Engineer's Mini-Notebook

Op Amp IC Circuits

Forrest M. Mims III
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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:

\[ \text{Gain} = \frac{R_F}{R_{IN}} \]

\[ V_{OUT} = -V_{IN} \left( \frac{R_F}{R_{IN}} \right) \]

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 differential amplifier.
THE FEEDBACK RESISTOR (RF) AND AN OP-AMP FORM A CLOSED FEEDBACK LOOP. WHEN RF 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:

\[ +9V \quad \text{---} \quad +9V \]
\[ \text{---} \quad \text{---} \quad \text{---} \quad \text{---} \quad \text{---} \quad \text{---} \]
\[ \text{GROUND} \]

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\,\mu F 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
POWER DISSIPATION
DIFFERENTIAL INPUT VOLTAGE
INPUT VOLTAGE (NOTE 1)
OUTPUT SHORT CIRCUIT TIME
OPERATING TEMPERATURE

±18 V
400 mW
±30 V
±15 V
INDEFINITE
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
INPUT RESISTANCE
VOLTAGE GAIN
COMMON-MODE REJECTION RATIO
SUPPLY CURRENT (NOTE 3)
POWER CONSUMPTION

1 TO 6 mV
.3 TO 1 MΩ
20,000 TO 160,000
70 TO 90 dB
3 TO 5.6 mA
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: -3 V to +36 V
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: 50 kΩ

TYPICAL APPLICATION

Gain = 20
BASIC INVERTING AMPLIFIER

\[ V = \pm 3 \text{ to } \pm 15 \text{ V} \]

\[ \text{IN} \]

\[ \text{R1} \]

\[ \text{R2} \]

\[ \text{R3} \]

\[ \text{OUT} \]

\[ \text{INPUT IS INVERTED AT OUTPUT.} \]

\[ \text{GAIN} = -\frac{R2}{R1} \]

\[ R3 = \frac{(R1 \cdot R2)}{(R1 + R2)} \]

EXAMPLE: IF \( R1 = 1000 \text{ OHMS} \) AND \( R2 = 10,000 \text{ OHMS} \), THEN \( \text{GAIN IS} \)

\[ -(10,000/1000) \text{ OR } -10. \]

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

\[ R1 \]

\[ 1K \]

\[ \text{VIN} \]

\[ +V \]

\[ R2 \]

\[ 1K \]

\[ \text{USE AS A BUFFER OR TO CONVERT} \]

\[ -V_{\text{OUT}} \text{ TO } +V_{\text{OUT}}. \]

\[ V_{\text{OUT}} = -V_{\text{IN}} \]

\[ V = \pm 3 \text{ TO } \pm 15 \text{ V} \]
NON-INVERTING AMPLIFIER

\[ V_{\text{in}} \]

\[ V = \pm 3 \text{ TO } \pm 15V \]

\[ \text{Gain} = 1 + \left( \frac{R_2}{R_1} \right) \]

**Example:** If \( R_1 = 1,000 \text{ OHMS} \) and \( R_2 = 10,000 \text{ OHMS} \), then Gain is \( 1 + \left( \frac{10,000}{1,000} \right) \) or 11.

**Note that** \( V_{\text{out}} \) **is an amplified but not inverted version of** \( V_{\text{in}} \).

UNITY-GAIN FOLLOWER

\[ V = \pm 3 \text{ TO } \pm 15V \]

\[ \text{Use to buffer signal from another circuit.} \]

\[ V_{\text{out}} = V_{\text{in}} \]
TRANS CONDUCTANCE AMPLIFIER

\[ V = \pm 3 \text{ to } \pm 15\text{V} \]

\[ V_{\text{in}} \]
\[ +V \]
\[ I_{\text{out}} = \text{CURRENT THROUGH LOAD.} \]
\[ \]  
\[ V_{\text{out}} \]
\[ R1 \text{ (LOAD)} \]
\[ R2 \]

\[ V_{\text{out}} = \left[ V_{\text{in}} (R1+R2) \right] / R2 \]

\[ I_{\text{out}} = V_{\text{out}} / (R1+R2) \]

\[ I_{\text{out}} = V_{\text{in}} / R2 \]

