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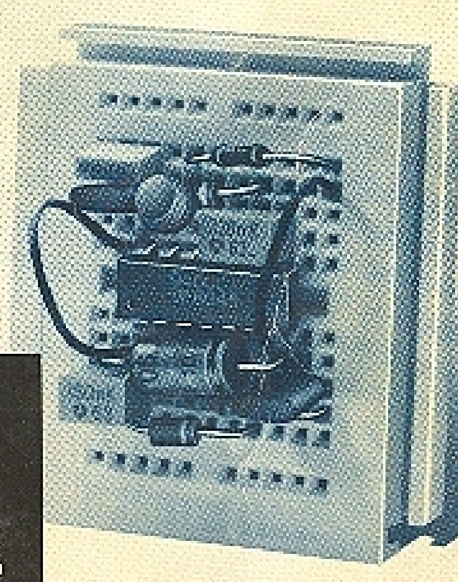
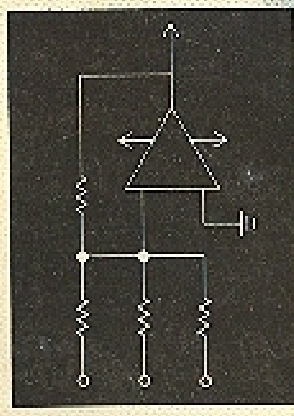
Engineer's Mini-Notebook

Op Amp IC Circuits





Forrest M. Mims III

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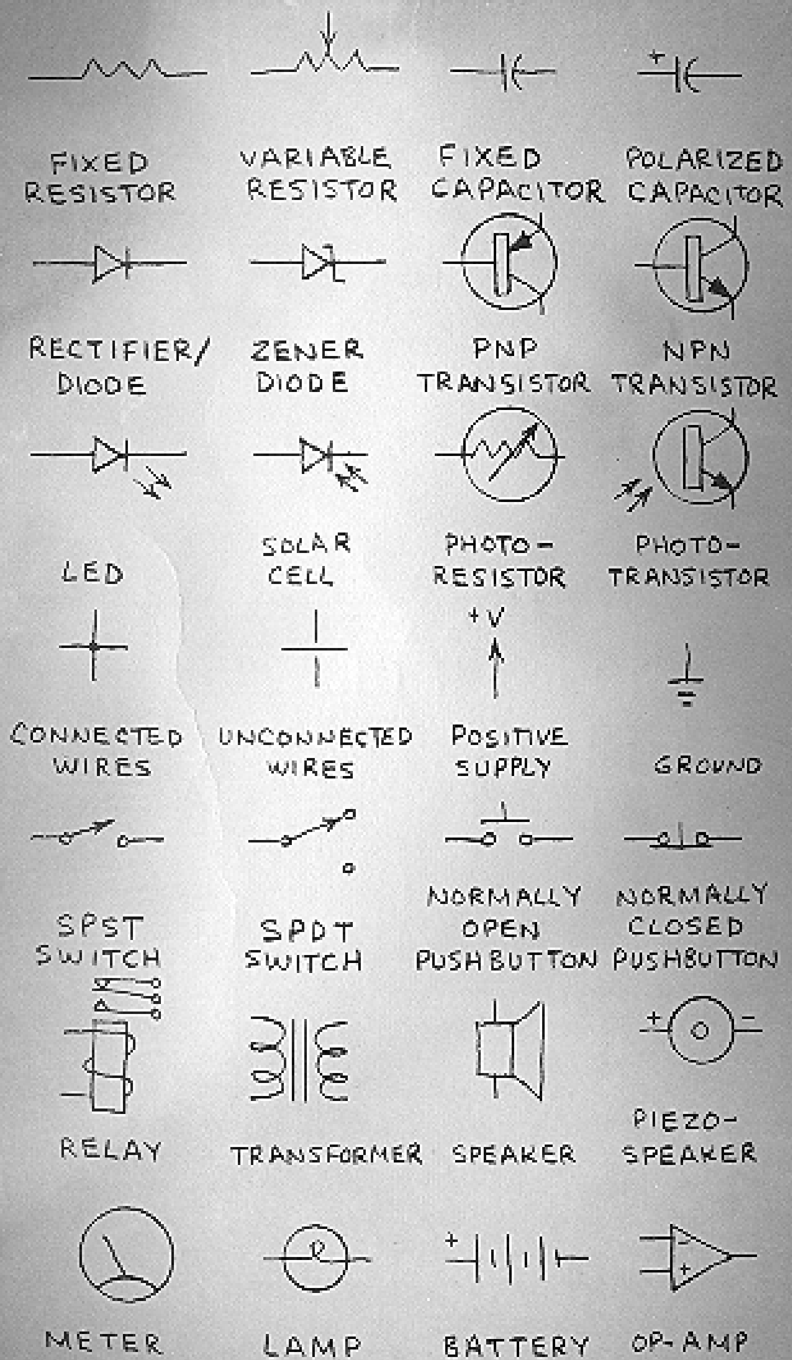
CIRCUIT SYMBOLS



ENGINEER'S MINI-NOTEBOOK

OP-AMP CIRCUITS

BY

FORREST M. MIMS, III

FIRST EDITION

A SILICONCEPTS™ BOOK

PRINTED IN THE UNITED STATES OF AMERICA

THIS BOOK INCLUDES STANDARD APPLICATION CIRCUITS AND CIRCUITS DESIGNED BY THE AUTHOR. EACH CIRCUIT WAS ASSEMBLED AND TESTED BY THE AUTHOR AS THE BOOK WAS DEVELOPED. AFTER THE BOOK WAS COMPLETED, THE AUTHOR REASSEMBLED EACH CIRCUIT TO CHECK FOR ERRORS. WHILE REASONABLE CARE WAS EXERCISED IN THE PREPARATION OF THIS BOOK, VARIATIONS IN COMPONENT TOLERANCES AND CONSTRUCTION METHODS MAY CAUSE THE RESULTS YOU OBTAIN TO DIFFER FROM THOSE GIVEN HERE. THEREFORE THE AUTHOR AND RADIO SHACK ASSUME NO RESPONSIBILITY FOR THE SUITABILITY OF THIS BOOK'S CONTENTS FOR ANY APPLICATION. SINCE WE HAVE NO CONTROL OVER THE USE TO WHICH THE INFORMATION IN THIS BOOK IS PUT, WE ASSUME NO LIABILITY FOR ANY DAMAGES RESULTING FROM ITS USE. OF COURSE IT IS YOUR RESPONSIBILITY TO DETERMINE IF COMMERCIAL USE, SALE OR MANUFACTURE OF ANY DEVICE THAT INCORPORATES INFORMATION IN THIS BOOK INFRINGES ANY PATENTS, COPYRIGHTS OR OTHER RIGHTS.

DUE TO THE MANY INQUIRIES RECEIVED BY RADIO SHACK AND THE AUTHOR, IT IS NOT POSSIBLE TO PROVIDE PERSONAL RESPONSES TO REQUESTS FOR ADDITIONAL INFORMATION (CUSTOM CIRCUIT DESIGN, TECHNICAL ADVICE, TROUBLESHOOTING ADVICE, ETC.). IF YOU WISH TO LEARN MORE ABOUT ELECTRONICS, SEE OTHER BOOKS IN THIS SERIES AND RADIO SHACK'S "GETTING STARTED IN ELECTRONICS." ALSO, READ MAGAZINES LIKE <u>MODERN ELECTRONICS</u> AND <u>RADIO-ELECTRONICS</u>. THE AUTHOR WRITES A MONTHLY COLUMN, "ELECTRONICS NOTEBOOK," FOR <u>MODERN ELECTRONICS</u>.

CONTENTS

CIRCUITS

HISTORICAL NOTE

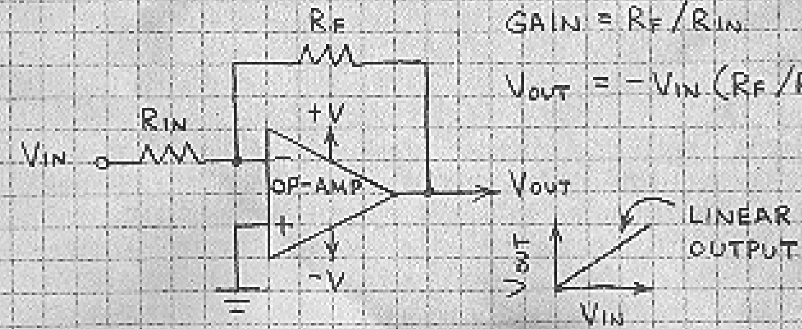
THE OPERATIONAL AMPLIFIER WAS DEVELOPED FOR USE IN ANALOG COMPUTERS IN THE 1940s. EARLY OP-AMPS USED VACUUM TUBES AND WERE LARGE IN SIZE AND CONSUMED CONSIDERABLE POWER. IN 1967 FAIRCHILD SEMICONDUCTOR INTRODUCED THE FIRST INTEGRATED CIRCUIT OP-AMP. TODAY'S IC OP-AMPS ARE FAR SUPERIOR TO THEIR VACUUM TUBE PREDECESSORS. AND THEY ARE MUCH SMALLER AND CAN BE PURCHASED FOR AS LITTLE AS A DOLLAR OR TWO.

INTRODUCTION

THE OPERATIONAL AMPLIFIER OR OP-AMP IS A HIGH PERFORMANCE LINEAR AMPLIFIER WITH AN AMAZING VARIETY OF USES. THE OP-AMP HAS TWO INPUTS, INVERTING (−) AND NON-INVERTING (+), AND ONE OUTPUT. THE POLARITY OF A SIGNAL APPLIED TO THE INVERTING INPUT IS REVERSED AT THE OUTPUT. A SIGNAL APPLIED TO THE NON-INVERTING INPUT RETAINS ITS POLARITY AT THE OUTPUT.

THE GAIN (DEGREE OF AMPLIFICATION) OF AN OP-AMP IS DETERMINED BY A FEEDBACK RESISTOR THAT FEEDS SOME OF THE AMPLIFIED SIGNAL FROM THE OUTPUT TO THE INVERTING INPUT. THIS REDUCES THE AMPLITUDE OF THE OUTPUT SIGNAL, HENCE THE GAIN. THE SMALLER THE RESISTOR, THE LOWER THE GAIN.

HERE IS A BASIC INVERTING AMPLIFIER MADE WITH AN OP-AMP:



$$\text{GAIN} = R_F / R_{IN}$$

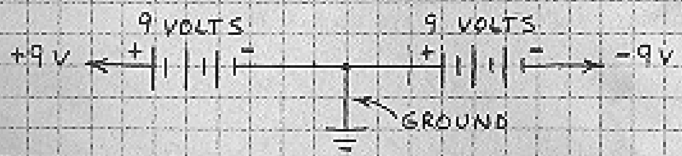
$$V_{OUT} = -V_{IN}(R_F / R_{IN})$$

THE GAIN IS INDEPENDENT OF THE SUPPLY VOLTAGE. NOTE THAT THE UNUSED INPUT IS GROUNDED. THEREFORE THE OP-AMP AMPLIFIES THE DIFFERENCE BETWEEN THE INPUT (V_{IN}) AND GROUND (0 VOLTS). THE OP-AMP IS THEN A <u>DIFFERENTIAL</u> AMPLIFIER.

THE FEEDBACK RESISTOR (R_F) AND AN OP-AMP FORM A CLOSED FEEDBACK LOOP. WHEN R_F IS OMITTED, THE OP-AMP IS SAID TO BE IN ITS OPEN LOOP MODE. THE OP-AMP THEN EXHIBITS MAXIMUM GAIN, BUT ITS OUTPUT THEN SWINGS FROM FULL ON TO FULL OFF OR VICE VERSA FOR VERY SMALL CHANGES IN INPUT VOLTAGE. THEREFORE THE OPEN LOOP MODE IS NOT PRACTICAL FOR LINEAR AMPLIFICATION. INSTEAD THIS MODE IS USED TO INDICATE WHEN THE VOLTAGE AT ONE INPUT DIFFERS FROM THAT AT THE OTHER. IN THIS MODE THE OP-AMP IS CALLED A COMPARATOR SINCE IT COMPARES ONE INPUT VOLTAGE WITH THE OTHER.

POWERING OP-AMPS

MOST OP-AMPS AND OP-AMP CIRCUITS REQUIRE A DUAL POLARITY POWER SUPPLY. HERE IS A SIMPLE DUAL POLARITY SUPPLY MADE FROM TWO 9-VOLT BATTERIES:



IMPORTANT: THE LEADS FROM THE SUPPLY TO THE OP-AMP SHOULD BE SHORT AND DIRECT. IF THEY EXCEED ABOUT 6 INCHES, THE OP-AMP'S SUPPLY PINS MUST BE BYPASSED BY CONNECTING A 0.1 μF CAPACITOR BETWEEN EACH POWER SUPPLY PIN AND GROUND. OTHERWISE THE OP-AMP MAY OSCILLATE OR FAIL TO OPERATE PROPERLY. ALWAYS USE FRESH BATTERIES. BOTH MUST SUPPLY THE SAME VOLTAGE. BE SURE THE BATTERY CLIPS ARE CLEAN AND TIGHT. NEVER APPLY AN INPUT SIGNAL WHEN THE POWER SUPPLY IS SWITCHED OFF.

OP-AMP SPECIFICATIONS

OP-AMPS ARE CHARACTERIZED BY DOZENS OF SPECIFICATIONS, SOME OF WHICH ARE GIVEN ON THE FOLLOWING PAGES. THOSE WHOSE MEANING IS NOT OBVIOUS ARE:

INPUT OFFSET VOLTAGE - EVEN WITH NO INPUT VOLTAGE AN OP-AMP GIVES A VERY SMALL OUTPUT VOLTAGE. THE OFFSET VOLTAGE IS THAT WHICH, WHEN APPLIED TO ONE INPUT, CAUSES THE OUTPUT TO BE AT 0 VOLTS.

COMMON MODE REJECTION RATIO - THIS IS A MEASURE OF THE ABILITY OF AN OP-AMP TO REJECT A SIGNAL SIMULTANEOUSLY APPLIED TO BOTH INPUTS.

BANDWIDTH - THE FREQUENCY RANGE OVER WHICH AN OP-AMP WILL FUNCTION. THE FREQUENCY AT WHICH THE GAIN FALLS TO 1 IS THE UNITY GAIN FREQUENCY.

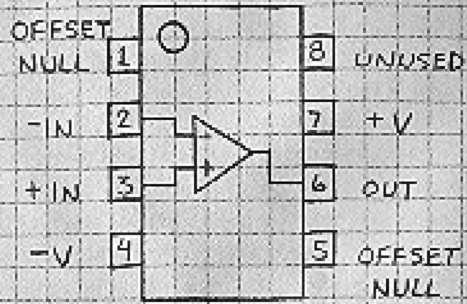
SLEW RATE - THE RATE OF CHANGE IN THE OUTPUT OF AN OP-AMP IN VOLTS PER MICROSECOND WHEN THE GAIN IS 1.

CIRCUIT ASSEMBLY TIPS

YOU CAN USUALLY SUBSTITUTE DIFFERENT OP-AMPS IN A CIRCUIT. FOR EXAMPLE, USE A 1458 DUAL OP-AMP IN A CIRCUIT THAT REQUIRES TWO 741 OP-AMPS. BE SURE TO KEEP TRACK OF PIN DIFFERENCES. FOR VERY HIGH INPUT RESISTANCE AND LOW OPERATING CURRENT, USE CMOS OP-AMPS. USE A HIGH-IMPEDANCE VOLTMETER TO MONITOR THE OUTPUT OF AN OP-AMP THAT IS AMPLIFYING A d.c. VOLTAGE. IF A CIRCUIT FAILS TO WORK, REMOVE INPUT SIGNAL FIRST. THEN DISCONNECT POWER AND CHECK THE WIRING. USE FRESH BATTERIES.

741 OP-AMP

THE 741 IS A HIGHLY POPULAR GENERAL PURPOSE OP-AMP. IT IS SIMPLE TO USE, RELIABLE, AND INEXPENSIVE. IT IS USED IN MOST CIRCUITS IN THIS BOOK.



MAXIMUM RATINGS

SUPPLY VOLTAGE	±18 V
POWER DISSIPATION	500 mW
DIFFERENTIAL INPUT VOLTAGE	±30 V
INPUT VOLTAGE (NOTE 1)	±15 V
OUTPUT SHORT CIRCUIT TIME	INDEFINITE
OPERATING TEMPERATURE	0°C TO 70°C

NOTE 1: INPUT VOLTAGE SHOULD NOT EXCEED SUPPLY VOLTAGE WHEN SUPPLY VOLTAGE IS LESS THAN ±15 VOLTS.

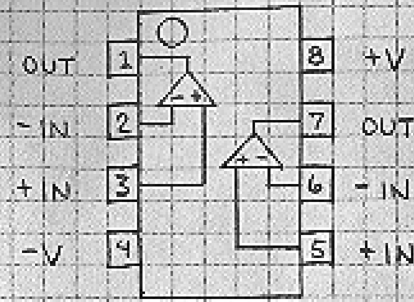
CHARACTERISTICS (NOTE 2)

INPUT OFFSET VOLTAGE	2 TO 6 mV
INPUT RESISTANCE	.3 TO 2 MΩ
VOLTAGE GAIN	20,000 TO 200,000
COMMON-MODE REJECTION RATIO	70 TO 90 dB
BANDWIDTH	.5 TO 1.5 MHz
SLEW RATE	.5 V / μSEC
SUPPLY CURRENT	1.7 TO 2.8 mA
POWER CONSUMPTION	50 TO 85 mW

NOTE 2: VALUES SHOWN ARE TYPICAL OR MINIMUM TO TYPICAL.

