ὀιστόν. τοῦτο δ' ἐστὶ ψεῦδος· οὐ γὰρ σύγκειται ὁ χρόνος ἐκ τῶν νῦν τῶν ἀδιαιρέτων, ὥσπερ οὐδ' ἄλλο μέγεθος οὐδέν.

Τέτταρες δ' εἰσὶν οἱ λόγοι περὶ κινήσεως Ζήνωνος οἱ παρέχοντες τὰς δυσκολίας τοῖς λύουσιν, πρῶτος μὲν ὁ περὶ τοῦ μὴ κινεῖσθαι διὰ τὸ πρότερον εἰς τὸ ἡμῖσι δεῖν ἀφικέσθαι τὸ φερόμενον ἢ πρὸς τὸ τέλος, περὶ οὗ διείλομεν ἐν τοῖς πρότερον λόγοις.

¹ Zeller would bracket ἢ κινεῖται, and he is followed by Ross, but not, it seems to me, with sufficient reason. Diels, followed by Lee, has the unnecessary addition of οὐδὲν δὲ κινεῖται after these words. The passage as it stands is satisfactorily explained by Brochard (*Études de philosophie ancienne et de philosophie moderne*, p. 6) and by Heath (*H.G.M.* i. 276).

^a Zeno of Elea, who is represented by Plato (*Parm.* 127 b) as "about forty" when Socrates was a "very young man" (say in 450 b.c.), was a disciple of Parmenides. The object of his four arguments on motion, here reproduced from Aristotle, was to show that the rejection of Parmenides' doctrine of the unity of being led to self-contradictory results.

X. ZENO OF ELEA^a

Aristotle, *Physics* Z 9, 239 b 5-240 a 18

ZENO's argument is fallacious; for, he says, if everything is either at rest or in motion when it occupies a space equal to itself, while the object moved is always in the instant, the moving arrow is unmoved. But this is false; for time is not made up of indivisible instants, any more than is any other magnitude.

Zeno has four arguments about motion which present difficulties to those who try to resolve them. The first is that which says there is no motion because the object moved must arrive at the middle before it arrives at the end,^b concerning which we have already treated.

A vast literature has grown round these arguments, but the student will find most help in W. D. Ross, *Aristotle's Physics*, pp. 655-666, H. D. P. Lee, *Zeno of Elea*, and Heath, *H.G.M.* i. 271-283.

^b Not only has it to pass through the half-way point, but through half of the remaining half, and so on to infinity. If a is the length of the course measured from the goal, then the moving object before it reaches its goal has to pass through the points $\frac{a}{2}$, $\frac{a}{2^2}$, $\frac{a}{2^3}$. . . and so on through an infinite series which cannot be enumerated. Aristotle's answer is that the moving object has indeed to pass through an infinite number of positions, but in a finite time it has an infinite number of instants in which to do so.

GREEK MATHEMATICS

* Διὸ καὶ ὁ Ζήνωνος λόγος ψεῦδος λαμβάνει τὸ μὴ ἐνδέχεται τὰ ἄπειρα διελθεῖν ἢ ἄψασθαι τῶν ἀπείρων καθ' ἕκαστον ἐν πεπερασμένῳ χρόνῳ. διχῶς γὰρ λέγεται καὶ τὸ μῆκος καὶ ὁ χρόνος ἄπειρον, καὶ ὅλως πᾶν τὸ συνεχές, ἥτοι κατὰ διαίρεσιν ἢ τοῖς ἐσχάτοις. τῶν μὲν οὖν κατὰ τὸ ποσὸν ἀπείρων οὐκ ἐνδέχεται ἄψασθαι ἐν πεπερασμένῳ χρόνῳ, τῶν δὲ κατὰ διαίρεσιν ἐνδέχεται· καὶ γὰρ αὐτὸς ὁ χρόνος οὕτως ἄπειρος. ὥστε ἐν τῷ ἀπείρῳ καὶ οὐκ ἐν τῷ πεπερασμένῳ συμβαίνει διέναι τὸ ἄπειρον, καὶ ἄπτεσθαι τῶν ἀπείρων τοῖς ἀπείροις, οὐ τοῖς πεπερασμένοις.*

Δεύτερος δ' ὁ καλούμενος Ἀχιλλεύς· ἔστι δ' οὗτος, ὅτι τὸ βραδύτατον οὐδέποτε καταληφθήσεται θεόν ὑπὸ τοῦ ταχίστου· ἔμπροσθεν γὰρ ἀναγκαῖον ἐλθεῖν τὸ διῶκον, ὅθεν ὤρμησε τὸ φεῦγον, ὥστ' αἰεὶ τι προέχειν ἀναγκαῖον τὸ βραδύτερον. ἔστι δὲ καὶ οὗτος ὁ αὐτὸς λόγος τῷ διχοτομεῖν, διαφέρει δ' ἐν τῷ διαιρεῖν μὴ δίχα τὸ προσλαμβανόμενον μέγεθος. τὸ μὲν οὖν μὴ καταλαμβάνεσθαι τὸ βραδύτερον συμβέβηκεν ἐκ τοῦ λόγου, γίνεται δὲ παρὰ ταῦτὸ τῇ διχοτομίᾳ (ἐν ἀμφοτέροις γὰρ συμβαίνει μὴ ἀφικνεῖσθαι πρὸς τὸ πέρασ διαιρου-

* The passage between the asterisks, to which Aristotle refers the reader, is *Phys. Z 2*, 233 a 21-31 and is reproduced here for convenience.

^b Aristotle's argument is correct. The *Achilles* is a more general form of the *Dichotomy*. If the speed of Achilles is n times that of the tortoise (we learn from Themistius and Simplicius that the tortoise was the object pursued), and the tortoise starts a unit ahead, then when Achilles has reached the point where the tortoise started the

ZENO OF ELEA

* Zeno's argument makes a false assumption in not allowing the possibility of passing through or touching an infinite number of positions one by one in a limited time. For there are two senses in which length and time, and, generally, any continuum, are said to be infinite, either in respect of division or of extension. So where the infinite is infinite in respect of quantity, it is not possible to make in a limited time an infinite number of contacts, but it is possible where the infinite is infinite in respect of division; for the time also is infinite in this respect. And so it is possible to pass through an infinite number of positions in a time which is in this sense infinite, but not in a time which is finite, and to make an infinite number of contacts because its moments are infinite, not finite.*^a

The second argument is the so-called *Achilles*; this asserts that the slowest will never be overtaken by the quickest; for that which is pursuing must first reach the point from which the fleeing object started, so that the slower must necessarily always be some distance ahead. This is the same reasoning as that of the *Dichotomy*, the only difference being that when the magnitude which is successively added is divided it is not necessarily bisected.^b The argument leads to the conclusion that the slower will never be overtaken, and it is for the same reason as in the *Dichotomy* (for in both by dividing the distance in some way it is

tortoise is $\frac{1}{n}$ ahead; when Achilles has reached this point the tortoise is $\frac{1}{n^2}$ ahead; and so on to infinity. Putting $n=2$ we get the special conditions of the *Dichotomy*. Both arguments emphasize that to traverse a finite distance means passing through an infinite number of positions.

GREEK MATHEMATICS

μένου πως τοῦ μεγέθους· ἀλλὰ πρόσκειται ἐν τούτῳ ὅτι οὐδὲ τὸ τάχιστον τετραγωνημένον ἐν τῷ διώκειν τὸ βραδύτατον), ὥστ' ἀνάγκη καὶ τὴν λύσιν εἶναι τὴν αὐτὴν. τὸ δ' ἀξιούν ὅτι τὸ προέχον οὐ καταλαμβάνεται, ψεῦδος· ὅτε γὰρ προέχει, οὐ καταλαμβάνεται· ἀλλ' ὅμως καταλαμβάνεται, εἴπερ δώσει διεξιέναι τὴν πεπερασμένην.

Οὗτοι μὲν οὖν οἱ δύο λόγοι, τρίτος δ' ὁ νῦν ῥηθείς, ὅτι ἡ οἰστός φερομένη ἔστηκεν. συμβαίνει δὲ παρὰ τὸ λαμβάνειν τὸν χρόνον συγκεῖσθαι ἐκ τῶν νῦν· μὴ διδομένου γὰρ τούτου οὐκ ἔσται ὁ συλλογισμός.

Τέταρτος δ' ὁ περὶ τῶν ἐν τῷ σταδίῳ κινουμένων ἐξ ἐναντίας ἴσων ὄγκων παρ' ἴσους, τῶν μὲν ἀπὸ τέλους τοῦ σταδίου τῶν δ' ἀπὸ μέσου, ἴσῳ τάχει, ἐν ᾧ συμβαίνειν οἶεται ἴσον εἶναι χρόνον τῷ διπλασίῳ τὸν ἡμισυν. ἔστι δ' ὁ παραλογισμὸς

^a Achilles overtakes the tortoise when he has travelled a distance $1 + \frac{1}{n} + \frac{1}{n^2} + \dots$ *ad inf.*

This is a convergent series whose sum is $\frac{n}{n-1}$. The ancients did not know how to sum an infinite series, but they knew that Achilles would catch the tortoise and that the problem *solvitur ambulando*.

^b Lachelier (*Revue de métaphysique et de morale*, xviii., pp. 346-347) and Ross explain that ἀπὸ τοῦ μέσου means from the turning point in the double course or δίαυλος. The race was from the τέλος to the μέσον and back again to the τέλος. On this interpretation it is possible to translate easily and naturally. Gaye, the Oxford translators and Lee, who do not accept this interpretation, but believe τὸ μέσον to refer

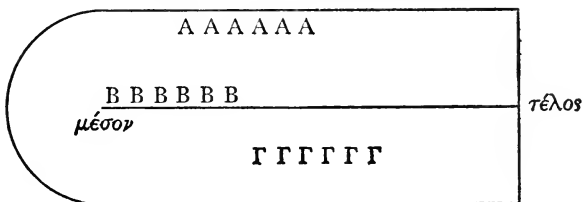
ZENO OF ELEA

concluded that the goal will not be reached ; but in this a dramatic effect is produced by saying that not even the swiftest will be successful in its pursuit of the slowest) and so the solution must necessarily be the same. The claim that the one in front is not overtaken is false ; for when in front he is not indeed overtaken, but he will nevertheless be overtaken if he give his pursuer a finite distance to go through.^a

These are two of the arguments, and the third is the one just mentioned, that the flying arrow is at rest. This conclusion follows from the assumption that time is composed of instants ; for if this is not granted the reasoning does not follow.

The fourth is that about the two rows of equal bodies moving past each other in the stadium with equal velocities in opposite directions, the one row starting from the end of the stadium, the other from the middle.^b This, he thinks, leads to the conclusion that half a given time is equal to its double. The

to the middle of the A s, are forced to paraphrase : “ The



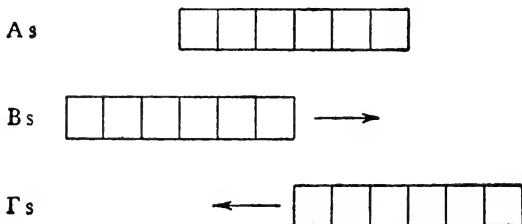
one row originally stretching from the goal to the middle-point of the stadium, the other from the middle-point to the starting-post.” Ross has to admit that τὸ μέσον is apparently not used elsewhere of the middle-point of the δίαυλος, but he rightly emphasizes the unnaturalness of any other interpretation.

GREEK MATHEMATICS

ἐν τῷ τὸ μὲν παρὰ κινούμενον τὸ δὲ παρ' ἡρεμοῦν τὸ ἴσον μέγεθος ἀξιοῦν τῷ ἴσῳ τάχει τὸν ἴσον φέρεσθαι χρόνον· τοῦτο δ' ἐστὶ ψεῦδος. οἷον ἔστωσαν οἱ ἐστῶτες ἴσοι ὄγκοι ἐφ' ὧν τὰ ΑΑ, οἱ δ' ἐφ' ὧν τὰ ΒΒ ἀρχόμενοι ἀπὸ τοῦ μέσου, ἴσοι τὸν ἀριθμὸν τούτοις ὄντες καὶ τὸ μέγεθος, οἱ δ' ἐφ' ὧν τὰ ΓΓ ἀπὸ τοῦ ἐσχάτου, ἴσοι τὸν ἀριθμὸν ὄντες τούτοις καὶ τὸ μέγεθος, καὶ ἰσοταχεῖς τοῖς Β. συμβαίνει δὴ τὸ πρῶτον Β ἅμα ἐπὶ τῷ ἐσχάτῳ εἶναι καὶ τὸ πρῶτον Γ, παρ' ἀλληλα κινουμένων. συμβαίνει δὲ τὸ Γ παρὰ πάντα [τὰ Β]¹ διεξεληλυθέναι, τὸ δὲ Β παρὰ τὰ ἡμίση· ὥστε ἡμισὺν εἶναι τὸν χρόνον· ἴσον γὰρ ἐκάτερόν ἐστι παρ'

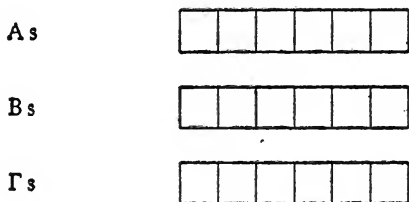
¹ τὰ Β del. Ross.

* There seems little doubt that initially the rows of bodies were symmetrically arranged in the following way (we will assume half a dozen of each for convenience):



ZENO OF ELEA

fallacy lies in assuming that a body takes an equal time to pass with equal speed a body in motion and a body of equal size at rest ; but this is untrue. For example, let AA be stationary bodies of equal size, let BB be the bodies equal in number and size that start from the middle, and let $\Gamma\Gamma$ be the bodies equal in number and size that start from the end, having a speed equal to that of the Bs.^a In consequence, the first B and the first Γ move past each other and come simultaneously to the end.^b It follows that Γ has passed all the bodies it is moving past, though B has passed only half the bodies it is moving past,^c so that B has taken half the time [taken by Γ]; for and that the final position they take up is :



But there are great difficulties in the text. Ross's interpretation seems to me to do least violence to the Greek.

^b *i.e.* the first B is under the right-hand A at the same time that the first Γ is under the left-hand A.

^c Ross explains, to my mind judiciously, that the Bs are thought of primarily as moving past the As and only secondarily as moving past the Γ s, while the Γ s are thought of primarily as moving past the Bs and only secondarily past the As. Zeno wishes to point out that the first B has moved past only three As while the first Γ has moved past six Bs. On the ground that to move past six Bs requires twice the time needed to move past three As, coupled with the knowledge that the time taken is in fact the same in

GREEK MATHEMATICS

ἕκαστον. ἅμα δὲ συμβαίνει τὸ πρῶτον Β' παρὰ πάντα τὰ Γ παρεληλυθέναι· ἅμα γὰρ ἔσται τὸ πρῶτον Γ καὶ τὸ πρῶτον Β ἐπὶ τοῖς ἐναντίοις ἐσχάτοις, [ἴσον χρόνον παρ' ἕκαστον γιγνόμενον τῶν Β ὅσον περ τῶν Α, ὡς φησιν],² διὰ τὸ ἀμφοτέρωθεν ἴσον χρόνον παρὰ τὰ Α γίνεσθαι. ὁ μὲν οὖν λόγος οὗτός ἐστιν, συμβαίνει δὲ παρὰ τὸ εἰρημένον ψεῦδος.

both cases, he gets his paradox, that half a given time is equal to the whole. He neglects the fact that the relative motion of Γ to Β is twice as great as the relative motion of Β to Α. If this is borne in mind, the paradox disappears. In order to support his interpretation Ross omits τὰ Β from the text: there is a rival reading τὰ Α and Ross suggests, with reason, that they are both glosses.

ZENO OF ELEA

each takes an equal time in passing each body. And it follows that at the same moment the first B has passed all the Γ s: for the first Γ and the first B will be simultaneously at opposite ends [of the A s], since both take an equal time in passing the A s. Such is his argument, and it comes about from the aforementioned fallacy.

¹ The vulgate has $\tau\alpha$ B, but it would be incorrect to say all the B s have passed all the Γ s. One manuscript has $\tau\delta$ α β , which would be a correct way of writing $\tau\delta$ $\pi\rho\omega\tau\omicron\nu$ B, and Ross accordingly adopts this.

² $\acute{\iota}\sigma\omicron\nu$. . . $\phi\eta\sigma\iota\nu$. These words will not stand interpretation and Ross omits them as a gloss in the margin on $\acute{\iota}\sigma\omicron\nu$ $\gamma\grave{\alpha}\rho$ $\acute{\epsilon}\kappa\acute{\alpha}\tau\epsilon\rho\acute{\omicron}\nu$ $\acute{\epsilon}\sigma\tau\iota\nu$ $\pi\alpha\rho'$ $\acute{\epsilon}\kappa\alpha\sigma\tau\omicron\nu$ which found its way into the text at the wrong place.

XI. THEAETETUS

XI. THEAETETUS

(a) GENERAL

Suidas, *s.v.* Θεαίτητος

Θεαίτητος, Ἀθηναῖος, ἀστρολόγος, φιλόσοφος, μαθητῆς Σωκράτους, ἐδίδαξεν ἐν Ἡρακλείᾳ. πρῶτος δὲ τὰ πέντε καλούμενα στερεὰ ἔγραψε. γέγονε δὲ μετὰ τὰ Πελοποννησιακά.

(b) THE FIVE REGULAR SOLIDS

Schol. i. in Eucl. *Elem.* xiii., Eucl. ed. Heiberg v. 654

Ἐν τούτῳ τῷ βιβλίῳ, τουτέστι τῷ ιγ', γράφεται τὰ λεγόμενα Πλάτωνος ἑ σχήματα, ἃ αὐτοῦ μὲν οὐκ ἔστιν, τρία δὲ τῶν προειρημένων ἑ σχημάτων τῶν Πυθαγορείων ἔστιν, ὃ τε κύβος καὶ ἡ πυραμὶς καὶ τὸ δωδεκάεδρον, Θεαιτήτου δὲ τό τε ὀκτάεδρον καὶ τὸ εἰκοσάεδρον. τὴν δὲ προσωνημίαν ἔλαβεν Πλάτωνος διὰ τὸ μεμνησθαι αὐτὸν ἐν τῷ Τιμαίῳ περὶ αὐτῶν.

^a Theaetetus lived about 415–369 B.C. He is the subject of a dissertation *De Theaeteto Atheniensi* by Eva Sachs (Berlin, 1914).

XI. THEAETETUS ^a

(a) GENERAL

Suidas, *s.v.* *Theaetetus*

THEAETETUS, an Athenian, astronomer, philosopher, a pupil of Socrates, taught in Heraclea. He was the first to describe ^b the five solids so-called. He lived after the Peloponnesian wars.

(b) THE FIVE REGULAR SOLIDS

Euclid, *Elements* xiii., Scholium i., Eucl.
ed. Heiberg v. 654

In this book, that is, the thirteenth, are described the five Platonic figures, which are however not his, three of the aforesaid five figures being due to the Pythagoreans,^c namely, the cube, the pyramid and the dodecahedron, while the octahedron and icosahedron are due to Theaetetus. They received the name Platonic because he discourses in the *Timaeus* about them.

^b Possibly "construct."

^c For the relation of the Pythagoreans to the five regular solids, see *supra*, pp. 216-225. Theaetetus was probably the first to construct all five theoretically; the Pythagoreans could not have done that. For a full discussion, see Eva Sachs, *Die fünf Platonischen Körper*.

GREEK MATHEMATICS

(c) THE IRRATIONAL

Schol. lxii. in Eucl. *Elem.* x., Eucl. ed. Heiberg
v. 450. 16-18

Τὸ θεώρημα τοῦτο Θεαιτήτειόν ἐστιν εὖρημα,
καὶ μέμνηται αὐτοῦ ὁ Πλάτων ἐν Θεαιτήτῳ, ἀλλ'
ἐκεῖ μὲν μερικώτερον ἔγκειται, ἐνταῦθα δὲ καθόλου.

Plat. *Theaet.* 147 D-148 B

ΘΕΑΙΤΗΤΟΣ. Περὶ δυνάμεών τι ἡμῖν Θεόδωρος
ὄδε ἔγραφε, τῆς τε τρίποδος πέρι καὶ πεντέ-
ποδος [ἀποφαίνων]¹ ὅτι μήκει οὐ σύμμετροι τῇ
ποδιαίᾳ, καὶ οὕτω κατὰ μίαν ἐκάστην προαιρού-
μενος μέχρι τῆς ἑπτακαιδεκάποδος· ἐν δὲ ταύτῃ
πως ἐνέσχετο. ἡμῖν οὖν εἰσηλθὲ τι τοιοῦτον,
ἐπειδὴ ἄπειροι τὸ πλῆθος αἱ δυνάμεις ἐφαίνοντο,
πειραθῆναι συλλαβεῖν εἰς ἓν, ὅτῳ πάσας ταύτας
προσαγορεύσομεν τὰς δυνάμεις.

¹ ἀποφαίνων secl. Burnet.

• The enunciation is: *The squares on straight lines commensurable in length have to one another the ratio which a square number has to a square number; and squares which have to one another the ratio which a square number has to a square number will also have their sides commensurable in length. But the squares on straight lines incommensurable in length have not to one another the ratio which a square number has to a square number; and squares which have not to one another the ratio which a square number has to a square number will not have their sides commensurable in length either.*

• Theodorus of Cyrene, claimed by Iamblichus (*Vit. Pythag.* 36) as a Pythagorean and said to have been Plato's teacher in mathematics (Diog. Laert. ii. 103).

• Several conjectures have been put forward to explain

THEAETETUS

(c) THE IRRATIONAL

Euclid, *Elements* x., Scholium lxii., ed. Heiberg
v. 450. 16-18

This theorem [Eucl. *Elem.* x. 9]^a is the discovery of Theaetetus, and Plato recalls it in the *Theaetetus*, but there it arises in a particular case, here it is treated generally.

Plato, *Theaetetus* 147 D-148 B

THEAETETUS. Theodorus^b was proving to us a certain thing about square roots, I mean the square roots of three square feet and five square feet, namely, that these roots are not commensurable in length with the foot-length, and he proceeded in this way, taking each case in turn up to the root of seventeen square feet; at this point for some reason he stopped.^c Now it occurred to us, since the number of square roots appeared to be unlimited, to try to gather them into one class, by which we could henceforth describe all the roots.

how Theodorus proved that $\sqrt{3}$, $\sqrt{5}$. . . $\sqrt{17}$ are incommensurable. They are summarized by Heath (*H.G.M.* i. 204-208). One theory is that Theodorus adapted the traditional proof (*supra*, p. 110) of the incommensurability of $\sqrt{2}$. Another, put forward by Zeuthen ("Sur la constitution des livres arithmétiques des *Éléments* d'Euclide et leur rapport à la question de l'irrationalité" in *Oversigt over det kgl. Danske videnskabernes Selskabs Forhandlinger*, 1915, pp. 422 ff.), depends on the process of finding the greatest common measure as stated in Eucl. x. 2. If two magnitudes are such that the process of finding their G.C.M. never comes to an end, the two magnitudes are incommensurable. The method is simple in theory, but the geometrical application is fairly complicated, though doubtless not beyond the capabilities of Theodorus.

GREEK MATHEMATICS

ΣΩΚΡΑΤΗΣ. Ἡ καὶ ἡὔρετέ τι τοιοῦτον;

ΘΕΑΙ. Ἐμοιγε δοκοῦμεν· σκόπει δὲ καὶ σύ.

ΣΩ. Λέγε.

ΘΕΑΙ. Τὸν ἀριθμὸν πάντα δίχα διελάβομεν τὸν μὲν δυνάμενον ἴσον ἰσάκεις γίγνεσθαι τῷ τετραγώνῳ τὸ σχῆμα ἀπεικάσαντες τετράγωνόν τε καὶ ἰσόπλευρον προσείπομεν.

ΣΩ. Καὶ εἶ γε.

ΘΕΑΙ. Τὸν τοίνυν μεταξὺ τούτου, ὧν καὶ τὰ τρία καὶ τὰ πέντε καὶ πᾶς ὅς ἀδύνατος ἴσος ἰσάκεις γενέσθαι, ἀλλ' ἢ πλείων ἐλαττονάκεις ἢ ἐλάττων πλεονάκεις γίγνεται, μείζων δὲ καὶ ἐλάττων αἰεὶ πλευρὰ αὐτὸν περιλαμβάνει, τῷ προμήκει αὐτοῦ σχήματι ἀπεικάσαντες προμήκη ἀριθμὸν ἐκαλέσαμεν.

ΣΩ. Κάλλιστα. ἀλλὰ τί τὸ μετὰ τοῦτο;

ΘΕΑΙ. Ὅσαι μὲν γραμμαὶ τὸν ἰσόπλευρον καὶ ἐπίπεδον ἀριθμὸν τετραγωνίζουσι, μῆκος ὠρισάμεθα, ὅσαι δὲ τὸν ἑτερομήκη, δυνάμεις, ὡς μήκει μὲν οὐ συμμέτρους ἐκείναις, τοῖς δ' ἐπιπέδοις ἀδύναται. καὶ περὶ τὰ στερεὰ ἄλλο τοιοῦτον.

^a It is not possible to give the full force of the Greek as *δυνάμεις*, which literally means "powers," has to be trans-

THEAETETUS

SOCRATES. And did you find such a class ?

THEAET. I think we did ; but see if you agree.

Soc. Speak on.

THEAET. We divided all numbers into two classes. The one, consisting of numbers which can be represented as the product of equal factors, we likened in shape to the square and called them square and equilateral numbers.

Soc. And properly so.

THEAET. The numbers between these, among which are three and five and all that cannot be represented as the product of equal factors, but only as the product of a greater by a less or a less by a greater, and are therefore contained by greater and less sides, we likened to oblong shape and called oblong numbers.

Soc. Excellent. And what after this ?

THEAET. Such lines as form the sides of equilateral plane numbers we called lengths, and such as form the oblong numbers we called roots, because they are not commensurable with the others in length, but only with the plane areas which they have the power to form.^a And similarly in the case of solids.

lated "roots" to conform with mathematical usage. *δυνάμεις*, it will be noticed, are here limited to the square roots of oblong numbers, and are therefore always incommensurable.

XII. PLATO

XII. PLATO

(a) GENERAL

Tzetzēs, *Chil.* viii. 972-973

Πρὸ τῶν προθύρων τῶν αὐτοῦ γράψας ὑπῆρχε
Πλάτων·

“Μηδεὶς ἀγεωμέτρητος εἰσίτω μου τὴν στέγην.”

Plut. *Quaes. Conv.* viii. 2. 1

Ἐκ δὲ τούτου γενομένης σιωπῆς, πάλιν ὁ Διογενιανὸς ἀρξάμενος “βούλεσθ’,” εἶπεν, “ἐπεὶ λόγοι περὶ θεῶν γεγόνασιν, ἐν τοῖς Πλάτωνος γενεθλίοις αὐτὸν Πλάτωνα κοινωνὸν παραλάβωμεν, ἐπισκεψάμενοι τίνα λαβὼν γνώμην ἀπεφήνατ’ αἰε γεωμετρεῖν τὸν θεόν; εἴ γε δὴ θετέον εἶναι τὴν ἀπόφασιν ταύτην Πλάτωνος.” ἐμοῦ δὲ ταῦτ’ εἰπόντος ὡς γέγραπται μὲν ἐν οὐδενὶ σαφῶς τῶν ἐκείνου βιβλίων, ἔχει δὲ πίστιν ἰκανὴν καὶ τοῦ Πλατωνικοῦ χαρακτῆρός ἐστιν.

Εὐθύς ὑπολαβὼν ὁ Τυνδάρης “οἶει γάρ,” εἶπεν, “ὦ Διογενιανέ, τῶν περιττῶν τι καὶ δυσθεωρήτων αἰνίττεσθαι τὸν λόγον, οὐχ ὅπερ αὐτὸς εἶρηκε καὶ γέγραφε πολλάκις, ὑμνῶν γεωμετρίαν, ὡς ἀπο-

• For Proclus’s notice of Plato, see *supra*, p. 150, and for 386

XII. PLATO ^a

(a) GENERAL

Tzetzes, *Book of Histories* viii. 972-973

OVER his front doors Plato wrote: "Let no one unversed in geometry come under my roof." ^b

Plutarch, *Convivial Questions* viii. 2. 1

Diogenianus broke the silence which followed this discussion by saying: "Since our discourse is about the gods, shall we make Plato share in it, especially as it is his birthday, and inquire what he meant when he said that God is for ever playing the geometer—if this saying is really Plato's?" I said that this saying is not plainly written in any of his works, but it is a credible saying and is of a Platonic character.

Thereupon Tyndares took up the discussion and said: "Do you think, Diogenianus, that this saying implies some subtle and recondite speculations, and not what he has so often mentioned, when he praises

the pseudo-Platonic instrument for finding two mean proportionals, *supra*, pp. 262-267. The mathematics in Plato is the subject of dissertations by C. Blass (*De Platone mathematico*, Bonn, 1861) and Seth Demel (*Platons Verhältnis zur Mathematik*, Leipzig, 1929).

^b Johannes Tzetzes, the Byzantine pedant who lived in the twelfth century A.D., is not the best of authorities, so this charming story must be accepted with caution. The doors are presumably those of the Academy.

GREEK MATHEMATICS

σπῶσαν ἡμᾶς προσισχομένους τῇ αἰσθήσει καὶ ἀποστρέφουσιν ἐπὶ τὴν νοητὴν καὶ αἰδίον φύσιν, ἣς θεὰ τέλος ἐστὶ φιλοσοφίας οἶον ἐποπτεία τελετῆς; . . . διὸ καὶ Πλάτων αὐτὸς ἐμέμψατο τοὺς περὶ Εὐδόξον καὶ Ἀρχύταν καὶ Μέναιχμον εἰς ὀργανικὰς καὶ μηχανικὰς κατασκευὰς τὸν τοῦ στερεοῦ διπλασιασμὸν ἀπάγειν ἐπιχειροῦντας, ὥσπερ πειρωμένους δι' ἀλόγου δύο μέσας ἀνάλογον, ἣ παρείκοι, λαβεῖν· ἀπόλλυσθαι γὰρ οὕτω καὶ διαφθείρεσθαι τὸ γεωμετρίας ἀγαθὸν αὐτὴς ἐπὶ τὰ αἰσθητὰ παλινδρομούσης καὶ μὴ φερομένης ἄνω μῆδ' ἀντιλαμβανομένης τῶν αἰδίων καὶ ἀσωμάτων εἰκόνων, πρὸς αἴσπερ ὧν ὁ θεὸς αἰεὶ θεὸς ἐστι."

Aristox. *Harm.* ii. *ad. init.*, ed. Macran 122. 3-16

Βέλτιον ἴσως ἐστὶ τὸ προδιελθεῖν τὸν τρόπον τῆς πραγματείας τίς ποτ' ἐστίν, ἵνα προγιγνώσκοντες ὥσπερ ὁδὸν ἢ βαδιστέον ῥάδιον πορευόμεθα εἰδότες τε κατὰ τί μέρος ἐσμὲν αὐτῆς καὶ μὴ λάθωμεν ἡμᾶς αὐτοὺς παρυπολαμβάνοντες τὸ πρᾶγμα. καθάπερ Ἀριστοτέλης αἰεὶ διηγείτο τοὺς πλείστους τῶν ἀκουσάντων παρὰ Πλάτωνος τὴν περὶ τὰγαθοῦ ἀκρόασιν παθεῖν· προσιέναι μὲν γὰρ ἕκαστον ὑπολαμβάνοντα λήψεσθαι τι τῶν νομιζομένων τούτων ἀνθρωπίνων ἀγαθῶν οἶον πλοῦτον ὑγίειαν ἰσχὺν τὸ ὅλον εὐδαιμονίαν τινὰ θαυμαστήν· ὅτε δὲ φανείησαν οἱ λόγοι περὶ μαθημάτων καὶ ἀριθμῶν καὶ γεωμετρίας καὶ ἀστρολογίας καὶ τὸ πέρασ ὅτι ἀγαθὸν ἐστὶν ἔν, παντελῶς οἶμαι παράδοξόν τι

^a The play on the words ἀλόγου, ἀνάλογον cannot be reproduced in English, but we may compensate ourselves by playing on the words "means," "mean proportionals."