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

\[ +9\text{V} \]
\[ \]
\[ R3 \] 10K
\[ R3 \text{ CONTROLS } V_{\text{in}}. \text{ VARY R3 TO ALTER } I_{\text{out}}; \text{ HENCE THE BRIGHTNESS OF THE LED.} \]

\[ \]

\[ \text{LED} \]
\[ R2 \] 4.7K
TRANSIMPEDANCE AMPLIFIER

$V = \pm 3 \text{ to } \pm 15V$

\[ \text{GAIN} = \frac{V_{out}}{I_{in}} \]
\[ \text{GAIN} = -R_1 \]

**EXAMPLE:** If $R_1 = 1,000$ 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:

![Silicon solar cell circuit diagram]

This circuit can amplify the signal from non-current generators like thermistors and photoresistors. Connect one side of the device to +9V and the other to pin 2. Ground pin 3.
SINGLE-SUPPLY AMPLIFIER

\[ V_{out} = - \left( \frac{R_2}{R_1} \right) \]

\[ +5 \text{ TO } +15 \text{V} \]

\[ C_1 \quad R_1 \quad 0.47 \quad 1K \]
\[ R_3 \quad 47K \]
\[ R_2 \quad 100K \]
\[ C_2 \quad 0.47 \]
\[ R_4 \quad 47K \]
\[ V_{in} \quad 0 \]
\[ V_{out} \quad \]
\[ R_L \]

THIS POINT IS \( \frac{1}{2} +V \).

This is an inverting amplifier designed to operate from a single-polarity supply. With the values for \( R_1 \) and \( R_2 \) given above, the gain is 100. Capacitors \( C_1 \) and \( C_2 \) must be used. Therefore, this circuit will amplify a fluctuating AC signal but not a DC signal.

\( C_1 \) should be approximately \( 1/(2\pi f_{\text{LOW}} R_1) \). \( \text{LOW} \) is the low frequency cutoff or 300 Hz for the circuit above. \( C_2 \) should be approximately \( 1/(2\pi f_{\text{LOW}} R_L) \). \( R_L \) 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 \( R_3 \) and \( R_4 \) sets \( V_{out} \) at \( 1/2 +V \). The output then fluctuates above and below \( 1/2 +V \) like this:

\[ \begin{align*}
  +V \\
  1/2V \\
  0V \\
  -1/2V \\
  -V
\end{align*} \]

\[ \text{OUTPUT SIGNAL} \]
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 0.1uF capacitors.

Audio Mixer

OK to use with the amplifier above.

Output

Use with multiple microphones.
SUMMING AMPLIFIER

Vin 1 10K
R1

Vin 2 10K
R2

R3 10K

R4 1K

741

R5 1K

1458

R6 1K

R7 1K

Vout

V = ±5 V TO ±15 V

FOR TEST AT LEFT V = ±10V.

TEST RESULT:

Vin1 = +4.0 V
Vin2 = +0.8 V
Vout = -4.8 V

Vout = -(Vin1 + Vin2)

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:

Vin 1 10K
R1

Vin 2 10K
R2

1458

1458

R6 1K

R5 1K

R4 1K

R7 1K

Vout

Vout = Vin1 + Vin2

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DIFFERENCE AMPLIFIER

\[ V = \pm5V \text{ to } \pm15V \]

FOR TEST BELOW
\[ V = \pm10V. \]

TEST RESULT:
\[
\begin{align*}
\text{Vin}_1 &= 0.9 \text{ V} \\
\text{Vin}_2 &= 5.0 \text{ V} \\
\text{Vout} &= 4.1 \text{ V}
\end{align*}
\]

\[ \text{Vout} = \text{Vin}_2 - \text{Vin}_1 \]

THE OUTPUT OF THE DIFFERENCE AMPLIFIER IS \( \text{Vin}_2 - \text{Vin}_1 \). THE INPUT VOLTAGES SHOULD NOT EXCEED \( \pm15 \text{ V} \). THE CIRCUIT BELOW REVERSES THE POLARITY OF \( \text{Vin}_2 - \text{Vin}_1 \):

\[ \text{Vout} = -(\text{Vin}_2 - \text{Vin}_1) \]
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.

\[ R_3 = \frac{R_1 \cdot R_2}{R_1 + R_2} \]

\[ \text{for values shown and } f = 2,000 \text{ Hz, } \pm 2.5 \text{-volt square wave, the output is a } \pm 1.3 \text{-volt triangle.} \]