1458 DUAL OP-AMP

THE 1458 INCLUDES TWO INDEPENDENT, GENERAL PURPOSE OP-AMPS IN A SINGLE PACKAGE. THE AMPLIFIERS SHARE COMMON POWER SUPPLY PINS. USE TO REPLACE TWO 741 OP-AMPS.



MAXIMUM RATINGS

SUPPLY VOLTAGE	±18 V
POWER DISSIPATION	400 mW
DIFFERENTIAL INPUT VOLTAGE	±30 V
INPUT VOLTAGE (NOTE 1)	±15 V
OUTPUT SHORT CIRCUIT TIME	INDEFINITE
OPERATING TEMPERATURE	0°C TO 70°C

NOTE 1: INPUT VOLTAGE SHOULD NOT EXCEED SUPPLY VOLTAGE WHEN SUPPLY VOLTAGE IS LESS THAN ±15 V.

CHARACTERISTICS (NOTE 2)

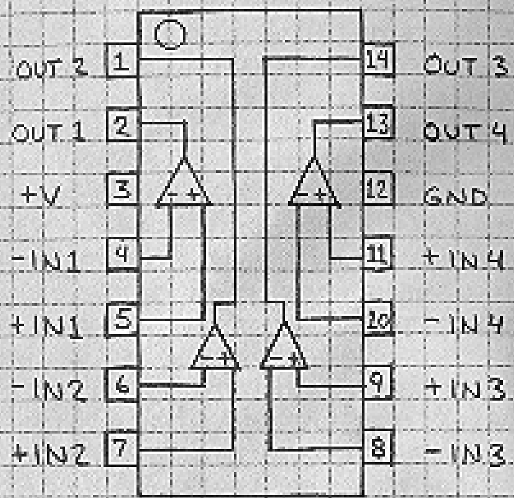
INPUT OFFSET VOLTAGE	1 TO 6 mV
INPUT RESISTANCE	.3 TO 1 MΩ
VOLTAGE GAIN	20,000 TO 160,000
COMMON-MODE REJECTION RATIO	70 TO 90 dB
SUPPLY CURRENT (NOTE 3)	3 TO 5.6 mA
POWER CONSUMPTION	85 mW

NOTE 2: VALUES SHOWN ARE TYPICAL OR MINIMUM TO TYPICAL.

NOTE 3: BOTH AMPLIFIERS.

339 QUAD COMPARATOR

THE 339 CONTAINS FOUR INDEPENDENT COMPARATORS, MAKING IT AN ECONOMICAL APPROACH TO COMPARATOR CIRCUITS. IT OPERATES FROM A SINGLE POLARITY POWER SUPPLY.



MAXIMUM RATINGS

SUPPLY VOLTAGE	+36V OR ±18V
POWER DISSIPATION	570 mW
DIFFERENTIAL INPUT VOLTAGE	36 V
INPUT VOLTAGE	-.3V TO +36V
OUTPUT SHORT CIRCUIT (NOTE 1)	CONTINUOUS
OPERATING TEMPERATURE	0°C TO 70°C

NOTE 1: OK TO SHORT OUTPUT TO GROUND. DO NOT SHORT OUTPUT TO +V SINCE CHIP WILL OVERHEAT.

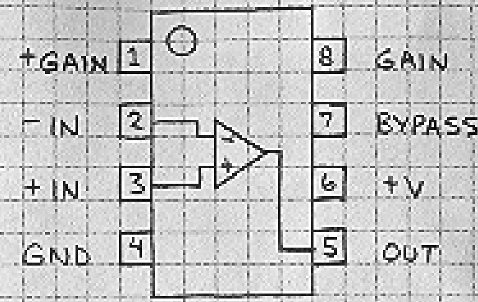
CHARACTERISTICS (NOTE 2)

INPUT OFFSET VOLTAGE	±3 TO ±20 mV
VOLTAGE GAIN	2,000 TO 30,000
SUPPLY CURRENT	.8 TO 2 mA
OUTPUT SINK CURRENT	6 TO 16 mA

NOTE 2: VALUES SHOWN ARE MINIMUM TO TYPICAL.

386 AUDIO AMPLIFIER

SIMPLE TO USE AUDIO AMPLIFIER WITH GAIN OF 20. OPERATES FROM SINGLE POLARITY SUPPLY. CONNECT 10 μF CAPACITOR BETWEEN PINS 1 AND 8 FOR GAIN OF 200.



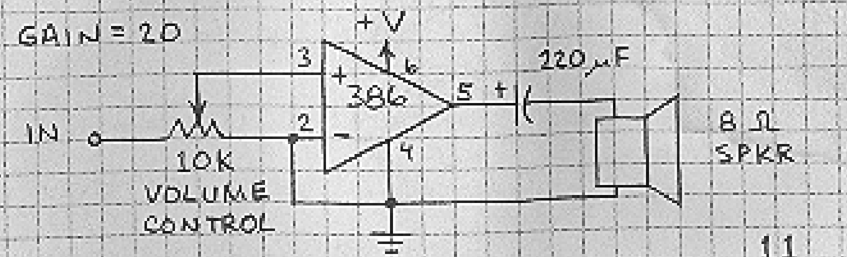
MAXIMUM RATINGS

SUPPLY VOLTAGE	+15 V
POWER DISSIPATION	660 mW
INPUT VOLTAGE	±0.4 V
OPERATING TEMPERATURE	0°C TO 70°C

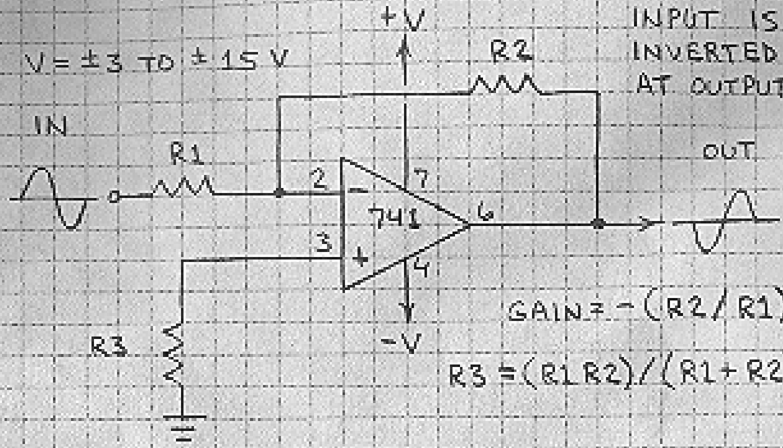
CHARACTERISTICS

SUPPLY VOLTAGE RANGE	+4 TO +12 V
STANDBY CURRENT	4 TO 8 mA
OUTPUT POWER	250 TO 325 mW
VOLTAGE GAIN	20 TO 200
BANDWIDTH	300 KHz
TOTAL HARMONIC DISTORTION	0.2 %
INPUT RESISTANCE	50KΩ

TYPICAL APPLICATION



BASIC INVERTING AMPLIFIER



INPUT IS INVERTED AT OUTPUT.

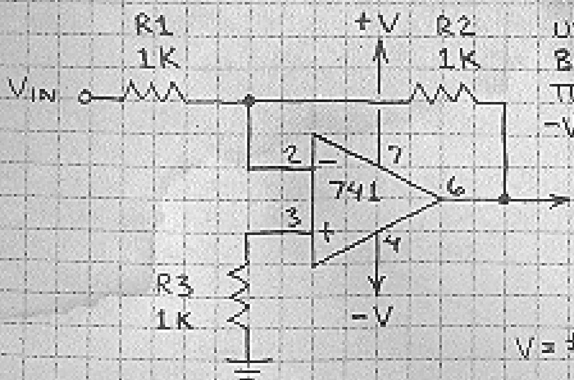
GAIN = $-(R2/R1)$

$R3 = (R1 R2)/(R1 + R2)$

EXAMPLE: IF R1 = 1000 OHMS AND R2 = 10,000 OHMS, THEN GAIN IS $-(10{,}000/1000)$ OR -10.

THIS IS ONE OF THE MOST COMMON OP-AMP CIRCUITS. FOR A NON-INVERTED OUTPUT USE THE AMPLIFIER ON THE FACING PAGE.

UNITY-GAIN INVERTER

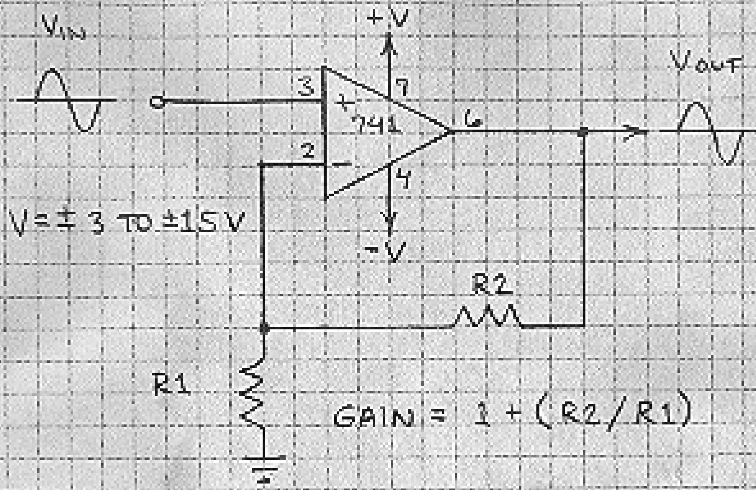


USE AS A BUFFER OR TO CONVERT $-V_{OUT}$ TO $+V_{OUT}$.

$V_{OUT} = -V_{IN}$

V = ±3 TO ±15 V

NON-INVERTING AMPLIFIER



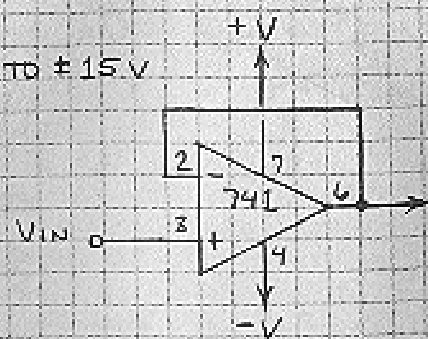
GAIN = $1 + (R2/R1)$

EXAMPLE: IF R1 = 1,000 OHMS AND R2 = 10,000 OHMS, THEN GAIN IS $1 + (10{,}000/1{,}000)$ OR 11.

NOTE THAT V_{OUT} IS AN AMPLIFIED BUT NOT INVERTED VERSION OF V_{IN}.

UNITY-GAIN FOLLOWER

V = ± 3 TO ± 15 V

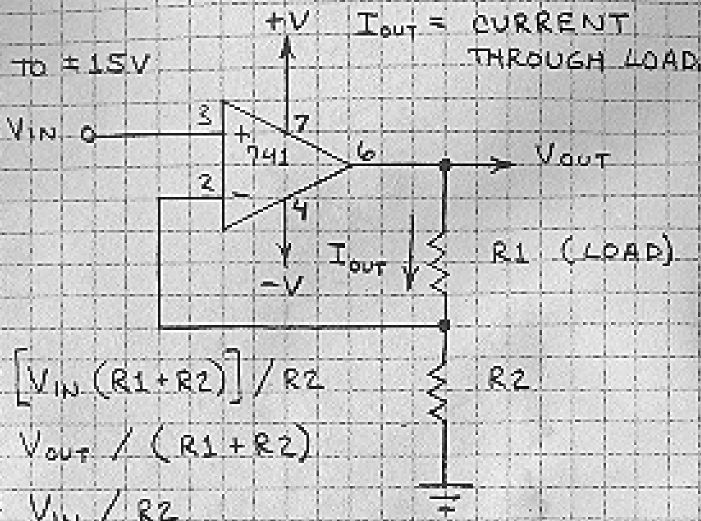


USE TO BUFFER SIGNAL FROM ANOTHER CIRCUIT.

$V_{OUT} = V_{IN}$

TRANSCONDUCTANCE AMPLIFIER

V = ±3 TO ±15V

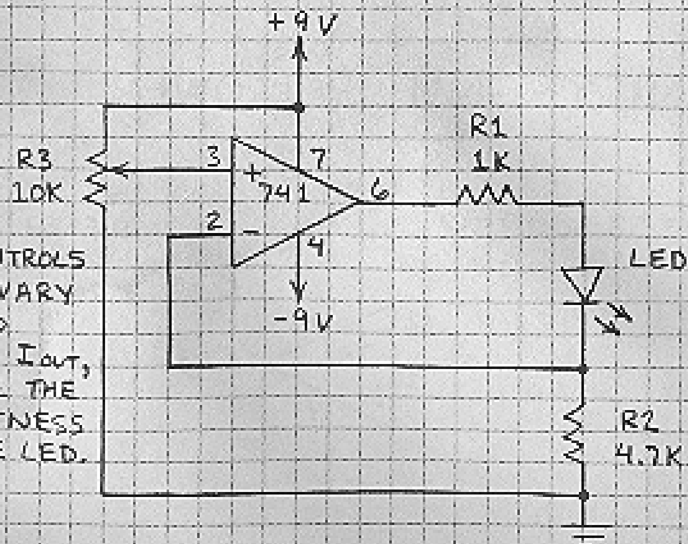


$V_{OUT} = \left[V_{IN} (R1+R2)\right] / R2$

$I_{OUT} = V_{OUT} / (R1+R2)$

$I_{OUT} = V_{IN} / R2$

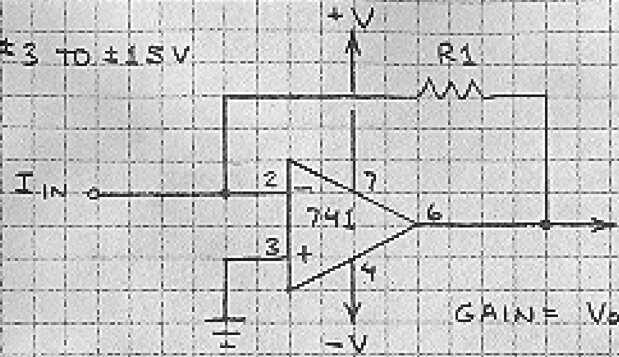
THIS CIRCUIT IS A VOLTAGE-TO-CURRENT CONVERTER. HERE'S HOW IT PERMITS AN INPUT VOLTAGE TO CONTROL THE BRIGHTNESS OF AN LED:



R3 CONTROLS VIN. VARY R3 TO ALTER IOUT, HENCE THE BRIGHTNESS OF THE LED.

TRANSIMPEDANCE AMPLIFIER

V = ±3 TO ±15V

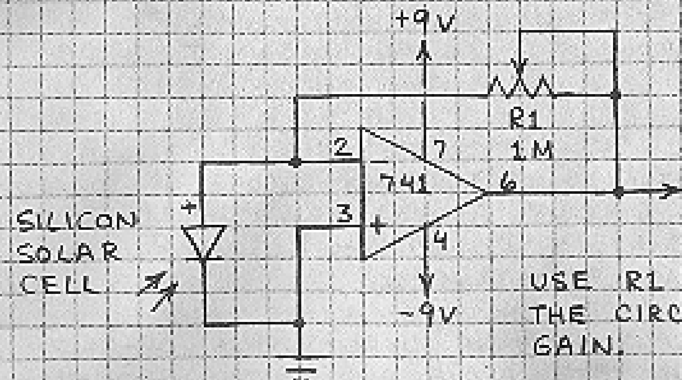


GAIN = V_{OUT} / I_{IN}

GAIN = $-R1$

EXAMPLE: IF R1 = 1,000 OHMS THEN GAIN = -1,000.

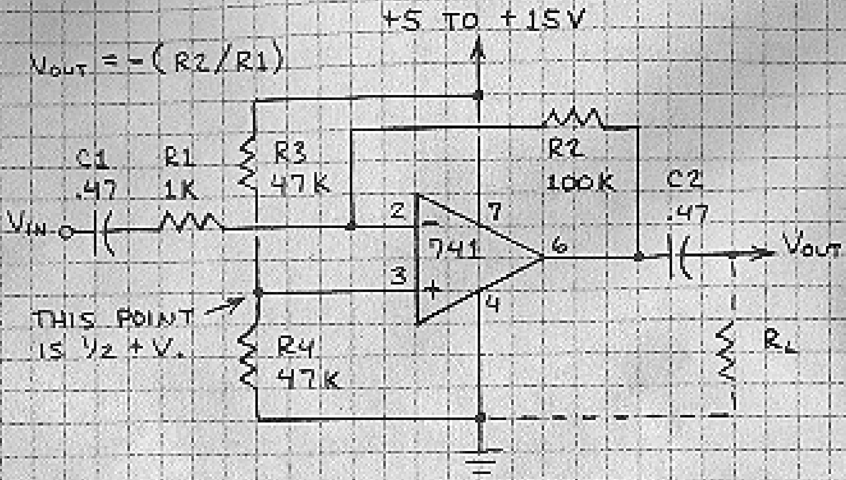
THIS CIRCUIT IS A CURRENT-TO-VOLTAGE CONVERTER. HERE'S HOW IT TRANSFORMS THE CURRENT GENERATED BY A SOLAR CELL INTO AN OUTPUT VOLTAGE:



USE R1 TO VARY THE CIRCUIT'S GAIN.

THIS CIRCUIT CAN AMPLIFY THE SIGNAL FROM NON-CURRENT GENERATORS LIKE THERMISTORS AND PHOTORESISTORS. CONNECT ONE SIDE OF DEVICE TO +9V AND THE OTHER TO PIN 2. GROUND PIN 3.