PLATO

geometry as a science that takes men away from sensible objects and turns them towards the intelligible and eternal, whose contemplation is the end of philosophy like the final grade of initiation into the mysteries? . . . Therefore Plato himself censured Eudoxus and Archytas and Menaechmus for endeavouring to solve the doubling of the cube by instruments and mechanical constructions, thus trying by irrational means to find two mean proportionals,^a so far as that is allowable : for in this way what is good in geometry would be corrupted and destroyed, falling back again into sensible objects and not rising upwards and laying hold of immaterial and eternal images, among which God has his being and remains for ever God."

Aristoxenus, *Elements of Harmony* ii. *ad init.*,
ed. Macran 122. 3-16

It is perhaps well to go through in advance the nature of our inquiry, so that, knowing beforehand the road along which we have to travel, we may have an easier journey, because we will know at what stage we are in, nor shall we harbour to ourselves a false conception of our subject. Such was the condition, as Aristotle often used to tell, of most of the audience who attended Plato's lecture on the Good. Every one went there expecting that he would be put in the way of getting one or other of the things accounted good in human life, such as riches or health or strength or, in fine, any extraordinary gift of fortune. But when they found that Plato's arguments were of mathematics and numbers and geometry and astronomy and that in the end he declared the One to be the Good, they were altogether taken by

GREEK MATHEMATICS

ἐφαίνετο αὐτοῖς· εἶθ' οἱ μὲν ὑποκατεφρόνουσαν τοῦ πράγματος οἱ δὲ κατεμέμφοντο.

(b) PHILOSOPHY OF MATHEMATICS

Plat. *Rep.* vi. 510 c-e

Οἶμαι γάρ σε εἰδέναί ὅτι οἱ περὶ τὰς γεωμετρίας τε καὶ λογισμοὺς καὶ τὰ τοιαῦτα πραγματευόμενοι, ὑποθέμενοι τό τε περιττὸν καὶ τὸ ἄρτιον καὶ τὰ σχήματα καὶ γωνιῶν τριττὰ εἶδη καὶ ἄλλα τούτων ἀδελφὰ καθ' ἐκάστην μέθοδον, ταῦτα μὲν ὡς εἰδότες, ποιησάμενοι ὑποθέσεις αὐτά, οὐδένα λόγον οὔτε αὐτοῖς οὔτε ἄλλοις ἔτι ἀξιοῦσι περὶ αὐτῶν διδόναι ὡς παντὶ φανερῶν, ἐκ τούτων δ' ἀρχόμενοι τὰ λοιπὰ ἤδη διεξιόντες τελευτῶσιν ὁμολογουμένως ἐπὶ τούτῳ οὐδ' ἂν ἐπὶ σκέψιν ὀρμήσωσι.

Πάνυ μὲν οὖν, ἔφη, τοῦτό γε οἶδα.

Οὐκοῦν καὶ ὅτι τοῖς ὀρωμένοις εἶδεσι προσχρῶνται καὶ τοὺς λόγους περὶ αὐτῶν ποιοῦνται, οὐ περὶ τούτων διανοοῦμενοι, ἀλλ' ἐκείνων περὶ οἷς ταῦτα ἔοικε, τοῦ τετραγώνου αὐτοῦ ἔνεκα τοὺς λόγους ποιούμενοι καὶ διαμέτρου αὐτῆς, ἀλλ' οὐ ταύτης ἦν γράφουσιν, καὶ τᾶλλα οὕτως, αὐτὰ μὲν ταῦτα ἅπλαττουςίν τε καὶ γράφουσιν, ὧν καὶ σκιαί καὶ ἐν ὕδασι εἰκόνες εἰσίν, τούτοις μὲν ὡς εἰκόσιν αὐτῶν χρώμενοι, ζητοῦντες δὲ αὐτὰ ἐκεῖνα ἰδεῖν ἅ οὐκ ἂν ἄλλως ἴδοι τις ἢ τῇ διανοίᾳ.

Plat. *Ep.* vii. 342 a-343 b

Ἔστιν τῶν ὄντων ἐκάστῳ, δι' ὧν τὴν ἐπιστήμην ἀνάγκη παραγίγνεσθαι, τρία, τέταρτον δ' αὐτή—

PLATO

surprise. The result was that some of them scoffed at the thing, while others found great fault with it.

(b) PHILOSOPHY OF MATHEMATICS

Plato, *Republic* vi. 510 c-e

I think you know that those who deal with geometrics and calculations and such matters take for granted the odd and the even, figures, three kinds of angles and other things cognate to these in each field of inquiry ; assuming these things to be known, they make them hypotheses, and henceforth regard it as unnecessary to give any explanation of them either to themselves or to others, treating them as if they were manifest to all ; setting out from these hypotheses, they go at once through the remainder of the argument until they arrive with perfect consistency at the goal to which their inquiry was directed.

Yes, he said, I am aware of that.

Therefore I think you also know that although they use visible figures and argue about them, they are not thinking about these figures but of those things which the figures represent ; thus it is the square in itself and the diameter in itself which are the matter of their arguments, not that which they draw ; similarly, when they model or draw objects, which may themselves have images in shadows or in water, they use them in turn as images, endeavouring to see those absolute objects which cannot be seen otherwise than by thought.

Plato, *Epistle* vii. 342 a-343 b

For everything that exists there are three things through which knowledge about it must come ; the

GREEK MATHEMATICS

πέμπτον δ' αὐτὸ τιθέναι δεῖ ὃ δὴ γνωστόν τε καὶ ἀληθῶς ἐστὶν ὄν—ἐν μὲν ὄνομα, δεύτερον δὲ λόγος, τὸ δὲ τρίτον εἶδωλον, τέταρτον δὲ ἐπιστήμη. περὶ ἐν οὖν λαβὲ βουλόμενος μαθεῖν τὸ νῦν λεγόμενον, καὶ πάντων οὕτω περὶ νόησον. κύκλος ἐστὶν τι λεγόμενον, ᾧ τοῦτ' αὐτὸ ἐστὶν ὄνομα ὃ νῦν ἐφθέγγεθα. λόγος δ' αὐτοῦ τὸ δεύτερον, ἐξ ὀνομάτων καὶ ῥημάτων συγκείμενος· τὸ γὰρ ἐκ τῶν ἐσχάτων ἐπὶ τὸ μέσον ἴσον ἀπέχον πάντη, λόγος ἂν εἴη ἐκείνου ᾧπερ στρογγύλον καὶ περιφερὲς ὄνομα καὶ κύκλος. τρίτον δὲ τὸ ζωγραφούμενόν τε καὶ ἐξαλειφόμενον καὶ τορνευόμενον καὶ ἀπολλύμενον· ὧν αὐτὸς ὁ κύκλος, ὃν περὶ πάντ' ἐστὶν ταῦτα, οὐδὲν πάσχει, τούτων ὡς ἕτερον ὄν. τέταρτον δὲ ἐπιστήμη καὶ νοῦς ἀληθῆς τε δόξα περὶ ταῦτ' ἐστὶν· ὡς δὲ ἐν τούτῳ αὐτὸ πᾶν θετέον, οὐκ ἐν φωναῖς οὐδ' ἐν σωματίων σχήμασιν ἀλλ' ἐν ψυχαῖς ἐνόν, ᾧ δῆλον ἕτερόν τε ὄν αὐτοῦ τοῦ κύκλου τῆς φύσεως τῶν τε ἔμπροσθεν λεχθέντων τριῶν. τούτων δὲ ἐγγύτατα μὲν συγγενεῖα καὶ ὁμοιότητι τοῦ πέμπτου νοῦς πεπλησίακεν, τᾶλλα δὲ πλέον ἀπέχει. . . . κύκλος ἕκαστος τῶν ἐν ταῖς πράξεσι γραφομένων ἢ καὶ τορνευθέντων μεστὸς τοῦ ἐναντίου ἐστὶν τῷ πέμπτῳ—τοῦ γὰρ εὐθέος ἐφάπτεται πάντη—αὐτὸς δέ, φαμέν, ὁ κύκλος οὔτε τι μικρότερον οὔτε μείζον τῆς ἐναντίας ἔχει ἐν αὐτῷ φύσεως. ὄνομα τε αὐτῶν φαμεν οὐδὲν οὐδενὶ βέβαιον εἶναι, κωλύειν δ' οὐδὲν τὰ νῦν στρογγύλα καλούμενα εὐθέα κεκλήσθαι τά τε εὐθέα δὴ στρογγύλα, καὶ

PLATO

knowledge itself is a fourth ; and as a fifth we must posit the actual object of knowledge which is the true reality. We have, then :—first, a name ; second, a description ; third, an image ; fourth, knowledge of the object. Take a particular case if you want to understand what I have just said, and then apply the theory to all objects in the same way. There is, for example, something called a circle, whose name is the very word I just now uttered. In the second place there is a description of it, made up of nouns and verbs. The description of the object whose name is round and circumference and circle would be : that which has everywhere the same distance between the extremities and the middle. In the third place there is the object which is drawn and erased and turned on the lathe and destroyed—processes which the real circle, in relation to which these other circles exist, can in no wise suffer, being different from them. In the fourth place there are knowledge and understanding and correct opinion about them—all of which must be posited as one thing more, inasmuch as it is found not in sounds nor in the shapes of bodies but in souls, whereby it manifestly differs in nature both from the real circle and from the aforesaid three. Of these understanding approaches nearest to the fifth in kinship and likeness, while the others are more distant. . . . Every circle drawn or turned on a lathe in practice abounds in the opposite to the fifth—for it everywhere touches the straight, while the real circle, we maintain, contains in itself neither more nor less of the opposite nature. The name, we maintain, is in no case stable ; there is nothing to prevent the things now called round from being called straight, and the straight round ; and those

GREEK MATHEMATICS

οὐδὲν ἦττον βεβαίως ἔξειν τοῖς μεταθεμένοις καὶ ἐναντίως καλοῦσιν.

Aristot. *Met.* A 5, 987 b 14-18

Ἔτι δὲ παρὰ τὰ αἰσθητὰ καὶ τὰ εἶδη τὰ μαθηματικὰ τῶν πραγμάτων εἶναί φησι μεταξύ, διαφέροντα τῶν μὲν αἰσθητῶν τῷ αἶδία καὶ ἀκίνητα εἶναι, τῶν δ' εἰδῶν τῷ τὰ μὲν πόλλ' ἄττα ὅμοια εἶναι τὸ δ' εἶδος αὐτὸ ἐν ἕκαστον μόνον.

(c) THE "DIORISMOS" IN THE "MENO"

Plat. *Meno* 86 e-87 b

Λέγω δὲ τὸ ἐξ ὑποθέσεως ὧδε, ὥσπερ οἱ γεωμέτραι πολλάκις σκοποῦνται, ἐπειδάν τις ἔρηται αὐτούς, οἷον περὶ χωρίου, εἰ οἷόν τε ἐς τόνδε τὸν κύκλον τόδε τὸ χωρίον τρίγωνον ἐνταθῆναι, εἶποι ἂν τις ὅτι "οὐπω οἶδα εἰ ἔστι τοῦτο τοιοῦτον, ἀλλ' ὥσπερ μὲν τινα ὑπόθεσιν προὔργου οἶμαι ἔχειν πρὸς τὸ πρᾶγμα τοιάνδε. εἰ μὲν ἔστι τοῦτο τὸ χωρίον τοιοῦτον, οἷον παρὰ τὴν δοθείσαν αὐτοῦ γραμμὴν παρατείναντα ἐλλείπειν τοιούτῳ χωρίῳ, οἷον ἂν αὐτὸ τὸ παρατεταμένον ἦ, ἄλλο τι συμβαίνειν μοι δοκεῖ, καὶ ἄλλο αὖ, εἰ ἀδύνατόν ἐστι ταῦτα παθεῖν· ὑποθέμενος οὖν ἐθέλω εἰπεῖν σοι

PLATO

who transpose them and use them in the opposite way will find them no less stable than they are now.

Aristotle, *Metaphysics* A 5, 987 b 14-18

Again, he [Plato] said that besides perceptible objects and forms there are the objects of mathematics, which occupy an intermediate position; they differ from perceptible objects in being eternal and unchangeable, and from forms in that there are many alike, while the form itself is in each case unique.

(c) THE "DIORISMOS" IN THE "MENO"

Plato, *Meno* 86 E-87 B

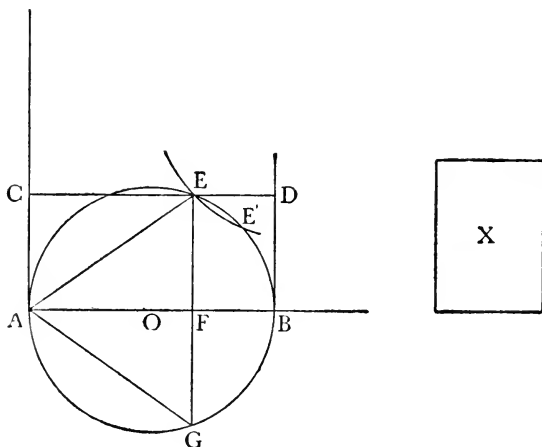
I mean "by way of hypothesis" what the geometers often envisage when they are asked, for example, as regards a given area, whether this area can be inscribed in the form of a triangle in a given circle. The answer might be, "I do not know whether this is so, but I think I have, if I may so put it, a useful hypothesis. If this area is such that when applied [as a rectangle] to the given straight line ^a in the circle it is deficient by a figure [rectangle] similar to that which is applied, then one result seems to me to follow, while another result follows if what I have described is not possible. Accordingly, by laying down a hypothesis I am willing to tell you

* "The given straight line" can only be the diameter. The "application" of areas so as to be "deficient" in a given way is explained above, pp. 186-187.

GREEK MATHEMATICS

τὸ συμβαῖνον περὶ τῆς ἐντάσεως αὐτοῦ εἰς τὸν κύκλον, εἴτε ἀδύνατον εἴτε μή.”

• If AB is the diameter of a circle of centre O, and E is a point on the circumference, and the rectangles ACEF,



FBDE are completed, and the chords EFG, AG are drawn, then the rectangle ACEF is “applied” to the straight line AB and “falls short” by the rectangle FBDE which is similar to the “applied” rectangle, for $AF : FE = EF : FB$. Moreover AEG is an isosceles triangle equal in area to the rectangle ACEF.

In order, therefore, to inscribe in the circle an isosceles

PLATO

what is the conclusion about the inscribing of the area in the circle, whether it is impossible or not." ^a

triangle equal to a given area X we have to find a point E on the circumference of the circle such that if EF be dropped perpendicular to AB

the rectangle AF . FE = the given area X.

Clearly E lies on a rectangular hyperbola of which AB, AC are asymptotes. If b^2 is equal to the given area, the equation of the hyperbola referred to its asymptotes as axes is $xy = b^2$. For a real solution it is necessary that b^2 should not be greater than the equilateral triangle inscribed in the circle, *i.e.*, not greater than $3\sqrt{3} \cdot \frac{a^2}{4}$, where a is the radius of the circle. If b^2 is equal to this area, the hyperbola touches the circle and there is only one solution. If b^2 is greater than this area, the hyperbola does not touch, and there is no solution. If b^2 is less than this area, the hyperbola cuts the circle in two points E, E', giving two solutions. It is to these facts that Plato refers.

The passage is an example of a *διορισμός* giving the conditions for the possibility of the solution of a problem. Proclus is therefore in error when he says that Leon, the pupil of Neoclides, who was younger than Plato, "invented *διορισμοί*" (*supra*, p. 150).

The above interpretation was first given by E. F. August in 1829. It was independently discovered by S. H. Butcher in *Journal of Philology*, xvii., pp. 219-225 and is accepted by Heath (*H.G.M.* i. 298-303), whose exposition I have closely followed. Many other explanations have been offered, the best known being that of Adolph Benecke (*Ueber die geometrische Hypothesis in Platons Menon*).

GREEK MATHEMATICS

(d) THE NUPTIAL NUMBER

Plat. *Rep.* viii. 546 B-D.

Ἔστι δὲ θείῳ μὲν γεννητῷ περίοδος ἦν ἀριθμὸς περιλαμβάνει τέλειος, ἀνθρωπείῳ δὲ ἐν ᾧ πρώτῳ αὐξήσεις δυνάμεναί τε καὶ δυναστευόμεναι, τρεῖς ἀποστάσεις, τέτταρας δὲ ὄρους λαβοῦσαι ὁμοιούντων τε καὶ ἀνομοιούντων καὶ αὐξόντων καὶ φθινόντων, πάντα προσήγορα καὶ ῥητὰ πρὸς ἄλληλα ἀπέφηναν· ὧν ἐπίτριτος πυθμὴν πεμπάδι συζυγεῖς δύο ἀρμονίας παρέχεται τρεῖς αὐξηθεῖς, τὴν μὲν ἴσην ἰσάκις, ἑκατὸν τοσαυτάκις, τὴν δὲ ἰσομήκη μὲν τῇ, προμήκη δέ, ἑκατὸν μὲν ἀριθμῶν ἀπὸ διαμέτρων ῥητῶν πεμπάδος, δεομένων ἐνὸς ἐκάστων, ἀρρήτων δὲ δυοῖν, ἑκατὸν δὲ κύβων τριάδος.

^a The passage is included here because of several interesting points for the history of Greek mathematics. Plato's language is so fancifully phrased that a completely satisfactory solution is difficult to get. The literature which has grown round this "nuptial number" is vast, but the most satisfying discussions are those by Adam, *The Republic of Plato* ii., pp. 204-208, 264-312, and A. G. Laird, *Plato's Geometrical Number and the Comment of Proclus*.

^b *δυναστευόμεναι* is a *ἅπαξ λεγομένον*, and its meaning is uncertain. A straight line is said *δύνασθαι* ("to be capable of") an area when the square on it is equal to the area. Hence *δυναμένη* should mean the side of a square, as it does in Eucl. x. Def. 4. *δυναστευομένη* is a kind of passive of *δυναμένη*, meaning presumably that of which the *δυναμένη* is capable, and so could mean the square itself. It is

PLATO

(d) THE NUPTIAL NUMBER

Plato, *Republic* viii. 546 B-D *

The divine race has a cycle comprehended by a perfect number, but the number of the human race's cycle is the first in which root and square increases,^b forming three intervals and four terms of elements that make like and unlike and wax and wane, show all things agreeable and rational towards one another. The base of these things, the four-three joined with five, when thrice increased furnishes two harmonies, the one a square, so many times a hundred, the other a rectangle, one of its sides being a hundred of the numbers from the rational diameters of five, each diminished by one (or a hundred of the numbers from the irrational diameters of five, each diminished by two), the other side being a hundred of the cubes of three.^c

temerarious to try and get a precise meaning out of *αὐξήσεις δυνάμεναί τε καὶ δυναστευόμεναί*, and perhaps we should not inquire too closely into what is more mystical than mathematical. Laird thinks it means "if a square is equal to a rectangle."

^c The chief mathematical interest of the passage lies in the part most easy to decipher, that about the two "harmonies." The "irrational diameter of five" is the diagonal of a side of square 5, *i.e.* $\sqrt{50}$. The "rational diameter" of five is the nearest integer to the "irrational diameter," *i.e.* $\sqrt{50} - 1$. The "number" from the "rational" or "irrational" diameter is the square. A "hundred of the numbers from the rational diameter of five, each diminished by one" is therefore $100 \times (49 - 1) = 4800$; and the same number is expressed as "a hundred of the numbers from the irrational diameter of five, each diminished by two," for this is $100 \times (50 - 2) = 4800$. This number gives one side of the oblong and the other is "a hundred of the cubes of three," or $100 \times 27 = 2700$. The rectangle of which these

GREEK MATHEMATICS

(e) GENERATION OF NUMBERS

Plat. *Epin.* 990 c-991 b

Διὸ μαθημάτων δέον ἂν εἶη· τὸ δὲ μέγιστόν τε καὶ πρῶτον καὶ ἀριθμῶν αὐτῶν, ἀλλ' οὐ σώματα ἔχόντων, ἀλλὰ ὅλης τῆς τοῦ περιττοῦ τε καὶ ἀρτίου γενέσεώς τε καὶ δυνάμεως, ὅσῃν παρέχεται πρὸς τὴν τῶν ὄντων φύσιν. ταῦτα δὲ μαθόντι τούτοις ἐφεξῆς ἐστὶν ὃ καλοῦσι μὲν σφόδρα γελοῖον ὄνομα γεωμετρίαν, τῶν οὐκ ὄντων δὲ ὁμοίων ἀλλήλοις φύσει ἀριθμῶν ὁμοίωσις πρὸς τὴν τῶν ἐπιπέδων μοῖραν γεγονυῖά ἐστι διαφανής· ὃ δὲ θάυμα οὐκ ἀνθρώπινον ἀλλὰ γεγονὸς θεῖον φανερόν ἂν γίγνοιτο τῷ δυναμένῳ συννοεῖν. μετὰ δὲ ταύτην τοὺς τρις

are sides is therefore $4800 \times 2700 = 12,960,000$, and this is 3600^2 , which is the other "harmony."

These "rational" and "irrational" diameters are a clear reference to the "side-" and "diameter-numbers" of the Pythagoreans, for which see *supra*, pp. 132-139.

There is fairly widespread agreement that the geometrical number is $12,960,000 = 3600^2 = 4800 \times 2700$, but on the method by which this number is reached the widest divergence exists. Hultsch and Adam suppose that two numbers are obtained, one in the first sentence down to ἀπέφηναν, the other (12,960,000) in the remainder of the passage. Both agree that the first number is 216, but Hultsch obtains it as $2^3 \times 3^3$ and Adam as $3^3 + 4^3 + 5^3$. Hultsch then takes "the four-three joined with a five" to mean $4 + 3 + 5 = 12$, which is then multiplied by three (τρὶς αὐξηθεῖς), giving 36, and as this has to be taken "so many times a hundred" we get 3600 as the side of the square which is one of the "harmonies," and therefore the final number is 3600^2 . Adam takes "the four-three joined with a five" to be $3 \times 4 \times 5 = 60$, and τρὶς αὐξηθεῖς to mean multiplied by itself three times (*i.e.* raised to the fourth power, which gives us immediately $60^4 = 3600^2$). Laird, on the other hand, believes there is only one number

PLATO

(e) GENERATION OF NUMBERS

Plato, *Epinomis* 990 c-991 b

There will therefore be need of studies ^a: the first and most important is of numbers in themselves, not of corporeal numbers, but of the whole genesis of the odd and even, and the greatness of their influence on the nature of things. When the student has learnt these matters there comes next in order after them what they call by the very ridiculous name of geometry, though it proves to be an evident likening, with reference to planes, of numbers not like one another by nature ^b; and that this is a marvel not of human but of divine origin will be clear to him who is able to understand. And after this the numbers

indicated (which he agrees in thinking to be $3600^2 = 4800 \times 2700$). He maintains, with the help of Proclus, that the first sentence gives a general method of forming "harmonies" which is then applied to the *triangle* of sides 3, 4 and 5 to give the geometrical number. The application gives the series 27, 36, 48, 64 (with four terms and three intervals), and the first three numbers multiplied by 100 give the elements of the geometrical number, $3600^2 = 2700 \times 4800$. Each solution has merits, but each raises problems which it is impossible to discuss here. However, we may be fairly confident that the final number obtained is 12,960,000.

^a In Plato the word *μάθημα* is used generally of any study, but the particular subjects here mentioned are all mathematical, and the word was already getting the special significance which it attained in Aristotle's time.

^b The most likely explanation of "numbers not like one another by nature" is "numbers incommensurable with each other"; drawn as two lines in a plane, *e.g.* as the side and diagonal of a square, they are made like to one another by the geometer's art, in that there is no outward difference between them as there is between an integer and an irrational number.

GREEK MATHEMATICS

ἠϋξημένους καὶ τῇ στερεᾷ φύσει ὁμοίους, τοὺς δὲ ἀνομοίους αὐτῶν γεγονότας ἑτέρα τέχνη ὁμοιοῖ, ταύτη ἦν δὴ στερεομετρίαν ἐκάλεσαν οἱ προστυχεῖς αὐτῇ γεγονότες· ὁ δὲ θεῖόν τ' ἐστὶ καὶ θαυμαστόν τοῖς ἐγκαθορῶσί τε καὶ διανοουμένοις, ὡς περὶ τὸ διπλάσιον ἀεὶ στρεφομένης τῆς δυνάμεως καὶ τῆς ἐξ ἐναντίας ταύτης καθ' ἑκάστην ἀναλογίαν εἶδος καὶ γένος ἀποτυπῶνται πᾶσα ἢ φύσις. ἡ μὲν δὴ πρώτη τοῦ διπλασίου κατ' ἀριθμὸν ἓν πρὸς δύο κατὰ λόγον φερομένη, διπλάσιον δὲ ἢ κατὰ δυνάμιν οὕσα· ἡ δ' εἰς τὸ στερεόν τε καὶ ἀπτόν πάλιν αὐτῶν διπλάσιον, ἀφ' ἑνὸς εἰς ὀκτῶν διαπορευθεῖσα· ἡ δὲ διπλασίου μὲν εἰς μέσον, ἴσως δὲ τοῦ ἐλάττονος πλέον ἔλαττόν τε τοῦ μείζονος, τὸ δ' ἕτερον τῶν αὐτῶν μέρει τῶν ἄκρων αὐτῶν ὑπερέχον τε καὶ ὑπερεχόμενον· ἐν μέσῳ δὲ τοῦ ἐξ πρὸς τὰ δώδεκα συνέβη τό τε ἡμιόλιον καὶ ἐπίτριτον· τούτων αὐτῶν

• These are probably cubes of integers.

• These will be numbers with irrational cube roots.

• What has been said about lines in the plane applies also to lines in three dimensions. Numbers incommensurable with each other, such as 1 and $\sqrt[3]{2}$, are made like when one is represented as the side of a unit cube and the other as the side of a cube twice as great. We know that this problem of doubling the cube was brought to Plato's notice (*supra*, pp. 258-259). The past tense suggests that Plato had in mind certain definite προστυχεῖς who coined the word στερεομετρία; the Pythagoreans, Theaetetus, Democritus and Eudoxus had all advanced the science.

^d What follows cannot be translated literally, and it is more than likely that the text is corrupt, or that it has reached us unrevised from Plato's first draft. But the general sense is clear. Successive multiplication of 1 by 2

PLATO

thrice increased and like to the solid nature,^a and those again which have been made unlike,^b he likens by another art, namely, that which its adepts called stereometry^c; and a divine and marvellous thing it is to those who contemplate it and reflect how the whole of nature is impressed with species and kind according to each proportion as power and its converse continually turn about the double.^d First the double operates on the number 1 by simple multiplication so as to give 2, and a second double yields the square; by further doubling we reach the solid and tangible, the process having gone from 1 to 8. Then comes the application of the double to give the mean which is as much greater than the less as it is less than the greater, and the other mean is that which exceeds and is exceeded by the same part of the extremes; between 6 and 12 come both the *sesquialter* [9] and the *sesquitertius* [8]; turning between these two, to

gives the series 1, 2, 4, 8, which represent a point, a line, a square and a cube. This is a series in geometric progression, 2 being a geometrical mean between 1 and 4, and 4 a geometrical mean between 2 and 8. Two other means were known to the Pythagoreans (*supra*, pp. 110-115)—and the whole passage is thoroughly Pythagorean—the arithmetic and the harmonic. The arithmetic mean is equidistant between the two terms; the harmonic exceeds one term, and is exceeded by the other, by the same fraction of each term. Thus the arithmetic mean between 1 and 2 is $\frac{3}{2}$ and

the harmonic mean is $\frac{4}{3}$; clearing of fractions, the arithmetic mean between 6 and 12 is 9 and the harmonic mean 8.

“Power and its converse”—*ἡ δύναμις καὶ ἡ ἐξ ἐναντίας ταύτης*—I take to mean “number and its reciprocal”; we have to multiply by 2 to get the series 1, 2, 4, 8 and then take $\frac{1}{2}$ of 6 + 12 to get the arithmetic mean.

GREEK MATHEMATICS

ἐν τῷ μέσῳ ἐπ' ἀμφοτέρα στρεφομένη τοῖς ἀνθρώποις σύμφωνον χρείαν καὶ σύμμετρον ἀπενείματο παιδιᾶς ῥυθμοῦ τε καὶ ἁρμονίας χάριν, εὐδαίμονι χορείᾳ Μουσῶν δεδομένη.

^a The reference to the choir of the Muses makes it clear, in my opinion, that the number 9 is referred to, though the construction of the sentence does not necessarily involve it. So W. R. M. Lamb in the Loeb version of the *Epinomis*, p. 482.

^b The whole passage should be compared with *Timaeus*, 35 B—36 B (see R. G. Bury's notes in the Loeb version, pp. 66-71, or A. E. Taylor, *A Commentary on Plato's Timaeus*, pp. 136-137). There Plato writes down the series 1, 2, 4, 8 and 1, 3, 9, 27, and then fills up the intervals between these

PLATO

one side or the other, this power [9]^a furnished men with concord and symmetry for the purpose of rhythm and harmony in their pastimes, and has been given to the blessed dance of the Muses.^b

numbers with arithmetic and harmonic means so as to get a series of 34 terms, 1, $\frac{9}{8}$, $\frac{81}{64}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{27}{128}$, $\frac{243}{8192}$, 2 . . . 27, which is intended to represent the notes of a musical scale having a compass of four octaves and a major "sixth."

Much prominence is given to this passage from the *Epinomis* by A. E. Taylor, *Mind*, xxxv., pp. 419-440, 1926, *ibid.* xxxvi., pp. 12-33, 1927, and D'Arcy Wentworth Thompson, *ibid.* xxxviii., pp. 43-55, 1929.

For a further discussion of this side of Plato's philosophy see Julius Stenzel, *Zahl und Gestalt bei Platon und Aristoteles* (Leipzig, 1924).

XIII. EUDOXUS OF CNIDOS

XIII. EUDOXUS OF CNIDOS

(a) THEORY OF PROPORTION

Schol. i. in Eucl. *Elem.* v., Eucl. ed. Heiberg v. 280. 1-9

Σκοπὸς τῷ πέμπτῳ βιβλίῳ περὶ ἀναλογιῶν δια-
λαβεῖν. . . . τὸ δὲ βιβλίον Εὐδόξου τινὲς εὕρεσιν
εἶναι λέγουσι τοῦ Πλάτωνος διδασκάλου.

(b) VOLUME OF CONE AND PYRAMID

Archim. *De Sphaera et Cyl.* i., Pref., Archim. ed. Heiberg
i. 4. 2-13

Διόπερ οὐκ ἂν ὀκνήσαιμι ἀντιπαραβαλεῖν αὐτὰ
πρὸς τε τὰ τοῖς ἄλλοις γεωμέτραις τεθεωρημένα
καὶ πρὸς τὰ δόξαντα πολὺ ὑπερέχειν τῶν ὑπὸ
Εὐδόξου περὶ τὰ στερεὰ θεωρηθέντων, ὅτι πᾶσα
πυραμὶς τρίτον ἐστὶ μέρος πρίσματος τοῦ βάσιν
ἔχοντος τὴν αὐτὴν τῇ πυραμίδι καὶ ὕψος ἴσον, καὶ
ὅτι πᾶς κῶνος τρίτον μέρος ἐστὶν τοῦ κυλίνδρου
τοῦ βάσιν ἔχοντος τὴν αὐτὴν τῷ κώνῳ καὶ ὕψος
ἴσον· καὶ γὰρ τούτων προυπαρχόντων φυσικῶς
περὶ ταῦτα τὰ σχήματα, πολλῶν πρὸ Εὐδόξου

XIII. EUDOXUS OF CNIDOS ^a

(a) THEORY OF PROPORTION

Euclid, *Elements* v., Scholium i., Eucl. ed. Heiberg
v. 280. 1-9

THE aim of the fifth [book of the *Elements*] is the treatment of proportionals. . . . Some say that the book is the discovery of Eudoxus, the pupil of Plato.