SINGLE-SUPPLY INTEGRATOR

For values shown and \( f = 2,000 \text{ Hz, } \pm 2.5 \text{ volts, the output is a } \pm 1.3 \text{-volt triangle wave.} \)

\( V = +5 \text{ to } +15 \text{ V} \)
DUAL-SUPPLY DIFFERENTIATOR

The output of the differentiator is proportional to the derivative of the input.

\[ V = \pm 5V \text{ to } \pm 15V \]

For values shown and \( f = 2,000 \text{ Hz}, \pm 2.5\text{-volt triangle wave}, \) the output is a \( \pm 10\text{-volt square wave}. \)

The differentiator will transform a square wave into pulses:

\[ f = 2,000 \text{ Hz}, V = \pm 10V \]
\[ \text{IN} = \pm 0.5V, \text{OUT} = \pm 7V \]

SINGLE-SUPPLY DIFFERENTIATOR

For values shown and \( f = 2,000 \text{ Hz}, \pm .5\text{ volt}, \) the output is \( \pm 2\text{ volt}. \)
PEAK DETECTOR

$V = \pm 5$ TO $\pm 15$ VOLTS

THIS OP-AMP IS A VOLTAGE FOLLOWER THAT BUFFERS C1 FROM THE OUTPUT.

THIS CIRCUIT FOLLOWS AN INCOMING VOLTAGE SIGNAL AND STORES THE MAXIMUM VOLTAGE IN C1. PRESS S1 TO DISCHARGE C1 AND RESET CIRCUIT. CONNECT A VOMETER 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

\[ V = \pm 5 \text{ TO } \pm 15 \text{ V} \]

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

R1
\[ 1K \]

INPUT

\[ 3 \]

\[ 4 \]

\[ -V \]

\[ 7 \]

\[ +V \]

R2
\[ 10K \]

D1

D2

\[ V \]

\[ 2 \]

\[ 6 \]

\[ \text{OUTPUT} \]

= \[ -R2/R1 \]

VALUES SHOWN GIVE \(-(\times 10)\) GAIN. \(D1 = D2 = 5 \text{ VOLTS.}\)

NON-INVERTING CLIPPER

\[ V = \pm 5 \text{ TO } \pm 15 \text{ V} \]

R1
\[ 1K \]

\[ 3 \]

\[ 7 \]

\[ +V \]

\[ 2 \]

\[ 6 \]

\[ \text{OUTPUT} \]

\[ 4 \]

\[ -V \]

R2
\[ 10K \]

D1

D2

\[ 1 \]

\[ \text{TYPICAL WAVEFORMS} \]

D1 = D2 = 5 V

VALUES SHOWN GIVE \(\times 11\) GAIN.
BISTABLE RS FLIP-FLOP

BISTABLE RS FLIP-FLOP

\[ +V \quad V = \pm 5 \text{ TO } \pm 15 \text{ VOLTS} \]

\[ \text{OK TO USE RED/GREEN BICOLOR LED FOR LEDS.} \]

\[ R_3 \quad 10K \]

\[ R_1 \quad 4.7K \]

\[ R_0 \quad 2 \]

\[ R_2 \quad 4.7K \]

\[ R_4 \quad 1K \]

\[ R_5 \quad 47K \]

\[ R_6 \quad 1K \]

\[ R_7 \quad 1K \]

\[ R_8 \quad 1K \]

\[ R_9 \quad 1K \]

\[ Q_2 \quad 2N2222 \]

\[ Q_1 \quad 2N2222 \]

\[ LED_1 \]

\[ LED_2 \]

D1 AND D2 ARE OPTIONAL S.1-VOLT ZENER DIODES. SEE BELOW.