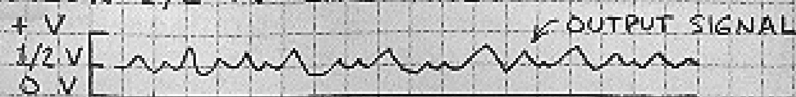
SINGLE-SUPPLY AMPLIFIER



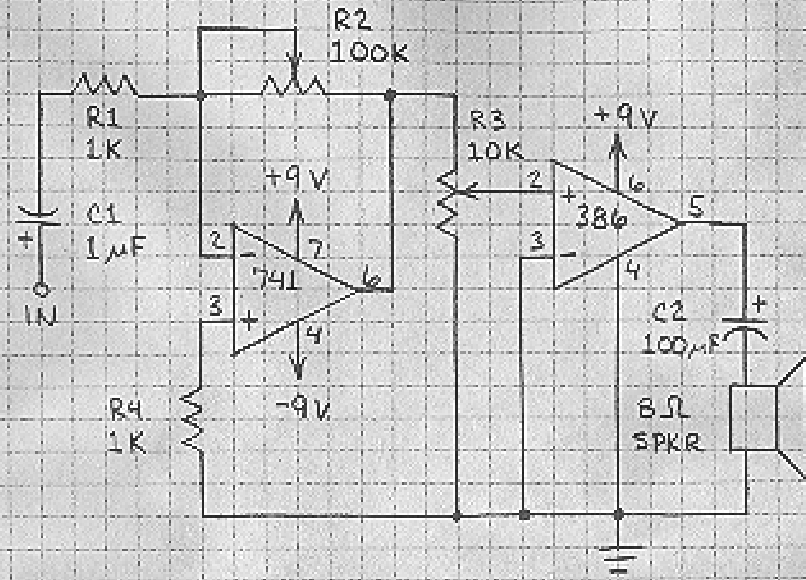
THIS IS AN INVERTING AMPLIFIER DESIGNED TO OPERATE FROM A SINGLE-POLARITY SUPPLY. WITH THE VALUES FOR R1 AND R2 GIVEN ABOVE, THE GAIN IS 100. CAPACITORS C1 AND C2 MUST BE USED. THEREFORE THIS CIRCUIT WILL AMPLIFY A FLUCTUATING AC SIGNAL BUT NOT A DC SIGNAL.

C1 SHOULD BE APPROXIMATELY $1/(2\pi f_{LOW} R1)$. (f_{LOW} IS THE LOW FREQUENCY CUTOFF OR 300 Hz FOR THE CIRCUIT ABOVE.) C2 SHOULD BE APPROXIMATELY $1/(2\pi f_{LOW} R_L)$. (R_L IS THE LOAD RESISTANCE.)

THE OUTPUT FROM A DUAL-SUPPLY OP-AMP CAN FLUCTUATE ABOVE AND BELOW GROUND (0 VOLTS). HERE THE DIVIDER FORMED BY R3 AND R4 SETS VOUT AT 1/2 +V. THE OUTPUT THEN FLUCTUATES ABOVE AND BELOW 1/2 +V LIKE THIS:

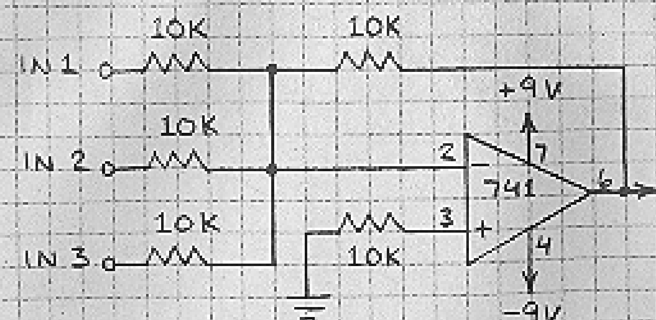


AUDIO AMPLIFIER



THE 741 IS A PREAMPLIFIER. R2 CONTROLS ITS GAIN. THE 386 IS A POWER AMPLIFIER. R3 CONTROLS THE VOLUME OF THE SPEAKER. OK TO USE FIXED 100K RESISTOR FOR R2. (REDUCE RESISTANCE OF R2 IF CIRCUIT OSCILLATES OR GIVES DISTORTED OUTPUT.) IMPORTANT: BYPASS THE POWER SUPPLY CONNECTIONS WITH 0.1 µF CAPACITORS.

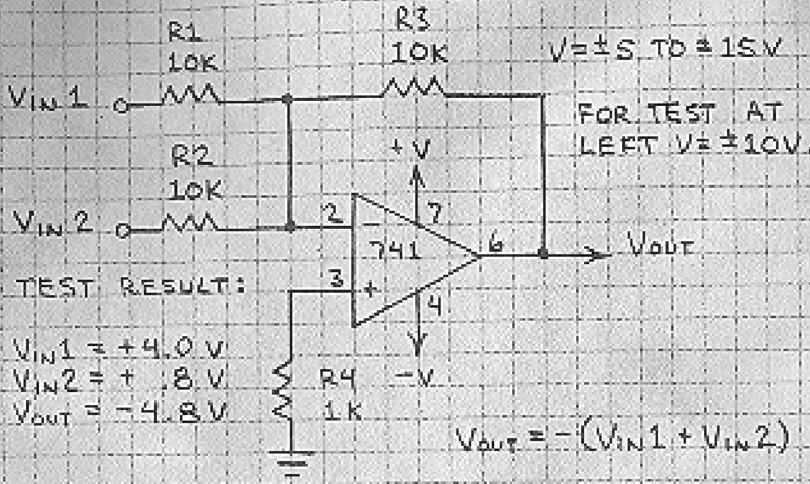
AUDIO MIXER



OK TO USE WITH THE AMPLIFIER ABOVE.

USE WITH MULTIPLE MICROPHONES.

SUMMING AMPLIFIER



V = ±5 TO ±15 V

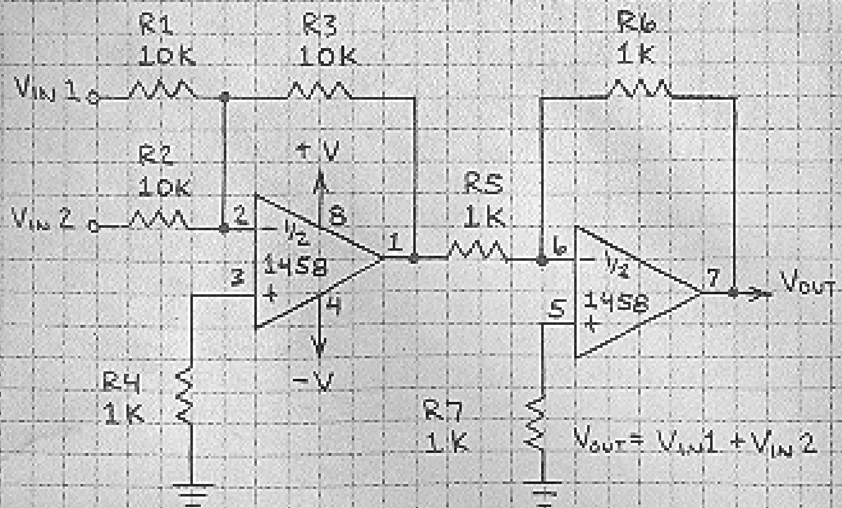
FOR TEST AT LEFT V = ±10V.

TEST RESULT:

$V_{IN}1 = +4.0$ V
$V_{IN}2 = +.8$ V
$V_{OUT} = -4.8$ V

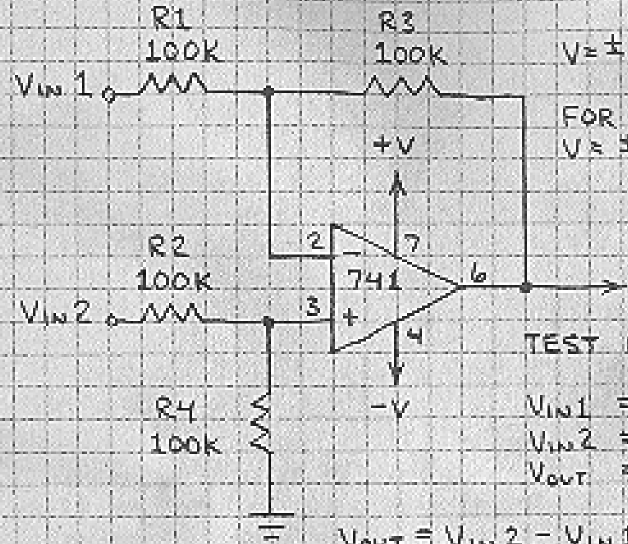
$$V_{OUT} = -(V_{IN}1 + V_{IN}2)$$

THE OUTPUT OF THE SUMMING AMPLIFIER IS THE SUM OF THE INPUT VOLTAGES. THE SUM OF THE INPUTS SHOULD NOT EXCEED ±V LESS A VOLT OR TWO. OK TO ADD MORE INPUTS. (USE 10K RESISTOR TO PIN 2 FOR EACH INPUT.) THE CIRCUIT BELOW PRESERVES THE POLARITY OF VIN:



$$V_{OUT} = V_{IN}1 + V_{IN}2$$

DIFFERENCE AMPLIFIER



V = ±5V TO ±15V

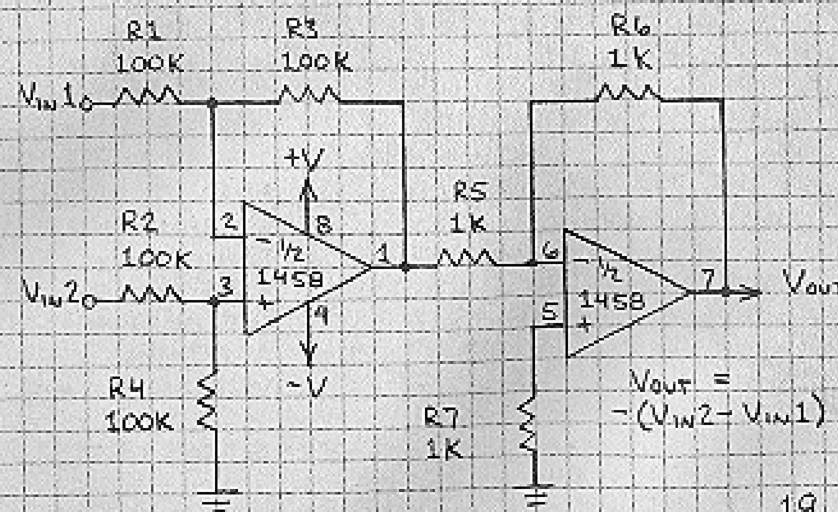
FOR TEST BELOW V = ±10V.

TEST RESULT:

$V_{IN}1 = 0.9$ V
$V_{IN}2 = 5.0$ V
$V_{OUT} = 4.1$ V

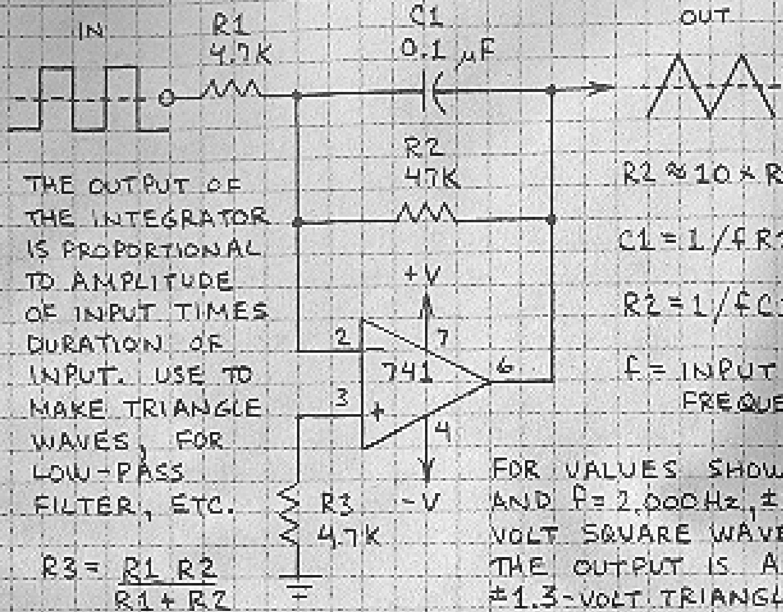
$$V_{OUT} = V_{IN}2 - V_{IN}1$$

THE OUTPUT OF THE DIFFERENCE AMPLIFIER IS $V_{IN}2 - V_{IN}1$. THE INPUT VOLTAGES SHOULD NOT EXCEED ±V. THE CIRCUIT BELOW REVERSES THE POLARITY OF $V_{IN}2 - V_{IN}1$:



$$V_{OUT} = -(V_{IN}2 - V_{IN}1)$$

DUAL-SUPPLY INTEGRATOR



THE OUTPUT OF THE INTEGRATOR IS PROPORTIONAL TO AMPLITUDE OF INPUT TIMES DURATION OF INPUT. USE TO MAKE TRIANGLE WAVES, FOR LOW-PASS FILTER, ETC.

$R3 = \frac{R1\ R2}{R1 + R2}$

$R2 \approx 10 \times R1$

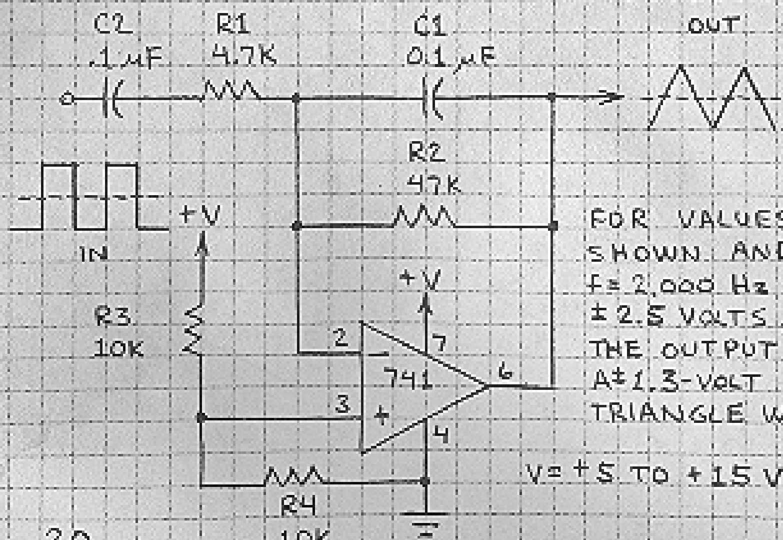
$C1 = 1/fR2$

$R2 = 1/fC1$

f = INPUT FREQUENCY

FOR VALUES SHOWN AND f = 2,000 Hz, ±2.5-VOLT SQUARE WAVE, THE OUTPUT IS A ±1.3-VOLT TRIANGLE.

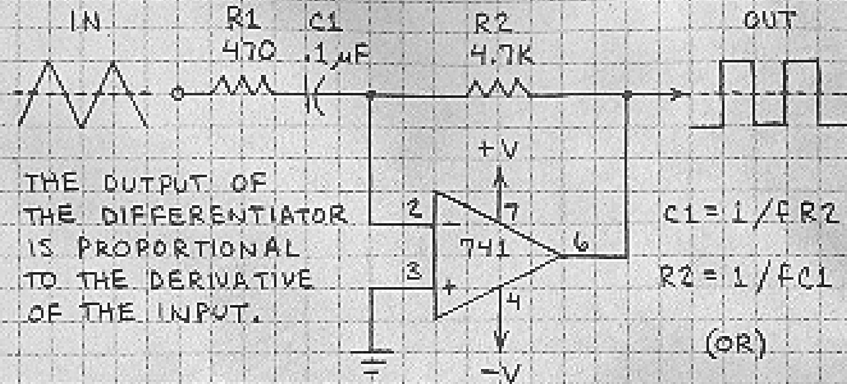
SINGLE-SUPPLY INTEGRATOR



FOR VALUES SHOWN AND f = 2,000 Hz, ±2.5 VOLTS, THE OUTPUT IS A ±1.3-VOLT TRIANGLE WAVE.

V = +5 TO +15 V

DUAL-SUPPLY DIFFERENTIATOR



THE OUTPUT OF THE DIFFERENTIATOR IS PROPORTIONAL TO THE DERIVATIVE OF THE INPUT.

V = ±5 V TO ±15 V

$C1 = 1/fR2$

$R2 = 1/fC1$

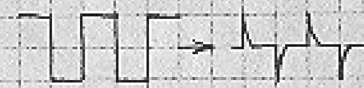
(OR)

$1/f = R2C1$

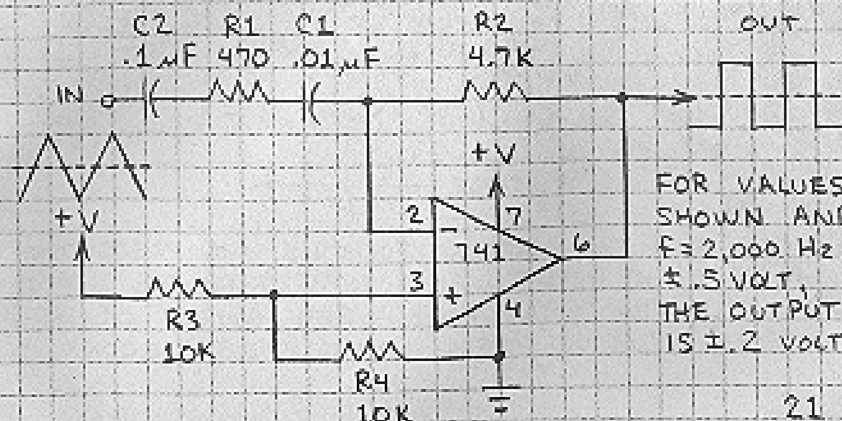
FOR VALUES SHOWN AND f = 2,000 Hz, ±2.5-VOLT TRIANGLE WAVE, THE OUTPUT IS A ±10-VOLT SQUARE WAVE.