(b) VOLUME OF CONE AND PYRAMID

Archimedes, *On the Sphere and Cylinder*, Preface to
Book i., Archim. ed. Heiberg i. 4. 2-13

For this reason I cannot feel any hesitation in setting these [theorems] side by side both with the investigations of other geometers and with those of the theorems of Eudoxus on solids which seem to stand out pre-eminently, namely, that any pyramid is a third part of the prism having the same base as the pyramid and equal height, and that any cone is a third part of the cylinder having the same base as the cone and equal height ; for though these properties were naturally inherent in these figures all along, yet

^a Eudoxus lived from about 408 to 355 B.C. For Proclus's notice of him, see *supra*, pp. 150-153.

GREEK MATHEMATICS

γεγενημένων ἀξίων λόγου γεωμετρῶν συνέβαινε
ὑπὸ πάντων ἀγνοεῖσθαι μηδ' ὑφ' ἐνὸς κατανοηθῆναι

(c) THEORY OF CONCENTRIC SPHERES

Aristot. *Met.* A 8, 1073 b 17-32

Εὐδοξος μὲν οὖν ἡλίου καὶ σελήνης ἑκατέρου
τὴν φορὰν ἐν τρισὶν ἐτίθετ' εἶναι σφαίραις, ὧν
τὴν μὲν πρώτην τὴν τῶν ἀπλανῶν ἄστρον εἶ-
ναι, τὴν δὲ δευτέραν κατὰ τὸν διὰ μέσων τῶν ζω-
δίων, τὴν δὲ τρίτην κατὰ τὸν λελοξωμένον ἐν τῷ

• In his preface to the *Method* (see *supra*, p. 230) Archimedes says that Democritus enunciated these theorems, but without proof. It may safely be inferred from Archimedes' preface to the *Quadrature of the Parabola* (Archim. ed. Heiberg ii. 264. 9-22) that Eudoxus used for the proof a lemma equivalent to Euclid x. 1 (*infra*, pp. 452-453), and that the credit belongs to him for having made the *exhaustion* of an area by means of inscribed polygons a regular method in Greek geometry; to some extent he had been preceded by Antiphon and Hippocrates.

^b We are told by Simplicius, on the authority of Eudemus, that Plato set astronomers the problem of finding what are the uniform and ordered movements which will "save the phenomena" of the planetary motions, and that Eudoxus was the first of the Greeks to concern himself with hypotheses of this sort. Eudoxus believed that the motion of the sun, moon and planets could be accounted for by a combination of circular movements, a view which remained unchallenged till Kepler. To account for the motion of the sun and moon he needed to use only three concentric spheres, but the motion of the planets required in each case four concentric spheres, the common centre being the centre of the earth. The spheres were of different sizes, one enclosing the other. Each planet was attached to a point on the equator of the innermost sphere, so that by the motion of this sphere alone the planet would describe a circle. But the poles of this

EUDOXUS OF CNIDOS

they were in fact unknown to the many competent geometers who lived before Eudoxus and had not been noticed by anyone.^a

(c) THEORY OF CONCENTRIC SPHERES

Aristotle, *Metaphysics* A 8, 1073 b 17-32

Eudoxus assumed that the motion both of the sun and of the moon takes place on three spheres,^b of which the first is that of the fixed stars, the second moves about the circle which passes through the middle of the signs of the zodiac, and the third moves about

sphere were not fixed, themselves moving on a larger sphere rotating about two different poles. The poles of this second sphere similarly lay on a third larger sphere moving about a different set of poles, and the poles of the third sphere on yet a fourth, moving about another set of poles. Each sphere rotated uniformly, but its speed was peculiar to itself. For the sun and moon only three spheres were needed, the two largest being the same as for the planets. The outermost circle (which comes first in the description by Aristotle and Simplicius), moving from east to west in twenty-four hours, reproduces the daily motion of the fixed stars. The second moves from west to east about an axis perpendicular to the plane of the zodiac circle (ecliptic), its equator accordingly revolving in the plane of the zodiac.

The subject belongs as much to Greek astronomy as to Greek mathematics, and for fuller information the reader is referred to the classic paper of Schiaparelli, *Le sfere omocentriche di Eudosso, di Callippo e di Aristotele* (Milan, 1875), to the works of Sir Thomas Heath (*Aristarchus of Samos*, pp. 193-224, *Greek Astronomy*, pp. 65-70, *H.G.M.* i. 329-335), and to W. D. Ross, *Aristotle's Metaphysics*, vol. ii., pp. 384-394. But Eudoxus's system of concentric rotating spheres is a geometrical *tour de force* of the highest order, and must find some notice here. In all the history of science there are few hypotheses that bear so unmistakably the stamp of genius.

GREEK MATHEMATICS

πλάτει τῶν ζωδίων (ἐν μείζονι δὲ πλάτει λελοξῶσθαι καθ' ὃν ἡ σελήνη φέρεται ἢ καθ' ὃν ὁ ἥλιος). τῶν δὲ πλανωμένων ἄστρων ἐν τέτταρσιν ἐκάστου σφαίραις, καὶ τούτων δὲ τὴν μὲν πρώτην καὶ δευτέραν τὴν αὐτὴν εἶναι ἐκείναις (τὴν τε γὰρ τῶν ἀπλανῶν τὴν ἀπάσας φέρουσιν εἶναι, καὶ τὴν ὑπὸ ταύτῃ τεταγμένην καὶ κατὰ τὸν διὰ μέσων τῶν ζωδίων τὴν φορὰν ἔχουσιν κοινὴν ἀπασῶν εἶναι), τῆς δὲ τρίτης ἀπάντων τοὺς πόλους ἐν τῷ διὰ μέσων τῶν ζωδίων εἶναι, τῆς δὲ τετάρτης τὴν φορὰν κατὰ τὸν λελοξωμένον πρὸς τὸν μέσον ταύτης· εἶναι δὲ τῆς τρίτης σφαίρας τοὺς πόλους τῶν μὲν ἄλλων ἰδίους, τοὺς δὲ τῆς Ἀφροδίτης καὶ τοῦ Ἑρμοῦ τοὺς αὐτοῦς.

Simpl. in *De caelo* ii. 12 (Aristot. 293 a 4), ed. Heiberg
496. 23-497. 5

Ἡ δὲ τρίτη σφαῖρα τοὺς πόλους ἔχουσα ἐπὶ τοῦ ἐν τῇ δευτέρᾳ διὰ μέσων τῶν ζωδίων ἀπὸ μεσημβρίας τε πρὸς ἄρκτον στρεφομένη καὶ ἀπ' ἄρκτου πρὸς μεσημβρίαν συνεπιστρέψει τὴν τετάρτην καὶ ἐν αὐτῇ τὸν ἀστέρα ἔχουσιν καὶ δὴ τῆς κατὰ πλάτος κινήσεως ἔξει τὴν αἰτίαν· οὐ μὴν αὐτὴ μόνη· ὅσον γὰρ ἐπὶ ταύτῃ καὶ πρὸς τοὺς πόλους τοῦ διὰ μέσων τῶν ζωδίων ἦκεν ἂν ὁ ἀστὴρ καὶ πλησίον τῶν τοῦ κόσμου πόλων ἐγίνετο· νυνὶ δὲ ἡ τετάρτη σφαῖρα περὶ τοὺς τοῦ <τοῦ>¹ ἀστέρος λοξοῦ κύκλου στρεφομένη πόλους ἐπὶ τὰναντία τῇ τρίτῃ ἀπ' ἀνατολῶν ἐπὶ δυσμᾶς καὶ ἐν ἴσῳ χρόνῳ

¹ τοῦ τοῦ Heiberg.

• *i.e.* the equator of the third sphere.
^b *i.e.* Venus and Mercury.

EUDOXUS OF CNIDOS

a circle latitudinally inclined to the zodiac circle (the circle in which the moon moves having a greater latitudinal inclination than that of the sun). The motion of the planets he assumed to take place in each case on four spheres; of these the first and second are the same as for the sun and moon (the first being the sphere of the fixed stars which carries all the spheres with it, and the second, next in order to it, being the sphere about the circle through the middle of the signs of the zodiac which is common to all the planets); the third is, in all cases, a sphere with its poles on the circle through the middle of the signs of the zodiac; and the fourth moves about a circle inclined to the middle circle^a of the third sphere; the poles of the third sphere are different for all the planets except Aphrodite and Hermes,^b but for these the poles are the same.

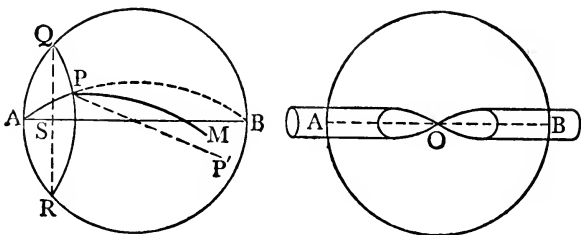
Simplicius, *Commentary on Aristotle's De caelo* ii. 12
(293 a 4), ed. Heiberg 496. 23-497. 5

The third sphere, which has its poles on the great circle of the second sphere passing through the middle of the signs of the zodiac, and which turns from south to north and from north to south, will carry round with it the fourth sphere, which has the planet attached to it, and will moreover be the cause of the planet's latitudinal movement. But not the third sphere only; for, in so far as it was on this sphere only, the planet would have reached the poles of the zodiac circle, and would have drawn near to the poles of the universe; but as matters are, the fourth sphere, which turns about the poles of the inclined circle carrying the planet and rotates in a sense opposite to the third, that is, from east to west, but in the same

GREEK MATHEMATICS

τὴν στροφήν αὐτῶν ποιουμένη τό τε ἐπὶ πλεόν ὑπερβάλλειν τὸν διὰ μέσων τῶν ζωδίων παραιτήσεται καὶ τὴν λεγομένην ὑπὸ Εὐδόξου ἵπποπέδην περὶ τὸν αὐτὸν τουτονὶ κύκλον τῷ ἀστέρι γράφειν παρέξεται, ὥστε, ὅποσον τὸ τῆς γραμμῆς ταύτης πλάτος, τοσοῦτον καὶ ὁ ἀστὴρ εἰς πλάτος δόξει παραχωρεῖν, ὅπερ ἐγκαλοῦσι τῷ Εὐδόξῳ.

- *i.e.* by the planet.
- *i.e.* "horse-fetter."
- Schiaparelli works out in detail the motion of a planet subject only to the rotations of the third and fourth spheres. The problem in its simplest expression, he says, is this:



'A sphere rotates uniformly about the fixed diameter AB. P, P' are opposite poles on this sphere, and a second sphere concentric with the first rotates uniformly about PP' in the same time as the former sphere takes to turn about AB, but in the opposite direction. M is a point on the second sphere equidistant from the poles P, P' (that is to say, M is a point on the equator of the second sphere). It is required to find the path of M.' Schiaparelli found a solution by means of seven geometrical propositions which Eudoxus could have known, and he proved that the path described by M was like a figure-of-eight on the surface of the sphere (see second figure). This curve, which Schiaparelli called a

EUDOXUS OF CNIDOS

period, will prevent any excessive deviation ^a from the circle through the middle of the signs of the zodiac, and will constrain the planet to describe about the same zodiac circle the curve called by Eudoxus the *hippopede*,^b so that the breadth of this curve measures the apparent latitudinal motion of the planet, a view for which Eudoxus has been attacked.^c

“spherical lemniscate,” agrees with Eudoxus’s description of it as a *hippopede* (horse-fetter). It is the intersection of the sphere with a certain cylinder touching it internally at the double point O, namely, a cylinder with diameter equal to AS, the *sagitta* of the diameter of the small circle of the sphere on which P revolves.

For the proof of these statements the reader must be referred to Schiaparelli’s paper. An analytical expression is given by Norbert Herz in *Geschichte der Bahnbestimmung von Planeten und Kometen*, Part i., pp. 20, 21, and reproduced by Heath, *Aristarchus of Samos*, pp. 204-205, with further details.

Summing up, Heath says (*Aristarchus of Samos*, p. 211): “For the sun and moon the hypothesis of Eudoxus sufficed to explain adequately enough the principal phenomena, except the irregularities due to the eccentricities, which were either unknown to Eudoxus or neglected by him. For Jupiter and Saturn, and to some extent for Mercury also, the system was capable of giving on the whole a satisfactory explanation of their motion in longitude, their stationary points and their retrograde motions; for Venus it was unsatisfactory, and it failed altogether in the case of Mars. The limits of motion in latitude represented by the various *hippopedes* were in tolerable agreement with observed facts, although the periods of their deviations and their places in the cycle were quite wrong. But, notwithstanding the imperfections of the system of homocentric spheres, we cannot but recognize in it a speculative achievement which was worthy of the great reputation of Eudoxus and all the more deserving of admiration because it was the first attempt at a scientific explanation of the apparent irregularities of the motions of the planets.”

XIV. ARISTOTLE

XIV. ARISTOTLE

(a) FIRST PRINCIPLES

Aristot. *Anal. Post.* i. 10, 76 a 30-77 a 2

Λέγω δ' ἀρχὰς ἐν ἐκάστῳ γένει ταύτας, ἃς ὅτι ἔστι μὴ ἐνδέχεται δεῖξαι. τί μὲν οὖν σημαίνει καὶ τὰ πρῶτα καὶ τὰ ἐκ τούτων, λαμβάνεται· ὅτι δ' ἔστι, τὰς μὲν ἀρχὰς ἀνάγκη λαμβάνειν, τὰ δ' ἄλλα δεικνύναι, οἷον τί μονὰς ἢ τί τὸ εὐθύ καὶ τρίγωνον· εἶναι δὲ τὴν μονάδα λαβεῖν καὶ μέγεθος, τὰ δ' ἕτερα δεικνύναι.

Ἔστι δ' ὧν χρῶνται ἐν ταῖς ἀποδεικτικαῖς ἐπιστήμαις τὰ μὲν ἴδια ἐκάστης ἐπιστήμης τὰ δὲ κοινά, κοινὰ δὲ κατ' ἀναλογίαν, ἐπεὶ χρήσιμόν γε ὅσον ἐν τῷ ὑπὸ τὴν ἐπιστήμην γένει.

Ἴδια μὲν οἷον γραμμὴν εἶναι τοιανδί, καὶ τὸ εὐθύ, κοινὰ δὲ οἷον τὸ ἴσα ἀπὸ ἴσων ἂν ἀφέλη, ὅτι ἴσα τὰ λοιπά. ἰκανὸν δ' ἕκαστον τούτων ὅσον ἐν τῷ γένει· ταυτό γὰρ ποιήσει, κἂν μὴ κατὰ πάντων

° Aristotle interspersed his writings with illustrations from mathematics, and as he lived just before Euclid he throws valuable light on the transformation which Euclid effected. A large number of the mathematical passages in Aristotle's works are translated, with valuable notes, in Sir Thomas Heath's posthumous book *Mathematics in Aristotle*.

XIV. ARISTOTLE ^a

(a) FIRST PRINCIPLES

Aristotle, *Posterior Analytics* i. 10, 76 a 30-77 a 2

I MEAN by the first principles in every genus those elements whose existence cannot be proved. The meaning both of these primary elements and of those deduced from them is assumed; in the case of first principles, their existence is also assumed, but in the case of the others deduced from them it has to be proved. Examples are given by the unit, the straight and triangular; for we must assume the existence of the unit and magnitude, but in the case of the others it has to be proved.

Of the first principles used in the demonstrative sciences some are peculiar to each science, and some are common, but common only by analogy, inasmuch as they are useful only in so far as they fall within the genus coming under the science in question.

Examples of peculiar first principles are given by the definitions of the line and the straight; common first principles are such as that, when equals are taken from equals, the remainders are equal. Only so much of these common first principles is needed as falls within the genus in question; for such a first principle will have the same force even though not

GREEK MATHEMATICS

λάβη ἀλλ' ἐπὶ μεγεθῶν μόνον, τῷ δ' ἀριθμητικῷ ἐπ' ἀριθμῶν.

Ἔστι δ' ἴδια μὲν καὶ ἅ λαμβάνεται εἶναι, περὶ ἅ ἡ ἐπιστήμη θεωρεῖ τὰ ὑπάρχοντα καθ' αὐτά, οἷον μονάδας ἢ ἀριθμητικὴ, ἢ δὲ γεωμετρία σημεῖα καὶ γραμμίας. ταῦτα γὰρ λαμβάνουσι τὸ εἶναι καὶ τοδὶ εἶναι. τὰ δὲ τούτων πάθη καθ' αὐτά, τί μὲν σημαίνει ἕκαστον, λαμβάνουσιν, οἷον ἡ μὲν ἀριθμητικὴ τί περιττὸν ἢ ἄρτιον ἢ τετράγωνον ἢ κύβος, ἢ δὲ γεωμετρία τί τὸ ἄλογον ἢ τὸ κεκλάσθαι ἢ νεύειν, ὅτι δ' ἔστι, δεικνύουσι διὰ τε τῶν κοινῶν καὶ ἐκ τῶν ἀποδεδειγμένων. καὶ ἡ ἀστρολογία ὡσαύτως. πᾶσα γὰρ ἀποδεικτικὴ ἐπιστήμη περὶ τρία ἐστίν, ὅσα τε εἶναι τίθεται (ταῦτα δ' ἐστὶ τὸ γένος, οὗ τῶν καθ' αὐτὰ παθημάτων ἐστὶ θεωρητικὴ), καὶ τὰ κοινὰ λεγόμενα ἀξιώματα, ἐξ ὧν πρώτων ἀποδείκνυσι, καὶ τρίτον τὰ πάθη, ὧν τί σημαίνει ἕκαστον λαμβάνει. ἐνίας μέντοι ἐπιστήμας οὐδὲν κωλύει ἔνια τούτων παρορᾶν, οἷον τὸ γένος μὴ ὑποτίθεσθαι εἶναι, ἂν ἦ φανερόν ὅτι ἔστιν (οὐ γὰρ ὁμοίως δῆλον ὅτι ἀριθμὸς ἐστὶ καὶ ὅτι ψυχρὸν καὶ θερμόν), καὶ τὰ πάθη μὴ λαμβάνειν τί σημαίνει, ἂν ἦ δῆλα· ὡσπερ οὐδὲ τὰ κοινὰ οὐ λαμβάνει τί σημαίνει τὸ ἴσα ἀπὸ ἴσων ἀφελεῖν, ὅτι γνώριμον. ἀλλ' οὐδὲν ἦττον τῇ γε φύσει τρία ταῦτά ἐστι, περὶ ὅ τε δείκνυσι καὶ ἅ δείκνυσι καὶ ἐξ ὧν.

Οὐκ ἔστι δ' ὑπόθεσις οὐδ' αἴτημα, ὃ ἀνάγκη

^a Euclid does not define κεκλάσθαι "to be inflected," or νεύειν, "to verge." For an example of "inflection," see *supra*, pp. 358-359, and of "verging," *supra* pp. 242-245.

ARISTOTLE

applied generally but only to magnitudes, or by the arithmetician only to numbers.

Also peculiar to a science are the first principles whose existence it assumes and whose essential attributes it investigates, for example, in arithmetic units, in geometry points and lines. Both their existence and their meaning are assumed. But of their essential attributes, only the meaning is assumed. For example, arithmetic assumes the meaning of odd and even, square and cube, geometry that of irrational or inflection or verging,^a but their existence is proved from the common first principles and propositions already demonstrated. Astronomy proceeds in the same way. For indeed every demonstrative science has three elements: (1) that which it posits (the genus whose essential attributes it examines); (2) the so-called common axioms, which are the primary premisses in its demonstrations; (3) the essential attributes, whose meaning it assumes. There is nothing to prevent some sciences passing over some of these elements; for example, the genus may not be posited if it is obvious (the existence of number, for instance, and the existence of hot and cold are not similarly evident); or the meaning of the essential attributes might be omitted if that were clear. In the case of the common axioms, the meaning of taking equals from equals is not expressly assumed, being well known. Nevertheless in the nature of the case there are these three elements, that about which the demonstration takes place, that which is demonstrated and those premisses by which the demonstration is made.

That which necessarily exists from its very nature and which we must necessarily believe is neither

GREEK MATHEMATICS

εἶναι δι' αὐτὸ καὶ δοκεῖν ἀνάγκη. οὐ γὰρ πρὸς τὸν ἔξω λόγον ἢ ἀπόδειξις, ἀλλὰ πρὸς τὸν ἐν τῇ ψυχῇ, ἐπεὶ οὐδὲ συλλογισμός. αἰεὶ γὰρ ἔστιν ἐνστήναι πρὸς τὸν ἔξω λόγον, ἀλλὰ πρὸς τὸν ἔσω λόγον οὐκ αἰεὶ. ὅσα μὲν οὖν δεικτὰ ὄντα λαμβάνει αὐτὸς μὴ δείξας, ταῦτ', ἐὰν μὲν δοκοῦντα λαμβάνῃ τῷ μαθάνοντι, ὑποτίθεται, καὶ ἔστιν οὐχ ἀπλῶς ὑπόθεσις ἀλλὰ πρὸς ἐκεῖνον μόνον· ἂν δὲ ἢ μηδεμιᾶς ἐνούσης δόξης ἢ καὶ ἐναντίας ἐνούσης λαμβάνῃ τὸ αὐτὸ αἰτεῖται. καὶ τούτῳ διαφέρει ὑπόθεσις καὶ αἴτημα· ἔστι γὰρ αἴτημα τὸ ὑπεναντίον τοῦ μαθάνοντος τῇ δόξῃ, [ἢ] ὃ ἂν τις ἀποδεικτὸν ὄν λαμβάνῃ καὶ χρῆται μὴ δείξας.

Οἱ μὲν οὖν ὄροι οὐκ εἰσὶν ὑποθέσεις (οὐδὲ γὰρ εἶναι ἢ μὴ λέγονται), ἀλλ' ἐν ταῖς προτάσεσιν αἱ ὑποθέσεις. τοὺς δ' ὄρους μόνον ξυνίεσθαι δεῖ· τοῦτο δ' οὐχ ὑπόθεσις, εἰ μὴ καὶ τὸ ἀκούειν ὑπόθεσίν τις εἶναι φήσῃ. ἀλλ' ὅσων ὄντων τῷ ἐκεῖνα εἶναι γίνεται τὸ συμπέρασμα. οὐδ' ὁ γεωμέτρης ψευδῇ ὑποτίθεται, ὥσπερ τινὲς ἔφασαν, λέγοντες ὡς οὐ δεῖ τῷ ψεύδει χρῆσθαι, τὸν δὲ γεωμέτρην ψεύδεσθαι λέγοντα ποδιαίαν τὴν οὐ ποδιαίαν ἢ εὐθείαν τὴν γεγραμμένην οὐκ εὐθείαν οὔσαν. ὁ δὲ γεωμέτρης οὐδὲν συμπεραίνεται τῷ τήνδε εἶναι γραμμὴν, ἣν αὐτὸς ἔφθεγκται, ἀλλὰ τὰ διὰ τούτων δηλούμενα. ἔτι τὸ αἴτημα καὶ ὑπόθεσις πᾶσα ἢ ὡς ὅλον ἢ ὡς ἐν μέρει, οἱ δ' ὄροι οὐδέτερον τούτων.

ARISTOTLE

hypothesis nor postulate. For demonstration is a matter not of external discourse but of meditation within the soul, since syllogism is such a matter. And objection can always be raised to external discourse but not to inward meditation. That which is capable of proof but assumed by the teacher without proof is, if the pupil believes and accepts it, *hypothesis*, though it is not hypothesis absolutely but only in relation to the pupil; if the pupil has no opinion on it or holds a contrary opinion, the same assumption is a *postulate*. In this lies the distinction between hypothesis and postulate; for a postulate is contrary to the pupil's opinion, demonstrable, but assumed and used without demonstration.

The *definitions* are not hypotheses (for they do not assert either existence or non-existence), but it is in the premisses of a science that hypotheses lie. Definitions need only to be understood; and this is not hypothesis, unless it be contended that the pupil's hearing is also a hypothesis. But hypotheses lay down facts on whose existence depends the existence of the fact inferred. Nor are the geometer's hypotheses false, as some have maintained, urging that falsehood must not be used, and that the geometer is speaking falsely in saying that the line which he draws is a foot long or straight when it is neither a foot long nor straight. The geometer draws no conclusion from the existence of the particular line of which he speaks, but from what his diagrams represent. Furthermore, all hypotheses and postulates are either universal or particular, but a definition is neither.

GREEK MATHEMATICS

(b) THE INFINITE

Aristot. *Phys.* Γ 6, 206 a 9-18

“Οτι δ’ εἰ μὴ ἔστιν ἄπειρον ἀπλῶς, πολλὰ ἀδύνατα συμβαίνει, δῆλον. τοῦ τε γὰρ χρόνου ἔσται τις ἀρχὴ καὶ τελευτὴ, καὶ τὰ μεγέθη οὐ διαιρετὰ εἰς μεγέθη, καὶ ἀριθμὸς οὐκ ἔσται ἄπειρος. ὅταν δὲ διωρισμένων οὕτως μηδετέρως φαίνεται ἐνδέχασθαι, διαιρετοῦ δεῖ, καὶ δῆλον ὅτι πῶς μὲν ἔστιν πῶς δ’ οὐ. λέγεται δὴ τὸ εἶναι τὸ μὲν δυνάμει τὸ δὲ ἐντελεχεία, καὶ τὸ ἄπειρον ἔστι μὲν προσθέσει ἔστι δὲ καὶ διαιρέσει. τὸ δὲ μέγεθος ὅτι μὲν κατ’ ἐνέργειαν οὐκ ἔστιν ἄπειρον, εἴρηται, διαιρέσει δ’ ἐστίν· οὐ γὰρ χαλεπὸν ἀνελεῖν τὰς ἀτόμους γραμμάς· λείπεται οὖν δυνάμει εἶναι τὸ ἄπειρον.

Ibid. Γ 6, 206 b 3-12

Τὸ δὲ κατὰ πρόσθεσιν τὸ αὐτὸ ἐστὶ πῶς καὶ τὸ κατὰ διαίρεσιν· ἐν γὰρ τῷ πεπερασμένῳ κατὰ πρόσθεσιν γίγνεται ἀντεστραμμένως· ἢ γὰρ διαιρούμενον ὁρᾶται εἰς ἄπειρον, ταύτῃ προστιθέμενον φανέται πρὸς τὸ ὠρισμένον. ἐν γὰρ τῷ πεπερασμένῳ μεγέθει ἂν λαβῶν τις ὠρισμένον προσλαμβάνῃ τῷ αὐτῷ λόγῳ, μὴ τὸ αὐτὸ τι τοῦ ὅλου μέγεθος περιλαμβάνων, οὐ διέξεισι τὸ πεπερασμένον· εἰ δ’ οὕτως αὔξη τὸν λόγον ὥστε αἰεὶ τι

° After criticizing the beliefs of the Pythagoreans and Plato's school, Aristotle has just shown that there cannot be an infinite sensible body.

° The doctrine of “indivisible lines” is attributed to Plato by Aristot. *Met.* 992 a 20-22 and to Xenocrates, who succeeded Speusippus as head of the Academy, by Proclus

ARISTOTLE

(b) THE INFINITE^a

Aristotle, *Physics* Γ 6, 206 a 9-18

But it is clear that the complete denial of an infinite leads to many impossibilities. Time will have a beginning and an end, there will be magnitudes not divisible into magnitudes, and number will not be infinite. Since neither of these opposing views can be accepted, there is need of an arbitrator, and clearly each view must be in some sense true, in some sense untrue. Now "to be" is used in the sense either to exist actually or to exist potentially, while what is infinite is infinite either by addition or by division. It has already been stated that spatial extension is not infinite in actuality, but it is so by division; for it is not difficult to refute the belief in indivisible lines^b; therefore it follows that the spatially infinite exists potentially.

Ibid. Γ 6, 206 b 3-12

The infinite in respect of addition is in a sense the same as the infinite in respect of division, the process of addition in a finite magnitude taking place conversely to that of division; but where division is seen to go on *ad infinitum*, the converse process of addition tends to a definite limit. For if in a finite magnitude you take a determinate part and add to it in the same ratio, provided the successive added terms are not of the same magnitude, you will not come to the end of the finite magnitude; but if the ratio is increased so that the terms added are always of the same

in Tim. 36 B, ed. Diehl ii. 246. and *in Eucl.* i., ed. Friedlein 279. 5, as well as by the commentators on Aristotle. The pseudo-Aristotelian tract *De lineis insecabilibus* seems directed against Xenocrates.

GREEK MATHEMATICS

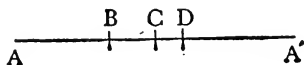
τὸ αὐτὸ περιλαμβάνειν μέγεθος, διέξεισι, διὰ τὸ πᾶν πεπερασμένον ἀναιρεῖσθαι ὅτωσὺν ὠρισμένῳ.

Ibid. Γ 6, 206 b 27–207 a 7

Πλάτων διὰ τοῦτο δύο τὰ ἄπειρα ἐποίησεν, ὅτι καὶ ἐπὶ τὴν αὔξην δοκεῖ ὑπερβάλλειν καὶ εἰς ἄπειρον ἰέναι καὶ ἐπὶ τὴν καθαίρεσιν. ποιήσας μέντοι δύο οὐ χρῆται· οὔτε γὰρ ἐν τοῖς ἀριθμοῖς τὸ ἐπὶ τὴν καθαίρεσιν ἄπειρον ὑπάρχει (ἢ γὰρ μονὰς ἐλάχιστον), οὔτε τὸ ἐπὶ τὴν αὔξην (μέχρι γὰρ δεκάδος ποιεῖ τὸν ἀριθμόν).

Συμβαίνει δὲ τούναντίον εἶναι ἄπειρον ἢ ὡς λέγουσιν. οὐ γὰρ οὐδὲ μηδὲν ἔξω, ἀλλ' οὐδ' αἰεὶ τι ἔξω ἐστί, τοῦτο ἄπειρόν ἐστιν. σημεῖον δέ· καὶ γὰρ τοὺς δακτυλίους ἀπίρους λέγουσι τοὺς μὴ ἔχοντας σφενδόνην, ὅτι αἰεὶ τι ἔξω ἐστί λαμβάνειν,

• From a finite magnitude AA' a "determinate part" (ὠρισμένον) AB is cut off. BA' is then divided at C , CA' at



D and so on, in such a manner that the fractions diminish in the same ratio, *i.e.*, $AB, BC, CD \dots$ form a geometrical progression. If the fractions diminish in this way, then AA' will never be exhausted by this process, which will proceed *ad infinitum*. We may then look on AA' as divided into an infinite number of parts, giving an *infinite by division*, or we may look on AB as having added to it an infinite number of parts, giving an *infinite by addition*. But if the successive added fractions are equal to each other, *i.e.* $AB = BC = CD = \dots$, then AA' will be exhausted in a finite number of steps. This statement is equivalent to the

ARISTOTLE

magnitude, you will come to the end, since any finite magnitude is exhausted by continually subtracting from it any definite fraction whatsoever.^a

Ibid. Γ 6, 206 b 27-207 a 7

Plato posited two infinities^b for this reason, that it is possible to proceed without limit both by way of increase and by way of diminution. But although he posits two infinities he does not use them; for in numbers there is for him no infinite by way of diminution (for the unit is a minimum), nor by way of increase (for he makes number go up to ten).^c

So it comes about that the infinite is the opposite of what it is usually said to be. Not that beyond which there is nothing, but that of which there is always something beyond, is infinite. An illustration is given by the rings not having a bezel which are called endless, because there is always something beyond any Axiom of Archimedes, already used by Eudoxus (see *supra*, p. 319 n. b).