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

<table>
<thead>
<tr>
<th>INPUT</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>R</td>
<td>S</td>
</tr>
<tr>
<td>GND</td>
<td>+V</td>
</tr>
<tr>
<td>GND</td>
<td>-V</td>
</tr>
<tr>
<td>+V</td>
<td>GND</td>
</tr>
<tr>
<td>-V</td>
<td>GND</td>
</tr>
</tbody>
</table>

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

USE D1 AND D2 TO LIMIT OUTPUT LEVEL.
**MONOSTABLE MULTIVIBRATOR**

![Circuit Diagram]

A negative trigger pulse causes the op-amp output to swing from low to high for a time approximately equal to $R_2 \times C_2$. Use to divide an incoming signal and to convert an irregular input pulse to a uniform output pulse. Typical results:

- **Trigger Pulses**
  - $V = \pm 9\, \text{V}$
- **Divide-by-1 Output**
  - $C_2 = 0.001\, \mu\text{F}$
  - $R_2 = 25\, \text{k}\Omega$
  - $V = \pm 9\, \text{V}$
  - Divide-by-2 Output
  - $C_2 = 0.01\, \mu\text{F}$
  - $R_2 = 18.2\, \text{k}\Omega$

**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 \( V_{\text{REF}} \) AND THE OTHER IS CALLED THE INPUT VOLTAGE \( V_{\text{IN}} \). WHEN \( V_{\text{IN}} \) RISES ABOVE OR FALLS BELOW \( V_{\text{REF}} \), 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 Diagram](image)

WHEN \( V_{\text{IN}} \) EXCEEDS \( V_{\text{REF}} \), OUTPUT SWITCHES FROM LOW TO HIGH.

![Inverting Comparator Diagram](image)

WHEN \( V_{\text{IN}} \) EXCEEDS \( V_{\text{REF}} \), OUTPUT SWITCHES FROM HIGH TO LOW.
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 $V_{IN}$.

\[ V_{OUT} = 1.9V \quad \text{at} \quad V_{IN} = 4.5V \]

\[ V_{OUT} = 8.2V \quad \text{at} \quad V_{IN} = 9V \]

LED OFF

LED ON
BASIC WINDOW COMPARATOR

$+V = 5 \text{ TO } 15 \text{ V}$

OK TO USE 741, 339, ETC.

THIS IS AMONG THE MOST VERSATILE OF COMPARATOR CIRCUITS. ASSUME $V_{\text{REF (HIGH)}}$ IS 5.5 VOLTS AND $V_{\text{REF (LOW)}}$ IS 2.5 VOLTS. CIRCUIT THEN OPERATES LIKE THIS:

$V_{\text{IN (VOLTS)}}$

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

$$V_{\text{REF}} = +V \left( \frac{R_2}{R_1 + R_2} \right)$$

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BUILD THIS CIRCUIT ON A BREADBOARD TO LEARN BASICS OF THE WINDOW COMPARATOR. USE VOLTOMETER 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

PRESS S1 TO RESET.

+9V USE TO START AN AUTOMATIC 3-STEP SEQUENCE

R1 4.7K
R4 1M
7/2 1458B
2
R5 1K
S1
LED1
D1 1N914
D2 1N914
R6 1K
C1 100µF
LED3
R7 10K
Q1 2N2222
R8 470
LED2

OK TO DRIVE EXTERNAL CIRCUIT.

<table>
<thead>
<tr>
<th>DELAY†</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10K</td>
</tr>
<tr>
<td>3</td>
<td>100K</td>
</tr>
<tr>
<td>4</td>
<td>1M</td>
</tr>
</tbody>
</table>

OUTPUT 1 = 0

†DELAY IN SECONDS

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.
LEDs glow in sequence as input voltage rises. LEDs also respond to change in resistance at input. Touch inputs with finger to observe. ConnectCdS cell across inputs to make lightmeter.
LIGHT-ACTIVATED RELAYS

PHOTOTRANSISTOR:

ILLUMINATE Q1 TO ACTIVATE RELAY.

PHOTORESISTOR:

+9 V ILLUMINATE CDS CELL TO ACTUATE RELAY.

REVERSE 741 INPUTS TO REVERSE OPERATION.
LIGHT-ACTIVATED ALERTER

CDS PHOTORESISTOR

+9 V

R1 100K
R2 100K
R3 10K
R4 4.7K
Q1 2N2222
PIEZO BUZZER

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

CDS PHOTORESISTOR

+9 V

R1 100K
R2 100K
R3 10K
R4 4.7K
Q1 2N2222
PIEZO BUZZER

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

FREQUENCY INCREASES AS LIGHT LEVEL AT Cds CELL RISES.

OK TO CONNECT TO 386 SPEAKER AMPLIFIER.