THE DIFFERENTIATOR WILL TRANSFORM A SQUARE WAVE INTO PULSES:

f = 2,000 Hz, V = ±10 V
IN = ±0.5 V, OUT = ±7 V



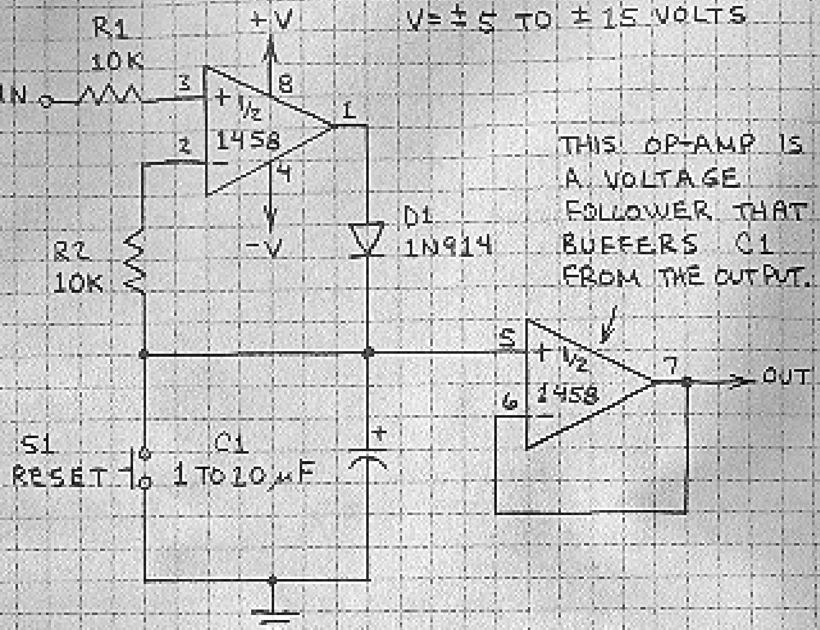
SINGLE-SUPPLY DIFFERENTIATOR



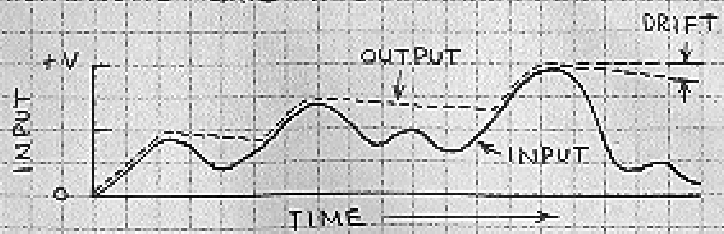
FOR VALUES SHOWN AND f = 2,000 Hz, ±.5 VOLT, THE OUTPUT IS ±.2 VOLT.

PEAK DETECTOR

V= ± 5 TO ± 15 VOLTS



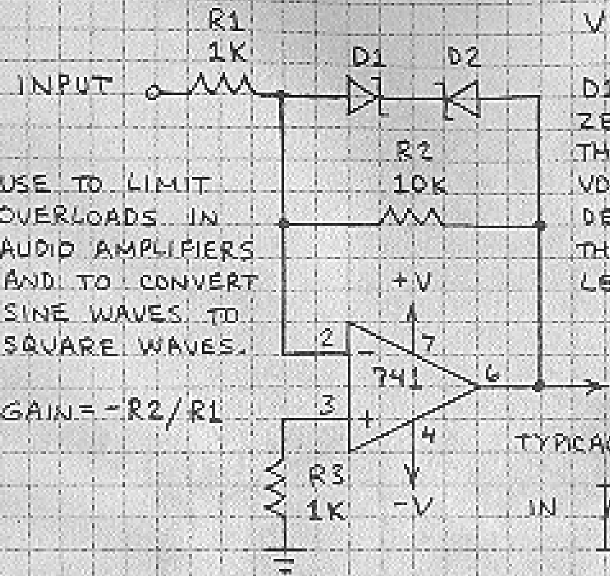
THIS CIRCUIT FOLLOWS AN INCOMING VOLTAGE SIGNAL AND STORES THE MAXIMUM VOLTAGE IN C1. PRESS S1 TO DISCHARGE C1 AND RESET CIRCUIT. CONNECT A VOLTMETER FROM OUTPUT TO GROUND TO MEASURE THE PEAK VOLTAGE STORED IN C1. THE CIRCUIT FUNCTIONS LIKE THIS:



NOTE HOW THE OUTPUT FOLLOWS THE PRECEEDING HIGH (PEAK) INPUT. ALSO NOTE THAT THE CHARGE ON C1 WILL GRADUALLY LEAK AWAY. C1 IN THE TEST CIRCUIT FELL 10 MILLIVOLTS / SECOND.

INVERTING CLIPPER

V= ± 5 TO ± 15 V

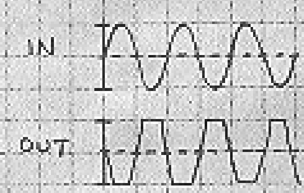


D1 AND D2 ARE ZENER DIODES. THEIR BREAKDOWN VOLTAGE IS WHAT DETERMINES THE CLIPPING LEVEL.

USE TO LIMIT OVERLOADS IN AUDIO AMPLIFIERS AND TO CONVERT SINE WAVES TO SQUARE WAVES.

GAIN = -R2/R1

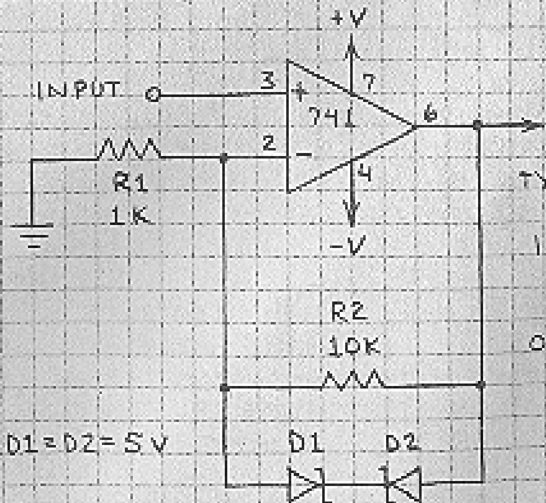
TYPICAL WAVEFORMS:



VALUES SHOWN GIVE -(x10) GAIN. D1 = D2 = 5 VOLTS.

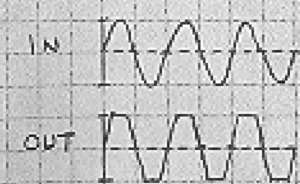
NON-INVERTING CLIPPER

V= ± 5 TO ± 15 V



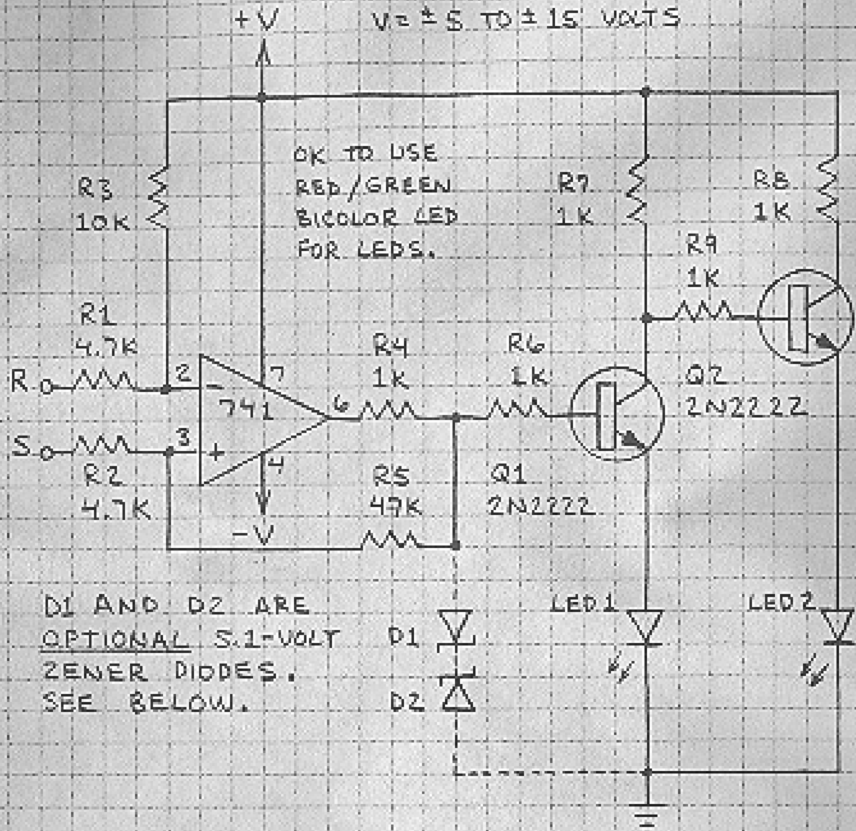
D1 = D2 = 5 V

TYPICAL WAVEFORMS



GAIN = 1 + R2/R1
VALUES SHOWN GIVE x11 GAIN.

BISTABLE RS FLIP-FLOP



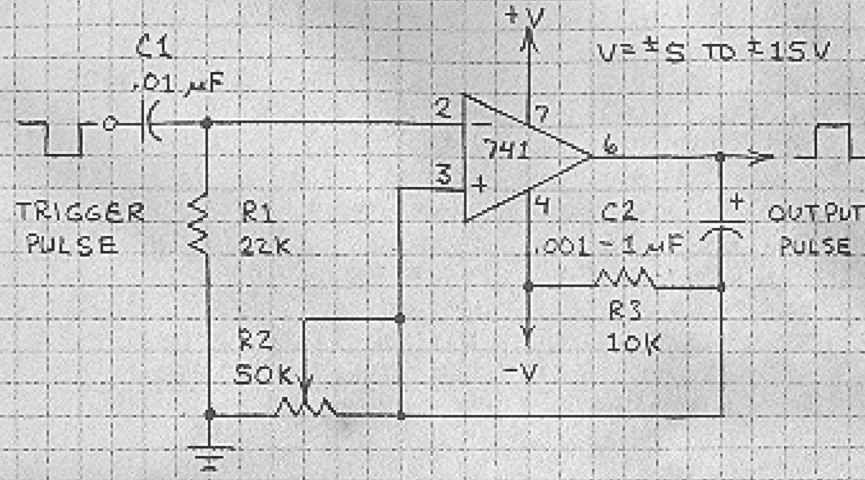
THIS CIRCUIT DEMONSTRATES HOW AN ANALOG CHIP CAN PERFORM A DIGITAL LOGIC FUNCTION. (THE COMPARATOR IS ANOTHER EXAMPLE.) HERE IS THE TRUTH TABLE:

INPUT		LED	
R	S	1	2
GND	+V	ON	OFF
GND	-V	OFF	ON
+V	GND	OFF	ON
-V	GND	ON	OFF

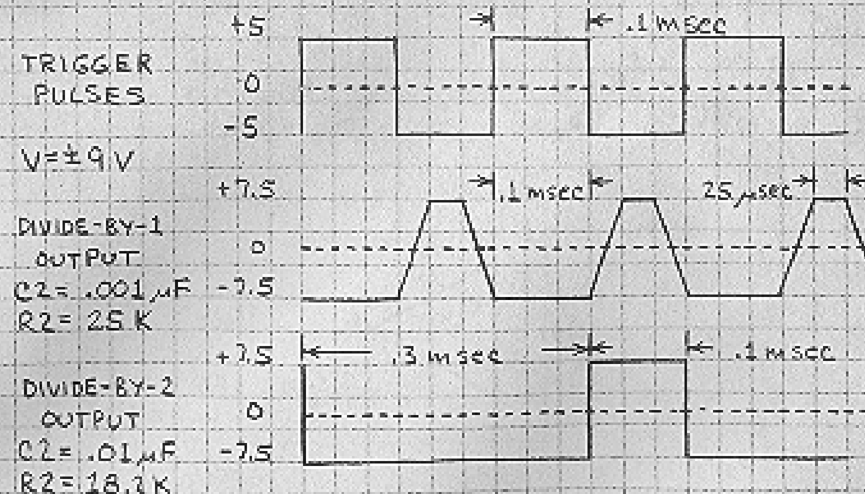
← THESE OUTPUTS HAVE MEMORY AND HOLD THEIR STATE EVEN WHEN S INPUT FLOATS.

USE D1 AND D2 TO LIMIT OUTPUT LEVEL.

MONOSTABLE MULTIVIBRATOR



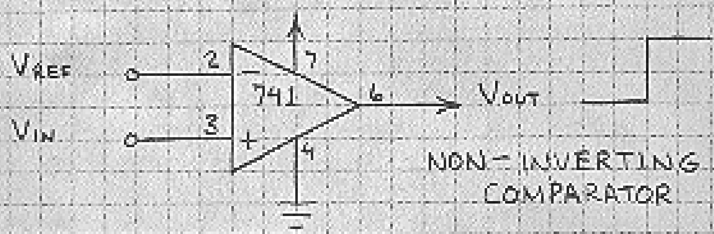
A NEGATIVE TRIGGER PULSE CAUSES THE OP-AMP OUTPUT TO SWING FROM LOW TO HIGH FOR A TIME APPROXIMATELY EQUAL TO R2 × C2. USE TO DIVIDE AN INCOMING SIGNAL AND TO CONVERT AN IRREGULAR INPUT PULSE TO A UNIFORM OUTPUT PULSE. TYPICAL RESULTS:



NOTE: USE THE 555 FOR MORE VERSATILITY.

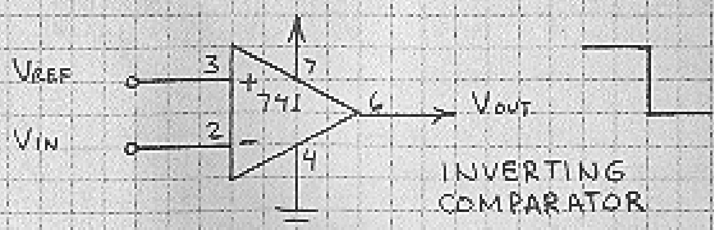
BASIC COMPARATOR

A COMPARATOR IS AN ANALOG CIRCUIT THAT MONITORS TWO INPUT VOLTAGES. ONE VOLTAGE IS CALLED THE REFERENCE VOLTAGE (V_{REF}) AND THE OTHER IS CALLED THE INPUT VOLTAGE (V_{IN}). WHEN V_{IN} RISES ABOVE OR FALLS BELOW V_{REF}, THE OUTPUT OF THE COMPARATOR CHANGES STATES. SOME CIRCUITS (LIKE THE 339) ARE DESIGNED SPECIFICALLY AS COMPARATORS. DUE TO ITS VERY HIGH OPEN-LOOP GAIN, AN OP-AMP WITHOUT A FEEDBACK RESISTOR CAN FUNCTION AS A COMPARATOR.



NON-INVERTING COMPARATOR

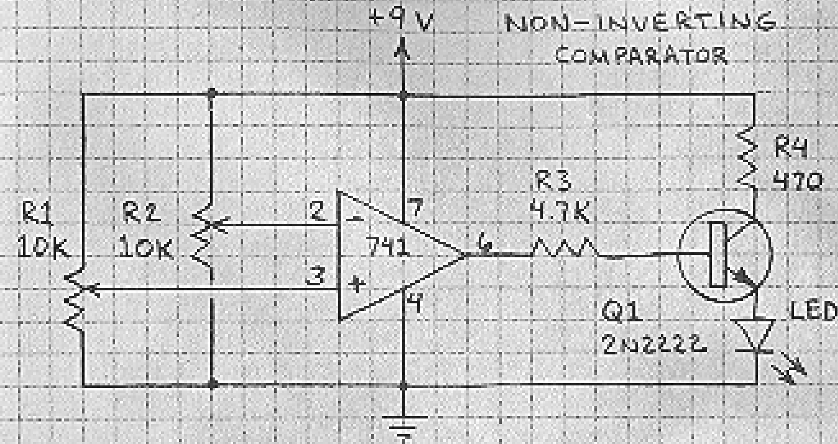
WHEN V_{IN} EXCEEDS V_{REF}, OUTPUT SWITCHES FROM LOW TO HIGH.



INVERTING COMPARATOR

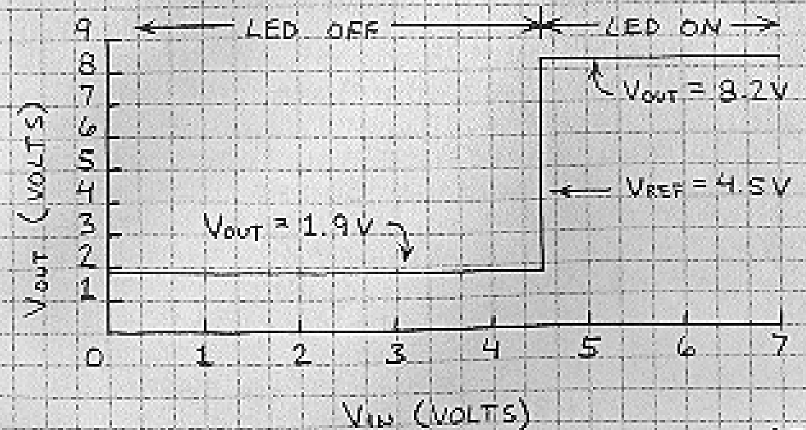
WHEN V_{REF} EXCEEDS V_{IN}, OUTPUT SWITCHES FROM HIGH TO LOW.