^b The reference is evidently to the famous "undetermined dyad of the great and small." A. E. Taylor (*Mind*, xxxv., pp. 419-440, 1926, and xxxvi., pp. 12-33, 1927) puts forward an ingenious theory of the nature of the "undetermined dyad." He sees a reference to the process of approximating more and more closely to a number by approximations alternately greater and less; D'Arcy Wentworth Thompson (*Mind*, xxxviii., pp. 43-55, 1929) adds the further refinement that the method is approximation by continued fractions. Though such conceptions were doubtless not beyond the mathematical capacity of Plato's Academy, they must remain guesses; and there is nothing to force us to believe that there is anything more profound in the concept of the undetermined dyad than Aristotle here indicates, viz., it is possible to proceed in an infinite series either by way of increase or by way of diminution.

Aristotle has probably misunderstood some *obiter dictum* of Plato's.

GREEK MATHEMATICS

καθ' ὁμοιότητα μὲν τινα λέγοντες, οὐ μέντοι κυρίως· δεῖ γὰρ τοῦτό τε ὑπάρχειν καὶ μηδέ ποτε τὸ αὐτὸ λαμβάνεσθαι· ἐν δὲ τῷ κύκλῳ οὐ γίγνεται οὕτως, ἀλλ' αἰεὶ τὸ ἐφεξῆς μόνον ἕτερον.

Ibid. Γ 7, 207 b 27-34

Οὐκ ἀφαιρεῖται δ' ὁ λόγος οὐδὲ τοὺς μαθηματικοὺς τὴν θεωρίαν, ἀναιρῶν οὕτως εἶναι ἄπειρον ὥστε ἐνεργεῖα εἶναι ἐπὶ τὴν αὐξήσιν ἀδιεξίτητον· οὐδὲ γὰρ νῦν δέονται τοῦ ἀπείρου (οὐ γὰρ χρῶνται), ἀλλὰ μόνον εἶναι ὄσσην ἂν βούλωνται πεπερασμένην· τῷ δὲ μεγίστῳ μεγέθει τὸν αὐτὸν ἔστι τετμηῆσθαι λόγον ὀπηλικονοῦν μέγεθος ἕτερον· ὥστε πρὸς μὲν τὸ δεῖξαι ἐκείνοις οὐδὲν διοίσει τὸ εἶναι ἐν τοῖς οὖσιν μεγέθεσιν.

(c) PROOF DIFFERING FROM EUCLID'S

Aristot. *Anal. Pr.* i. 24, 41 b 5-22

Μᾶλλον δὲ γίνεται φανερόν ἐν τοῖς διαγράμμασιν, οἷον ὅτι τοῦ ἰσοσκελοῦς ἴσαι αἰ πρὸς τῇ βάσει· ἔστωσαν εἰς τὸ κέντρον ἠγμέναι αἰ AB· εἰ οὖν ἴσην λαμβάνοι τὴν ΑΓ γωνίαν τῇ ΒΔ μὴ ὅλως

^a Aristotle had been arguing that in any syllogism one of the propositions must be affirmative and universal.

^b Lit. "drawn."

^c For this method of expressing the sum of two angles by the juxtaposition of the letters representing them, see Archytas's method of representing the sum of two numbers

ARISTOTLE

point on them, but they are so called only after a certain resemblance, and not strictly ; for this ought to be an essential attribute, and the same point should never do duty again ; but in the circle this is not so, but the same point is used over and over.

Ibid. Γ 7, 207 b 27-34

But the argument does not deprive mathematicians of their study, although it denies that the infinite exists in the sense of actual existence as something increased to such an extent that it cannot be gone through ; for even as it is they do not need the infinite (or use it), but only require that the finite straight line shall be as long as they please. Now any other magnitude may be divided in the same ratio as the largest magnitude. Hence it will make no difference to them, for the purpose of demonstration, whether there is actually an infinite among existing magnitudes.

(c) PROOF DIFFERING FROM EUCLID'S

Aristotle, *Prior Analytics* i. 24, 41 b 5-22

This^a is made clearer by geometrical theorems, such as that the angles at the base of an isosceles triangle are equal [Eucl. i. 5]. For let A, B be joined^b to the centre. If then we assumed that the angle AΓ [i.e. A + Γ]^c is equal to the angle BΔ [i.e. B + Δ]

supra, p. 130. The angles A, B are the angles OAB, OBA, and are the same as those later described, in a confusing manner, as E, Z. The angles Γ, Δ are the smaller angles between AB and the *arc* of the circle. There is other evidence that such "mixed" angles played a big part in pre-Euclidean geometry, but Euclid himself scarcely uses them.

GREEK MATHEMATICS

ἀξιῶσας ἴσας τὰς τῶν ἡμικυκλίων, καὶ πάλιν τὴν Γ τῇ Δ μὴ πᾶσαν προσλαβὼν τὴν τοῦ τμήματος, ἔτι δ' ἀπ' ἴσων οὐσῶν τῶν ὅλων γωνιῶν καὶ ἴσων ἀφηρημένων ἴσας εἶναι τὰς λοιπὰς τὰς EZ , τὸ ἐξ ἀρχῆς αἰτήσεται, εἰ μὴ λάβῃ ἀπὸ τῶν ἴσων ἴσων ἀφαιρουμένων ἴσα λείπεσθαι.

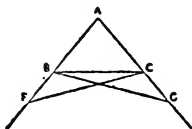
(d) MECHANICS

(i.) Principle of the Lever

[Aristot.] *Mech.* 3, 850 a-b

Ἐπεὶ δὲ θάπτον ὑπὸ τοῦ ἴσου βάρους κινεῖται ἢ μείζων τῶν ἐκ τοῦ κέντρου, ἔστι δὲ τρία τὰ περὶ τὸν μοχλόν, τὸ μὲν ὑπομόχλιον, σπάρτον καὶ κέντρον, δύο δὲ βάρη, ὃ τε κινῶν καὶ τὸ κινούμενον· ὃ οὖν τὸ κινούμενον βᾶρος πρὸς τὸ κινῶν, τὸ μῆκος πρὸς τὸ μῆκος ἀντιπέπονθεν. αἰεὶ δὲ ὄσω ἂν μείζον ἀφεστήκη τοῦ ὑπομοχλίου, ῥᾶον κινήσει. αἰτία δὲ ἔστιν ἢ προλεχθεῖσα, ὅτι ἢ πλείον ἀπ-

^a Euclid proves this theorem by producing the equal sides AB , AC of an isosceles triangle to F , G where AF is

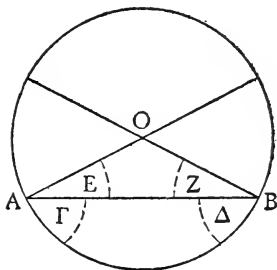


equal to AG . He shows that the triangle AFC is congruent with the triangle AGB , hence that the triangle BFC is congruent with the triangle CGB , and so finally that the angle ABC is equal to the angle ACB .

^b The *Mechanics* is not by Aristotle, but must have been

ARISTOTLE

without asserting generally that the angles of semi-circles are equal, and again that the angle Γ is equal to the angle Δ without assuming generally that the two angles of all segments are equal, and if we further inferred that, since the whole angles are equal, and equal angles have been subtracted from them, the remaining angles E, Z are equal, we should commit a *petitio principii* unless we assumed generally that if equals are subtracted from equals the remainders are equal.^a



(d) MECHANICS

(i.) *Principle of the Lever*

[Aristotle], *Mechanics* 3, 850 a-b^b

Since the greater radius is moved more quickly than the less by an equal weight, and there are three elements in the lever, the fulcrum, that is the cord^c or centre, and two weights, that which moves and that which is moved, therefore the ratio of the weight moved to the moving weight is the inverse ratio of their distances from the fulcrum. It is always true that the farther the moving weight is away from the fulcrum, the more easily will it move. The reason is written by someone under his influence at a not much later date; it may be taken as reflecting Aristotle's own ideas.

^c The author has compared the fulcrum supporting a lever to the cord by which the beam of a balance is suspended.

GREEK MATHEMATICS

έχουσα ἐκ τοῦ κέντρου μείζονα κύκλον γράφει.
ὥστε ἀπὸ τῆς αὐτῆς ἰσχύος πλέον μεταστήσεται
τὸ κινοῦν τὸ πλείον τοῦ ὑπομοχλίου ἄπεχον.

(ii.) *Parallelogram of Velocities*

[Aristot.] *Mech.* 1, 848 b

Ὄταν μὲν οὖν ἐν λόγῳ τινὶ φέρηται, ἐπ' εὐθείας
ἀνάγκη φέρεσθαι τὸ φερόμενον, καὶ γίνεται διά-
μετρος αὐτῆ τοῦ σχήματος ὃ ποιοῦσιν αἱ ἐν τούτῳ
τῷ λόγῳ συντεθείσαι γραμμαί.

Ἔστω γὰρ ὁ λόγος ὃν φέρεται τὸ φερόμενον,
ὃν ἔχει ἡ AB πρὸς τὴν AG· καὶ τὸ μὲν AG φερέσθω
πρὸς τὸ B, ἡ δὲ AB ὑποφερέσθω πρὸς τὴν HG·
ἐνηνέχθω δὲ τὸ μὲν A πρὸς τὸ Δ, ἡ δὲ ἐφ' ἣ AB
πρὸς τὸ E. εἰ οὖν ἐπὶ τῆς φορᾶς ὁ λόγος ἦν ὃν
ἡ AB ἔχει πρὸς τὴν AG, ἀνάγκη καὶ τὴν AD πρὸς
τὴν AE τοῦτον ἔχειν τὸν λόγον. ὁμοιον ἄρα ἐστὶ
τῷ λόγῳ τὸ μικρὸν τετράπλευρον τῷ μείζονι, ὥστε
καὶ ἡ αὐτῆ διάμετρος αὐτῶν, καὶ τὸ A ἔσται πρὸς
Z. τὸν αὐτὸν δὴ τρόπον δειχθήσεται κἂν ὅπου-
οὖν διαληφθῇ ἡ φορὰ· αἰεὶ γὰρ ἔσται ἐπὶ τῆς δια-
μέτρου. φανερόν οὖν ὅτι τὸ κατὰ τὴν διάμετρον
φερόμενον ἐν δύο φοραῖς ἀνάγκη τὸν τῶν πλευρῶν
φέρεσθαι λόγον.

^a *i.e.* has two linear movements in a constant ratio to each other.

^b *i.e.* parallelogram.

ARISTOTLE

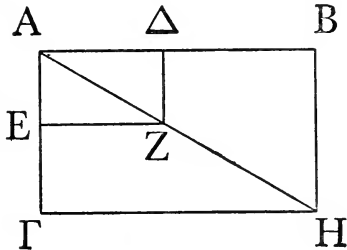
that already stated, that the point which is farther from the centre describes the greater circle. As a result, if the power applied is the same, that which moves the system will have a greater effect the farther it is from the fulcrum.

(ii.) *Parallelogram of Velocities*

[Aristotle], *Mechanics* 1, 848 b

When a body is moved in a certain ratio,^a it must move in a straight line, and this straight line is the diagonal of the figure^b formed from the two straight lines which have the given ratio.

For let the ratio according to which the body moves be that of AB to AΓ; let AΓ be moved towards B while AB be moved towards HΓ; and let A travel to Δ, while AB travels to a position marked by E. If the ratio of the movement is that of AB to AΓ, then AΔ must needs have the same ratio to AE. Therefore the small quadri-



lateral is similar to the larger, so that they have the same diagonal, and A will be at Z. It may be shown that it will behave in the same manner wherever the motion be interrupted; it will be always on the diagonal. Therefore it is also manifest that a body travelling along the diagonal with two movements will travel according to the ratio of the sides.

XV. EUCLID

XV. EUCLID

(a) GENERAL

Stob. *Ecl.* ii. 31. 114, ed. Wachsmuth ii. 228. 25-29

Παρ' Εὐκλείδῃ τις ἀρξάμενος γεωμετρῆιν, ὡς τὸ πρῶτον θεώρημα ἔμαθεν, ἤρето τὸν Εὐκλείδην· “ τί δέ μοι πλέον ἔσται ταῦτα μαθόντι; ” καὶ ὁ Εὐκλείδης τὸν παῖδα καλέσας “ δός, ” ἔφη, “ αὐτῷ τριώβολον, ἐπειδὴ δεῖ αὐτῷ ἐξ ὧν μανθάνει κερδαίνειν.”

(b) THE ELEMENTS

(i.) Foundations

Eucl. *Elem.* i.

ᾠοροι

α'. Σημεῖόν ἐστιν, οὗ μέρος οὐθέν.

β'. Γραμμὴ δὲ μῆκος ἀπλατές.

γ'. Γραμμῆς δὲ πέρατα σημεῖα.

* Hardly anything is known of the life of Euclid beyond what has already been stated in the passage quoted from Proclus (*supra*, p. 154). From Pappus vii. 35, ed. Hultsch ii. 678. 10-12, *infra*, p. 489, we infer the additional detail that he taught at Alexandria and founded a school there. Arabian references are summarized by Heath, *The Thirteen Books of Euclid's Elements*, 2nd edn., 1926, vol. i. pp. 4-6. Euclid must have flourished c. 300 B.C.

XV. EUCLID^a

(a) GENERAL

Stobaeus, *Extracts* ii. 31. 114, ed. Wachsmuth ii. 228.
25-29

SOMEONE who had begun to read geometry with Euclid, when he had learnt the first theorem asked Euclid, "But what advantage shall I get by learning these things?" Euclid called his slave and said, "Give him threepence, since he must needs make profit out of what he learns."

(b) THE ELEMENTS^b

(i.) Foundations

Euclid, *Elements* i.

DEFINITIONS^c

1. A *point* is that which has no part.
2. A *line* is length without breadth.
3. The extremities of a line are points.

^b For the meaning of *elements*, see *supra*, p. 150 n. c.

^c For a full discussion of the many problems raised by Euclid's definitions, postulates and common notions the reader is referred to Heath, *The Thirteen Books of Euclid's Elements*, vol. i. pp. 155-240.

GREEK MATHEMATICS

δ'. Εὐθεία γραμμὴ ἐστίν, ἣτις ἐξ ἴσου τοῖς ἐφ' αὐτῆς σημείοις κείται.

ε'. Ἐπιφάνεια δὲ ἐστίν, ὃ μῆκος καὶ πλάτος μόνον ἔχει.

ς'. Ἐπιφανείας δὲ πέρατα γραμμαί.

ζ'. Ἐπίπεδος ἐπιφάνειά ἐστίν, ἣτις ἐξ ἴσου ταῖς ἐφ' αὐτῆς εὐθείαις κείται.

η'. Ἐπίπεδος δὲ γωνία ἐστίν ἢ ἐν ἐπιπέδῳ δύο γραμμῶν ἀπτομένων ἀλλήλων καὶ μὴ ἐπ' εὐθείας κειμένων πρὸς ἀλλήλας τῶν γραμμῶν κλίσις.

θ'. Ὄταν δὲ αἱ περιέχουσαι τὴν γωνίαν γραμμαὶ εὐθεῖαι ὦσιν, εὐθύγραμμος καλεῖται ἢ γωνία.

ι'. Ὄταν δὲ εὐθεῖα ἐπ' εὐθείαν σταθεῖσα τὰς ἐφεξῆς γωνίας ἴσας ἀλλήλαις ποιῇ, ὀρθὴ ἑκατέρα τῶν ἴσων γωνιῶν ἐστίν, καὶ ἢ ἐφεστηκυῖα εὐθεῖα κάθετος καλεῖται, ἐφ' ἣν ἐφέστηκεν.

ια'. Ἀμβλεία γωνία ἐστίν ἢ μείζων ὀρθῆς.

ιβ'. Ὄξεια δὲ ἢ ἐλάσσων ὀρθῆς.

ιγ'. Ὄρος ἐστίν, ὃ τινός ἐστι πέρασ.

ιδ'. Σχήμα ἐστίν τὸ ὑπὸ τινος ἢ τινῶν ὄρων περιεχόμενον.

ιε'. Κύκλος ἐστίν σχῆμα ἐπίπεδον ὑπὸ μιᾶς γραμμῆς περιεχόμενον [ἢ καλεῖται περιφέρεια], πρὸς ἣν ἀφ' ἐνὸς σημείου τῶν ἐντὸς τοῦ σχήματος κειμένων πᾶσαι αἱ προσπίπτουσαι εὐθεῖαι [πρὸς τὴν τοῦ κύκλου περιφέρειαν] ἴσαι ἀλλήλαις εἰσίν.

ισ'. Κέντρον δὲ τοῦ κύκλου τὸ σημεῖον καλεῖται.

ιζ'. Διάμετρος δὲ τοῦ κύκλου ἐστίν εὐθεῖα τις διὰ τοῦ κέντρου ἡγμένη καὶ περατουμένη ἐφ'

^a Plato (*Parmenides* 137 ε) defines a straight line as "that of which the middle covers the ends." Euclid appears to be trying to say the same kind of thing in more geometrical

EUCLID

4. A *straight line* is a line which lies evenly with the points on itself.^a

5. A *surface* is that which has length and breadth only.

6. The extremities of a surface are lines.

7. A *plane surface* is a surface which lies evenly with the straight lines on itself.

8. A *plane angle* is the inclination towards one another of two lines in a plane which meet one another and do not lie in a straight line.

9. And when the lines containing the angle are straight, the angle is called *rectilineal*.

10. When a straight line set up on a straight line makes the adjacent angles equal one to another, each of the equal angles is *right*, and the straight line standing on the other is called a *perpendicular* to that on which it stands.

11. An *obtuse angle* is an angle greater than a right angle.

12. An *acute angle* is an angle less than a right angle.

13. A *boundary* is that which is the extremity of anything.

14. A *figure* is that which is contained by any boundary or boundaries.

15. A *circle* is a plane figure contained by one line such that all the straight lines falling on it from one point among those lying within the figure are equal one to another.

16. And the point is called the *centre* of the circle.

17. A *diameter* of the circle is any straight line drawn through the centre and terminated in both

language. Neither statement is satisfactory as a definition (*cf.* Def. 7).

GREEK MATHEMATICS

ἐκάτερα τὰ μέρη ὑπὸ τῆς τοῦ κύκλου περιφερείας, ἥτις καὶ δίχα τέμνει τὸν κύκλον.

ιη'. Ἡμικύκλιον δέ ἐστι τὸ περιεχόμενον σχῆμα ὑπὸ τε τῆς διαμέτρου καὶ τῆς ἀπολαμβανομένης ὑπ' αὐτῆς περιφερείας. κέντρον δὲ τοῦ ἡμικυκλίου τὸ αὐτό, ὃ καὶ τοῦ κύκλου ἐστίν.

ιβ'. Σχήματα εὐθύγραμμά ἐστι τὰ ὑπὸ εὐθειῶν περιεχόμενα, τρίπλευρα μὲν τὰ ὑπὸ τριῶν, τετράπλευρα δὲ τὰ ὑπὸ τεσσάρων, πολύπλευρα δὲ τὰ ὑπὸ πλειόνων ἢ τεσσάρων εὐθειῶν περιεχόμενα.

κ'. Τῶν δὲ τριπλεύρων σχημάτων ἰσόπλευρον μὲν τρίγωνόν ἐστι τὸ τὰς τρεῖς ἴσας ἔχον πλευράς, ἰσοσκελὲς δὲ τὸ τὰς δύο μόνας ἴσας ἔχον πλευράς, σκαληνὸν δὲ τὸ τὰς τρεῖς ἀνίσους ἔχον πλευράς.

κα'. Ἐτι δὲ τῶν τριπλεύρων σχημάτων ὀρθογώνιον μὲν τρίγωνόν ἐστι τὸ ἔχον ὀρθὴν γωνίαν, ἀμβλυγώνιον δὲ τὸ ἔχον ἀμβλείαν γωνίαν, ὀξυγώνιον δὲ τὸ τὰς τρεῖς ὀξείας ἔχον γωνίας.

κβ'. Τῶν δὲ τετραπλεύρων σχημάτων τετράγωνον μὲν ἐστίν, ὃ ἰσόπλευρόν τε ἐστὶ καὶ ὀρθογώνιον, ἑτερόμηκες δέ, ὃ ὀρθογώνιον μὲν, οὐκ ἰσόπλευρον δέ, ῥόμβος δέ, ὃ ἰσόπλευρον μὲν, οὐκ ὀρθογώνιον δέ, ῥομβοειδὲς δὲ τὸ τὰς ἀπεναντίον πλευράς τε καὶ γωνίας ἴσας ἀλλήλαις ἔχον, ὃ οὔτε ἰσόπλευρόν ἐστίν οὔτε ὀρθογώνιον· τὰ δὲ παρὰ ταῦτα τετράπλευρα τραπέζια καλεῖσθω.

κγ'. Παράλληλοί εἰσιν εὐθεῖαι, αἵτινες ἐν τῷ αὐτῷ ἐπιπέδῳ οὔσαι καὶ ἐκβαλλόμεναι εἰς ἄπειρον ἐφ' ἐκάτερα τὰ μέρη ἐπὶ μηδέτερα συμπίπτουσιν ἀλλήλαις.

^a Heath classifies modern definitions of parallel straight
440

EUCLID

directions by the circumference of the circle, and such a straight line bisects the circle.

18. A *semicircle* is the figure contained by the diameter and the circumference cut off by it. And the centre of the semicircle is the same as that of the circle.

19. *Rectilineal figures* are those contained by straight lines, *trilateral* figures being those contained by three, *quadrilateral* those contained by four, and *multilateral* those contained by more than four straight lines.

20. Of trilateral figures an *equilateral triangle* is that which has its three sides equal, an *isosceles triangle* that which has only two of its sides equal, and a *scalene triangle* that which has its three sides unequal.

21. Further, of trilateral figures, a *right-angled triangle* is that which has a right angle, an *obtuse-angled triangle* is that which has an obtuse angle, and an *acute-angled triangle* is that which has its three angles acute.

22. Of quadrilateral figures, a *square* is that which is both equilateral and right-angled; an *oblong* is that which is right-angled but not equilateral; a *rhombus* is that which is equilateral but not right-angled; and a *rhomboid* is that which has its opposite sides and angles equal one to another but is neither equilateral nor right-angled; and let quadrilaterals other than these be called *trapezia*.

23. *Parallel* straight lines are straight lines which, being in the same plane and produced indefinitely in both directions, do not meet one another in either direction.^a

lines into three main groups: (1) *Parallel straight lines have no point common*, under which general conception the following varieties of statement are included: (a) *they do*

GREEK MATHEMATICS

Αιτήματα

α'. Ἡιτήσθω ἀπὸ παντὸς σημείου ἐπὶ πᾶν σημείον εὐθεΐαν γραμμὴν ἀγαγεῖν.

β'. Καὶ πεπερασμένην εὐθεΐαν κατὰ τὸ συνεχὲς ἐπ' εὐθείας ἐκβαλεῖν.

γ'. Καὶ παντὶ κέντρῳ καὶ διαστήματι κύκλον γράφεισθαι.

δ'. Καὶ πάσας τὰς ὀρθὰς γωνίας ἴσας ἀλλήλαις εἶναι.

ε'. Καὶ ἐὰν εἰς δύο εὐθείας εὐθεΐα ἐμπίπτουσα τὰς ἐντὸς καὶ ἐπὶ τὰ αὐτὰ μέρη γωνίας δύο ὀρθῶν ἐλάσσονας ποιῆ, ἐκβαλλομένας τὰς δύο εὐθείας ἐπ' ἄπειρον συμπίπτειν, ἐφ' ἃ μέρη εἰσὶν αἱ τῶν δύο ὀρθῶν ἐλάσσονες.

not cut one another, (b) they meet at infinity, (c) they have a common point at infinity; (2) parallel straight lines have the same, or like, direction or directions; (3) parallel straight lines have the distance between them constant. Euclid's definition belongs to 1(a), and he avoids many fallacies latent in the other definitions, showing himself superior not only to many ancient, but to many modern, geometers.

^a The chief purpose of these first three postulates is perhaps not to lay down that straight lines and circles can be drawn, but to delineate the nature of Euclidean space. They imply that space is continuous (not discrete) and infinite (not limited).

^b This gives a determinate magnitude by which angles

EUCLID

POSTULATES

1. Let the following be postulated: to draw a straight line from any point to any point.
2. To produce a finite straight line continuously in a straight line.
3. To describe a circle with any centre and diameter.^a
4. All right angles are equal one to another.^b
5. If a straight line falling on two straight lines make the interior angles on the same side less than two right angles, the two straight lines, if produced indefinitely, meet on that side on which are the angles less than two right angles.^c

can be measured, but it does far more. To prove this statement it would be necessary to assume the *invariability of figures*. Euclid preferred to postulate the equality of right angles, which amounts to an assumption of the *invariability of figures* or the *homogeneity of space*.

^a Heath says that this postulate "must ever be regarded as among the most epoch-making achievements in the domain of geometry," and observes: "When we consider the countless successive attempts made through more than twenty centuries to prove the postulate, many of them by geometers of ability, we cannot but admire the genius of the man who concluded that such a hypothesis, which he found necessary to the validity of his whole system of geometry, was really indemonstrable."

The postulate was frequently attacked in antiquity and many attempts have been made to prove it—by Ptolemy and Proclus in ancient days, by Wallis, Saccheri, Lambert and Legendre in modern times. All have failed. By omitting this postulate, Lobachewsky, Bolyai and Riemann developed "non-Euclidean" systems of geometry. Saccheri, in his book *Euclides ab omni naevo vindicatus* (1733), saw the possibility of alternative hypotheses, and worked out the consequences of several; but his faith in Euclidean geometry as the sole possible geometry was so strong that he failed to realize the full implications of his work.

GREEK MATHEMATICS

Κοιναὶ ἔννοιαι

- α'. Τὰ τῷ αὐτῷ ἴσα καὶ ἀλλήλοις ἐστὶν ἴσα.
β'. Καὶ ἐὰν ἴσοις ἴσα προστεθῆ, τὰ ὅλα ἐστὶν ἴσα.
γ'. Καὶ ἐὰν ἀπὸ ἴσων ἴσα ἀφαιρεθῆ, τὰ καταλειπόμενά ἐστὶν ἴσα.
[δ'. Καὶ ἐὰν ἀνίσοις ἴσα προστεθῆ, τὰ ὅλα ἐστὶν ἄνισα.
ε'. Καὶ τὰ τοῦ αὐτοῦ διπλάσια ἴσα ἀλλήλοις ἐστὶν.
ς'. Καὶ τὰ τοῦ αὐτοῦ ἡμίση ἴσα ἀλλήλοις ἐστὶν.]
ζ'. Καὶ τὰ ἐφαρμόζοντα ἐπ' ἀλλήλα ἴσα ἀλλήλοις ἐστὶν.
η'. Καὶ τὸ ὅλον τοῦ μέρους μεῖζόν [ἐστὶν].
[θ'. Καὶ δύο εὐθεῖαι χωρίον οὐ περιέχουσιν.]

(ii.) *Theory of Proportion*

Eucl. *Elem.* v.

Ὅροι

- α'. Μέρος ἐστὶ μέγεθος μεγέθους τὸ ἔλασσον τοῦ μείζονος, ὅταν καταμετρῆ τὸ μείζον.
β'. Πολλαπλάσιον δὲ τὸ μείζον τοῦ ἐλάττονος, ὅταν καταμετρῆται ὑπὸ τοῦ ἐλάττονος.
γ'. Λόγος ἐστὶ δύο μεγεθῶν ὁμογενῶν ἢ κατὰ πηλικιότητά ποια σχέσις.
δ'. Λόγον ἔχειν πρὸς ἄλληλα μεγέθη λέγεται, ἂ δύναται πολλαπλασιαζόμενα ἀλλήλων ὑπερέχειν.
ε'. Ἐν τῷ αὐτῷ λόγῳ μεγέθη λέγεται εἶναι πρῶτον πρὸς δεύτερον καὶ τρίτον πρὸς τέταρτον,

EUCLID

COMMON NOTIONS

1. Things which are equal to the same thing are equal one to another.

2. If equals are added to equals, the wholes are equal.

3. If equals are subtracted from equals, the remainders are equal.

7. Things which coincide with one another are equal one to another.

8. The whole is greater than the part.^a

(ii.) *Theory of Proportion*

Euclid, *Elements* v.

DEFINITIONS

1. A magnitude is a *part* of a magnitude, the less of the greater, when it measures the greater.

2. The greater is a multiple of the less when it is measured by the less.

3. A *ratio* is a sort of relation in respect of size between two magnitudes of the same kind.

4. Magnitudes are said to have a ratio one to another which are capable, when multiplied, of exceeding one another.

5. Magnitudes are said to be in the same ratio, the first to the second and the third to the fourth, when,

^a The MSS. have four other Common Notions, but they are unnecessary, and their genuineness was suspected even in antiquity. They are : 4. If equals are added to unequals, the wholes are unequal ; 5. Things which are double of the same thing are equal one to another ; 6. Things which are halves of the same thing are equal one to another ; 9. Two straight lines do not enclose a space.

GREEK MATHEMATICS

ὅταν τὰ τοῦ πρώτου καὶ τρίτου ἰσάκεις πολλαπλάσια τῶν τοῦ δευτέρου καὶ τετάρτου ἰσάκεις πολλαπλασίων καθ' ὅποιονοῦν πολλαπλασιασμόν ἑκάτερον ἑκατέρου ἢ ἅμα ὑπερέχη ἢ ἅμα ἴσα ἢ ἢ ἅμα ἐλλείπη ληφθέντα κατάλληλα.

ς'. Τὰ δὲ τὸν αὐτὸν ἔχοντα λόγον μεγέθη ἀνάλογον καλείσθω.

ζ'. Ὄταν δὲ τῶν ἰσάκεις πολλαπλασίων τὸ μὲν τοῦ πρώτου πολλαπλάσιον ὑπερέχη τοῦ τοῦ δευτέρου πολλαπλασίου, τὸ δὲ τοῦ τρίτου πολλαπλάσιον μὴ ὑπερέχη τοῦ τοῦ τετάρτου πολλαπλασίου, τότε τὸ πρῶτον πρὸς τὸ δεύτερον μείζονα λόγον ἔχειν λέγεται, ἢπερ τὸ τρίτον πρὸς τὸ τέταρτον.

η'. Ἀναλογία δὲ ἐν τρισὶν ὄροις ἐλαχίστη ἐστίν.

θ'. Ὄταν δὲ τρία μεγέθη ἀνάλογον ἢ, τὸ πρῶτον πρὸς τὸ τρίτον διπλασίονα λόγον ἔχειν λέγεται ἢπερ πρὸς τὸ δεύτερον.

* In the translation of this remarkable definition I cannot improve on Heath. Literal translation is difficult because the words καθ' ὅποιονοῦν πολλαπλασιασμόν come only once in the Greek but refer both to τὰ . . . ἰσάκεις πολλαπλάσια in the nominative and τῶν . . . ἰσάκεις πολλαπλασίων in the genitive.

The definition, which avoids all mention of a part of a magnitude (unlike *Elements* vii. Def. 21), is applicable to all magnitudes, commensurable and incommensurable. It must be due, in substance at least, to Eudoxus (see *supra*, p. 408). The definition has often been assailed through misunderstanding, but has been brilliantly defended by such great mathematicians as Barrow and De Morgan, and was adopted by Weierstrass for his definition of equal numbers.

EUCLID

if any equimultiples whatever be taken of the first and third, and any equimultiples whatever of the second and fourth, the former equimultiples alike exceed, are alike equal to, or alike fall short of, the latter equimultiples respectively taken in corresponding order.^a

6. Let magnitudes which have the same ratio be called *proportional*.

7. When, of the equimultiples, the multiple of the first magnitude exceeds the multiple of the second, but the multiple of the third does not exceed the multiple of the fourth, then the first is said to *have a greater ratio* to the second than the third has to the fourth.