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

ADJUST R5 FOR BALANCE. R5 50K
CAUTION:
THIS CIRCUIT IS
VERY SENSITIVE.
TOO MUCH LIGHT
WILL "SLAM" THE
NEEDLE OF AN
ANALOG METER.

FULL-SCALE METER READINGS:

<table>
<thead>
<tr>
<th>S1</th>
<th>METER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-10mA</td>
</tr>
<tr>
<td>2</td>
<td>0-1μA</td>
</tr>
<tr>
<td>3</td>
<td>0-1mA</td>
</tr>
</tbody>
</table>

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 90 dB. 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 mA.
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 and 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 10K controls volume.
CAUTION: 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.

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LOW-PASS FILTER

\[ V = \pm 5 \text{ TO } \pm 15 \text{ VOLTS} \]

\[ R_1 = R_2 = R \]
\[ C_1 = C_2 = C \]

**CUT-OFF FREQUENCY (\(f_c\)) IS 0.707 TIMES MAXIMUM OUTPUT.**

\[ f_c = \frac{1}{2\pi RC} \]

**GAIN = \(R_4/R_3\)**
(About 1.59).

THIS IS AN EQUAL COMPONENT SALLEN-KEY FILTER. \(R_3\) SHOULD BE \(.586 \times R_4\). SHOWN BELOW IS RESPONSE OF FILTER WHEN INPUT WAS A 1-VOLT SINE WAVE:

\[ R = 4,700 \ \Omega \]
\[ C = .01 \mu F \]

**CALCULATED** \(f_c = 3,386 \text{ Hz} \)
**MEASURED** \(f_c = 3,000 \text{ Hz} \)

![Graph showing frequency response](image-url)
HIGH-PASS FILTER

IN

C1

R1

V = ±5 to ±15 Volts

R2 = R
C1 = C2 = C

CUT OFF FREQUENCY IS 0.707 TIMES MAXIMUM OUTPUT.

f_C = \frac{1}{2\pi RC}

GAIN = \frac{R4}{R3} (ABOUT 1.59)

R3 33K

R2

R4 56K

OUT

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 ohm
C = 0.01 µF

CALCULATED f_C = 3,386 Hz
MEASURED f_C = 3,000 Hz
60-HZ NOTCH FILTER

Wien Bridge

\[ R_1 = R_2 = R_3 = R_4 = R_5 = 27 \, \text{K} \]

\[ f_0 = \frac{1}{2\pi RC} \]

TWIN TEE

\[ R = R_1 = R_2 = 2 \times R_3 \]

\[ C = C_1 = C_2 = C_3/2 \]

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

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:

- R2 = 930 Ω, f₀ = 1 kHz
- R2 = 350 Ω, f₀ = 1.5 kHz
- R2 = 130 Ω, f₀ = 2 kHz
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.

*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:

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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 \( \frac{1}{2} \), thereby eliminating R1 and R3. Typical results:

<table>
<thead>
<tr>
<th>C1</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>.001</td>
<td>11,480 Hz</td>
</tr>
<tr>
<td>.047</td>
<td>3,848 Hz</td>
</tr>
<tr>
<td>.01</td>
<td>2,155 Hz</td>
</tr>
<tr>
<td>.047</td>
<td>462 Hz</td>
</tr>
<tr>
<td>.1</td>
<td>227 Hz</td>
</tr>
<tr>
<td>.47</td>
<td>45 Hz</td>
</tr>
<tr>
<td>1.0</td>
<td>24 Hz</td>
</tr>
</tbody>
</table>

For these results, R1-R2-R3 replaced by 4.7 K from pin 3 to +V and 4.7 K from pin 3 to ground. R4 + R5 = 100 K, R6 + R7 = 22 K, and +V = +12 Volts.

OK to add follower stage to buffer output.
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/(2πRC).

**Typical Results**

<table>
<thead>
<tr>
<th>R3 = R4</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7 k</td>
<td>2926 Hz</td>
</tr>
<tr>
<td>10 k</td>
<td>1356 Hz</td>
</tr>
<tr>
<td>15 k</td>
<td>927 Hz</td>
</tr>
</tbody>
</table>
FUNCTION GENERATOR

Circuit as shown operates at 1kHz. Use 1M pot for R9 to vary the rate. Increase C3 for slower rate.

SINE WAVE

TRIANGLE WAVE

SQUARE WAVE

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