BASIC COMPARATOR (CONT.)

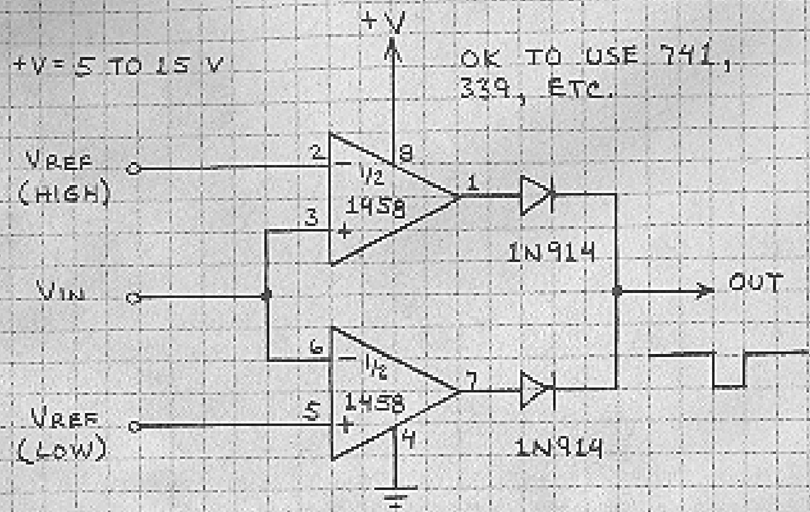


BUILD THIS SIMPLE CIRCUIT ON A PLASTIC BREADBOARD TO LEARN BASICS OF THE COMPARATOR. R1 AND R2 FUNCTION AS VOLTAGE DIVIDERS THAT SUPPLY A RANGE OF VOLTAGES TO BOTH 741 INPUTS. Q1 SWITCHES CURRENT TO THE LED WHEN THE OUTPUT OF THE 741 GOES HIGH. THE CIRCUIT WORKS LIKE THIS:

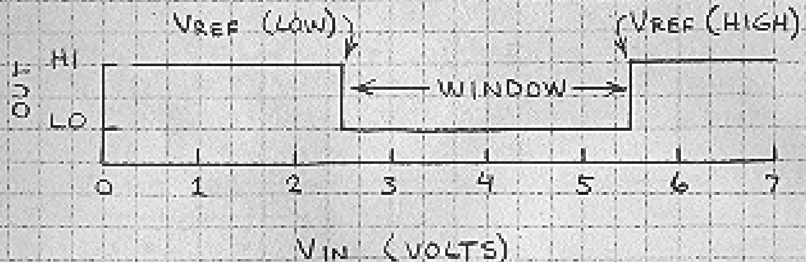
ASSUME R2 IS SET TO ITS CENTER POSITION TO GIVE V_{REF} = 4.5 VOLTS (9V/2 = 4.5V). R1 THEN CONTROLS V_{IN}.



BASIC WINDOW COMPARATOR



THIS IS AMONG THE MOST VERSATILE OF COMPARATOR CIRCUITS. ASSUME VREF (HIGH) IS 5.5 VOLTS AND VREF (LOW) IS 2.5 VOLTS. CIRCUIT THEN OPERATES LIKE THIS:



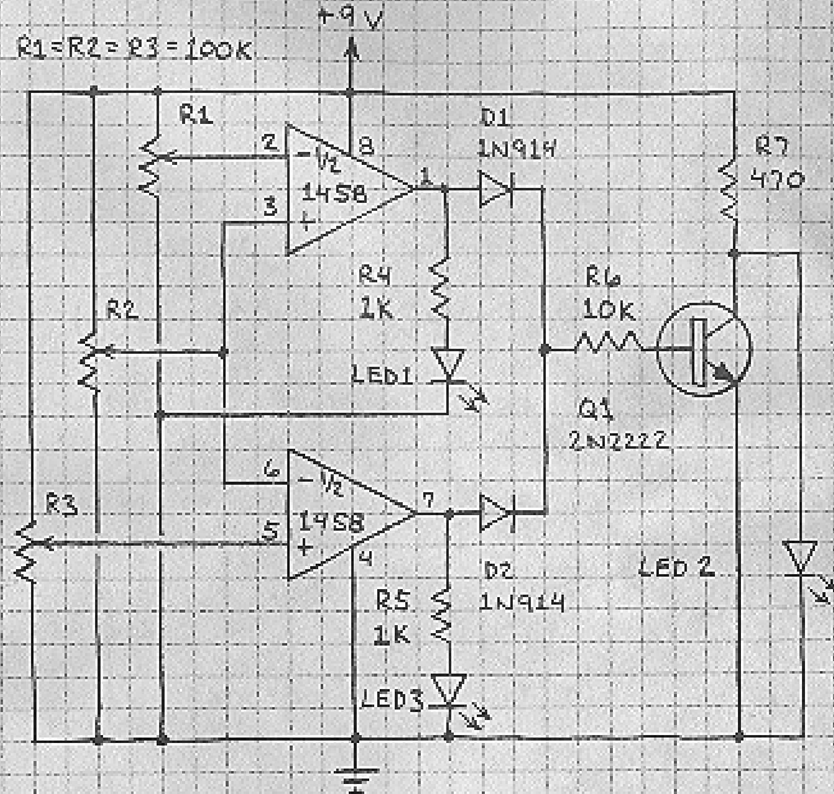
ONE OR BOTH REFERENCE VOLTAGES CAN BE SUPPLIED BY A VOLTAGE DIVIDER:

OR

$V_{REF} = +V \left(\frac{R2}{R1 + R2} \right)$

VREF VARIES

WINDOW COMPARATOR (CONT.)

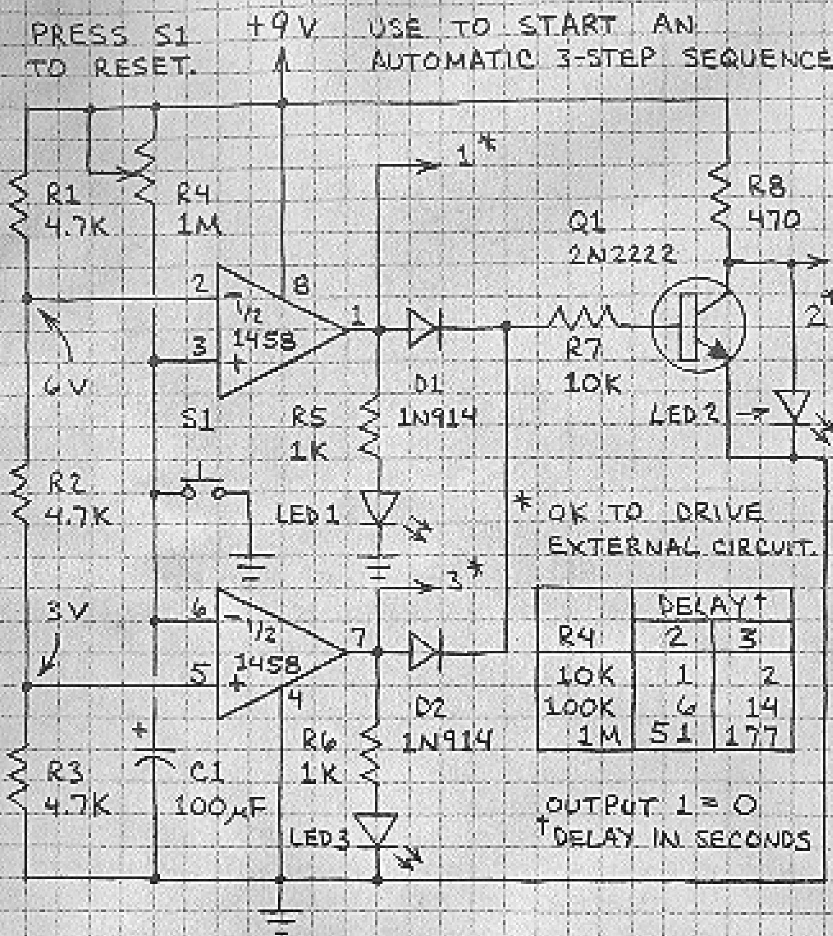


BUILD THIS CIRCUIT ON A BREADBOARD TO LEARN BASICS OF THE WINDOW COMPARATOR. USE VOLTMETER TO SET VREF HIGH (R1) AND VREF LOW (R3). (CONNECT PROBES ACROSS PIN 2 OF 1458 AND GROUND; ADJUST R1. REPEAT FOR PIN 5 AND GROUND; ADJUST R3.) ADJUST R2 TO VARY VIN.

VIN AT OR ABOVE VREF HIGH:	LED 1 ON
VIN WITHIN WINDOW:	LED 2 ON
VIN AT OR BELOW VREF LOW:	LED 3 ON

WHEN VIN IS BELOW 0.6 VOLT, BOTH LED 1 AND LED 3 SWITCH ON.

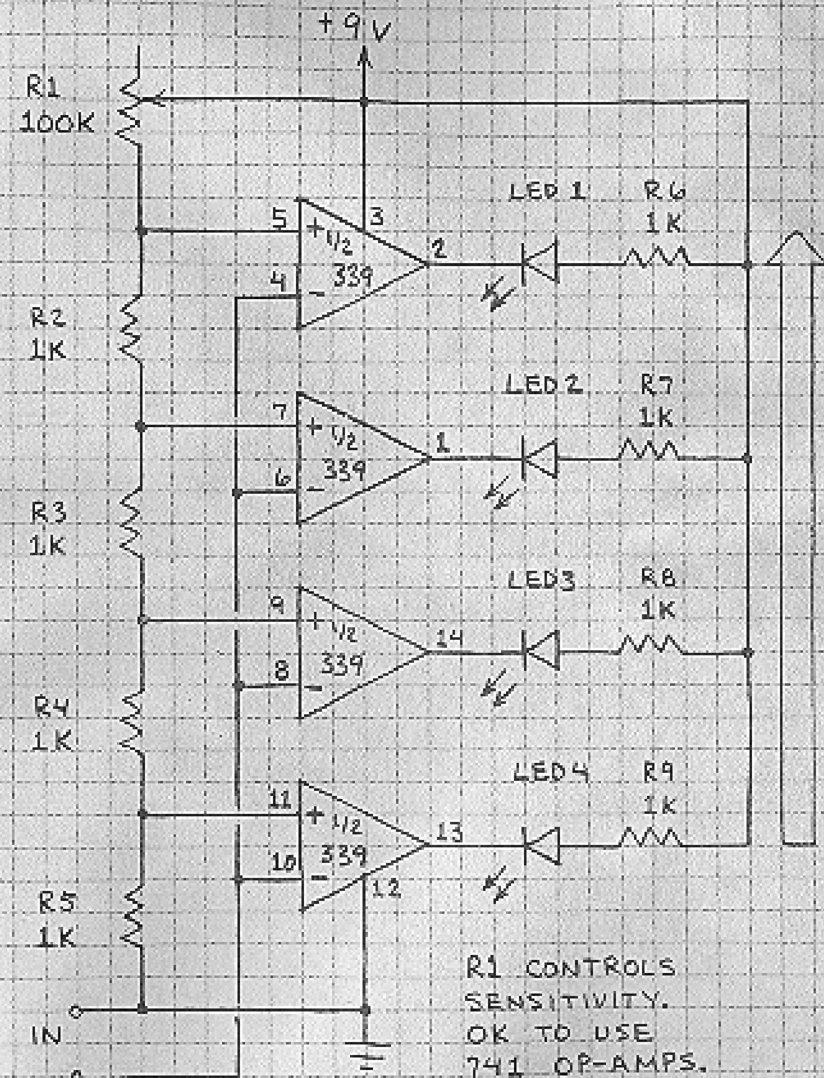
3-STEP SEQUENCER



R4	DELAY† 2	3
10K	1	2
100K	6	14
1M	51	177

THIS IS A WINDOW COMPARATOR THAT SUPPLIES A 3-STEP SEQUENCE OF OUTPUT SIGNALS. PRESSING S1 DISCHARGES C1 AND LIGHTS LED 1 (AND LED 2 BRIEFLY). C1 THEN CHARGES THROUGH R4. AS CHARGE ON C1 PASSES 3 AND 6 VOLTS, LEDS 2 AND 3 GLOW IN SEQUENCE. REDUCE R2 TO BALANCE TIME DELAY SEQUENCE AND REDUCE DELAY TIME. DELAYS SHOWN WILL VARY WITH TOLERANCE OF C1.

BARGRAPH VOLTMETER

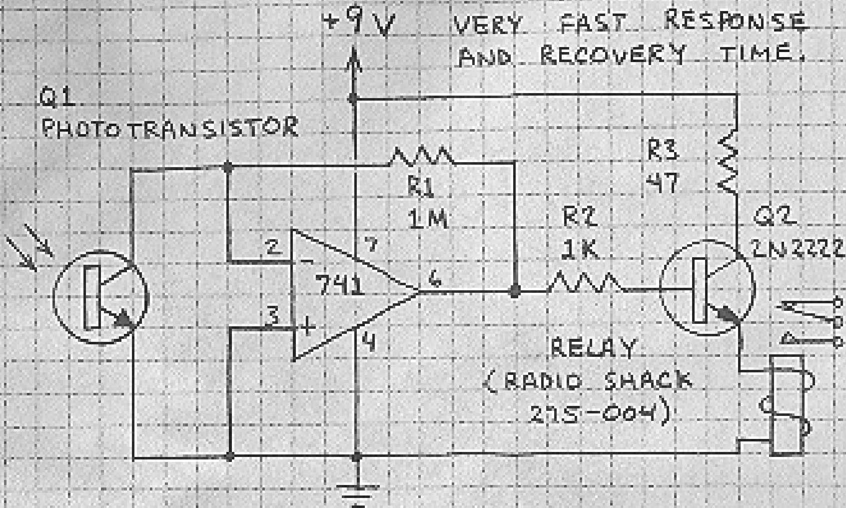


R1 CONTROLS SENSITIVITY. OK TO USE 741 OP-AMPS.

LEDS GLOW IN SEQUENCE AS INPUT VOLTAGE RISES. LEDS ALSO RESPOND TO CHANGE IN RESISTANCE AT INPUT. TOUCH INPUTS WITH FINGER TO OBSERVE. CONNECT CdS CELL ACROSS INPUTS TO MAKE LIGHTMETER.

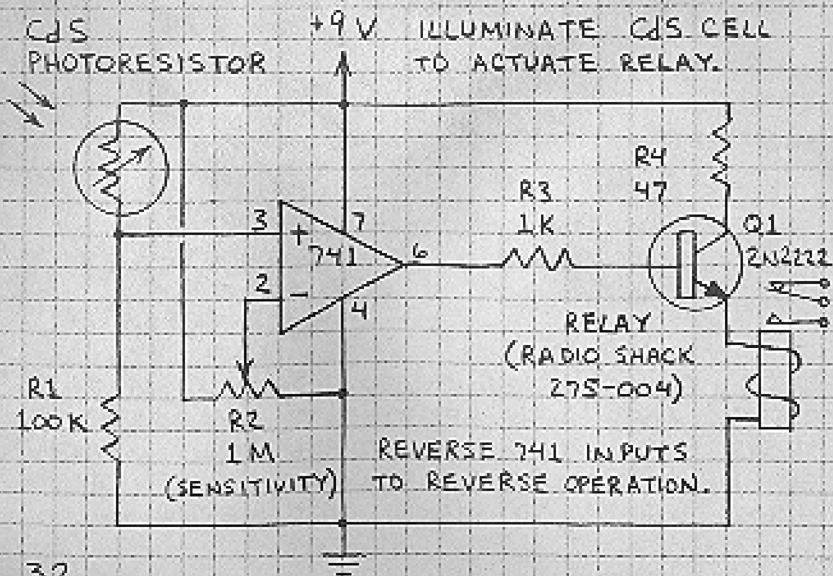
LIGHT-ACTIVATED RELAYS

PHOTOTRANSISTOR:

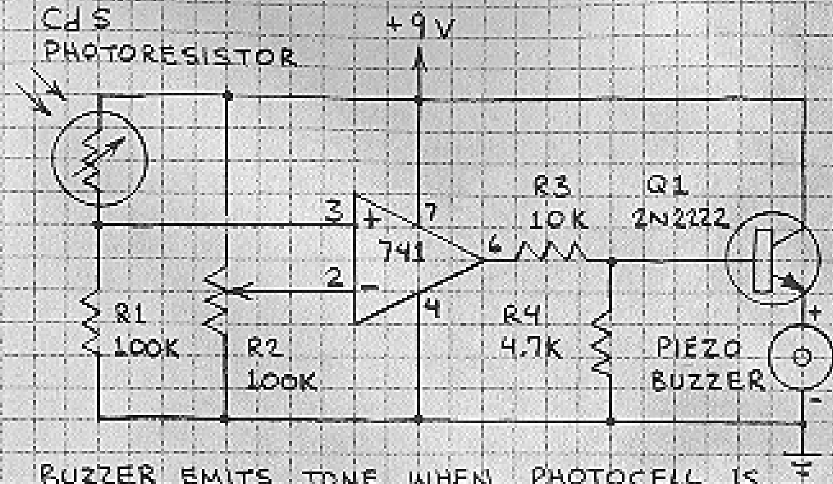


ILLUMINATE Q1 TO ACTIVATE RELAY.