8. A proportion in three terms is the least possible.

9. When three magnitudes are proportional, the first is said to have to the third the *duplicate ratio* of that which it has to the second.^b

Max Simon (*Euclid und die sechs planimetrischen Bücher*, p. 110) thinks it is clear from this definition that the Greeks possessed a notion of number as general as modern mathematicians. Heath (*The Thirteen Books of Euclid's Elements*, ii., pp. 124-126) shows how Euclid's definition divides all rational numbers into two *coextensive* classes, and so defines equal ratios in a manner exactly corresponding to Dedekind's theory of the irrational.

De Morgan gives the following modern equivalent of the definition. "Four magnitudes, A and B of one kind, and C and D of the same or another kind, are proportional when all the multiples of A can be distributed among the multiples of B in the same intervals as the corresponding multiples of C among those of D." That is to say, m, n being any numbers whatsoever, if mA lies between nB and $(n+1)B$, mC lies between nD and $(n+1)D$.

^b If $\frac{a}{x} = \frac{x}{b}$, then $\frac{a}{b} = \frac{x^2}{x^2}$, and a has to b the *duplicate ratio* of a to x .

GREEK MATHEMATICS

ι'. Όταν δὲ τέσσαρα μεγέθη ἀνάλογον ἦ, τὸ πρῶτον πρὸς τὸ τέταρτον τριπλασίονα λόγον ἔχειν λέγεται ἤπερ πρὸς τὸ δεύτερον, καὶ ἀεὶ ἐξῆς ὁμοίως, ὡς ἂν ἡ ἀναλογία ὑπάρχη.

ια'. Ὁμόλογα μεγέθη λέγεται τὰ μὲν ἡγούμενα τοῖς ἡγουμένοις τὰ δὲ ἐπόμενα τοῖς ἐπομένοις.

ιβ'. Ἐναλλάξ λόγος ἐστὶ λήψις τοῦ ἡγουμένου πρὸς τὸ ἡγούμενον καὶ τοῦ ἐπομένου πρὸς τὸ ἐπόμενον.

ιγ'. Ἀνάπαλιν λόγος ἐστὶ λήψις τοῦ ἐπομένου ὡς ἡγουμένου πρὸς τὸ ἡγούμενον ὡς ἐπόμενον.

ιδ'. Σύνθεσις λόγου ἐστὶ λήψις τοῦ ἡγουμένου μετὰ τοῦ ἐπομένου ὡς ἑνὸς πρὸς αὐτὸ τὸ ἐπόμενον.

ιε'. Διαίρεσις λόγου ἐστὶ λήψις τῆς ὑπεροχῆς, ἣ ὑπερέχει τὸ ἡγούμενον τοῦ ἐπομένου, πρὸς αὐτὸ τὸ ἐπόμενον.

ισ'. Ἀναστροφή λόγου ἐστὶ λήψις τοῦ ἡγουμένου πρὸς τὴν ὑπεροχὴν, ἣ ὑπερέχει τὸ ἡγούμενον τοῦ ἐπομένου.

ιζ'. Δι' ἴσου λόγος ἐστὶ πλειόνων ὄντων μεγεθῶν καὶ ἄλλων αὐτοῖς ἴσων τὸ πλῆθος σύνδυο λαμβανομένων καὶ ἐν τῷ αὐτῷ λόγῳ, ὅταν ἦ ὡς ἐν τοῖς πρώτοις μεγέθεσι τὸ πρῶτον πρὸς τὸ ἔσχατον, οὕτως ἐν τοῖς δευτέροις μεγέθεσι τὸ

^a The magnitudes must be in continuous proportion. If $\frac{a}{x} = \frac{x}{y} = \frac{y}{b}$, then $\frac{a}{b} = \frac{a^3}{x^3}$, and a has to b the *triplicate* ratio of a to x . Alternatively, a cube with side a has the same ratio to a cube with side x as a to b (see *supra*, p. 258 n. b).

EUCLID

10. When four magnitudes are proportional ^a the first is said to have to the fourth the *triplicate* ratio of that which it has to the second, and so on continually, whatever the proportion.

11. The term *corresponding magnitudes* is used of antecedents in relation to antecedents and of consequents in relation to consequents.^b

12. *Alternate ratio* means taking the antecedent in relation to the antecedent, and the consequent in relation to the consequent.^c

13. *Inverse ratio* means taking the consequent as antecedent in relation to the antecedent as consequent.^d

14. *Composition of a ratio* means taking the antecedent together with the consequent as one in relation to the consequent by itself.^e

15. *Separation of a ratio* means taking the excess by which the antecedent exceeds the consequent in relation to the consequent by itself.^f

16. *Conversion of a ratio* means taking the antecedent in relation to the excess by which the antecedent exceeds the consequent.^g

17. A ratio *ex aequali* arises when, there being several magnitudes and another set equal to them in multitude which taken two by two are in the same proportion, as the first is to the last in the first set of magnitudes, so is the first to the last in the second

^a "Antecedents" are literally "leading terms," "consequents" the "following terms." In the ratio $a : b$, a is the antecedent, b the consequent.

^c If $a : b :: A : B$, then $a : A :: b : B$.

^d If $a : b :: A : B$, then $b : a :: B : A$.

^e *i.e.* the transformation of the ratio $a : b$ into $a + b : b$.

^f *i.e.* the transformation of the ratio $a : b$ into $a - b : b$.

^g *i.e.* the transformation of the ratio $a : b$ into $a : a - b$.

πρῶτον πρὸς τὸ ἔσχατον· ἢ ἄλλως· λήψις τῶν ἄκρων καθ' ὑπεξαίρεσιν τῶν μέσων.

ιη'. Τεταραγμένη δὲ ἀναλογία ἐστίν, ὅταν τριῶν ὄντων μεγεθῶν καὶ ἄλλων αὐτοῖς ἴσων τὸ πλήθος γίνηται ὡς μὲν ἐν τοῖς πρώτοις μεγέθεσιν ἡγούμενον πρὸς ἐπόμενον, οὕτως ἐν τοῖς δευτέροις μεγέθεσιν ἡγούμενον πρὸς ἐπόμενον, ὡς δὲ ἐν τοῖς πρώτοις μεγέθεσιν ἐπόμενον πρὸς ἄλλο τι, οὕτως ἐν τοῖς δευτέροις ἄλλο τι πρὸς ἡγούμενον.

(iii.) *Theory of Incommensurables*

Eucl. *Elem.* x.

ᾠροι

α'. Σύμμετρα μεγέθη λέγεται τὰ τῷ αὐτῷ μέτρῳ μετρούμενα, ἀσύμμετρα δέ, ὧν μηδὲν ἐνδέχεται κοινὸν μέτρον γενέσθαι.

β'. Εὐθείαι δυνάμει σύμμετροί εἰσιν, ὅταν τὰ ἀπ' αὐτῶν τετράγωνα τῷ αὐτῷ χωρίῳ μετρηῖται, ἀσύμμετροι δέ, ὅταν τοῖς ἀπ' αὐτῶν τετραγώνοις μηδὲν ἐνδέχεται χωρίον κοινὸν μέτρον γενέσθαι.

γ'. Τούτων ὑποκειμένων δείκνυται, ὅτι τῇ προτεθείσῃ εὐθείᾳ ὑπάρχουσιν εὐθείαι πλήθει ἄπειροι σύμμετροί τε καὶ ἀσύμμετροι αἱ μὲν μήκει μόνον, αἱ δὲ καὶ δυνάμει. καλείσθω οὖν ἡ μὲν προτεθείσα εὐθεῖα ῥητή, καὶ αἱ ταύτη σύμμετροι εἴτε μήκει

* δι' ἴσου must mean "at an equal distance," i.e., after an equal number of terms. If $a, b, c \dots m, n$ is one set of magnitudes and $A, B, C \dots M, N$ the other, and $a : b = A : B$, and so on, up to $m : n = M : N$, then $a : n = A : N$. This is proved in v. 22. The definition merely serves to give a name to the inference.

EUCLID

set of magnitudes ; in other words, a taking of the extremes by removal of the intermediate terms.^a

18. A *perturbed proportion* arises when, there being three magnitudes and another set equal to them in multitude, as antecedent is to consequent in the first magnitudes, so is antecedent to consequent in the second magnitudes, while as the consequent is to the other term in the first magnitudes, so is the other term to the antecedent in the second magnitudes.^b

(iii.) *Theory of Incommensurables*

Euclid, *Elements* x.

DEFINITIONS

1. Those magnitudes are said to be *commensurable* which are measured by the same common measure, and those incommensurable which cannot have any common measure.

2. Straight lines are *commensurable in square*, when the squares on them are measured by the same area, and *incommensurable in square* when the squares on them cannot have any area as a common measure.

3. With these hypotheses, it is proved that there exist straight lines infinite in multitude which are commensurable and incommensurable respectively, some in length only, and others in square also, with an assigned straight line. Let then the assigned straight line be called *rational*, and those straight lines which are commensurable with it, whether in length

^b If a, b, c and A, B, C are the two sets of magnitudes, and $a : b = B : C$, $b : c = A : B$ the proportion is said to be *perturbed*. It follows that $a : c = A : C$. This is a particular case of the inference $\delta\iota' \text{ } \textit{\iota}\sigma\sigma\upsilon$ and is proved in v. 23.

GREEK MATHEMATICS

καὶ δυνάμει εἴτε δυνάμει μόνον ῥηταί, αἱ δὲ ταύτη ἀσύμμετροι ἄλογοι καλεῖσθωσαν.

δ'. Καὶ τὸ μὲν ἀπὸ τῆς προτεθείσης εὐθείας τετράγωνον ῥητόν, καὶ τὰ τούτῳ σύμμετρα ῥητά, τὰ δὲ τούτῳ ἀσύμμετρα ἄλογα καλεῖσθω, καὶ αἱ δυνάμεναι αὐτὰ ἄλογοι, εἰ μὲν τετράγωνα εἴη, αὐταὶ αἱ πλευραί, εἰ δὲ ἕτερα ἅτινα εὐθύγραμμα, αἱ ἴσα αὐτοῖς τετράγωνα ἀναγράφουσαι.

α'

Δύο μεγεθῶν ἀνίσων ἐκκειμένων, ἐὰν ἀπὸ τοῦ μείζονος ἀφαιρεθῇ μείζον ἢ τὸ ἥμισυ καὶ τοῦ καταλειπομένου μείζον ἢ τὸ ἥμισυ, καὶ τοῦτο ἀεὶ γίγνηται, λειφθήσεται τι μέγεθος, ὃ ἔσται ἔλασσον τοῦ ἐκκειμένου ἐλάσσονος μεγέθους.

Ἐστω δύο μεγέθη ἄνισα τὰ ΑΒ, Γ, ὧν μείζον τὸ ΑΒ· λέγω, ὅτι ἐὰν ἀπὸ τοῦ ΑΒ ἀφαιρεθῇ μείζον ἢ τὸ ἥμισυ καὶ τοῦ καταλειπομένου μείζον ἢ τὸ ἥμισυ, καὶ τοῦτο ἀεὶ γίγνηται, λειφθήσεται τι μέγεθος, ὃ ἔσται ἔλασσον τοῦ Γ μεγέθους.

Τὸ Γ γὰρ πολλαπλασιαζόμενον ἔσται ποτὲ τοῦ

EUCLID

and in square or in square only, be called *rational*, but those which are incommensurable with it be called *irrational*.

4. And let the square on the assigned straight line be called *rational*, and those areas which are commensurable with it *rational*, but those which are incommensurable with it *irrational*, and the straight lines which produce them *irrational*, that is, if the areas are squares, the sides themselves, but if the areas are any other rectilineal figures, the straight lines on which are described squares equal to them.

Prop. 1

Two unequal magnitudes being set out, if from the greater there be subtracted a magnitude greater than the half, and from the remainder a magnitude greater than its half, and so on continually, there will be left some magnitude which will be less than the lesser magnitude set out.

Let AB, Γ be the two unequal magnitudes, of which AB is the greater; I say that, if from AB there be



subtracted a magnitude greater than its half, and from the remainder a magnitude greater than its half, and so on continually, there will be left some magnitude which will be less than the magnitude Γ .

For Γ , if multiplied, will at some time be greater

GREEK MATHEMATICS

AB μείζον. πεπολλαπλασιάσθω, καὶ ἔστω τὸ ΔE τοῦ μὲν Γ πολλαπλάσιον, τοῦ δὲ AB μείζον, καὶ διηρήσθω τὸ ΔE εἰς τὰ τῷ Γ ἴσα τὰ $\Delta Z, ZH, HE$, καὶ ἀφηρήσθω ἀπὸ μὲν τοῦ AB μείζον ἢ τὸ ἥμισυ τὸ $B\Theta$, ἀπὸ δὲ τοῦ $A\Theta$ μείζον ἢ τὸ ἥμισυ τὸ ΘK , καὶ τοῦτο αἰὲ γιγνέσθω, ἕως ἂν αἰ ἐν τῷ AB διαιρέσεις ἰσοπληθεῖς γένωνται ταῖς ἐν τῷ ΔE διαιρέσεσιν.

Ἔστωσαν οὖν αἰ $AK, K\Theta, \Theta B$ διαιρέσεις ἰσοπληθεῖς οὔσαι ταῖς $\Delta Z, ZH, HE$. καὶ ἐπεὶ μείζον ἐστὶ τὸ ΔE τοῦ AB , καὶ ἀφήρηται ἀπὸ μὲν τοῦ ΔE ἔλασσον τοῦ ἡμίσεως τὸ EH , ἀπὸ δὲ τοῦ AB μείζον ἢ τὸ ἥμισυ τὸ $B\Theta$, λοιπὸν ἄρα τὸ $H\Delta$ λοιποῦ τοῦ ΘA μείζον ἐστίν. καὶ ἐπεὶ μείζον ἐστὶ τὸ $H\Delta$ τοῦ ΘA , καὶ ἀφήρηται τοῦ μὲν $H\Delta$ ἥμισυ τὸ HZ , τοῦ δὲ ΘA μείζον ἢ τὸ ἥμισυ τὸ ΘK , λοιπὸν ἄρα τὸ ΔZ λοιποῦ τοῦ AK μείζον ἐστίν. ἴσον δὲ τὸ ΔZ τῷ Γ . καὶ τὸ Γ ἄρα τοῦ AK μείζον ἐστίν. ἔλασσον ἄρα τὸ AK τοῦ Γ .

Καταλείπεται ἄρα ἀπὸ τοῦ AB μεγέθους τὸ AK μέγεθος ἔλασσον ὄν τοῦ ἐκκειμένου ἐλάσσονος μεγέθους τοῦ Γ . ὅπερ ἔδει δεῖξαι—ὁμοίως δὲ δειχθήσεται, κἂν ἡμίση ἢ τὰ ἀφαιρούμενα.

EUCLID

than AB [see v. Def. 4]. Let it be multiplied, and let ΔE be a multiple of Γ , greater than AB , and let ΔE be divided into the parts ΔZ , ZH , HE equal to Γ , and from AB let there be subtracted $B\Theta$ greater than its half, and from $A\Theta$ let there be subtracted ΘK greater than its half, and so on continually, until the divisions in AB are equal in multitude to the divisions in ΔE .

Let, then, AK , $K\Theta$, ΘB be divisions equal in multitude with ΔZ , ZH , HE ; now since ΔE is greater than AB , and from ΔE there has been subtracted EH less than its half, and from AB there has been subtracted $B\Theta$ greater than its half, therefore the remainder $H\Delta$ is greater than the remainder ΘA . And since $H\Delta$ is greater than ΘA , and from $H\Delta$ there has been subtracted the half, HZ , and from ΘA there has been subtracted ΘK greater than its half, therefore the remainder ΔZ is greater than the remainder AK . Now ΔZ is equal to Γ ; and therefore Γ is greater than AK . Therefore AK is less than Γ .

There is therefore left of the magnitude AB the magnitude AK which is less than the lesser magnitude set out, namely, Γ ; which was to be proved—and this can be similarly proved even if the parts to be subtracted be halves.^a

^a This important theorem is often known as the Axiom of Archimedes because of the use to which he puts it, or a similar lemma: "The excess by which the greater of two unequal areas exceeds the lesser can, by being continually added to itself, be made to exceed any given finite area." Archimedes makes no claim to have discovered this lemma, which is doubtless due to Eudoxus. The chief use of the "axiom" by Euclid is to prove *Elements* xii. 2, that circles are to one another as the squares on their diameters.

GREEK MATHEMATICS

Prop. 111, coroll.

Ἡ ἀποτομή καὶ αἱ μετ' αὐτὴν ἄλογοι οὐτε τῆ μέσῃ οὐτε ἀλλήλαις εἰσὶν αἱ αὐταί. . . .

Καὶ ἐπεὶ δέδεικται ἡ ἀποτομή οὐκ οὔσα ἢ αὐτῆ τῆ ἐκ δύο ὀνομάτων, ποιούσι δὲ πλάτη παρὰ ῥητὴν

* Much of Eucl. *Elem.* x. is devoted to an elaborate classification of irrational straight lines. Zeuthen (*Geschichte der Mathematik im Altertum und Mittelalter*, p. 56) suggests that, inasmuch as one straight line looks very much like another, the Greeks could not perceive by simple inspection that difference among irrational quantities which our system of algebraic symbols enables us to see; consequently they were led to classify irrational straight lines in the manner of Eucl. *Elem.* x., and we know from an Arabic commentary on this book discovered by Woepcke (*Mémoires présentés à l'Académie des Sciences*, xiv., 1856, pp. 658-720) that Theaetetus had to some extent preceded Euclid. In this system irrational straight lines are classified according to the areas they produce when "applied" (v. *supra*, pp. 186-187) to other straight lines. For full details the reader must be referred to Loria, *Le scienze esatte nell' antica Grecia*, pp. 225-231, Heath's notes in *The Thirteen Books of Euclid's Elements*, vol. iii., and *H.G.M.* i. 404-411, but it may be useful to give here, in Heath's notation, the modern algebraic equivalents of Euclid's irrational straight lines. A medial line is of the form $k^{\frac{1}{2}}\rho$, i.e., the positive solution of the equation $x^2 - \rho\sqrt{k}\cdot\rho = 0$. The other twelve irrational lines are compound, and may best be arranged in pairs as follows:

$$\left. \begin{array}{l} 1. \text{ Binomial} \\ \text{Apotome} \end{array} \right\} \quad \rho \pm \sqrt{k} \cdot \rho,$$

being the positive roots of the equation

$$x^4 - 2(1+k)\rho^2 \cdot x^2 + (1-k)^2\rho^4 = 0.$$

$$\left. \begin{array}{l} 2. \text{ First bimedral} \\ \text{First apotome of a medial} \end{array} \right\} \quad k^{\frac{1}{2}}\rho \pm k^{\frac{1}{4}}\rho,$$

being the positive roots of the equation

$$x^4 - 2\sqrt{k}(1+k)\rho^2 \cdot x^2 + k(1-k)^2\rho^4 = 0.$$

EUCLID

Prop. 111, corollary

The apotome and the irrational straight lines following it are the same neither with the medial straight line nor with one another.^a . . .

Since the apotome has been proved not to be the same as the binomial straight line [x. 111], and, if

$$\left. \begin{array}{l} 3. \text{ Second bimedial} \\ \text{Second apotome of a medial} \end{array} \right\} k^{\frac{1}{2}}\rho \pm \frac{\lambda^{\frac{1}{2}}\rho}{k^{\frac{1}{2}}}$$

being the positive roots of the equation

$$x^4 - 2\frac{k+\lambda}{\sqrt{k}}\rho^2 \cdot x^2 + \frac{(k-\lambda)^2}{k}\rho^4 = 0.$$

$$4. \left. \begin{array}{l} \text{Major} \\ \text{Minor} \end{array} \right\} \frac{\rho}{\sqrt{2}} \sqrt{\left(1 + \frac{k}{\sqrt{1+k^2}}\right)} \pm \frac{\rho}{\sqrt{2}} \sqrt{\left(1 - \frac{k}{\sqrt{1+k^2}}\right)},$$

being the positive roots of the equation

$$x^4 - 2\rho^2 \cdot x^2 + \frac{k^2}{1+k^2}\rho^4 = 0.$$

$$5. \left. \begin{array}{l} \text{Side of a rational plus a} \\ \text{medial area} \\ \text{Producing with a rational} \\ \text{area a medial whole} \end{array} \right\} \begin{array}{l} \frac{\rho}{\sqrt{2(1+k^2)}} \sqrt{(\sqrt{1+k^2}+k)} \\ \pm \frac{\rho}{\sqrt{2(1+k^2)}} \sqrt{(\sqrt{1+k^2}-k)}, \end{array}$$

being the positive roots of the equation

$$x^4 - \frac{2}{\sqrt{1+k^2}}\rho^2 \cdot x^2 + \frac{k^2}{(1+k^2)^2}\rho^4 = 0.$$

$$6. \left. \begin{array}{l} \text{Side of the sum of two} \\ \text{medial areas} \\ \text{Producing with a med-} \\ \text{ial area a medial} \\ \text{whole} \end{array} \right\} \begin{array}{l} \frac{\rho\lambda^{\frac{1}{2}}}{\sqrt{2}} \sqrt{\left(1 + \frac{k}{\sqrt{1+k^2}}\right)} \\ \pm \frac{\rho\lambda^{\frac{1}{2}}}{\sqrt{2}} \sqrt{\left(1 - \frac{k}{\sqrt{1+k^2}}\right)}, \end{array}$$

being the positive roots of the equation

$$x^4 - 2\sqrt{\lambda} \cdot x^2\rho^2 + \lambda\frac{k^2}{1+k^2}\rho^4 = 0.$$

GREEK MATHEMATICS

παραβαλλόμενοι αἱ μετὰ τὴν ἀποτομὴν ἀποτομὰς ἀκολουθῶς ἐκάστη τῇ τάξει τῇ καθ' αὐτήν, αἱ δὲ μετὰ τὴν ἐκ δύο ὀνομάτων τὰς ἐκ δύο ὀνομάτων καὶ αὐταὶ τῇ τάξει ἀκολουθῶς, ἕτεραι ἄρα εἰσὶν αἱ μετὰ τὴν ἀποτομὴν καὶ ἕτεροι αἱ μετὰ τὴν ἐκ δύο ὀνομάτων, ὡς εἶναι τῇ τάξει πάσας ἀλόγους $\iota\gamma$,

Μέσην,

Ἐκ δύο ὀνομάτων,

Ἐκ δύο μέσων πρώτην,

Ἐκ δύο μέσων δευτέραν,

Μείζονα,

Ῥητὸν καὶ μέσον δυναμένην,

Δύο μέσα δυναμένην,

Ἀποτομήν,

Μέσης ἀποτομὴν πρώτην,

Μέσης ἀποτομὴν δευτέραν,

Ἐλάσσονα,

Μετὰ ῤητοῦ μέσον τὸ ὅλον ποιούσαν,

Μετὰ μέσου μέσον τὸ ὅλον ποιούσαν.

(iv.) *Method of Exhaustion*

Eucl. *Elem.* xii. 2

Οἱ κύκλοι πρὸς ἀλλήλους εἰσὶν ὡς τὰ ἀπὸ τῶν διαμέτρων τετράγωνα.

Ἔστωσαν κύκλοι οἱ ΑΒΓΔ, ΕΖΗΘ, διάμετροι δὲ αὐτῶν αἱ ΒΔ, ΖΘ· λέγω, ὅτι ἐστὶν ὡς ὁ ΑΒΓΔ κύκλος πρὸς τὸν ΕΖΗΘ κύκλον, οὕτως τὸ ἀπὸ τῆς ΒΔ τετράγωνον πρὸς τὸ ἀπὸ τῆς ΖΘ τετράγωνον.

• Eudemus attributed the discovery of this important theorem to Hippocrates (see *supra*, p. 238). Unfortunately we do not know how Hippocrates proved it.

EUCLID

applied to a rational straight line, the straight lines following the apotome produce, as breadths, apotomes according to their order, and those following the binomial straight line produce, as breadths, binomials according to their order, therefore the straight lines following the apotome are different, and the straight lines following the binomial straight line are different, so that in all there are, in order, thirteen straight lines,

Medial,
Binomial,
First bimedial,
Second bimedial,
Major,
Side of a rational plus a medial area,
Side of the sum of two medial areas,
Apotome,
First apotome of a medial straight line,
Second apotome of a medial straight line,
Minor,
Producing with a rational area a medial whole,
Producing with a medial area a medial whole.

(iv.) *Method of Exhaustion*

Euclid, *Elements* xii. 2 ^a

Circles are to one another as the squares on the diameters.

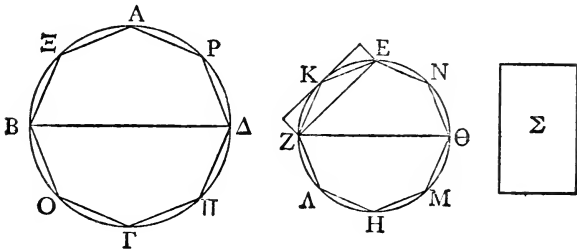
Let $AB\Gamma\Delta$, $EZH\Theta$ be circles, and $B\Delta$, $Z\Theta$ their diameters; I say that, as the circle $AB\Gamma\Delta$ is to the circle $EZH\Theta$, so is the square on $B\Delta$ to the square on $Z\Theta$.

GREEK MATHEMATICS

Εἰ γὰρ μή ἐστὶν ὡς ὁ $ΑΒΓΔ$ κύκλος πρὸς τὸν $ΕΖΗΘ$, οὕτως τὸ ἀπὸ τῆς $ΒΔ$ τετράγωνον πρὸς τὸ ἀπὸ τῆς $ΖΘ$, ἔσται ὡς τὸ ἀπὸ τῆς $ΒΔ$ πρὸς τὸ ἀπὸ τῆς $ΖΘ$, οὕτως ὁ $ΑΒΓΔ$ κύκλος ἦτοι πρὸς ἔλασσόν τι τοῦ $ΕΖΗΘ$ κύκλου χωρίον ἢ πρὸς μείζον. ἔστω πρότερον πρὸς ἔλασσον τὸ $Σ$. καὶ ἐγγεγράφθω εἰς τὸν $ΕΖΗΘ$ κύκλον τετράγωνον τὸ $ΕΖΗΘ$. τὸ δὴ ἐγγεγραμμένον τετράγωνον μείζον ἐστὶν ἢ τὸ ἥμισυ τοῦ $ΕΖΗΘ$ κύκλου, ἐπειδήπερ ἐὰν διὰ τῶν $Ε, Ζ, Η, Θ$ σημείων ἐφαπτομένας τοῦ κύκλου ἀγάγωμεν, τοῦ περιγραφομένου περὶ τὸν κύκλον τετραγώνου ἡμισὺ ἐστὶ τὸ $ΕΖΗΘ$ τετράγωνον, τοῦ δὲ περιγραφέντος τετραγώνου ἐλάττων ἐστὶν ὁ κύκλος· ὥστε τὸ $ΕΖΗΘ$ ἐγγεγραμμένον τετράγωνον μείζον ἐστὶ τοῦ ἡμίσεως τοῦ $ΕΖΗΘ$ κύκλου. τετμήσθωσαν δίχα αἱ $ΕΖ, ΖΗ, ΗΘ, ΘΕ$ περιφέρειαι κατὰ τὰ $Κ, Λ, Μ, Ν$ σημεία, καὶ ἐπεζεύχθωσαν αἱ $ΕΚ, ΚΖ, ΖΛ, ΛΗ, ΗΜ, ΜΘ, ΘΝ, ΝΕ$. καὶ ἕκαστον ἄρα τῶν $ΕΚΖ, ΖΛΗ, ΗΜΘ, ΘΝΕ$ τριγώνων μείζον ἐστὶν ἢ τὸ ἥμισυ τοῦ καθ' ἑαυτὸ τμήματος τοῦ κύκλου, ἐπειδήπερ ἐὰν διὰ τῶν $Κ, Λ, Μ, Ν$ σημείων ἐφαπτομένας τοῦ κύκλου ἀγάγωμεν καὶ ἀναπληρώσωμεν τὰ ἐπὶ τῶν $ΕΖ, ΖΗ, ΗΘ, ΘΕ$ εὐθειῶν παραλληλόγραμμα, ἕκαστον τῶν $ΕΚΖ, ΖΛΗ, ΗΜΘ, ΘΝΕ$ τριγώνων ἡμισυ ἔσται τοῦ καθ' ἑαυτὸ παραλληλογράμμου, ἀλλὰ τὸ καθ'

EUCLID

For if the circle $AB\Gamma\Delta$ is not to the circle $EZH\Theta$ as the square on $B\Delta$ to the square on $Z\Theta$, then the square on $B\Delta$ will be to the square on $Z\Theta$ as the circle $AB\Gamma\Delta$ is to some area either less than the circle $EZH\Theta$ or greater. Let it first be in that ratio to a lesser area Σ . And let the square $EZH\Theta$ be inscribed in the circle $EZH\Theta$; then the inscribed square is greater than the half of the circle $EZH\Theta$, inasmuch as, if through the points E, Z, H, Θ we draw tangents to the circle, the square $EZH\Theta$ is half the square circumscribed about the circle, and the circle is less



than the circumscribed square; so that the inscribed square $EZH\Theta$ is greater than the half of the circle $EZH\Theta$. Let the circumferences $EZ, ZH, H\Theta, \Theta E$ be bisected at the points K, Λ, M, N , and let $EK, KZ, Z\Lambda, \Lambda H, HM, M\Theta, \Theta N, NE$ be joined; therefore each of the triangles $EKZ, Z\Lambda H, HM\Theta, \Theta NE$ is greater than the half of the segment of the circle about it, inasmuch as, if through the points K, Λ, M, N we draw tangents to the circle and complete the parallelograms on the straight lines $EZ, ZH, H\Theta, \Theta E$, each of the triangles $EKZ, Z\Lambda H, HM\Theta, \Theta NE$ will be half of the parallelogram about it, while the segment

GREEK MATHEMATICS

ἑαυτὸ τμήμα ἑλαττόν ἐστι τοῦ παραλληλογράμμου ὥστε ἕκαστον τῶν ΕΚΖ, ΖΑΗ, ΗΜΘ, ΘΝΕ τριγώνων μείζον ἐστὶ τοῦ ἡμίσεως τοῦ καθ' ἑαυτὸ τμήματος τοῦ κύκλου. τέμνοντες δὴ τὰς ὑπολειπομένας περιφερείας δίχα καὶ ἐπιζευγνύντες εὐθείας καὶ τοῦτο αἰεὶ ποιούντες καταλείβομεν τινα ἀποτμήματα τοῦ κύκλου, ἃ ἔσται ἐλάσσονα τῆς ὑπεροχῆς, ἣ ὑπερέχει ὁ ΕΖΗΘ κύκλος τοῦ Σ χωρίου. ἐδείχθη γὰρ ἐν τῷ πρώτῳ θεωρήματι τοῦ δεκάτου βιβλίου, ὅτι δύο μεγεθῶν ἀνίσων ἐκκειμένων, ἐὰν ἀπὸ τοῦ μείζονος ἀφαιρεθῇ μείζον ἢ τὸ ἡμισυ καὶ τοῦ καταλειπομένου μείζον ἢ τὸ ἡμισυ, καὶ τοῦτο αἰεὶ γίγνηται, λειφθήσεται τι μέγεθος, ὃ ἔσται ἔλασσον τοῦ ἐκκειμένου ἐλάσσονος μεγέθους. λελείφθω οὖν, καὶ ἔστω τὰ ἐπὶ τῶν ΕΚ, ΚΖ, ΖΑ, ΑΗ, ΗΜ, ΜΘ, ΘΝ, ΝΕ τμήματα τοῦ ΕΖΗΘ κύκλου ἐλάττονα τῆς ὑπεροχῆς, ἣ ὑπερέχει ὁ ΕΖΗΘ κύκλος τοῦ Σ χωρίου. λοιπὸν ἄρα τὸ ΕΚΖΛΗΜΘΝ πολύγωνον μείζον ἐστὶ τοῦ Σ χωρίου. ἐγγεγράφθω καὶ εἰς τὸν ΑΒΓΔ κύκλον τῷ ΕΚΖΛΗΜΘΝ πολυγώνῳ ὅμοιον πολύγωνον τὸ ΑΞΒΟΓΠΔΡ· ἔστιν ἄρα ὡς τὸ ἀπὸ τῆς ΒΔ τετράγωνον πρὸς τὸ ἀπὸ τῆς ΖΘ τετράγωνον, οὕτως τὸ ΑΞΒΟΓΠΔΡ πολύγωνον πρὸς τὸ ΕΚΖΛΗΜΘΝ πολύγωνον. ἀλλὰ καὶ ὡς τὸ ἀπὸ τῆς ΒΔ τετράγωνον πρὸς τὸ ἀπὸ τῆς ΖΘ, οὕτως ὁ ΑΒΓΔ κύκλος πρὸς τὸ Σ χωρίον· καὶ ὡς ἄρα ὁ ΑΒΓΔ κύκλος πρὸς τὸ Σ χωρίον, οὕτως τὸ ΑΞΒΟΓΠΔΡ πολύγωνον πρὸς τὸ ΕΚΖΛΗΜΘΝ πολύγωνον· ἐναλλάξ ἄρα ὡς ὁ ΑΒΓΔ κύκλος πρὸς τὸ ἐν αὐτῷ πολύγωνον, οὕτως τὸ Σ χωρίον πρὸς τὸ ΕΚΖΛΗΜΘΝ πολύγωνον. μείζων δὲ ὁ ΑΒΓΔ

EUCLID

about it is less than the parallelogram ; so that each of the triangles EKZ , $Z\Lambda H$, $HM\Theta$, ΘNE is greater than the half of the segment of the circle about it. Thus, by bisecting the remaining circumferences and joining straight lines, and doing this continually, we shall leave some segments of the circle which will be less than the excess by which the circle $EZH\Theta$ exceeds the area Σ . For it was proved in the first theorem of the tenth book that, if two unequal magnitudes be set out, and if from the greater there be subtracted a magnitude greater than its half, and from the remainder a magnitude greater than its half, and so on continually, there will be left some magnitude which is less than the lesser magnitude set out. Let such segments be then left, and let the segments of the circle $EZH\Theta$ on EK , KZ , $Z\Lambda$, ΛH , HM , $M\Theta$, ΘN , NE be less than the excess by which the circle $EZH\Theta$ exceeds the area Σ . Therefore the remainder, the polygon $EKZ\Lambda HM\Theta N$, is greater than the area Σ . Let there be inscribed, also, in the circle $AB\Gamma\Delta$ the polygon $A\Xi B\O\Gamma\Pi\Delta P$ similar to the polygon $EKZ\Lambda HM\Theta N$; therefore as the square on $B\Delta$ is to the square on $Z\Theta$, so is the polygon $A\Xi B\O\Gamma\Pi\Delta P$ to the polygon $EKZ\Lambda HM\Theta N$ [xii. 1]. But as the square on $B\Delta$ is to the square on $Z\Theta$, so is the circle $AB\Gamma\Delta$ to the area Σ ; therefore also as the circle $AB\Gamma\Delta$ is to the area Σ , so is the polygon $A\Xi B\O\Gamma\Pi\Delta P$ to the polygon $EKZ\Lambda HM\Theta N$ [v. 11] ; therefore, alternately, as the circle $AB\Gamma\Delta$ is to the polygon in it, so is the area Σ to the polygon $EKZ\Lambda HM\Theta N$. Now the circle

GREEK MATHEMATICS

κύκλος τοῦ ἐν αὐτῷ πολυγώνου· μείζον ἄρα καὶ τὸ Σ χωρίον τοῦ ΕΚΖΛΗΜΘΝ πολυγώνου. ἀλλὰ καὶ ἔλαττον· ὅπερ ἐστὶν ἀδύνατον. οὐκ ἄρα ἐστὶν ὡς τὸ ἀπὸ τῆς ΒΔ τετράγωνον πρὸς τὸ ἀπὸ τῆς ΖΘ, οὕτως ὁ ΑΒΓΔ κύκλος πρὸς ἔλασσόν τι τοῦ ΕΖΗΘ κύκλου χωρίον. ὁμοίως δὴ δεῖξομεν, ὅτι οὐδὲ ὡς τὸ ἀπὸ ΖΘ πρὸς τὸ ἀπὸ ΒΔ, οὕτως ὁ ΕΖΗΘ κύκλος πρὸς ἔλασσόν τι τοῦ ΑΒΓΔ κύκλου χωρίον.

Λέγω δὴ, ὅτι οὐδὲ ὡς τὸ ἀπὸ τῆς ΒΔ πρὸς τὸ ἀπὸ τῆς ΖΘ, οὕτως ὁ ΑΒΓΔ κύκλος πρὸς μείζον τι τοῦ ΕΖΗΘ κύκλου χωρίον.

Εἰ γὰρ δυνατόν, ἔστω πρὸς μείζον τὸ Σ . ἀνάπαλιν ἄρα ὡς τὸ ἀπὸ τῆς ΖΘ τετράγωνον πρὸς τὸ ἀπὸ τῆς ΔΒ, οὕτως τὸ Σ χωρίον πρὸς τὸν ΑΒΓΔ κύκλον. ἀλλ' ὡς τὸ Σ χωρίον πρὸς τὸν ΑΒΓΔ κύκλον, οὕτως ὁ ΕΖΗΘ κύκλος πρὸς ἔλαττόν τι τοῦ ΑΒΓΔ κύκλου χωρίον· καὶ ὡς ἄρα τὸ ἀπὸ τῆς ΖΘ πρὸς τὸ ἀπὸ τῆς ΒΔ, οὕτως ὁ ΕΖΗΘ κύκλος πρὸς ἔλασσόν τι τοῦ ΑΒΓΔ κύκλου χωρίον· ὅπερ ἀδύνατον ἐδείχθη. οὐκ ἄρα ἐστὶν ὡς τὸ ἀπὸ ΒΔ τετράγωνον πρὸς τὸ ἀπὸ τῆς ΖΘ, οὕτως ὁ ΑΒΓΔ κύκλος πρὸς μείζον τι τοῦ ΕΖΗΘ κύκλου χωρίον. ἐδείχθη δέ, ὅτι οὐδὲ πρὸς ἔλασσον· ἐστὶν ἄρα ὡς τὸ ἀπὸ τῆς ΒΔ τετράγωνον πρὸς τὸ ἀπὸ τῆς ΖΘ, οὕτως ὁ ΑΒΓΔ κύκλος πρὸς τὸν ΕΖΗΘ κύκλον.

Οἱ ἄρα κύκλοι πρὸς ἀλλήλους εἰσὶν ὡς τὰ ἀπὸ τῶν διαμέτρων τετράγωνα· ὅπερ ἔδει δεῖξαι.

EUCLID

$AB\Gamma\Delta$ is greater than the polygon in it ; therefore the area Σ also is greater than the polygon $EKZ\Lambda HM\Theta N$. But it is also less ; which is impossible. Therefore it is not true that, as is the square on $B\Delta$ to the square on $Z\Theta$, so is the circle $AB\Gamma\Delta$ to some area less than the circle $EZH\Theta$. Similarly we shall prove that neither is it true that, as the square on $Z\Theta$ is to the square on $B\Delta$, so is the circle $EZH\Theta$ to some area less than the circle $AB\Gamma\Delta$.

I say now that neither is the circle $AB\Gamma\Delta$ towards some area greater than the circle $EZH\Theta$ as the square on $B\Delta$ is to the square on $Z\Theta$.

For, if possible, let it be in that ratio to some greater area Σ . Therefore, inversely, as the square on $Z\Theta$ is to the square on ΔB , so is the area Σ to the circle $AB\Gamma\Delta$. But as the area Σ is to the circle $AB\Gamma\Delta$, so is the circle $EZH\Theta$ to some area less than the circle $AB\Gamma\Delta$; therefore also, as the square on $Z\Theta$ is to the square on $B\Delta$, so is the circle $EZH\Theta$ to some area less than the circle $AB\Gamma\Delta$ [v. 11] ; which was proved impossible. Therefore it is not true that, as the square on $B\Delta$ is to the square on $Z\Theta$, so is the circle $AB\Gamma\Delta$ to some area greater than the circle $EZH\Theta$. And it was proved not to be in that relation to a less area ; therefore as the square on $B\Delta$ is to the square on $Z\Theta$, so is the circle $AB\Gamma\Delta$ to the circle $EZH\Theta$.

Therefore circles are to one another as the squares on the diameters ; which was to be proved.

GREEK MATHEMATICS

(v.) *Regular Solids*

Eucl. *Elem.* xiii. 18

Τὰς πλευρὰς τῶν πέντε σχημάτων ἐκθέσθαι καὶ συγκρῖναι πρὸς ἀλλήλας.

Ἐκκείσθω ἡ τῆς δοθείσης σφαίρας διάμετρος ἡ AB , καὶ τετμήσθω κατὰ τὸ Γ ὥστε ἴσην εἶναι τὴν $A\Gamma$ τῇ ΓB , κατὰ δὲ τὸ Δ ὥστε διπλασίονα εἶναι τὴν $A\Delta$ τῆς ΔB , καὶ γεγράψθω ἐπὶ τῆς AB ἡμικύκλιον τὸ AEB , καὶ ἀπὸ τῶν Γ , Δ τῇ AB πρὸς ὀρθὰς ἤχθωσαν αἱ ΓE , ΔZ , καὶ ἐπεζεύχθωσαν αἱ AZ , ZB , EB . καὶ ἐπεὶ διπλῆ ἐστὶν ἡ $A\Delta$ τῆς ΔB , τριπλῆ ἄρα ἐστὶν ἡ AB τῆς $B\Delta$. ἀναστρέψαντι ἡμιολία ἄρα ἐστὶν ἡ BA τῆς $A\Delta$. ὡς δὲ ἡ BA πρὸς τὴν $A\Delta$, οὕτως τὸ ἀπὸ τῆς BA πρὸς τὸ ἀπὸ τῆς AZ . ἰσογώνιον γάρ ἐστι τὸ AZB τρίγωνον τῷ $AZ\Delta$ τριγώνῳ· ἡμιόλιον ἄρα ἐστὶ τὸ ἀπὸ τῆς BA τοῦ ἀπὸ τῆς AZ . ἔστι δὲ καὶ ἡ τῆς σφαίρας διάμετρος δυνάμει ἡμιολία

^a For the earlier history of the regular, cosmic or Platonic figures, *v. supra*, pp. 216-225, 378-379.

^b This proposition cannot be fully understood without the previous propositions in the book which it assumes, but it will give an insight into the thoroughness and comprehensiveness of Euclid's methods.

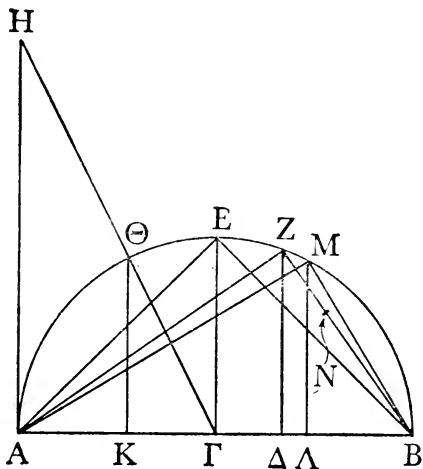
EUCLID

(v.) *Regular Solids* ^a

Euclid, *Elements* xiii. 18 ^b

To set out the sides of the five figures and to compare them one with another.

Let AB , the diameter of the given sphere, be set out, and let it be cut at Γ so that $A\Gamma$ is equal to ΓB , and at Δ so that $A\Delta$ is double of ΔB ; and on AB let the semicircle AEB be drawn, and from Γ, Δ let $\Gamma E, \Delta Z$ be drawn at right angles to AB , and let AZ, ZB, EB be joined. Then since $A\Delta = 2\Delta B$, therefore $AB = 3\Delta B$. *Convertendo*, therefore $BA = \frac{3}{2}A\Delta$. But $BA : A\Delta = BA^2 : AZ^2$ [v. Def. 9], for the triangle AZB is equiangular with the triangle $AZ\Delta$ [vi. 8];



therefore $BA^2 = \frac{3}{2}AZ^2$. But the square on the diameter of the sphere is also one-and-a-half times the

τῆς πλευρᾶς τῆς πυραμίδος. καὶ ἐστὶν ἡ AB ἡ τῆς σφαίρας διάμετρος· ἡ AZ ἄρα ἴση ἐστὶ τῇ πλευρᾷ τῆς πυραμίδος.

Πάλιν, ἐπεὶ διπλασίων ἐστὶν ἡ AD τῆς AB , τριπλῆ ἄρα ἐστὶν ἡ AB τῆς BD . ὡς δὲ ἡ AB πρὸς τὴν BD , οὕτως τὸ ἀπὸ τῆς AB πρὸς τὸ ἀπὸ τῆς BZ · τριπλάσιον ἄρα ἐστὶ τὸ ἀπὸ τῆς AB τοῦ ἀπὸ τῆς BZ . ἔστι δὲ καὶ ἡ τῆς σφαίρας διάμετρος δυνάμει τριπλασίων τῆς τοῦ κύβου πλευρᾶς. καὶ ἐστὶν ἡ AB ἡ τῆς σφαίρας διάμετρος· ἡ BZ ἄρα τοῦ κύβου ἐστὶ πλευρά.

Καὶ ἐπεὶ ἴση ἐστὶν ἡ AG τῇ GB , διπλῆ ἄρα ἐστὶν ἡ AB τῆς BG . ὡς δὲ ἡ AB πρὸς τὴν BG , οὕτως τὸ ἀπὸ τῆς AB πρὸς τὸ ἀπὸ τῆς BE · διπλάσιον ἄρα ἐστὶ τὸ ἀπὸ τῆς AB τοῦ ἀπὸ τῆς BE . ἔστι δὲ καὶ ἡ τῆς σφαίρας διάμετρος δυνάμει διπλασίων τῆς τοῦ ὀκταέδρου πλευρᾶς. καὶ ἐστὶν ἡ AB ἡ τῆς δοθείσης σφαίρας διάμετρος· ἡ BE ἄρα τοῦ ὀκταέδρου ἐστὶ πλευρά.

Ἦχθω δὴ ἀπὸ τοῦ A σημείου τῇ AB εὐθείᾳ πρὸς ὀρθὰς ἡ AH , καὶ κείσθω ἡ AH ἴση τῇ AB , καὶ ἐπεζεύχθω ἡ HG , καὶ ἀπὸ τοῦ Θ ἐπὶ τὴν AB κάθετος ἤχθω ἡ ΘK . καὶ ἐπεὶ διπλῆ ἐστὶν ἡ HA τῆς AG · ἴση γὰρ ἡ HA τῇ AB · ὡς δὲ ἡ HA πρὸς τὴν AG , οὕτως ἡ ΘK πρὸς τὴν KG , διπλῆ ἄρα καὶ ἡ ΘK τῆς KG . τετραπλάσιον ἄρα ἐστὶ τὸ ἀπὸ τῆς ΘK τοῦ ἀπὸ τῆς KG · τὰ ἄρα ἀπὸ τῶν ΘK , KG , ὅπερ ἐστὶ τὸ ἀπὸ τῆς ΘG , πενταπλάσιόν ἐστι τοῦ ἀπὸ τῆς KG . ἴση δὲ ἡ ΘG τῇ GB · πενταπλάσιον ἄρα ἐστὶ τὸ ἀπὸ τῆς BG τοῦ ἀπὸ τῆς $ΓK$. καὶ ἐπεὶ διπλῆ ἐστὶν ἡ AB τῆς $ΓB$, ὡν ἡ AD τῆς $ΔB$ ἐστὶ διπλῆ, λοιπὴ ἄρα ἡ BD λοιπῆς

EUCLID

square on the side of the pyramid [xiii. 13]. And AB is the diameter of the sphere ; therefore AZ is equal to the side of the pyramid.

Again, since $A\Delta = 2\Delta B$, therefore $AB = 3B\Delta$. But $AB : B\Delta = AB^2 : BZ^2$ [vi. 8, v. Def. 9]; therefore $AB^2 = 3BZ^2$. But the square on the diameter of the sphere is also three times the square on the side of the cube [xiii. 15]. And AB is the diameter of the sphere ; therefore BZ is the side of the cube.

And since $A\Gamma = \Gamma B$, therefore $AB = 2B\Gamma$. But $AB : B\Gamma = AB^2 : BE^2$ [vi. 8, v. Def. 9]. Therefore $AB^2 = 2BE^2$. But the square on the diameter of the sphere is also double of the square on the side of the octahedron [xiii. 14]. And AB is the diameter of the given sphere ; therefore BE is the side of the octahedron.

Now let AH be drawn from the point A at right angles to the straight line AB , and let AH be made equal to AB , and let $H\Gamma$ be joined, and from Θ let ΘK be drawn perpendicular to AB . Then since $HA = 2A\Gamma$ (for $HA = AB$), and $HA : A\Gamma = \Theta K : K\Gamma$ [vi. 4], therefore $\Theta K = 2K\Gamma$. Therefore $\Theta K^2 = 4K\Gamma^2$. Therefore $\Theta K^2 + K\Gamma^2 = 5K\Gamma^2 = \Theta\Gamma^2$ [i. 47]. But $\Theta\Gamma = \Gamma B$; therefore $B\Gamma^2 = 5\Gamma K^2$. And since $AB = 2\Gamma B$, and in them $A\Delta = 2\Delta B$, therefore the remainder

GREEK MATHEMATICS

τῆς ΔΓ ἔστι διπλῆ. τριπλῆ ἄρα ἡ ΒΓ τῆς ΓΔ·
 ἐνναπλάσιον ἄρα τὸ ἀπὸ τῆς ΒΓ τοῦ ἀπὸ τῆς ΓΔ.
 πενταπλάσιον δὲ τὸ ἀπὸ τῆς ΒΓ τοῦ ἀπὸ τῆς ΓΚ·
 μείζον ἄρα τὸ ἀπὸ τῆς ΓΚ τοῦ ἀπὸ τῆς ΓΔ.
 μείζων ἄρα ἔστιν ἡ ΓΚ τῆς ΓΔ. κείσθω τῇ ΓΚ
 ἴση ἡ ΓΛ, καὶ ἀπὸ τοῦ Λ τῇ ΑΒ πρὸς ὀρθὰς
 ἦχθω ἡ ΛΜ, καὶ ἐπεζεύχθω ἡ ΜΒ. καὶ ἐπεὶ
 πενταπλάσιόν ἐστι τὸ ἀπὸ τῆς ΒΓ τοῦ ἀπὸ τῆς
 ΓΚ, καὶ ἔστι τῆς μὲν ΒΓ διπλῆ ἡ ΑΒ, τῆς δὲ ΓΚ
 διπλῆ ἡ ΚΛ, πενταπλάσιον ἄρα ἔστι τὸ ἀπὸ τῆς
 ΑΒ τοῦ ἀπὸ τῆς ΚΛ. ἔστι δὲ καὶ ἡ τῆς σφαι-
 ρας διάμετρος δυνάμει πενταπλασίῳ τῆς ἐκ τοῦ
 κέντρου τοῦ κύκλου, ἀφ' οὗ τὸ εἰκοσάεδρον ἀνα-
 γέγραπται. καὶ ἔστιν ἡ ΑΒ ἡ τῆς σφαιρας διά-
 μετρος· ἡ ΚΛ ἄρα ἐκ τοῦ κέντρου ἔστι τοῦ
 κύκλου, ἀφ' οὗ τὸ εἰκοσάεδρον ἀναγέγραπται· ἡ
 ΚΛ ἄρα ἐξαγώνου ἔστι πλευρὰ τοῦ εἰρημένου
 κύκλου. καὶ ἐπεὶ ἡ τῆς σφαιρας διάμετρος σύγ-
 κειται ἔκ τε τῆς τοῦ ἐξαγώνου καὶ δύο τῶν τοῦ
 δεκαγώνου τῶν εἰς τὸν εἰρημένον κύκλον ἐγγρα-
 φομένων, καὶ ἔστιν ἡ μὲν ΑΒ ἡ τῆς σφαιρας
 διάμετρος, ἡ δὲ ΚΛ ἐξαγώνου πλευρὰ, καὶ ἴση ἡ
 ΑΚ τῇ ΛΒ, ἑκάτερα ἄρα τῶν ΑΚ, ΛΒ δεκαγώνου
 ἔστι πλευρὰ τοῦ ἐγγραφομένου εἰς τὸν κύκλον, ἀφ'
 οὗ τὸ εἰκοσάεδρον ἀναγέγραπται. καὶ ἐπεὶ δεκα-
 γώνου μὲν ἡ ΛΒ, ἐξαγώνου δὲ ἡ ΜΛ· ἴση γάρ
 ἔστι τῇ ΚΛ, ἐπεὶ καὶ τῇ ΘΚ· ἴσον γὰρ ἀπέχουσιν

^a Euclid's procedure, in constructing the icosahedron inscribable in a given sphere, is first to construct a circle with radius r such that $r^2 = \frac{1}{2}d^2$, where d is the diameter of the sphere. In this he inscribes a regular decagon, and from its

EUCLID

$B\Delta$ is double of the remainder $\Delta\Gamma$. Therefore $B\Gamma = 3\Gamma\Delta$; therefore $B\Gamma^2 = 9\Gamma\Delta^2$. But $B\Gamma^2 = 5\Gamma K^2$; therefore $\Gamma K^2 > \Gamma\Delta^2$. Therefore $\Gamma K > \Gamma\Delta$. Let $\Gamma\Lambda$ be made equal to ΓK , and from Λ let ΛM be drawn at right angles to AB , and let MB be joined. Then since $B\Gamma^2 = 5\Gamma K^2$, and $AB = 2B\Gamma$, $K\Lambda = 2\Gamma K$, therefore $AB^2 = 5K\Lambda^2$. But the square on the diameter of the sphere is also five times the square on the radius of the circle from which the icosahedron has been described [xiii. 16, coroll.].^a And AB is the diameter of the sphere; therefore $K\Lambda$ is the radius of the circle from which the icosahedron has been described; therefore $K\Lambda$ is a side of the hexagon in the said circle [iv. 15, coroll.]. And since the diameter of the sphere is made up of the side of the hexagon and two of the sides of the decagon inscribed in the same circle [xiii. 16, coroll.], and AB is the diameter of the sphere, while $K\Lambda$ is the side of the hexagon, and $AK = \Lambda B$, therefore each of the straight lines AK , ΛB is a side of the decagon inscribed in the circle from which the icosahedron has been described. And since ΛB belongs to a decagon and $M\Lambda$ to a hexagon (for $M\Lambda$ is equal to $K\Lambda$ since it is also equal to ΘK ,

angular points draws straight lines perpendicular to the plane of the circle and equal in length to r ; this determines the angular points of another decagon inscribed in an equal parallel circle. By joining alternate angular points of one decagon, he obtains a pentagon, and then does the same with the other decagon, but in such a manner that the angular points are not opposite one another. Joining the angular points of one pentagon to the nearest angular points of the other, he obtains ten equilateral triangles, which are faces of the icosahedron. He completes the procedure by finding the common vertices of the five equilateral triangles standing on each of the pentagons, which form the remaining faces of the icosahedron.

GREEK MATHEMATICS

ἀπὸ τοῦ κέντρου· καὶ ἐστὶν ἑκατέρα τῶν ΘΚ, ΚΛ διπλασίων τῆς ΚΓ· πενταγώνου ἄρα ἐστὶν ἡ ΜΒ. ἡ δὲ τοῦ πενταγώνου ἐστὶν ἡ τοῦ εἰκοσαέδρου· εἰκοσαέδρου ἄρα ἐστὶν ἡ ΜΒ.

Καὶ ἐπεὶ ἡ ΖΒ κύβου ἐστὶ πλευρά, τετμήσθω ἄκρον καὶ μέσον λόγον κατὰ τὸ Ν, καὶ ἔστω μείζον τμήμα τὸ ΝΒ· ἡ ΝΒ ἄρα δωδεκαέδρου ἐστὶ πλευρά.

Καὶ ἐπεὶ ἡ τῆς σφαίρας διάμετρος ἐδείχθη τῆς μὲν ΑΖ πλευρᾶς τῆς πυραμίδος δυνάμει ἡμιολία, τῆς δὲ τοῦ ὀκταέδρου τῆς ΒΕ δυνάμει διπλασίων, τῆς δὲ τοῦ κύβου τῆς ΖΒ δυνάμει τριπλασίων, οἷων ἄρα ἡ τῆς σφαίρας διάμετρος δυνάμει ἕξ, τοιούτων ἡ μὲν τῆς πυραμίδος τεσσάρων, ἡ δὲ τοῦ ὀκταέδρου τριῶν, ἡ δὲ τοῦ κύβου δύο. ἡ μὲν ἄρα τῆς πυραμίδος πλευρὰ τῆς μὲν τοῦ ὀκταέδρου πλευρᾶς δυνάμει ἐστὶν ἐπίτριτος, τῆς δὲ τοῦ κύβου δυνάμει διπλῆ, ἡ δὲ τοῦ ὀκταέδρου τῆς τοῦ κύβου δυνάμει ἡμιολία. αἱ μὲν οὖν εἰρημέναι τῶν τριῶν σχημάτων πλευραί, λέγω δὴ πυραμίδος καὶ ὀκταέδρου καὶ κύβου, πρὸς ἀλλήλας εἰσὶν ἐν λόγοις ῥητοῖς. αἱ δὲ λοιπαὶ δύο, λέγω δὴ ἡ τε τοῦ εἰκοσαέδρου καὶ ἡ τοῦ δωδεκαέδρου, οὔτε πρὸς ἀλλήλας οὔτε πρὸς τὰς προειρημένας εἰσὶν ἐν

EUCLID

being the same distance from the centre, and each of the straight lines ΘK , $K\Lambda$ is double of $K\Gamma$), therefore MB belongs to a pentagon [xiii. 10, i. 47]. But the side of the pentagon is the side of the icosahedron [xiii. 16]; therefore MB is a side of the icosahedron.

Now, since ZB is a side of the cube, let it be cut in extreme and mean ratio at N , and let NB be the greater segment; therefore NB is a side of the dodecahedron [xiii. 17, coroll.].^a

And, since the square on the diameter of the sphere was proved to be one-and-a-half times the square on the side AZ of the pyramid, double of the square on the side BE of the octahedron, and triple of the square on the side ZB of the cube, therefore, of parts of which the square on the diameter of the sphere contains six, the square on the side of the pyramid contains four, the square on the side of the octahedron contains three, and the square on the side of the cube contains two. Therefore the square on the side of the pyramid is four-thirds of the square on the side of the octahedron, and double of the square on the side of the cube; while the square on the side of the octahedron is one-and-a-half times the square on the side of the cube. The said sides of the three figures, I mean the pyramid, the octahedron and the cube, are therefore in rational ratios one to another. But the remaining two, I mean the side of the icosahedron and the side of the dodecahedron, are not in rational ratios either to one another or to the afore-

^a To construct the dodecahedron inscribable in a given sphere Euclid begins with the cube inscribed in the same sphere, and draws pentagons having the edges of the cube as diagonals.

GREEK MATHEMATICS

λόγοις ῥητοῖς· ἄλογοι γάρ εἰσιν, ἡ μὲν ἐλάττων, ἡ δὲ ἀποτομή.

Ὅτι μείζων ἐστὶν ἡ τοῦ εἰκοσαέδρου πλευρὰ ἡ MB τῆς τοῦ δωδεκαέδρου τῆς NB, δείξομεν οὕτως.

Ἐπεὶ γὰρ ἰσογώνιον ἐστὶ τὸ ZΔB τρίγωνον τῷ ZAB τριγώνῳ, ἀνάλογόν ἐστιν ὡς ἡ ΔB πρὸς τὴν BZ, οὕτως ἡ BZ πρὸς τὴν BA. καὶ ἐπεὶ τρεῖς εὐθεῖαι ἀνάλογόν εἰσιν, ἐστὶν ὡς ἡ πρώτη πρὸς τὴν τρίτην, οὕτως τὸ ἀπὸ τῆς πρώτης πρὸς τὸ ἀπὸ τῆς δευτέρας¹. ἐστὶν ἄρα ὡς ἡ ΔB πρὸς τὴν BA, οὕτως τὸ ἀπὸ τῆς ΔB πρὸς τὸ ἀπὸ τῆς BZ· ἀνάπαλιν ἄρα ὡς ἡ AB πρὸς τὴν BΔ, οὕτως τὸ ἀπὸ τῆς ZB πρὸς τὸ ἀπὸ τῆς BΔ. τριπλῆ δὲ ἡ AB τῆς BΔ· τριπλάσιον ἄρα τὸ ἀπὸ τῆς ZB τοῦ ἀπὸ τῆς BΔ. ἐστὶ δὲ καὶ τὸ ἀπὸ τῆς AΔ τοῦ ἀπὸ τῆς ΔB τετραπλάσιον· διπλῆ γὰρ ἡ AΔ τῆς ΔB· μείζων ἄρα τὸ ἀπὸ τῆς AΔ τοῦ ἀπὸ τῆς ZB· μείζων ἄρα ἡ AΔ τῆς ZB· πολλῶ ἄρα ἡ AΔ τῆς ZB μείζων ἐστίν. καὶ τῆς μὲν AΔ ἄκρον καὶ μέσον λόγον τεμνομένης τὸ μείζων τμήμα ἐστὶν ἡ ΚΛ, ἐπειδήπερ ἡ μὲν ΛΚ ἐξαγώνου ἐστίν, ἡ δὲ ΚΑ δεκαγώνου· τῆς δὲ ZB ἄκρον καὶ μέσον λόγον τεμνομένης τὸ μείζων τμήμα ἐστὶν ἡ NB· μείζων ἄρα ἡ ΚΛ τῆς NB. ἴση δὲ ἡ ΚΛ τῇ ΛΜ· μείζων ἄρα ἡ ΛΜ τῆς NB· [τῆς δὲ ΛΜ μείζων ἐστὶν ἡ

¹ καὶ ἐπεὶ . . . δευτέρας. "Miramur, cur haec definitio hoc loco omnibus verbis citetur, praesertim forma parum Euclidea, cum tamen antea in hac ipsa propositione toties tacite sit usurpata. itaque puto, verba καὶ ἐπεὶ . . . δευτέρας subditiva esse."—Heiberg.

• If r be the radius of the sphere circumscribing the five regular solids,

EUCLID

said sides; for they are irrational, the one being *minor* [xiii. 16], the other an *apotome* [xiii. 17].^a

That the side MB of the icosahedron is greater than the side NB of the dodecahedron we shall prove thus.

For since the triangle ZΔB is equiangular with the triangle ZAB [vi. 8], the proportion arises, ΔB : BZ = BZ : BA [vi. 4]. And since the three straight lines are in proportion, as the first is to the third, so is the square on the first to the square on the second [v. Def. 9]; therefore ΔB : BA = ΔB² : BZ²; therefore, inversely, AB : BΔ = ZB² : BΔ². But AB = 3BΔ; therefore ZB² = 3BΔ². But AΔ² = 4ΔB², for AΔ = 2ΔB; therefore AΔ² > ZB²; therefore AΔ > ZB; therefore AΛ is by far greater than ZB. And, when AΛ is cut in extreme and mean ratio, KΛ is the greater segment, since ΛK belongs to a hexagon, and KA to a decagon [xiii. 9]; and when ZB is cut in extreme and mean ratio, NB is the greater segment; therefore KΛ is greater than NB. But KΛ = ΛM; therefore ΛM > NB. Therefore MB,

side of pyramid	$= \frac{2}{3}\sqrt{6} \cdot r$
side of octahedron	$= \sqrt{2} \cdot r$
side of cube	$= \frac{2}{3}\sqrt{3} \cdot r$
side of icosahedron	$= \frac{r}{5}\sqrt{10(5 - \sqrt{5})}$
side of dodecahedron	$= \frac{r}{3}(\sqrt{15} - \sqrt{3})$.