PHOTORESISTOR:

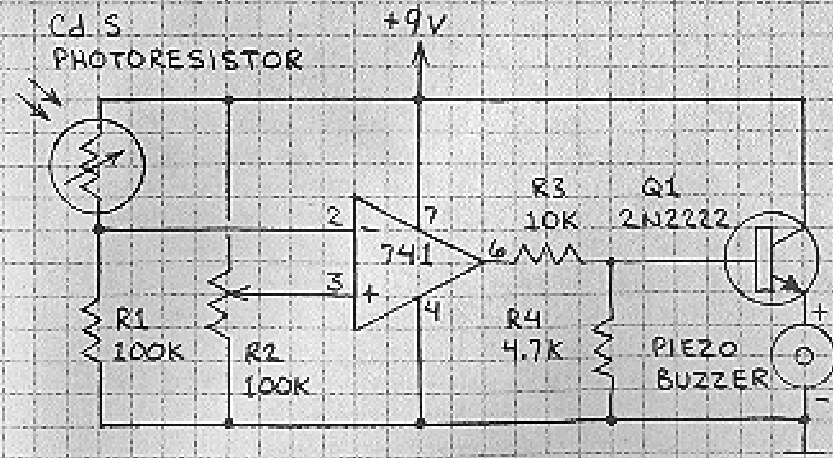


LIGHT-ACTIVATED ALERTER



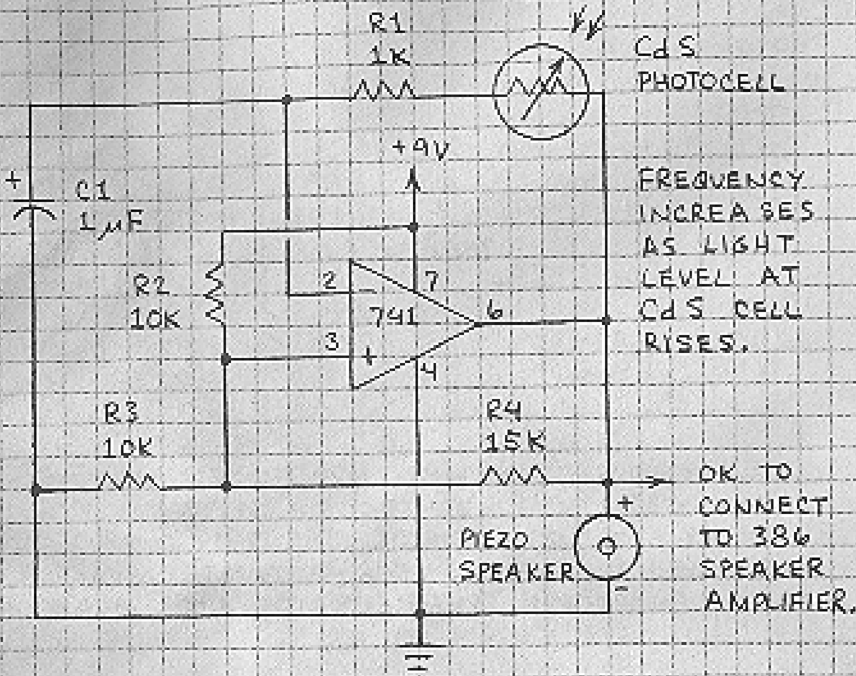
BUZZER EMITS TONE WHEN PHOTOCELL IS ILLUMINATED. R2 CONTROLS SENSITIVITY. R4 KEEPS Q1 OFF UNTIL THE 741 OUTPUT GOES HIGH. USE AS SUN-ACTIVATED WAKEUP ALARM AND OPEN REFRIGERATOR DOOR ALARM.

DARK-ACTIVATED ALERTER

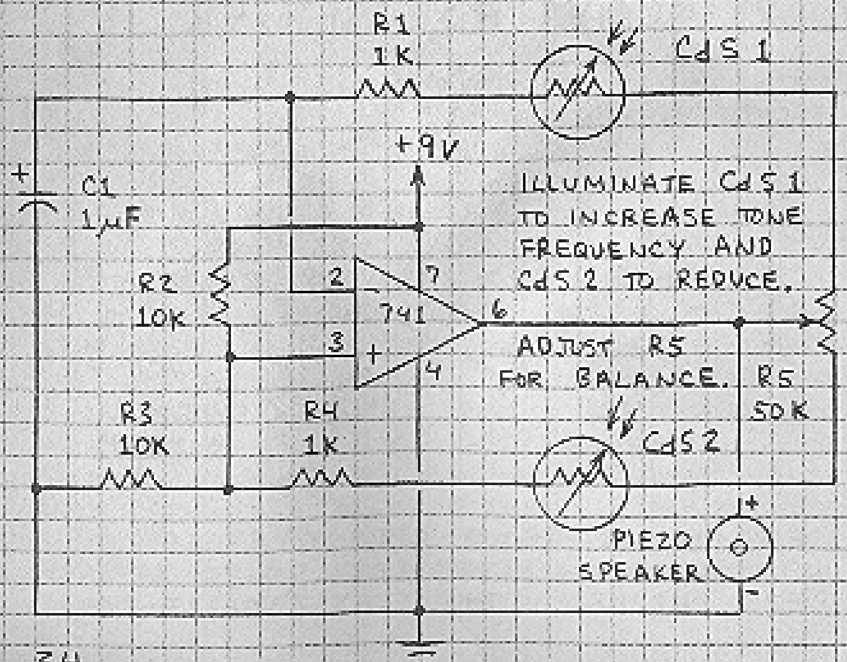


IDENTICAL TO ABOVE CIRCUIT EXCEPT INPUTS TO 741 REVERSED. OK TO REPLACE PIEZO BUZZER WITH RELAY (NO. 275-004).

LIGHT-SENSITIVE OSCILLATORS



FREQUENCY INCREASES AS LIGHT LEVEL AT CdS CELL RISES.



ILLUMINATE CdS 1 TO INCREASE TONE FREQUENCY AND CdS 2 TO REDUCE.

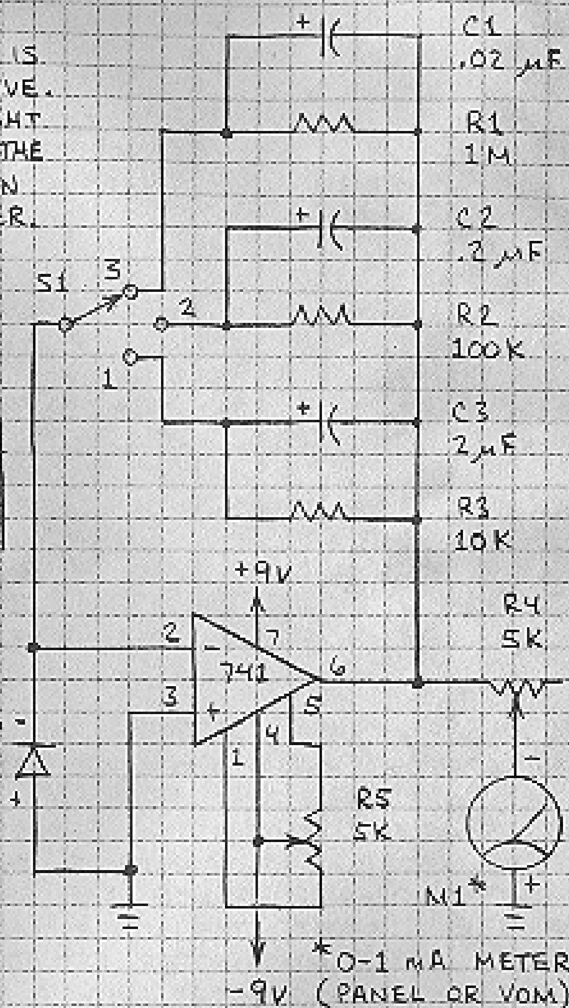
ADJUST R5 FOR BALANCE.

HIGH-SENSITIVITY LIGHT METER

CAUTION:
THIS CIRCUIT IS VERY SENSITIVE. TOO MUCH LIGHT WILL "SLAM" THE NEEDLE OF AN ANALOG METER.

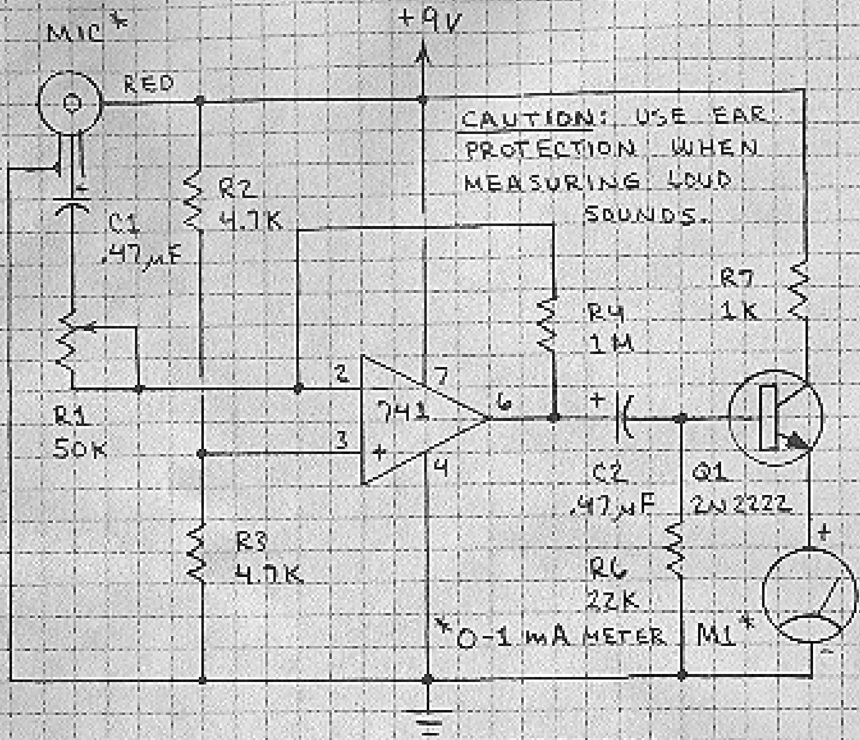
FULL-SCALE METER READINGS:

S1	METER
1	0-10 μA
2	0-1 μA
3	0-.1 μA



THIS CIRCUIT IS BASED UPON THOSE USED IN SOME PRECISION, LABORATORY-QUALITY LIGHT METERS. TO ZERO METER, CONNECT PIN 2 TO GROUND AND ADJUST OFFSET (R5) UNTIL METER READS 0. THEN DISCONNECT PIN 2 FROM GROUND. R4 IS AN OPTIONAL CONTROL FOR ALTERING SENSITIVITY OF THE CIRCUIT.

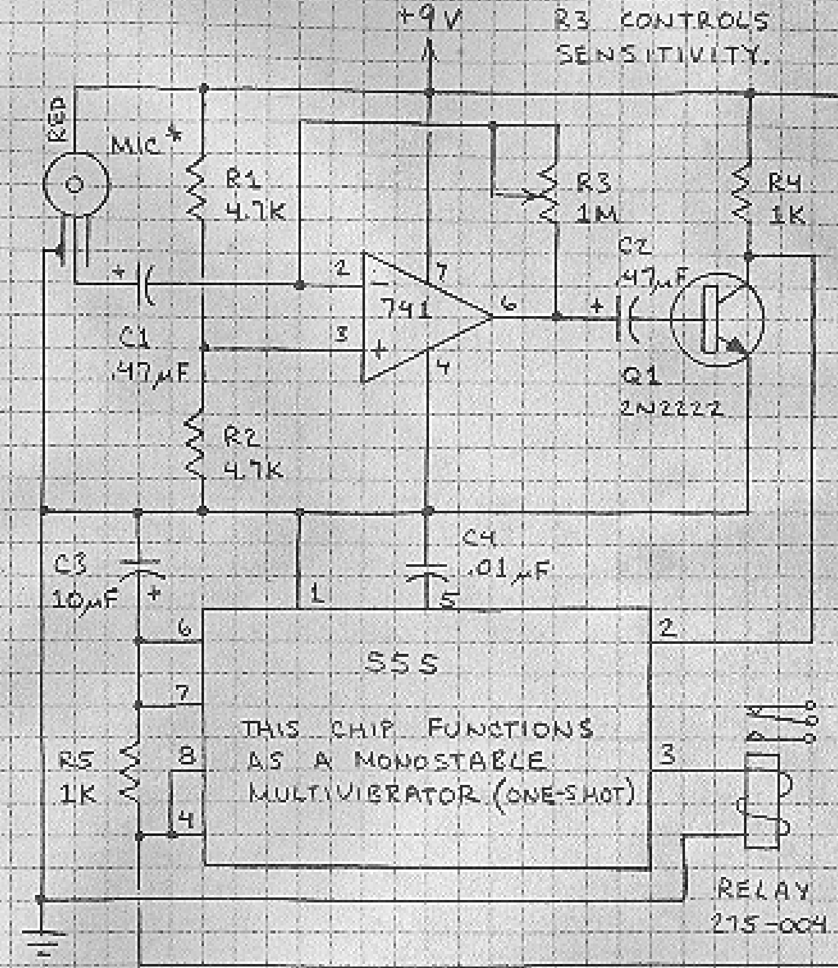
SOUND-LEVEL METER



*MICROPHONE (RADIO SHACK 270-092 OR SIMILAR).

THIS SIMPLE CIRCUIT IS AN EFFECTIVE SOUND-LEVEL METER. R1 CONTROLS THE GAIN OF THE 741 OP-AMP, HENCE THE SENSITIVITY OF THE CIRCUIT. THE METER CAN BE A PANEL METER OR A MULTIMETER SET TO READ CURRENT. THE CIRCUIT WAS TESTED WITH A PIEZO BUZZER THAT EMITTED A 6.5 KHz TONE AT A SOUND PRESSURE OF 90dB. WHEN THE BUZZER WAS 2" FROM THE MICROPHONE AND R1 WAS SET FOR MAXIMUM GAIN, THE METER INDICATED 1 mA. AT 12" THE OUTPUT FELL TO 0.4 mA. NORMAL SPEECH AT 12" GAVE FLUCTUATING SIGNAL UP TO 10 μA.

SOUND-ACTIVATED RELAY



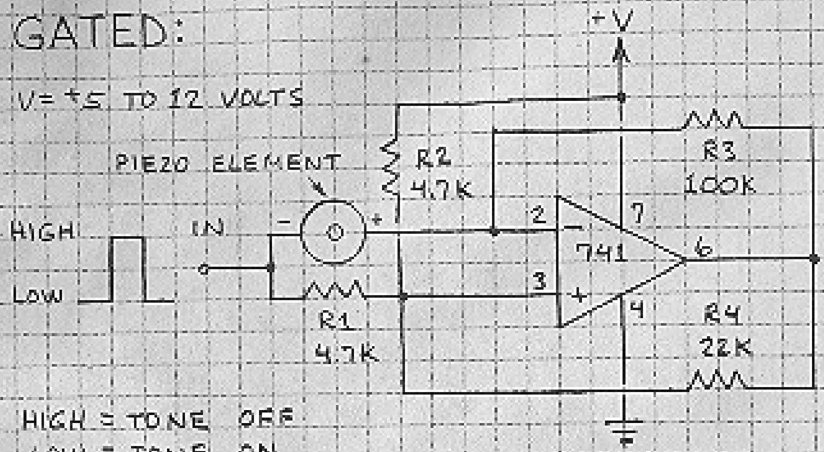
*MICROPHONE (RADIO SHACK 270-092 OR SIMILAR).

THIS CIRCUIT TRIPS RELAY IN RESPONSE TO LOUD SOUND (VOICE, CLAP, ETC.). R5 AND C3 CONTROL TIME RELAY STAYS PULLED IN (VALUES SHOWN GIVE ~12 SECONDS). IMPORTANT: USE 0.1μF CAPACITOR ACROSS POWER SUPPLY PINS OF BOTH THE 741 AND 555. REDUCE RESISTANCE OF R3 TO REDUCE SENSITIVITY.

PIEZO ELEMENT DRIVERS

GATED:

V= +5 TO 12 VOLTS

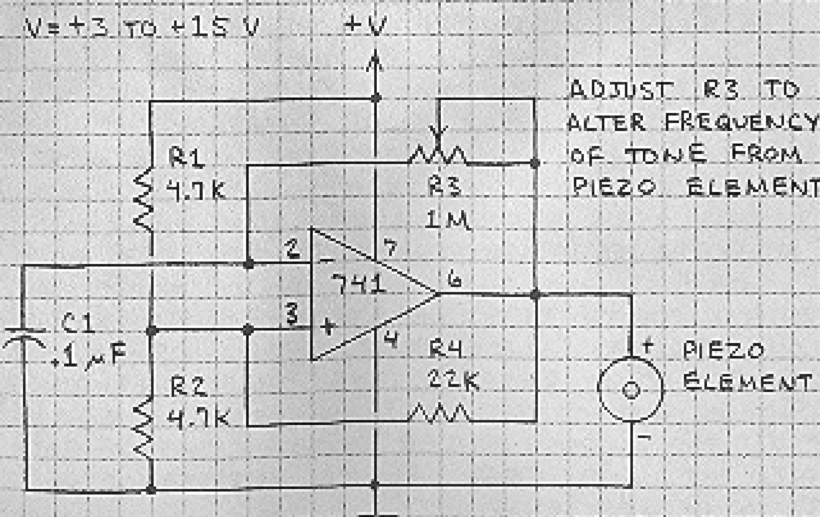


HIGH = TONE OFF
LOW = TONE ON

THIS CIRCUIT IS AN ASTABLE MULTIVIBRATOR IN WHICH A PIEZO ELEMENT DOUBLES AS THE TIMING CAPACITOR <u>AND</u> THE TONE SOURCE. TRIGGER WITH LOGIC SIGNAL OR BY CONNECTING SWITCH FROM INPUT TO GROUND.