In the sense of the term irrational as used by Euclid's predecessors and by modern mathematicians, all these expressions are irrational; but in the special sense of Eucl. *Elem.* x. Def. 3, the first three are rational, because their squares are commensurable one with another. The fourth and fifth expressions are irrational even in Euclid's sense, belonging to two species of irrational lines investigated in Book x.

MB].¹ πολλῶ ἄρα ἢ MB πλευρὰ οὔσα τοῦ εἰκοσαέδρου μείζων ἐστὶ τῆς NB πλευρᾶς οὔσης τοῦ δωδεκαέδρου· ὅπερ ἔδει δεῖξαι.

Λέγω δὴ, ὅτι παρὰ τὰ εἰρημένα πέντε σχήματα οὐ συσταθήσεται ἕτερον σχῆμα περιεχόμενον ὑπὸ ἰσοπλεύρων τε καὶ ἰσογωνίων ἴσων ἀλλήλοις.

Ἰπὸ μὲν γὰρ δύο τριγώνων ἢ ὅλως ἐπιπέδων στερεὰ γωνία οὐ συνίσταται. ὑπὸ δὲ τριῶν τριγώνων ἢ τῆς πυραμίδος, ὑπὸ δὲ τεσσάρων ἢ τοῦ ὀκταέδρου, ὑπὸ δὲ πέντε ἢ τοῦ εἰκοσαέδρου· ὑπὸ δὲ ἕξ τριγώνων ἰσοπλεύρων τε καὶ ἰσογωνίων πρὸς ἐνὶ σημείῳ συνισταμένων οὐκ ἔσται στερεὰ γωνία· οὔσης γὰρ τῆς τοῦ ἰσοπλεύρου τριγώνου γωνίας διμοίρου ὀρθῆς ἔσονται αἱ ἕξ τέσσαρσιν ὀρθαῖς ἴσαι· ὅπερ ἀδύνατον· ἅπαντα γὰρ στερεὰ γωνία ὑπὸ ἐλασσόνων ἢ τεσσάρων ὀρθῶν περιέχεται. διὰ τὰ αὐτὰ δὴ οὐδὲ ὑπὸ πλειόνων ἢ ἕξ γωνιῶν ἐπιπέδων στερεὰ γωνία συνίσταται.

Ἰπὸ δὲ τετραγώνων τριῶν ἢ τοῦ κύβου γωνία περιέχεται· ὑπὸ δὲ τεσσάρων ἀδύνατον· ἔσονται γὰρ πάλιν τέσσαρες ὀρθαί.

Ἰπὸ δὲ πενταγώνων ἰσοπλεύρων καὶ ἰσογωνίων, ὑπὸ μὲν τριῶν ἢ τοῦ δωδεκαέδρου· ὑπὸ δὲ τεσσάρων ἀδύνατον· οὔσης γὰρ τῆς τοῦ πενταγώνου ἰσοπλεύρου γωνίας ὀρθῆς καὶ πέμπτου, ἔσονται αἱ τέσσαρες γωνίαι τεσσάρων ὀρθῶν μείζους· ὅπερ ἀδύνατον.

Οὐδὲ μὴν ὑπὸ πολυγώνων ἐτέρων σχημάτων περισχεθήσεται στερεὰ γωνία διὰ τὸ αὐτὸ ἄτοπον.

Οὐκ ἄρα παρὰ τὰ εἰρημένα πέντε σχήματα

¹ τῆς . . . MB del Heiberg.

EUCLID

which is a side of the icosahedron, is much greater than NB, which is a side of the dodecahedron ; which was to be proved.

I say now that *no other figure, besides the said five figures, can be constructed so as to be contained by equilateral and equiangular figures equal one to another.*

For a solid angle cannot be constructed out of two triangles, or, generally, planes. With three triangles there is constructed the angle of the pyramid, with four the angle of the octahedron, with five the angle of the icosahedron ; but no solid angle can be formed by placing together at one point six equilateral and equiangular triangles ; for inasmuch as the angle of the equilateral triangle is two-thirds of a right angle, the six will be equal to four right angles ; which is impossible, for any solid angle is contained by angles less than four right angles [xi. 21]. For the same reasons no solid angle can be constructed out of more than six plane angles.

By three squares the angle of the cube is contained ; but it is impossible for a solid angle to be contained by four squares ; for they will again be four right angles [xi. 21].

By three equilateral and equiangular pentagons the angle of the dodecahedron is contained ; but by four it is impossible for a solid angle to be contained ; for inasmuch as the angle of the equilateral pentagon is a right angle and a fifth, the four angles will be greater than four right angles ; which is impossible [xi. 21].

Nor will a solid angle be contained by any other polygonal figures by reason of the same absurdity.

Therefore no other figure, besides the said five

GREEK MATHEMATICS

ἕτερον σχῆμα στερεὸν συνταθήσεται ὑπὸ ἰσοπλεύρων τε καὶ ἰσογωνίων περιεχόμενον· ὅπερ ἔδει δεῖξαι.

(c) THE DATA

Eucl., ed. Heiberg-Menge vi. 2. 1-15

Ὅροι

α'. Δεδομένα τῷ μεγέθει λέγεται χωρία τε καὶ γραμμαὶ καὶ γωνίαι, οἷς δυνάμεθα ἴσα πορίσασθαι.

β'. Λόγος δεδοσθαι λέγεται, ᾧ δυνάμεθα τὸν αὐτὸν πορίσασθαι.

γ'. Εὐθύγραμμα σχήματα τῷ εἶδει δεδοσθαι λέγεται, ὧν αἱ τε γωνίαι δεδομένοι εἰσὶ κατὰ μίαν καὶ οἱ λόγοι τῶν πλευρῶν πρὸς ἀλλήλας δεδομένοι.

δ'. Τῇ θέσει δεδοσθαι λέγονται σημεία τε καὶ γραμμαὶ καὶ γωνίαι, ἃ τὸν αὐτὸν ἀεὶ τόπον ἐπέχει.

ε'. Κύκλος τῷ μεγέθει δεδοσθαι λέγεται, οὗ δέδοται ἢ ἐκ τοῦ κέντρου τῷ μεγέθει.

ς'. Τῇ θέσει δὲ καὶ τῷ μεγέθει κύκλος δεδοσθαι λέγεται, οὗ δέδοται τὸ μὲν κέντρον τῇ θέσει, ἢ δὲ ἐκ τοῦ κέντρου τῷ μεγέθει.

(d) THE PORISMS

Procl. in Eucl. i., ed Friedlein 301. 21-302. 13; Eucl., ed. Heiberg-Menge viii. 237. 9-27

Ἐν τι τῶν γεωμετρικῶν ἐστὶν ὀνομάτων τὸ πόρισμα. τοῦτο δὲ σημαίνει διπτόν· καλοῦσι γὰρ

^a Euclid's *Data* (Δεδομένα) is his only work in pure geometry to have survived in Greek apart from the *Elements*. (His book *On Divisions of Figures* has survived in Arabic, v. *supra*, p. 156 n. c.) It is closely connected with Books i.-vi. of the *Elements*, and its general character will be suffi-

EUCLID

figures, can be constructed so as to be contained by equilateral and equiangular figures ; which was to be proved.

(c) THE DATA ^a

Eucl., ed. Heiberg-Menge vi. 2. 1-15

Definitions

1. Areas, lines and angles are said to be given in magnitude when we can make others equal to them.

2. A ratio is said to be given when we can make another equal to it.

3. Rectilinear figures are said to be given in species when their angles are severally given and the ratios of the sides one towards another are also given.

4. Points, lines and angles are said to be given in position when they always occupy the same place.

5. A circle is said to be given in magnitude when the radius is given in magnitude.

6. A circle is said to be given in position and in magnitude when the centre is given in position and the radius in magnitude.

(d) THE PORISMS

Proclus, *On Euclid* i., ed. Friedlein 301. 21-302. 13 ;

Eucl., ed. Heiberg-Menge viii. 237. 9-27

Porism is one of the terms used in geometry. It has a twofold meaning. For porisms are in the first

ciently indicated by these first few definitions. The object of a proposition called a *datum* is to prove that, if in a figure certain properties are given, other properties are also given, in one or other of the senses defined in the definitions. Pappus included the book in his *Τόπος ἀναλύμενος* (*Treasury of Analysis*).

GREEK MATHEMATICS

πορίσματα, καὶ ὅσα θεωρήματα συγκατασκευάζεταιαι ταῖς ἄλλων ἀποδείξεσιν οἷον ἔρμαια καὶ κέρδη τῶν ζητούντων ὑπάρχοντα, καὶ ὅσα ζητεῖται μὲν, εὐρέσεως δὲ χρήζει καὶ οὔτε γενέσεως μόνης οὔτε θεωρίας ἀπλῆς. ὅτι μὲν γὰρ τῶν ἰσοσκελῶν αἱ πρὸς τῇ βάσει ἴσαι θεωρηῖσαι δεῖ, καὶ ὄντων δὴ τινων¹ πραγμάτων ἐστὶν ἡ τοιαύτη γνῶσις. τὴν δὲ γωνίαν δίχα τεμεῖν ἢ τρίγωνον συστήσασθαι ἢ ἀφελεῖν ἢ προσθέσθαι,² ταῦτα πάντα ποιήσιν τινος ἀπαιτεῖ· τοῦ δὲ δοθέντος κύκλου τὸ κέντρον εὐρεῖν, ἢ δύο δοθέντων συμμετρων μεγεθῶν τὸ μέγιστον καὶ κοινὸν μέτρον εὐρεῖν, ἢ ὅσα τοιάδε, μεταξύ πῶς ἐστὶ προβλημάτων καὶ θεωρημάτων. οὔτε γὰρ γενέσεις εἰσὶν ἐν τούτοις τῶν ζητουμένων, ἀλλ' εὐρέσεις, οὔτε θεωρία ψιλή. δεῖ γὰρ ὑπ' ὄψιν ἀγαγεῖν καὶ πρὸ ὀμμάτων ποιήσασθαι τὸ ζητούμενον. τοιαῦτα ἄρα ἐστὶν καὶ ὅσα Εὐκλείδης πορίσματα γέγραφε, γ' βιβλία Πορισμάτων συντάξας.

Papp. *Coll.* vii., ed. Hultsch 648. 18-660. 16 ; Eucl., ed. Heiberg-Menge viii. 238. 10-243. 5

Μετὰ δὲ τὰς Ἐπαφὰς ἐν τρισὶ βιβλίοις Πορίσματά ἐστὶν Εὐκλείδου, πολλοῖς ἄθροισμα φιλοτεχνότατον εἰς τὴν ἀνάλυσιν τῶν ἐμβριθεστέρων προβλημάτων . . .

¹ τινων Heiberg, τῶν codd.

² προσθέσθαι Heiberg, θέσθαι codd.

* A porism in this sense is commonly called a *corollary*.
 † Euclid's *Porisms* has unfortunately not survived, which is a great misfortune as it appears to have been the most original and advanced of all his works. Our knowledge of its contents comes solely from Pappus.

‡ Pappus is describing the books comprised in his *Τόπος ἀναλυόμενος* (*Treasury of Analysis*). He proceeds to give an

EUCLID

place such theorems as can be established by means of the proofs of other theorems, being a kind of windfall or bonus in the investigation^a; and in the second place porisms are things which are sought, but need some finding, being neither brought into existence simply nor yet investigated by theory alone. For to prove that the angles at the base of an isosceles triangle are equal is a matter for theoretic inquiry only, and such knowledge is of certain things already in existence. But to bisect an angle or to construct a triangle, to cut off or to add—all these things require the making of something; and to find the centre of a given circle, or to find the greatest common measure of two given commensurable magnitudes, and so on, is in some way intermediate between problems and theorems. For in these cases there is no bringing into existence of the things sought, but a finding of them; nor is the inquiry pure theory. For it is necessary to bring what is sought into view and to exhibit it before the eyes. To this class belong the porisms which Euclid wrote and arranged in his three books of *Porisms*.^b

Pappus, *Collection* vii., ed. Hultsch 648. 18–660. 16 :
Eucl. ed. Heiberg-Menge viii. 238. 10–243. 5

After the *Contacts* (of Apollonius) come, in three books, the *Porisms* of Euclid, a collection most skilfully framed, in the opinion of many, for the analysis of the more weighty problems^c . . .

explanation of the term *porism* as used by Euclid with which Proclus's account is in substantial agreement. In addition, he gave another definition by "more recent geometers" (*ὑπὸ τῶν νεωτέρων*), viz., "a porism is that which falls short of a locus-theorem in respect of its hypothesis" (*πόρισμα ἔστιν τὸ λείπον ὑποθέσει τοπικοῦ θεωρήματος*).

GREEK MATHEMATICS

Περιλαβεῖν δὲ πολλὰ μιᾷ προτάσει ἥκιστα δυνα-
 τὸν ἐν τούτοις διὰ τὸ καὶ αὐτὸν Εὐκλείδην οὐ πολλὰ
 ἐξ ἐκάστου εἶδους τεθεικέναι, ἀλλὰ δείγματος
 ἕνεκα ἐκ τῆς πολυπληθείας ἐν ἧ' ὀλίγα. πρὸς
 ἀρχῇ δὲ ὅμως² τοῦ πρώτου βιβλίου τέθεικεν ὁμο-
 ειδῆ τινα³ ἐκείνου τοῦ δαψιλεστέρου εἶδους τῶν
 τόπων, ὡς ἰ τὸ πλῆθος. διὸ καὶ περιλαβεῖν ταύτας
 μιᾷ προτάσει ἐνδεχόμενον εὐρόντες οὕτως ἐγρά-
 ψαμεν· ἐὰν ὑπτίου ἢ παρυπτίου τρία τὰ ἐπὶ μιᾷς
 σημεία [ἢ παραλλήλου τῆς ἐτέρας τὰ δύο]⁴ δε-
 δομένα ἦ, τὰ δὲ λοιπὰ πλὴν ἐνὸς ἄπτηται θέσει
 δεδομένης εὐθείας, καὶ τοῦθ' ἄψεται θέσει δεδο-
 μένης εὐθείας. τοῦτ' ἐπὶ τεσσάρων μὲν εὐθειῶν
 εἴρηται μόνων, ὧν οὐ πλείονες ἢ δύο διὰ τοῦ αὐτοῦ
 σημείου εἰσίν, ἀγνοεῖται δὲ ἐπὶ παντὸς τοῦ προ-

¹ ἐν ἧ Litré, ἕνα Hultsch.

² δὲ ὅμως Heiberg, δεδομένον cod. (sequente lacuna) del. Hultsch.

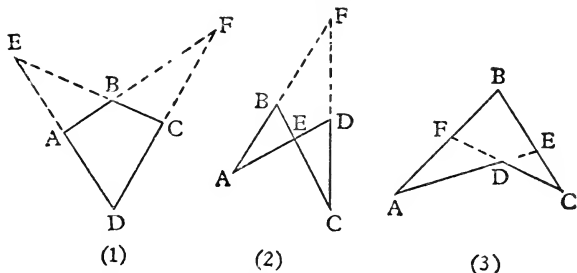
³ τινα Heiberg, πᾶν cod., πάντ' Hultsch.

⁴ ἢ . . . δύο interpolatori trib. Hultsch.

* The four straight lines are described in the Greek as (the sides) ὑπτίου ἢ παρυπτίου, i.e., as the sides of *supine* and *hyper-supine* quadrilaterals. Robert Simson (*Opera quaedam reliqua*, p. 348) explains a ὑπτιον σχῆμα as being of the

EUCLID

Now to comprehend many propositions in one enunciation is far from easy in these porisms, because Euclid himself has not given many of each species, but out of a great number he has selected one or a few by way of example. But at the beginning of the first book he has given certain allied propositions, ten in number, from that more abundant species consisting of loci. Finding that these can be comprehended in one enunciation, we have therefore written it out in this manner: *If, in a system of four straight lines which cut one another two and two, the three points [of intersection] on one straight line be given, while the rest except one lie on different straight lines given in position, the remaining point also will be on a straight line given in position.*^a This has been enunciated in the case of four straight lines only, of which not more than two pass through the same point, and it is not nature of (1) in the accompanying diagrams, while (2) and (3) are *παρύπτια σχήματα*. He also explained the correct



meaning of the rather loose proviso, *τὰ δὲ λοιπὰ πλὴν ἑνὸς ἄπτηται θέσει δεδομένης εὐθείας*. Applied to these figures, the enunciation states that if A, B, F are given, while the loci of C and D are straight lines, then the locus of E is also a straight line.

GREEK MATHEMATICS

τεινομένου πλήθους ἀληθῆς ὑπάρχον οὕτως λεγόμενον· ἂν ὅποσαι οὖν εὐθεῖαι τέμνωσιν ἀλλήλας, μὴ πλείονες ἢ δύο διὰ τοῦ αὐτοῦ σημείου, πάντα δὲ ἐπὶ μιᾶς αὐτῶν δεδομένα ἦ, καὶ τῶν ἐπὶ ἑτέρας ἕκαστον ἄπτηται θέσει δεδομένης εὐθείας, ἢ καθολικωτέραν οὕτως· ἂν ὅποσαι οὖν εὐθεῖαι τέμνωσιν ἀλλήλας, μὴ πλείονες ἢ δύο διὰ τοῦ αὐτοῦ σημείου, πάντα δὲ τὰ ἐπὶ μιᾶς αὐτῶν σημεία δεδομένα ἦ, τῶν δὲ λοιπῶν τὸ πλήθος ἐχόντων τρίγωνον ἀριθμὸν ἢ πλευρὰ τούτου ἕκαστον ἔχη σημείον ἀπτόμενον εὐθείας θέσει δεδομένης, τῶν τριῶν μὴ πρὸς γωνίαις ὑπαρχόντων τριγώνου χωρίου, ἕκαστον λοιπὸν σημεῖον ἄψεται θέσει δεδομένης εὐθείας. τὸν δὲ Στοιχειωτὴν οὐκ εἰκὸς ἀγνοῆσαι τοῦτο, τὴν δ' ἀρχὴν μόνην τάξαι. . . .

Ἔχει δὲ τὰ τρία βιβλία τῶν Πορισμάτων λήμματα λη, αὐτὰ δὲ θεωρημάτων ἐστὶν ροα.

^a Sc. a triangle having as its sides three of the given straight lines.

^b The meaning of this enunciation was discovered by Simson, and is given by Loria (*Le scienze esatte nell' antica Grecia*, p. 256 n. 3) as follows: "If a complete n -lateral be deformed so that its sides respectively turn about n points on a straight line, and $(n-1)$ of its $\frac{1}{2}n(n-1)$ vertices move each on a straight line, the remaining $\frac{1}{2}(n-1)(n-2)$ of its vertices likewise move on straight lines; provided that it is not possible to form with the $(n-1)$ vertices any triangle having for sides the sides of the polygon." We may sympathize with the frank confession of Edmond Halley (*Apollonii Pergaei De sectione rationis*, p. xxxvii) that he could make no sense out of this passage.

EUCLID

generally known that it is true of any assigned number of straight lines when thus enunciated: *If any number of straight lines cut one another, not more than two passing through the same point, and all the points [of intersection] on one of them be given, and if each of those which are on another lie on a straight line given in position—or still more generally in this manner: If any number of straight lines cut one another, not more than two passing through the same point, and all the points [of intersection] on one of them be given, while of the remaining points of intersection, in multitude equal to a triangular number, a number corresponding to the side of this triangular number lie respectively on straight lines given in position, provided that of these latter points no three are at the vertices of a triangle,^a each of the remaining points will lie on a straight line given in position.^b* The writer of the *Elements* was probably not unaware of this, but he merely laid down the principle.^c . . .

The three books of the *Porisms* involve 38 lemmas^d; of the theorems themselves there are 171.^e

^a Pappus proceeds to state in order 28 propositions from Euclid's work.

^d Pappus gives these lemmas to the *Porisms* (Pappus, ed. Hultsch 866. 1-918. 20; Eucl. ed. Heiberg-Menge viii. 243. 10-274. 10).

^e The reconstruction of the *Porisms* has been one of the most fascinating inquiries pursued by students of Greek mathematics, and thereby Chasles was led to the idea of anharmonic ratios. Further details will be found in Loria, *loc. cit.*, pp. 253-265, Heath, *H.G.M.* i. 431-438, and I am greatly indebted to the translations and notes in these works.

GREEK MATHEMATICS

(e) THE CONICS

Papp. *Coll.* vii. 30-36, ed. Hultsch 672. 18-678. 24

Τὰ Εὐκλείδου βιβλία δὲ Κωνικῶν Ἀπολλώνιος ἀναπληρώσας καὶ προσθεῖς ἕτερα δὲ παρέδωκεν ἢ Κωνικῶν τεύχη. Ἀρισταῖος δέ, ὃς γέγραφε τὰ μέχρι τοῦ νῦν ἀναδιδόμενα στερεῶν τόπων τεύχη ἔσυνεχῆ τοῖς κωνικοῖς, ἐκάλει [καὶ οἱ πρὸ Ἀπολλωνίου]¹ τῶν τριῶν κωνικῶν γραμμῶν τὴν μὲν ὀξυγωνίου, τὴν δὲ ὀρθογωνίου, τὴν δὲ ἀμβλυγωνίου κώνου τομήν. . . . ὃν δὲ φησιν [*sc.* Ἀπολλώνιος] ἐν τῷ τρίτῳ τόπον ἐπὶ γ καὶ δὲ γραμμὰς μὴ τελειωθῆναι ὑπὸ Εὐκλείδου, οὐδ' ἂν αὐτὸς ἠδυνήθη οὐδ' ἄλλος οὐδεὶς ἀλλ' οὐδὲ μικρόν τι προσθεῖναι τοῖς ὑπὸ Εὐκλείδου γραφεῖσιν² διὰ γε μόνων τῶν προδεδειγμένων ἤδη κωνικῶν ἄχρι τῶν κατ' Εὐκλείδην, ὡς καὶ αὐτὸς μαρτυρεῖ λέγων ἀδύνατον εἶναι τελειωθῆναι, χωρὶς ὧν αὐτὸς προγράφει ἠναγκάσθη. ὁ δὲ Εὐκλείδης ἀποδεχόμενος τὸν Ἀρισταῖον ἄξιον ὄντα ἐφ' οἷς ἤδη παραδεδώκει κωνικοῖς, καὶ μὴ φθάσας ἢ μὴ θελήσας ἐπικαταβάλλεσθαι τούτων τὴν αὐτὴν πραγματείαν, ἐπιεικέστατος ὧν καὶ πρὸς ἅπαντας εὐμενῆς τοὺς καὶ κατὰ ποσὸν συναύξειν δυναμένους τὰ μαθήματα, ὡς δεῖ, καὶ μηδαμῶς προσκρουστικὸς ὑπάρχων, καὶ ἀκριβῆς μὲν οὐκ ἀλαζονικὸς δὲ καθάπερ οὗτος, ὅσον δυνατὸν ἦν δεῖξαι τοῦ τόπου διὰ τῶν ἐκείνου

¹ καὶ οἱ πρὸ Ἀπολλωνίου del. Hultsch.

² ἀλλ' . . . γραφεῖσιν del. Hultsch.

• Euclid's *Conics* has not survived, but an idea of its contents can be obtained from Archimedes' references to propositions proved in the *Elements of Conics* (ἐν τοῖς κωνικοῖς

EUCLID

(e) THE CONICS ^a

Pappus, *Collection* vii. 30-36, ed. Hultsch 672. 18-678. 24

Apollonius, who completed the four books of Euclid's *Conics* and added another four, gave us eight books of *Conics*. Aristaeus, who wrote the still extant ^b five books of *Solid Loci* supplementary to the *Conics*, called the three conic sections of an acute-angled, right-angled and obtuse-angled cone respectively. . . . Apollonius says in his third book that the "locus with respect to three or four lines" had not been fully worked out by Euclid, and in fact neither Apollonius himself nor anyone else could have added anything to what Euclid wrote, using only those properties of conics which had been proved up to Euclid's time; as Apollonius himself bears witness when he says that the locus could not be fully investigated without the propositions that he had been compelled to work out for himself. Now Euclid regarded Aristaeus as deserving credit for his contributions to conics, and did not try to anticipate him or to overthrow his system; for he showed scrupulous fairness and exemplary kindness towards all who were able in any degree to advance mathematics, and was never offensive, but aimed at accuracy, and did not boast like the other. Accordingly he wrote so much about the locus as was possible by means of στοιχείοις), a term which would cover the treatises both of Aristaeus and of Euclid. The *Surface-Loci* and the *Porisms* of Euclid appear to have contained further developments in the theory of conics.

^b This has been taken to imply that Euclid's *Conics* was already lost when Pappus wrote. Nothing more is known of this Aristaeus, unless he is identical with the Aristaeus said by Hypsicles (Eucl. ed. Heiberg-Menge v. 6. 22-23) to have written a book called *Comparison of the Five Regular Solids*.

GREEK MATHEMATICS

Κωνικῶν ἔγραφεν, οὐκ εἰπὼν τέλος ἔχειν τὸ δεικνύμενον. τότε γὰρ ἦν ἀναγκαῖον ἐξελέγκειν, νῦν δ' οὐδαμῶς, ἐπειτοὶ καὶ αὐτὸς ἐν τοῖς Κωνικοῖς ἀτελῆ τὰ πλεῖστα καταλιπὼν οὐκ εὐθύνεται. προσθεῖναι δὲ τῷ τόπῳ τὰ λειπόμενα δεδύνηται προφαντασιωθεῖς τοῖς ὑπὸ Εὐκλείδου γεγραμμένοις ἤδη περὶ τοῦ τόπου καὶ συσχολάσας τοῖς ὑπὸ Εὐκλείδου μαθηταῖς ἐν Ἀλεξανδρείᾳ πλεῖστον χρόνον, ὅθεν ἔσχε καὶ τὴν τοιαύτην ἕξιν οὐκ ἀμαθῆ.

Οὗτος δὲ ὁ ἐπὶ γ καὶ δ γραμμὰς τόπος, ἐφ' ᾧ μέγα φρονεῖ προσθεῖς χάριν ὀφείλειν εἰδέναι τῷ πρώτῳ γράψαντι, τοιοῦτός ἐστιν.¹ ἔαν γάρ, θέσει δεδομένων τριῶν εὐθειῶν, ἀπὸ τινος τοῦ αὐτοῦ² σημείου καταχθῶσιν ἐπὶ τὰς τρεῖς ἐν δεδομέναις γωνίαις εὐθεῖαι, καὶ λόγος ἧ̄ δοθεῖς τοῦ ὑπὸ δύο κατηγμένων περιεχομένου ὀρθογωνίου πρὸς τὸ ἀπὸ τῆς λοιπῆς τετράγωνον, τὸ σημεῖον ἄψεται θέσει δεδομένου στερεοῦ τόπου, τουτέστιν μιᾶς τῶν τριῶν κωνικῶν γραμμῶν. καὶ ἔαν ἐπὶ δ εὐθείας θέσει δεδομένας καταχθῶσιν εὐθεῖαι ἐν δεδομέναις γωνίαις, καὶ λόγος ἧ̄ δοθεῖς τοῦ ὑπὸ δύο κατηγμένων πρὸς τὸ ὑπὸ τῶν λοιπῶν δύο κατηγμένων, ὁμοίως τὸ σημεῖον ἄψεται θέσει δεδομένης κώνου τομῆς.

¹ ὁ δὲ Εὐκλείδης . . . τοιοῦτός ἐστιν "scholiastae cuidam historiae quidem veterum mathematicorum non imperito, sed qui dicendi genere languido et inconcinno usus sit" tribuit Hultsch.

² τοῦ αὐτοῦ del. Hultsch.

• The three-line locus is, of course, a particular example of the four-line locus. It seems clear that Apollonius himself did not have a complete solution of the four-line locus, but

EUCLID

the *Conics* of Aristaeus, but did not claim finality for his proofs. If he had done so, we should have been obliged to censure him, but as things are he is in no wise to blame, seeing that Apollonius himself is not called to account, though he left the most part of his *Conics* incomplete. Moreover Apollonius was able to add the lacking portion of the theory of the locus through having become familiar beforehand with what had been written about it by Euclid, and through having spent much time with Euclid's pupils at Alexandria, whence he derived his scientific habit of mind.

Now this "locus with respect to three and four lines," the theory of which he is so proud of having expanded—though he ought rather to acknowledge his debt to the original author—is of this kind. If three straight lines be given in position, and from one and the same point straight lines be drawn to meet the three straight lines at given angles, and if the ratio of the rectangle contained by two of the straight lines towards the square on the remaining straight line be given, then the point will lie on a solid locus given in position, that is on one of the three conic sections. And if straight lines be drawn to meet at given angles four straight lines given in position, and the ratio of the rectangle contained by two of the straight lines so drawn towards the rectangle contained by the remaining two be given, then in the same way the point will lie on a conic section given in position.^a

his *Conics* iii. 53-56 [Props. 74-76] amounts to a demonstration of the converse of the three-line locus, viz., *if from any point of a conic there be drawn three straight lines in fixed directions to meet respectively two fixed tangents to the conic and their chord of contact, the ratio of the rectangle contained*

GREEK MATHEMATICS

Eucl. *Phaen.* Praef., Eucl. ed. Heiberg-Menge viii. 6. 5-7

Ἐὰν γὰρ κῶνος ἢ κύλινδρος ἐπιπέδῳ τμηθῆ μὴ παρὰ τὴν βάσιν, ἢ τομὴ γίγνεται ὀξυγωνίου κώνου τομῆ, ἣτις ἐστὶν ὁμοία θυρεῶ.

(f) THE SURFACE-LOCI

Papp. *Coll.* vii., ed. Hultsch 636. 23-24

Εὐκλείδου Τόπων τῶν πρὸς ἐπιφανείᾳ β̄.

Procl. in *Eucl.* i., ed. Friedlein 394. 16-395. 2

Καλῶ δὲ τοπικὰ μὲν, ὅσοις ταῦτὸν σύμπτωμα πρὸς ὄλῳ τινὶ τόπῳ συμβέβηκεν, τόπον δὲ γραμμῆς ἢ ἐπιφανείας θέσιν ποιούσαν ἔν καὶ ταῦτὸν σύμπτωμα. τῶν γὰρ τοπικῶν τὰ μὲν ἐστὶ πρὸς γραμμαῖς συνιστάμενα, τὰ δὲ πρὸς ἐπιφανείαις. καὶ ἐπειδὴ τῶν γραμμῶν αἱ μὲν εἰσιν ἐπίπεδοι, αἱ δὲ στερεαῖ—ἐπίπεδοι μὲν, ὧν ἐν ἐπιπέδῳ ἀπλῆ ἢ νόησις, ὡς τῆς εὐθείας, στερεαὶ δέ, ὧν ἢ γένεσις ἔκ τινος τομῆς ἀναφαίνεται στερεοῦ σχήματος, ὡς τῆς κυλινδρικήσ ἔλικος καὶ τῶν κωνικῶν γραμμῶν

by the first two lines so drawn to the square on the third line is constant. For a solution and full discussion of the four-line locus, reference should be made to Zeuthen, *Die Lehre von den Kegelschnitten im Altertum*, pp. 126 ff., or Heath, *Apollonius of Perga*, pp. cxxxviii-cl.

^a Euclid's *Phenomena* is an astronomical work largely based on two treatises by Autolycus of Pitane (c. 315-240 B.C.) which are also extant.

^b Menaechmus is believed to have discovered the conic sections as sections of a right-angled, acute-angled and obtuse-angled cone respectively by a plane perpendicular

EUCLID

Euclid, Preface to *Phenomena*,^a Eucl. ed. Heiberg-Menge
viii. 6. 5-7

If a cone or cylinder be cut by a plane not parallel to the base, the resulting section is a section of an acute-angled cone which is similar to a shield.^b

(f) THE SURFACE-LOCI

Pappus, *Collection* vii., ed. Hultsch 636. 23-24

Euclid's two books of *Surface-Loci*.^c

Proclus, *On Euclid* i., ed. Friedlein 394. 16-395. 2

I call locus-theorems those which deal with the same property throughout the whole of a locus, and a locus I call a position of a line or surface which has throughout one and the same property. Some locus-theorems are constructed on lines and others on surfaces. Furthermore, since lines may be plane or solid—plane being those which are simply generated in a plane, like the straight line, and solid those which are generated from some section of a solid figure, like the cylindrical helix or the conic sections

to a generating line. This passage shows that Euclid, at least, was also aware that an ellipse could be obtained as a section of a right cylinder by a plane not parallel to the base, and the fact may well have been known before his time; Heiberg (*Literär-geschichtliche Studien über Euklid*, p. 88) thinks that Menaechmus probably used *θυρεός* as the name for the ellipse.

^c This entry is taken from the list of books in Pappus's *Τόπος ἀναλυόμενος* (*Treasury of Analysis*). The work is lost, but we can conjecture what surface-loci were from remarks by Proclus and Pappus himself, and we can get some idea of the contents of Euclid's treatise from two lemmas given to it by Pappus.

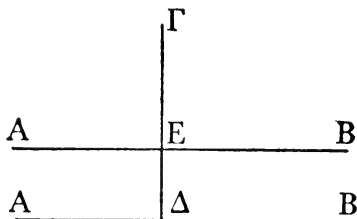
GREEK MATHEMATICS

—φαίην ἂν καὶ τῶν πρὸς γραμμαῖς τοπικῶν τὰ μὲν ἐπίπεδον ἔχειν τόπον, τὰ δὲ στερεόν.

Papp. *Coll.* vii. 312-316, ed. Hultsch 1004. 16-1010. 15;
Eucl. ed. Heiberg-Menge viii. 274. 18-278. 15

Εἰς τοὺς πρὸς ἐπιφανείᾳ

α'. Ἐὰν ᾗ εὐθεία ἡ AB καὶ παρὰ θέσει ἡ ΓΔ, καὶ ᾗ λόγος τοῦ ὑπὸ ΛΔΒ πρὸς τὸ ἀπὸ ΔΓ, τὸ Γ



ἄπτεται κωνικῆς γραμμῆς. ἔὰν οὖν ἡ μὲν AB στερηθῆ τῆς θέσεως, καὶ τὰ Α, Β στερηθῆ τοῦ δοθέντα¹ εἶναι, γένηται δὲ πρὸς θέσει εὐθείαις² ταῖς ΑΕ, ΕΒ, τὸ Γ μετεωρισθὲν γίνεται πρὸς θέσει ἐπιφανείᾳ. τοῦτο δὲ ἐδείχθη.

β'. Ἐὰν ᾗ θέσει εὐθεία ἡ AB καὶ δοθὲν τὸ Γ

¹ δοθέντα Heiberg, δοθέντος cod., Hultsch.

² εὐθείαις Tannery, εὐθεία cod.

^a From this passage, confirmed by Eutocius, line-loci would appear to be loci which *are* lines, and surface-loci would seem to be loci which *are* surfaces. Pappus, in *Coll.* iv. 33, ed. Hultsch 258. 20-25, implies, however, that surface-loci are loci *traced on* surfaces, and he gives the cylindrical helix as an example of such a locus. Cf. *supra*, p. 348 n. a.

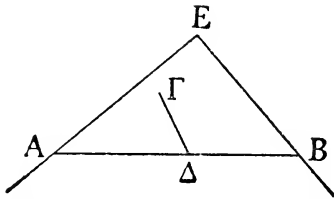
EUCLID

—it would appear that line-loci may be plane loci or solid loci.^a

Pappus, *Collection* vii. 312-316, ed. Hultsch 1004. 16-1010. 15; Eucl. ed. Heiberg-Menge viii. 274. 18-278. 15

Lemmas to the Surface-Loci

1. If AB be a straight line and $\Gamma\Delta$ be parallel to a straight line given in position, and if the ratio



$A\Delta \cdot \Delta B : \Delta\Gamma^2$ be given, the point Γ lies on a conic section. If AB be no longer given in position and A, B be no longer given but lie on straight lines AE, EB given in position, the point Γ raised above [the plane containing AE, EB] is on a surface given in position. And this was proved.^b

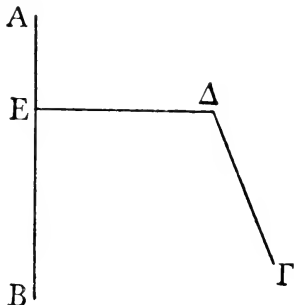
2. If AB be a straight line given in position, and

^b The Greek text and the figure in it (given on the left-hand page) are unsatisfactory, but Tannery pointed out that by reading *εὐθέτως* instead of *εὐθεία* a satisfactory meaning can be obtained (*Bulletin des sciences mathématiques*, 2^e série, vi. 149-150). He also indicated the correct figure, which was first printed by Zeuthen (*Die Lehre von der Kegelschnitten im Altertum*, pp. 423-430). *The Works of Archimedes*, by T. L. Heath, pp. lxii-lxiv, should also be consulted.

The first sentence states one of the fundamental properties of conic sections. A literal translation of the opening words in the second sentence would run: "If AB be deprived of its position, and the points A, B be deprived of their character

GREEK MATHEMATICS

ἐν τῷ αὐτῷ ἐπιπέδῳ, καὶ διαχθῆ ἢ $\Delta\Gamma$, καὶ πρὸς ὀρθὰς¹ ἀχθῆ ἢ ΔE , λόγος δὲ ἦ τῆς $\Gamma\Delta$ πρὸς ΔE ,



τὸ Δ ἄπτεται θέσει κωνικῆς τομῆς· δεικτέον² δέ, ὅτι γραμμῆς (μέρος ποιεῖ τὸν τόπον).³ δειχθήσεται δὲ οὕτως προγραφέντος τόπου⁴ τοῦδε.

γ'. Δύο δοθέντων τῶν A, B καὶ ὀρθῆς τῆς $\Gamma\Delta$ λόγος ἔστω τοῦ ἀπὸ $A\Delta$ πρὸς τὰ ἀπὸ $\Gamma\Delta, \Delta B$. λέγω, ὅτι τὸ Γ ἄπτεται κώνου τομῆς, ἐάν τε ἦ ὁ λόγος ἴσος πρὸς ἴσον ἢ μείζων πρὸς ἐλάσσονα ἢ ἐλάσσων πρὸς μείζονα.

Ἔστω γὰρ πρότερον ὁ λόγος ἴσος πρὸς ἴσον. καὶ ἐπεὶ ἴσον ἐστὶν τὸ ἀπὸ $A\Delta$ τοῖς ἀπὸ $\Gamma\Delta, \Delta B$, κείσθω τῇ $B\Delta$ ἴση ἢ ΔE . ἴσον ἄρα ἐστὶ τὸ ὑπὸ BAE τῷ ἀπὸ $\Delta\Gamma$. τετμήσθω δίχα ἢ AB τῷ Z .

¹ πρὸς ὀρθὰς Hultsch, παρὰ θέσει cod.

² δεικτέον Hultsch in adn., δείκνυται cod.

³ μέρος ποιεῖ τὸν τόπον add. Gerhardt, Hultsch.

⁴ τόπου "immo τοῦ λήμματος" Hultsch.

of being given . . ." The text leaves it uncertain whether, when AB is no longer given in position, it remains constant

EUCLID

the point Γ be given in the same plane, and $\Delta\Gamma$ be drawn, and ΔE be drawn perpendicular [to the given straight line AB], and if the ratio $\Gamma\Delta : \Delta E$ be given, the point Δ will lie on a conic section.^a But it must be shown that part of the curve forms the locus. This will be proved as follows by means of this lemma.

3. Given ^b the two points A, B and the perpendicular $\Gamma\Delta$, let the ratio $A\Delta^2 : \Gamma\Delta^2 + \Delta B^2$ be given. I say that the point Γ lies on a conic section, whether the ratio be of equal to equal, or greater to less, or less to greater.

For in the first place let the ratio be of equal to equal. Since $A\Delta^2 = \Gamma\Delta^2 + \Delta B^2$, let ΔE be made equal to $B\Delta$.

	Then	$[BA \cdot AE + E\Delta^2 = A\Delta^2$	[Eucl. ii. 6
		$= \Gamma\Delta^2 + \Delta B^2$	[<i>ex. hyp.</i> ,
and so]	$BA \cdot AE$	$= \Gamma\Delta^2.$	

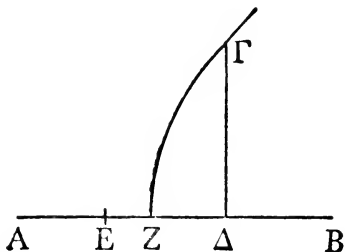
in length or varies. Zeuthen conjectures that two cases were considered by Euclid: (1) AB remains of constant length, while AE, EB are parallel instead of meeting in a point; and (2) AE, EB meet in a point and AB always moves parallel to itself, so varying in length. In the former case Γ lies on the surface described by a conic section moving bodily, in the latter case the surface is a cone.

^a This is the definition of a conic in terms of its focus and directrix, AB being the directrix, Γ the focus, Δ any point on the curve, and the ratio $\Gamma\Delta : \Delta E$ the eccentricity of the conic. Since Pappus proves this property for all three conics by transforming it to the more familiar axial form, it must have been assumed by Euclid without proof, and was presumably first demonstrated by Aristaeus. This is all the more remarkable as the focus-directrix property is nowhere mentioned by Apollonius, and, indeed, is found in only two other places in the whole of the Greek mathematical writings, *v. supra*, p. 362 n. a.

^b Diagram on p. 496.

GREEK MATHEMATICS

δοθέν ἄρα τὸ Ζ. καὶ ἔσται διπλῆ ἡ ΑΕ τῆς ΖΔ
ὥστε τὸ ὑπὸ ΒΑΕ τὸ δῖς ἔστιν ὑπὸ τῶν ΑΒ, ΖΔ.



καὶ ἔστιν ἡ διπλῆ τῆς ΑΒ δουθείσα· τὸ ἄρα ὑπὸ
δοθείσης καὶ τῆς ΖΔ ἴσον ἔστιν τῷ ἀπὸ τῆς ΔΓ.
τὸ Γ ἄρα ἄπτεται θέσει παραβολῆς ἐρχομένης
διὰ τοῦ Ζ.

δ'. Συντεθήσεται δὴ ὁ τόπος οὕτως·

Ἔστω τὰ δοθέντα Α, Β, ὁ δὲ λόγος ἔστω ἴσος
πρὸς ἴσον, καὶ τετμήσθω ἡ ΑΒ δίχα τῷ Ζ, τῆς
δὲ ΑΒ διπλῆ ἔστω ἡ Ρ, καὶ θέσει οὔσης εὐθείας
τῆς ΖΒ πεπερασμένης κατὰ τὸ Ζ, τῆς δὲ Ρ δεδο-
μένης τῷ μεγέθει, γεγράψθω περιᾶξονα τὸν ΖΒ
παραβολὴ ἡ ΗΖ, ὥστε, οἷον ἐὰν ἐπ' αὐτῆς
σημεῖον ληφθῆ ὡς τὸ Γ, κάθετος δὲ ἀχθῆ ἡ ΓΔ,
ἴσον εἶναι τὸ ὑπὸ Ρ, ΖΔ, τῷ ἀπὸ ΔΓ. καὶ
ἦχθω ὀρθὴ ἡ ΒΗ. λέγω, ὅτι τὸ ΓΗ μέρος τῆς
παραβολῆς ἔστιν.¹

Ἦχθω γὰρ κάθετος ἡ ΓΔ, καὶ τῇ ΒΔ ἴση κείσθω
ἡ ΔΕ. ἐπεὶ οὖν διπλῆ ἔστιν ἡ μὲν ΑΒ τῆς ΒΖ,
ἡ δὲ ΕΒ τῆς ΒΔ, διπλῆ ἄρα καὶ ἡ ΑΕ τῆς ΖΔ· τὸ
ἄρα ὑπὸ ΒΑΕ ἴσον ἔστιν τῷ δῖς ὑπὸ τῶν ΑΒ,

EUCLID

Let AB be bisected at Z; the point Z is therefore given.

$$\begin{aligned} \text{And} \quad \quad \quad \text{AE} \quad & [= AB - EB \\ & = 2BZ - 2B\Delta] \\ & = 2Z\Delta. \end{aligned}$$

$$\text{Therefore} \quad \quad \text{BA} \cdot \text{AE} = 2\text{BA} \cdot \text{Z}\Delta,$$

$$[\text{and so} \quad \quad \quad 2\text{BA} \cdot \text{Z}\Delta = \Gamma\Delta^2].$$

Now 2BA is given; therefore the rectangle contained by a given straight line and $\text{Z}\Delta$ is equal to the square on $\Delta\Gamma$. Therefore the point Γ lies on a parabola passing through Z.

4. The synthesis of the locus is accomplished in this way.^a

Let the given points be A, B, let the ratio be of equal to equal, let AB be bisected at Z, let P be double of AB; and since ZB with an end point Z is a straight line given in position, and P is given in magnitude, with ZB as axis, let there be drawn [Apoll. *Conics* i. 52] the parabola HZ, such that, if any point Γ be taken upon it, and the perpendicular $\Gamma\Delta$ be drawn, the rectangle contained by P, $\text{Z}\Delta$ is equal to the square on $\Delta\Gamma$; and let the perpendicular BH be drawn. I say that ΓH is a part of the parabola [forming the locus].

For let the perpendicular $\Gamma\Delta$ be drawn, and let ΔE be made equal to $\text{B}\Delta$. Then since $\text{AB} = 2\text{BZ}$, $\text{EB} = 2\text{B}\Delta$, therefore $\text{AE} [= \text{AB} - \text{EB}] = 2\text{Z}\Delta$;

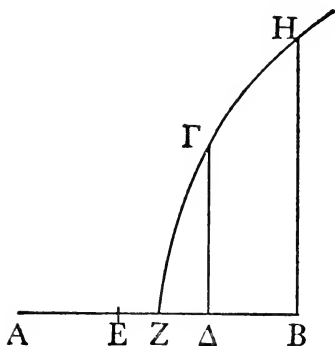
$$\begin{aligned} \text{therefore} \quad \quad \text{BA} \cdot \text{AE} & = 2\text{AB} \cdot \text{Z}\Delta \\ & = \Delta\Gamma^2. \quad [\text{by construction} \end{aligned}$$

• Diagram on p. 498.

¹ ἔστιν; we should expect ποιεί τὸν τόπον.

GREEK MATHEMATICS

$Z\Delta$, τουτέστιν τῷ ἀπὸ $\Delta\Gamma$. κοινὸν προσκείσθω τὸ ἀπὸ $E\Delta$ ἴσον ὃν τῷ ἀπὸ ΔB . ὅλον ἄρα τὸ ἀπὸ



P

$A\Delta$ ἴσον ἐστὶν τοῖς ἀπὸ τῶν $\Gamma\Delta$, ΔB . ἡ ZGH ἄρα γραμμὴ ποιεῖ τὸν τόπον.

ε'. Ἐστω δὴ πάλιν τὰ δύο δοθέντα σημεῖα τὰ A , B , καὶ εὐθεῖά τε ἡ $\Delta\Gamma$ καὶ ὀρθή,¹ λόγος δὲ ἔστω τοῦ ἀπὸ $A\Delta$ πρὸς τὰ ἀπὸ $B\Delta$, $\Delta\Gamma$ ἐπὶ μὲν τῆς πρώτης πτώσεως μείζων πρὸς ἐλάσσονα,² ἐπὶ δὲ τῆς δευτέρας ἐλάσσων πρὸς μείζονα³. λέγω, ὅτι τὸ Γ ἄπτεται κώνου τομῆς, ἐπὶ μὲν τῆς πρώτης πτώσεως ἐλλείψεως, ἐπὶ δὲ τῆς δευτέρας ὑπερβολῆς.

Ἐπεὶ γὰρ λόγος ἐστὶν τοῦ ἀπὸ $A\Delta$ πρὸς τὰ ἀπὸ $B\Delta$, $\Delta\Gamma$, ὁ αὐτὸς αὐτῷ γεγονέτω ὁ τοῦ ἀπὸ $E\Delta$

EUCLID

Let the equals $E\Delta^2$, ΔB^2 be added to either side ;

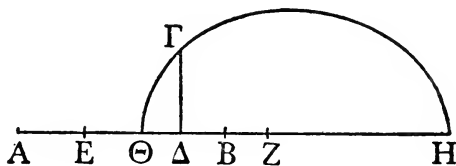
then \ast $[BA \cdot AE + E\Delta^2 = \Gamma\Delta^2 + \Delta B^2$

and so] $A\Delta^2 = \Gamma\Delta^2 + \Delta B^2$. [Eucl. ii. 6

Therefore the curve $Z\Gamma H$ forms the locus.

5. Again, let the two given points be A , B , and let $\Delta\Gamma$ be a perpendicular straight line, and let the ratio $A\Delta^2 : B\Delta^2 + \Delta\Gamma^2$ be in the first case the ratio of a greater to a less, and in the second case of a less to a greater. I say, that the point Γ lies on a conic section, which is in the first case an ellipse and in the second case a hyperbola.^a

Since the given ratio is $A\Delta^2 : B\Delta^2 + \Delta\Gamma^2$, let $[E$ be taken on AB so that] $E\Delta^2 : \Delta B^2$ be in the same



^a The Greek text from this point onwards is unsatisfactory, and contains mathematical errors which Commandinus and Hultsch corrected. The demonstration also leaves many gaps which I have filled, again following those commentators.

¹ *εὐθεία τε ἡ ΔΓ καὶ ὀρθή*, Heiberg; *κατήχθω ὀρθή ἡ ΔΓ*, Commandinus, Hultsch; *ἐφάπτεται ἡ ΔΓ καὶ ὀρθή* cod.

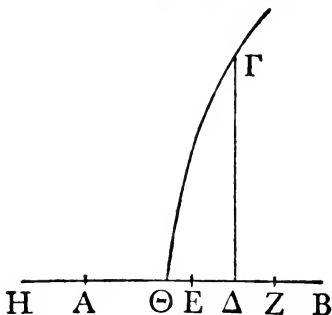
² *μείζων πρὸς ἐλάσσονα* Hultsch, *ἐλάσσων πρὸς μείζονα* cod.

³ *ἐλάσσων πρὸς μείζονα* Hultsch, *μείζων πρὸς ἐλάσσονα* cod.

⁴ *EΔ* Hultsch, *BΔ* cod.

GREEK MATHEMATICS

πρὸς τὸ ἀπὸ ΔΒ.¹ ἐπὶ μὲν οὖν τῆς πρώτης πτώσεως ἐλάσσων ἐστὶν ἡ ΒΔ τῆς ΔΕ, ἐπὶ δὲ τῆς



δευτέρας μείζων ἐστὶν ἡ ΒΔ τῆς ΔΕ. κείσθω οὖν τῇ ΕΔ ἴση ἡ ΔΖ. ἐπεὶ λόγος ἐστὶν τοῦ ἀπὸ ΑΔ πρὸς τὰ ἀπὸ ΓΔ, ΔΒ, καὶ ἐστὶν αὐτῶ ὁ αὐτὸς ὁ τοῦ ἀπὸ ΕΔ πρὸς τὸ ἀπὸ ΔΒ, καὶ λοιπὸς ἄρα τοῦ ὑπὸ ΖΑΕ πρὸς τὸ ἀπὸ ΔΓ λόγος ἐστὶν δοθείς. ἐπεὶ δὲ λόγος ἐστὶν τῆς ΕΔ πρὸς ΔΒ [καὶ τῆς ΖΔ πρὸς ΔΒ]² καὶ τῆς ΖΒ πρὸς ΒΔ, ὁ αὐτὸς αὐτῶ γεγονέτω ὁ τῆς ΑΒ πρὸς ΒΗ· καὶ ὅλης ἄρα τῆς ΑΖ πρὸς ΔΗ λόγος ἐστὶν δοθείς. πάλιν, ἐπεὶ λόγος ἐστὶν τῆς ΕΔ πρὸς ΔΒ δοθείς, [καὶ τῆς ΕΒ ἄρα πρὸς ΒΔ λόγος ἐστὶν δοθείς].³ ὁ αὐτὸς αὐτῶ γεγονέτω ὁ τῆς ΑΘ⁴ πρὸς ΒΘ· λόγος ἄρα καὶ τῆς ΑΒ πρὸς ΒΘ ἐστὶν δοθείς· [δοθέν ἄρα τὸ Θ].⁵ καὶ λοιπὸς τῆς ΑΕ πρὸς ΘΔ λόγος ἐστὶν δοθείς· καὶ τοῦ ὑπὸ ΖΑΕ ἄρα πρὸς τὸ ὑπὸ ΘΔΗ λόγος ἐστὶν δοθείς. τοῦ δὲ ὑπὸ ΖΑΕ πρὸς τὸ ἀπὸ ΓΔ λόγος ἐστὶν δοθείς· καὶ τοῦ ὑπὸ ΗΔΘ ἄρα πρὸς τὸ ἀπὸ

¹ ΔΒ Hultsch, ΔΕ cod.

² καὶ . . . πρὸς ΔΒ del. Hultsch.

EUCLID

ratio ; then in the first case $B\Delta$ is less than ΔE , while in the second case $B\Delta$ is greater than ΔE . Let ΔZ be made equal to $E\Delta$. Since the given ratio is $A\Delta^2 : \Gamma\Delta^2 + \Delta B^2$, and $E\Delta^2 : \Delta B^2$ is equal to it, the ratio

$$[A\Delta^2 - E\Delta^2 : \Gamma\Delta^2 + \Delta B^2 - \Delta B^2,$$

that is, by Eucl. ii. 6,]

$$ZA . AE : \Delta\Gamma^2$$

is given. Now since the ratio $[E\Delta^2 : \Delta B^2$ is given, therefore] $E\Delta : \Delta B$ is given, therefore $[\Delta Z : \Delta B$ is given. Accordingly, in the first case $\Delta Z : BZ$, and therefore $BZ : \Delta B$, is given ; in the second case, because $\Delta Z : \Delta B$ or inversely $\Delta B : \Delta Z$ is given, therefore $\Delta B : BZ$ or inversely] $BZ : \Delta B$ is given. Let $[H$ be taken on AB produced so that] $AB : BH = BZ : \Delta B$. Then [in the first case $AB + BZ : BH + \Delta B$, in the second case $AB - BZ : BH - \Delta B$, that is in either case] $AZ : \Delta H$ is given. Let $[\Theta$ be taken on AB such that] $A\Theta : B\Theta = E\Delta : \Delta B$. Then the ratio $AB : B\Theta$ is given. And [because by construction $A\Theta : B\Theta = E\Delta : B\Delta$, *componendo* $A\Theta + B\Theta : B\Theta = E\Delta + B\Delta : B\Delta$, or $AB : B\Theta = EB : \Delta B$. Therefore $AB - EB : B\Theta - \Delta B$, that is,] $AE : \Theta\Delta$ is given. [Now $AZ : \Delta H$ was given ;] therefore $AE . AZ : \Theta\Delta . \Delta H$ is given. But $ZA . AE : \Delta\Gamma^2$ was given ; therefore the ratio $H\Delta . \Delta\Theta : \Delta\Gamma^2$ is given. [But the point Δ is given, and by construction the points E, Z are given ; and because $AB : BH = BZ : \Delta B$ and also

³ καὶ . . . δοθείς del. Hultsch.

⁴ $A\Theta$ Hultsch, AB cod.

⁵ $\deltaοθὲν ἄρα τὸ \Theta$ del. Hultsch.

GREEK MATHEMATICS

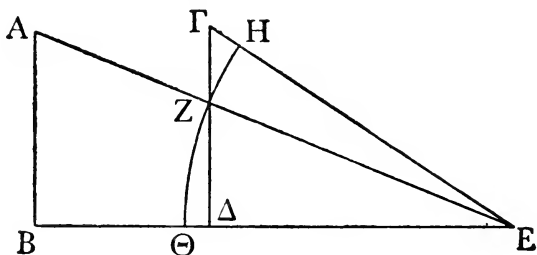
ΔΓ λόγος ἐστὶν δοθείς. καὶ ἐστὶν δύο δοθέντα τὰ Θ, Η· ἐπὶ μὲν ἄρα τῆς πρώτης πτώσεως τὸ Γ ἄπτεται ἐλλείψεως, ἐπὶ δὲ τῆς δευτέρας ὑπερβολῆς.

(g) THE OPTICS

Eucl. *Optic.* 8, Eucl. ed. Heiberg-Menge vii. 14. 1-16. 5

Τὰ ἴση μεγέθη καὶ παράλληλα ἄνισον διεστηκότα ἀπὸ τοῦ ὀμματος οὐκ ἀναλόγως τοῖς διαστήμασιν ὁράται.

Ἔστω δύο μεγέθη τὰ ΑΒ, ΓΔ ἄνισον διεστηκότα ἀπὸ τοῦ ὀμματος τοῦ Ε. λέγω, ὅτι οὐκ ἐστὶν, ὡς



φαίνεται ἔχον, ὡς τὸ ΓΔ πρὸς τὸ ΑΒ, οὕτως τὸ ΒΕ πρὸς τὸ ΕΔ. προσπιπέτωσαν γὰρ ἀκτῖνες αἱ ΑΕ, ΕΓ, καὶ κέντρῳ μὲν τῷ Ε διαστήματι δὲ τῷ ΕΖ κύκλου γεγράφθω περιφέρεια ἡ ΗΖΘ. ἐπεὶ οὖν τὸ ΕΖΓ τρίγωνον τοῦ ΕΖΗ τομέως μειζόν ἐστὶν, τὸ δὲ ΕΖΔ τρίγωνον τοῦ ΕΖΘ τομέως ἔλαττόν ἐστιν, τὸ ΕΖΓ ἄρα τρίγωνον πρὸς τὸν

* Pappus proceeds to make the formal synthesis, as in the case of the parabola, and then formally proves his original

EUCLID

$A\theta : B\theta = E\Delta : \Delta B$, therefore] the points H, θ are also given. [Therefore in the first case $H\theta$ is the diameter of an ellipse, in the second it is the diameter of a hyperbola; and] therefore the point Γ lies in the first case on an ellipse, in the second on a hyperbola.^a

(g) THE OPTICS ^b

Euclid, *Optics* 8, Eucl. ed. Heiberg-Menge vii. 14. 1-16. 5

The apparent sizes of equal and parallel magnitudes at unequal distances from the eye are not proportional to those distances.

Let $AB, \Gamma\Delta$ be the two magnitudes at unequal distances from the eye, E . I say that the ratio of the apparent size of $\Gamma\Delta$ to the apparent size of AB is not equal to the ratio of BE to $E\Delta$. For let the rays $AE, E\Gamma$ fall,^c and with centre E and radius EZ let the arc of a circle, $HZ\theta$, be drawn. Then since the triangle $EZ\Gamma$ is greater than the sector EZH , while the triangle $EZ\Delta$ is less than the sector $EZ\theta$, therefore

proposition in the case where the locus is a parabola; the proof where the locus is an ellipse or hyperbola has been lost, but can easily be supplied.

^b Euclid's *Optics* exists in two recensions, both contained in vol. vii. of the Heiberg-Menge edition of Euclid's works. One is the recension of Theon, but Heiberg discovered in Viennese and Florentine mss. an earlier and markedly different recension, and there is every reason to believe it is Euclid's own work; it is from this earlier text that the proposition here quoted is given. The *Optics* is an elementary treatise on perspective. It is based on some false physical hypotheses, but has some interesting mathematical theorems.

^c Euclid, like Plato, believed [*Optics*, Def. 1] that rays of light proceed from the eye to the object, and not from the object to the eye.

GREEK MATHEMATICS

ΕΖΗ τομέα μείζονα λόγον ἔχει ἥπερ τὸ ΕΖΔ τρίγωνον πρὸς τὸν ΕΖΘ τομέα. καὶ ἐναλλάξ τὸ ΕΖΓ τρίγωνον πρὸς τὸ ΕΖΔ τρίγωνον μείζονα λόγον ἔχει ἥπερ ὁ ΕΖΗ τομεὺς πρὸς τὸν ΕΖΘ τομέα, καὶ συνθέντι τὸ ΕΓΔ τρίγωνον πρὸς τὸ ΕΖΔ τρίγωνον μείζονα λόγον ἔχει ἥπερ ὁ ΕΗΘ τομεὺς πρὸς τὸν ΕΖΘ τομέα. ἀλλ' ὡς τὸ ΕΔΓ πρὸς τὸ ΕΖΔ τρίγωνον, οὕτως ἡ ΓΔ πρὸς τὴν ΔΖ. ἡ δὲ ΓΔ τῇ ΑΒ ἐστὶν ἴση, καὶ ὡς ἡ ΑΒ πρὸς τὴν ΔΖ, ἡ ΒΕ πρὸς τὴν ΕΔ. ἡ ΒΕ ἄρα πρὸς τὴν ΕΔ μείζονα λόγον ἔχει ἥπερ ὁ ΕΗΘ τομεὺς πρὸς τὸν ΕΖΘ τομέα. ὡς δὲ ὁ τομεὺς πρὸς τὸν τομέα, οὕτως ἡ ὑπὸ ΗΕΘ γωνία πρὸς τὴν ὑπὸ ΖΕΘ γωνίαν. ἡ ΒΕ ἄρα πρὸς τὴν ΕΔ μείζονα λόγον ἔχει ἥπερ ἡ ὑπὸ ΗΕΘ γωνία πρὸς τὴν ὑπὸ ΖΕΘ. καὶ ἐκ μὲν τῆς ὑπὸ ΗΕΘ γωνίας βλέπεται τὸ ΓΔ, ἐκ δὲ τῆς ὑπὸ ΖΕΘ τὸ ΑΒ. οὐκ ἀνάλογον ἄρα τοῖς ἀποστήμασιν ὁράται τὰ ἴσα μεγέθη.

- This is equivalent, of course, to saying that

$$\frac{\tan \overline{HE\Theta}}{\tan \overline{ZE\Theta}} > \frac{\text{angle } \overline{ZE\Theta}}{\text{angle } \overline{HE\Theta}},$$

a well-known theorem in trigonometry; the full expression

EUCLID

triangle $EZ\Gamma$: sector EZH > triangle $EZ\Delta$: sector $EZ\Theta$.

Invertendo,

triangle $EZ\Gamma$: triangle $EZ\Delta$ > sector EZH : sector $EZ\Theta$,

and *componendo*,

triangle $E\Gamma\Delta$: triangle $EZ\Delta$ > sector $E\Theta$: sector $EZ\Theta$.

But triangle $E\Gamma\Delta$: triangle $EZ\Delta$ = $\Gamma\Delta$: ΔZ .

Now $\Gamma\Delta = AB$, and $AB : \Delta Z = BE : E\Delta$.

Therefore $BE : E\Delta$ > sector $E\Theta$: sector $EZ\Theta$.

Now

sector $E\Theta$: sector $EZ\Theta$ = angle $HE\Theta$: angle $ZE\Theta$.

Therefore

$BE : E\Delta$ > angle $HE\Theta$: angle $ZE\Theta$.^a

And $\Gamma\Delta$ is seen in the angle $HE\Theta$, while AB is seen in the angle $ZE\Theta$. Therefore ^b the apparent sizes of equal magnitudes are not proportional to their distances.

of the theorem is: If α, β are two angles such that $\alpha < \beta < \frac{1}{2}\pi$, then

$$\frac{\tan \alpha}{\tan \beta} < \frac{\alpha}{\beta}.$$

^b By Def. 4, which asserts: "Things seen under a greater angle appear greater, and those seen under a lesser angle appear less, while things seen under equal angles appear equal."

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