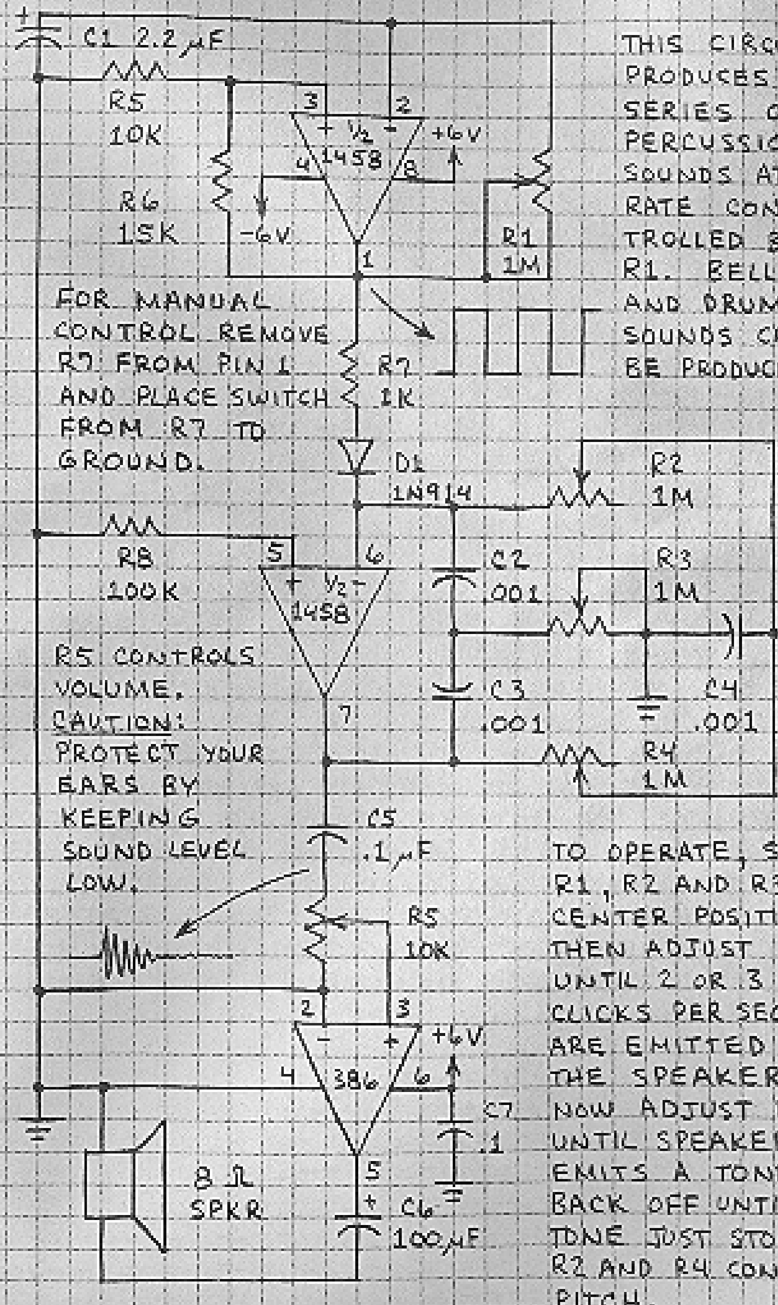
VARIABLE FREQUENCY

V= +3 TO +15 V



ADJUST R3 TO ALTER FREQUENCY OF TONE FROM PIEZO ELEMENT.

PERCUSSION SYNTHESIZER



THIS CIRCUIT PRODUCES A SERIES OF PERCUSSION SOUNDS AT A RATE CONTROLLED BY R1. BELL AND DRUM SOUNDS CAN BE PRODUCED.

FOR MANUAL CONTROL REMOVE R7 FROM PIN 1 AND PLACE SWITCH FROM R7 TO GROUND.

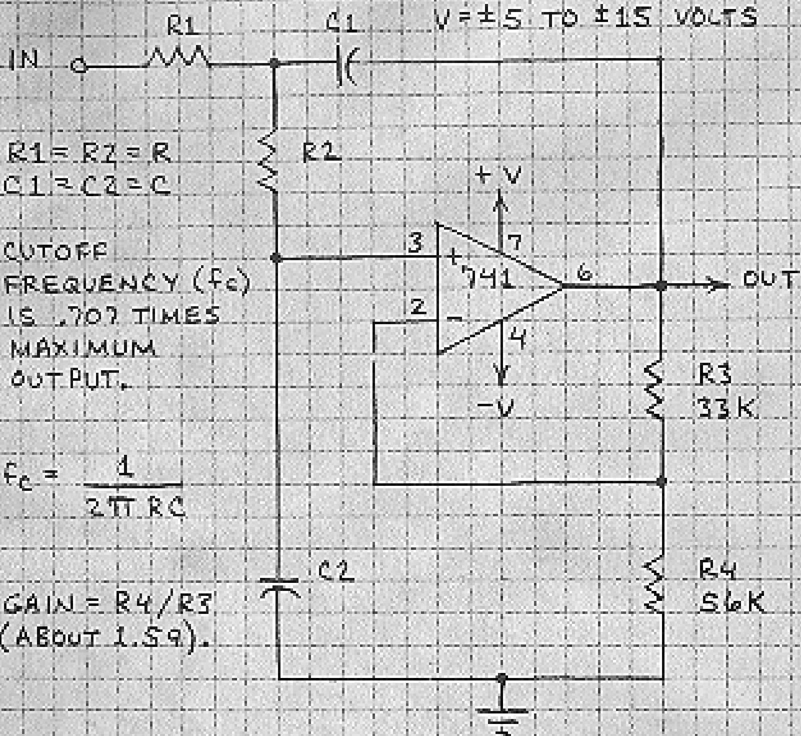
R5 CONTROLS VOLUME.

<u>CAUTION:</u> PROTECT YOUR EARS BY KEEPING SOUND LEVEL LOW.

TO OPERATE, SET R1, R2 AND R3 TO CENTER POSITIONS. THEN ADJUST R1 UNTIL 2 OR 3 CLICKS PER SECOND ARE EMITTED BY THE SPEAKER. NOW ADJUST R3 UNTIL SPEAKER EMITS A TONE. BACK OFF UNTIL TONE JUST STOPS. R2 AND R4 CONTROL PITCH.

LOW-PASS FILTER

V = ±5 TO ±15 VOLTS



R1 = R2 = R
C1 = C2 = C

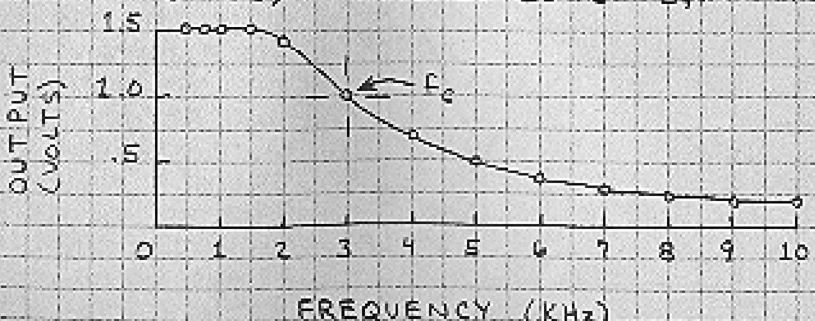
CUTOFF FREQUENCY (f_c) IS .707 TIMES MAXIMUM OUTPUT.

$$f_c = \frac{1}{2\pi RC}$$

GAIN = R4/R3 (ABOUT 1.59).

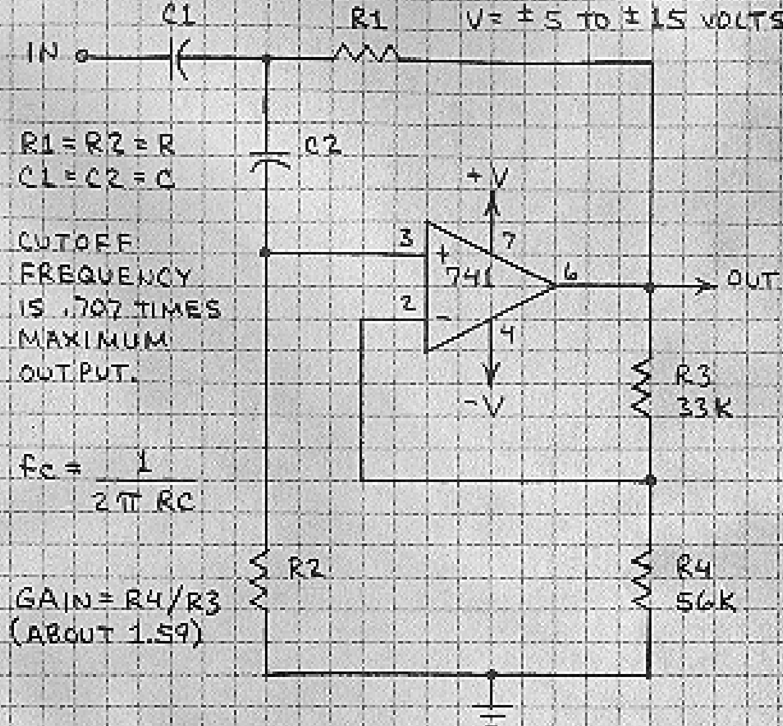
THIS IS AN EQUAL COMPONENT SALLEN-KEY FILTER. R3 SHOULD BE .586 x R4. SHOWN BELOW IS RESPONSE OF FILTER WHEN INPUT WAS A 1-VOLT SINE WAVE:

R = 4,700 Ω CALCULATED f_c = 3,386 Hz
C = .01 μF MEASURED f_c = 3,000 Hz



HIGH-PASS FILTER

V = ±5 TO ±15 VOLTS



R1 = R2 = R
C1 = C2 = C

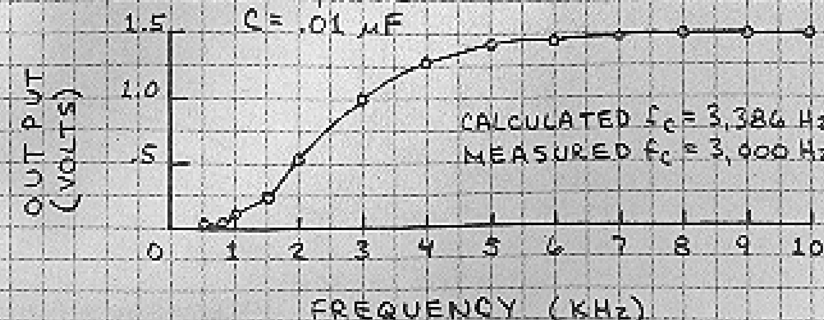
CUTOFF FREQUENCY IS .707 TIMES MAXIMUM OUTPUT.

$$f_c = \frac{1}{2\pi RC}$$

GAIN = R4/R3 (ABOUT 1.59)

THIS CIRCUIT IS IDENTICAL TO THE EQUAL COMPONENT SALLEN-KEY FILTER ON FACING PAGE EXCEPT R1 AND R2 AND C1 AND C2 HAVE BEEN INTERCHANGED. BELOW IS RESPONSE WHEN INPUT WAS A 1-VOLT SINE WAVE:

R = 4,700 Ω
C = .01 μF

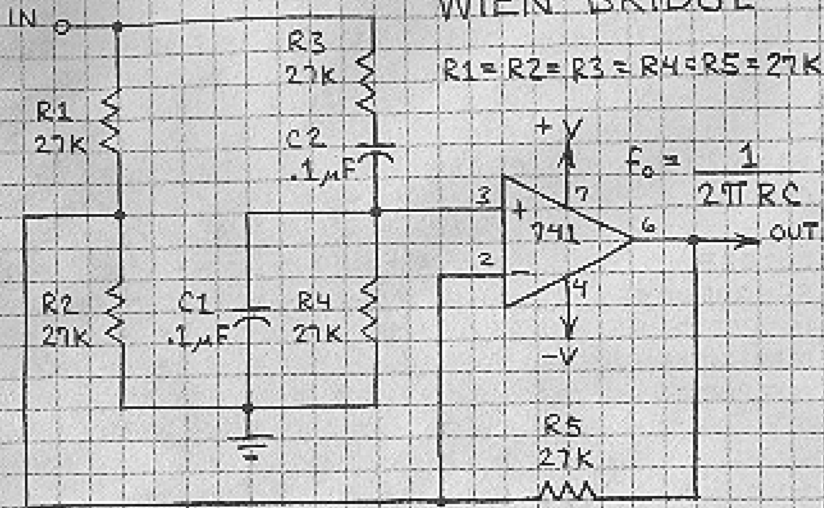


60-HZ NOTCH FILTER

WIEN BRIDGE

R1 = R2 = R3 = R4 = R5 = 27K

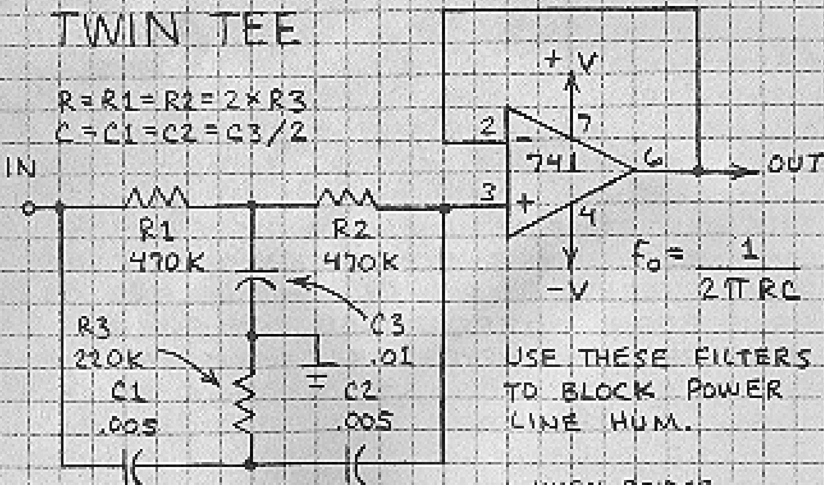
$$f_o = \frac{1}{2\pi RC}$$



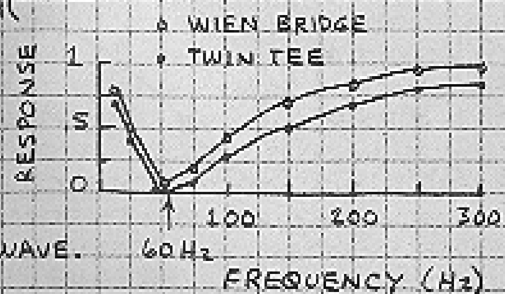
TWIN TEE

R = R1 = R2 = 2 × R3
C = C1 = C2 = C3/2

$$f_o = \frac{1}{2\pi RC}$$

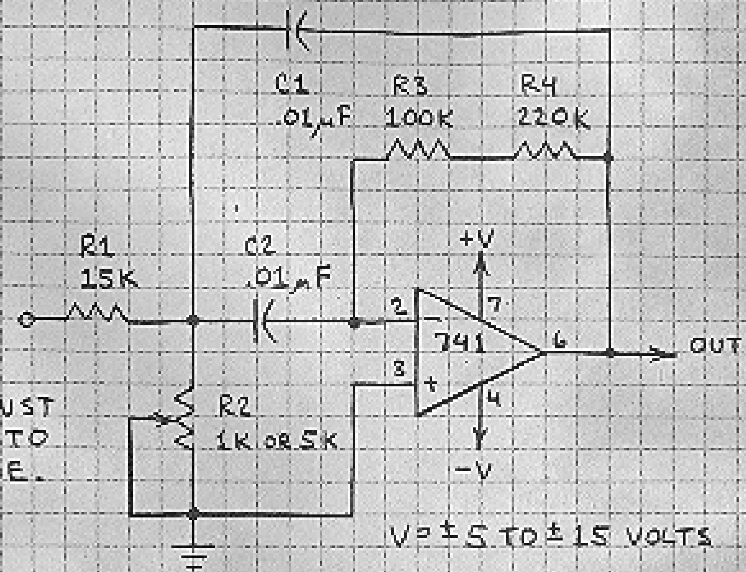


USE THESE FILTERS TO BLOCK POWER LINE HUM.



GRAPH SHOWS RESULTS FOR TEST VERSIONS OF BOTH FILTERS. INPUT WAS 1-VOLT PEAK-TO-PEAK SINE WAVE.

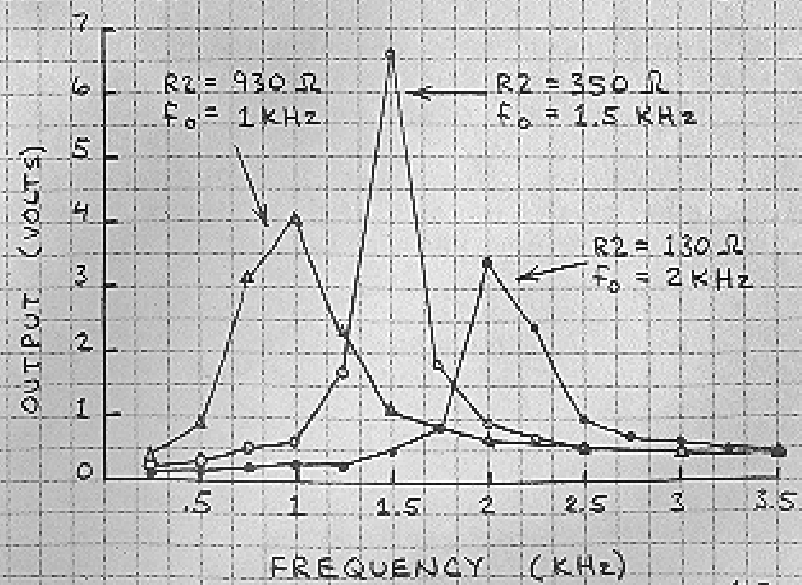
TUNABLE BANDPASS FILTER



ADJUST R2 TO TUNE.

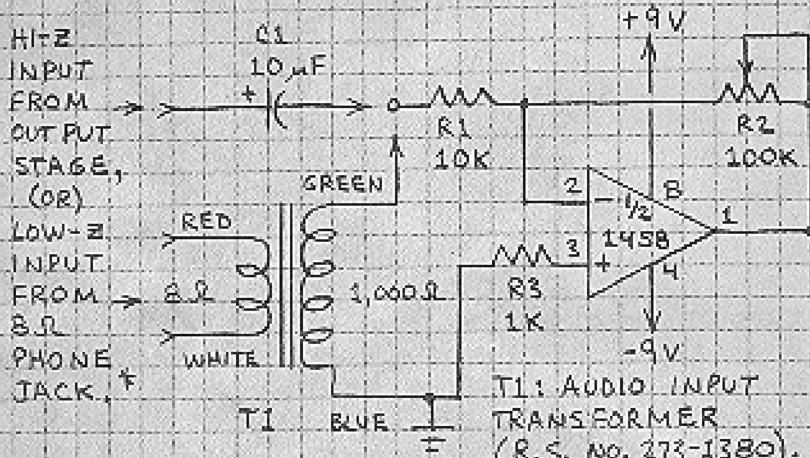
V = ±5 TO ±15 VOLTS

THIS FILTER CAN BE TUNED BY R2 TO PASS A NARROW FREQUENCY BAND BETWEEN A FEW HUNDRED Hz AND ABOUT 3,000 Hz. USE TO DETECT PRESENCE OF A TONE IN A SIGNAL. ACTUAL RESPONSE TO A 1-VOLT SINE WAVE:



MINI-COLOR ORGAN

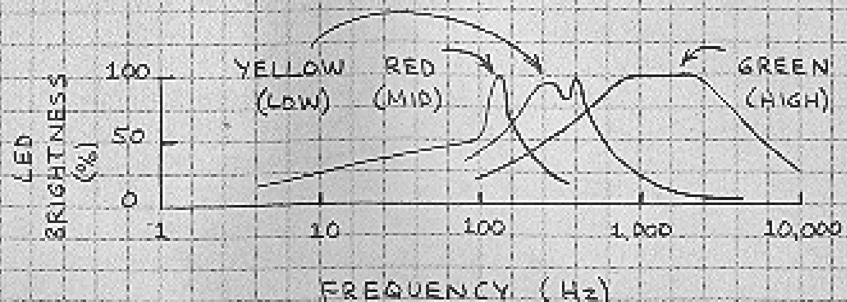
THIS ARRAY OF ACTIVE FILTERS WILL CONVERT THE AUDIO SIGNAL FROM A SMALL RADIO OR TAPE PLAYER INTO A FLICKERING PATTERN OF COLORS. R2 CONTROLS GAIN OF THE INPUT AMPLIFIER BELOW. USE RADIO/TAPE PLAYER VOLUME CONTROL AND R2 TO ADJUST INTENSITY OF LEDs.



T1: AUDIO INPUT TRANSFORMER (R.S. NO. 273-1380).

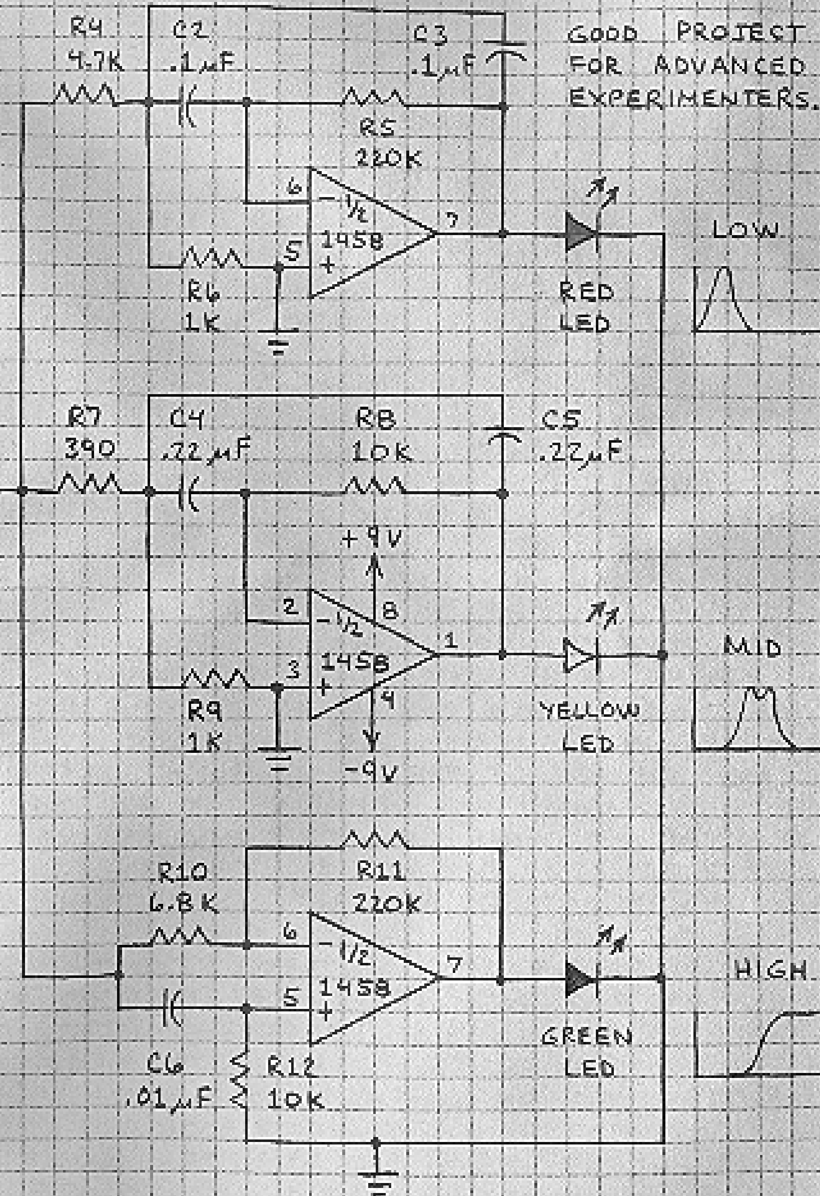
*INSERT PHONE PLUG CONNECTED TO T1 PART WAY IN PHONE JACK SO SPEAKER WILL NOT BE SWITCHED OFF.

LEDs VARY IN BRIGHTNESS. EXPERIMENT WITH DIFFERENT LEDs FOR BEST RESULTS. HERE IS ACTUAL RESPONSE OF CIRCUIT:



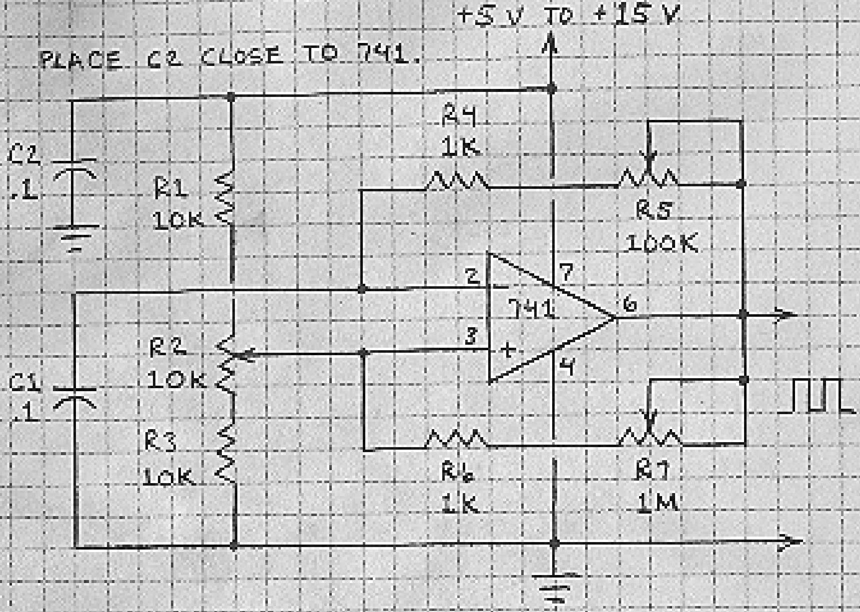
MINI-COLOR ORGAN (CONT.)

GOOD PROJECT FOR ADVANCED EXPERIMENTERS.



REDUCE R4 AND R7 TO INCREASE RED AND YELLOW BRIGHTNESS. INCREASE R11 TO INCREASE GREEN BRIGHTNESS.

SQUARE WAVE GENERATOR



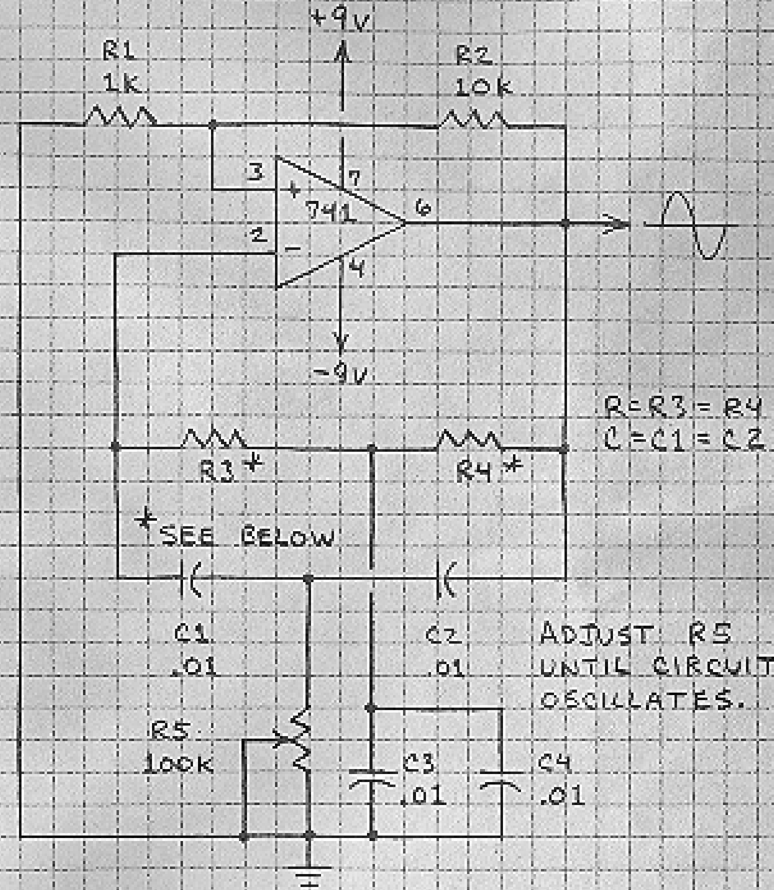
THIS CIRCUIT IS AN EASILY ADJUSTABLE SQUARE WAVE GENERATOR. THE TIMING COMPONENTS ARE C1, R4, R5, R6 AND R7. R1-R2-R3 CONTROL THE DURATION (OR "WIDTH") OF THE PULSES. THE PULSES ARE SYMMETRICAL WHEN R2 IS AT ITS CENTER POSITION. OK TO CONNECT R2 DIRECTLY TO +V AND ⏚, THEREBY ELIMINATING R1 AND R3. TYPICAL RESULTS:

C1	FREQUENCY
.001	11,480 Hz
.047	3,848 Hz
.01	2,155 Hz
.047	462 Hz
.1	227 Hz
.47	45 Hz
1.0	24 Hz

FOR THESE RESULTS, R1-R2-R3 REPLACED BY 4.7K FROM PIN 3 TO +V AND 4.7K FROM PIN 3 TO GROUND. R4 + R5 = 100K, R6 + R7 = 22K, AND +V = +12 VOLTS.

OK TO ADD FOLLOWER STAGE TO BUFFER OUTPUT.

SINE WAVE OSCILLATOR

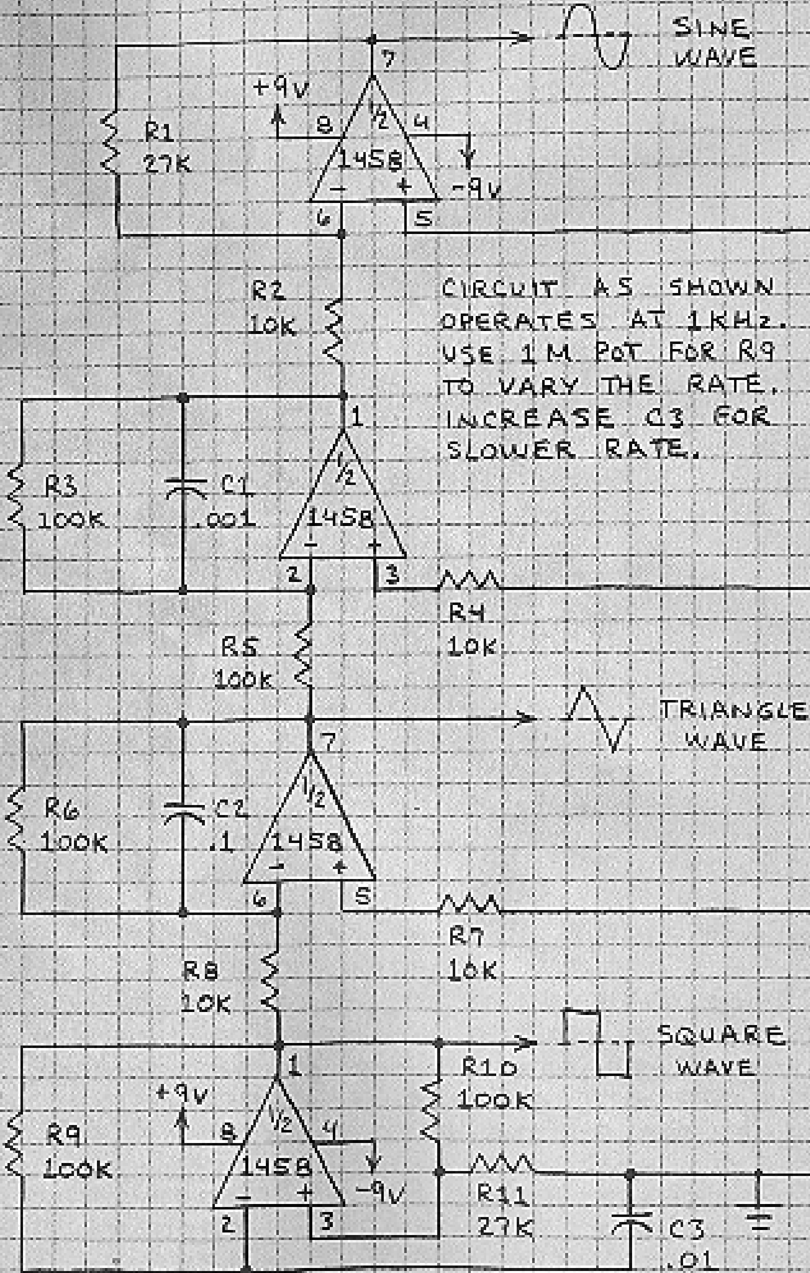


R3, R4, R5, C1, C2, C3, AND C4 FORM A TWIN-TEE FILTER. WHEN CONNECTED IN THE FEEDBACK LOOP OF AN OP-AMP, THE RESULTING CIRCUIT GENERATES A SINE WAVE. THE FREQUENCY IS $1/(2\pi RC)$.

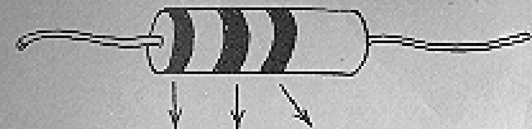
TYPICAL RESULTS FROM TEST CIRCUIT:

R3 = R4	FREQUENCY
4.7K	2926 Hz
10 K	1356 Hz
15 K	927 Hz

FUNCTION GENERATOR



RESISTOR COLOR CODE



BLACK	0	0	× 1
BROWN	1	1	× 10
RED	2	2	× 100
ORANGE	3	3	× 1,000
YELLOW	4	4	× 10,000
GREEN	5	5	× 100,000
BLUE	6	6	× 1,000,000
VIOLET	7	7	× 10,000,000
GRAY	8	8	× 100,000,000
WHITE	9	9	—

FOURTH BAND INDICATES TOLERANCE (ACCURACY):
GOLD = ± 5 %   SILVER = ± 10 %   NONE = ± 20 %

OHM'S LAW:

$V = IR$ $R = V/I$
$I = V/R$ $P = VI = I^2R$

ABBREVIATIONS

A = AMPERE   R = RESISTANCE
F = FARAD   V = VOLT
I = CURRENT   W = WATT
P = POWER   Ω = OHM

M (MEG-) = × 1,000,000
K (KILO-) = × 1,000
m (MILLI-) = .001
μ (MICRO-) = .000 001
n (NANO-) = .000 000 001
p (PICO-) = .000 000 000 001