Engineer's Mini-Notebook
Op Amp IC Circuits
Forrest M. Mims III
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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.


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

![Diagram]

\[ V_{out} = -\frac{R_f}{R_{in}} V_{in} \]

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 VOUT). 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 MAX-
IMUM 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:

\[
\begin{align*}
+9 \text{V} & \quad 9 \text{V} \\
\text{+} & \quad | \quad | \\
\text{+} & \quad | \quad | \\
\text{G} & \quad | \quad | \\
\end{align*}
\]

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 PIN MUST BE BYPASSED BY CONNECT-
ING A 0.1uF 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 CHOPS OP-AMPS.
USE A HIGH-IMPEDANCE VOLTOMETER 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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>±18 V</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>500 mA</td>
</tr>
<tr>
<td>Differential Input Voltage</td>
<td>±100 mV</td>
</tr>
<tr>
<td>Input Voltage (Note 1)</td>
<td>±15 V</td>
</tr>
<tr>
<td>Output Short-Circuit Time</td>
<td>Indefinite</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>0°C to 70°C</td>
</tr>
</tbody>
</table>

**CHARACTERISTICS (Note 2)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Offset Voltage</td>
<td>2 to 6 mV</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>1 to 2 MΩ</td>
</tr>
<tr>
<td>Voltage Gain</td>
<td>20,000 to 200,000 mV</td>
</tr>
<tr>
<td>Common-Mode Rejection Ratio</td>
<td>70 to 80 dB</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1.5 to 1.5 MHz</td>
</tr>
<tr>
<td>Slew Rate</td>
<td>1.5 V/μsec</td>
</tr>
<tr>
<td>Supply Current</td>
<td>1.7 to 2.8 mA</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>50 to 85 mW</td>
</tr>
</tbody>
</table>

**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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>±18 V</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>400 mA</td>
</tr>
<tr>
<td>Differential Input Voltage</td>
<td>±100 mV</td>
</tr>
<tr>
<td>Input Voltage (Note 1)</td>
<td>±15 V</td>
</tr>
<tr>
<td>Output Short-Circuit Time</td>
<td>Indefinite</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>0°C to 70°C</td>
</tr>
</tbody>
</table>

**CHARACTERISTICS (Note 2)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Offset Voltage</td>
<td>1 to 6 mV</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>1.3 to 2 MΩ</td>
</tr>
<tr>
<td>Voltage Gain</td>
<td>20,000 to 110,000 mV</td>
</tr>
<tr>
<td>Common-Mode Rejection Ratio</td>
<td>70 to 90 dB</td>
</tr>
<tr>
<td>Supply Current (Note 3)</td>
<td>3 to 6 mA</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>85 mW</td>
</tr>
</tbody>
</table>

**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: ±36 V or ±18 V
- DIFFERENTIAL INPUT VOLTAGE: 36 V
- INPUT VOLTAGE RANGE: -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: 1.8 to 2 mA
- OUTPUT SINK CURRENT: 260 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 GND AND 7 FOR GAIN OF 200.

MAXIMUM RATINGS

- SUPPLY VOLTAGE: +15 V
- POWER DISSIPATION: 500 mW
- INPUT VOLTAGE RANGE: ±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: 0.5 TO 3.25 W
- VOLTAGE GAIN: 30 TO 200
- BANDWIDTH: 300 kHz
- TOTAL HARMONIC DISTORTION: 0.2 %
- INPUT RESISTANCE: 50 kΩ

TYPICAL APPLICATION

GAIN = 20

IN 3 +V 2
                    386 5 +1
                    210 µF
                    8.0
                    SPKR
                    VOL VOLUME CONTROL
                    10K
BASIC INVERTING AMPLIFIER

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

\[ \text{IN} \]

\[ R_1 \]

\[ R_2 \]

\[ R_3 \]

\[ \text{OUT} \]

\[ +V \]

\[ -V \]

\[ \text{GAIN} = -\left( \frac{R_2}{R_1} \right) \]

\[ R_3 = \frac{(R_1 R_2)}{(R_1 + R_2)} \]

EXAMPLE: IF \( R_1 = 1000 \) OHMS AND \( R_2 = 10,000 \) OHMS, THEN GAIN IS \(-\left( \frac{10,000}{1000} \right) \) 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

\[ V_{\text{IN}} \]

\[ 1\text{K} \]

\[ +V \]

\[ R_1 \]

\[ R_2 \]

\[ 1\text{K} \]

\[ \text{GAIN} = -\left( \frac{R_2}{R_1} \right) \]

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

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

NON-INVERTING AMPLIFIER

\[ V_{\text{IN}} \]

\[ +V \]

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

\[ R_1 \]

\[ R_2 \]

EXAMPLE: IF \( R_1 = 1000 \) OHMS AND \( R_2 = 10,000 \) 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

\[ V_{\text{IN}} \]

\[ +V \]

\[ \text{USE TO BUFFER SIGNAL FROM ANOTHER CIRCUIT.} \]

\[ V_{\text{OUT}} = V_{\text{IN}} \]
TRANSCONDUCTANCE AMPLIFIER

\[ V_{\text{in}} \leq 1 \text{ to } 15 \text{ V} \]

\[ I_{\text{out}} = \text{CURRENT THROUGH LOAD} \]

\[ V_{\text{out}} = \left[ V_{\text{in}} \left( R_1 + R_2 \right) \right] / R_2 \]

\[ I_{\text{out}} = V_{\text{out}} / (R_1 + R_2) \]

\[ I_{\text{out}} = V_{\text{in}} / R_2 \]

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 V_{\text{in}}, V_{\text{out}}, and R2 to alter I_{\text{out}} hence the brightness of the LED.

EXAMPE: If \( R_1 = 1,000 \text{ ohms then } GAIN = -1,000. \)

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

+9 V

R1

4.7 K

R2

-9 V

USE R1 TO VARY THE CIRCUIT'S GAIN.

This circuit can amplify the signal from non-current generators like thermistors and phototransistors. Connect one side of device to +9 V 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 \( \frac{1}{2(2\pi f \text{flow} R1)} \). (f low is the low-frequency cutoff or 300 Hz for the circuit above.) C2 should be approximately \( \frac{1}{2(2\pi f \text{low} R2)} \). (R2 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:

\[
\begin{align*}
+V & \quad 1/2 + V \quad 0 \quad -9V
\end{align*}
\]

AUDIO AMPLIFIER

The 741 is a preamplifier. R2 controls its gain. The 384 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\mu\text{F} capacitors.

AUDIO MIXER

OK to use with the amplifier above.
SUMMING AMPLIFIER

\[ R_1 \quad 10K \quad \text{V} = \pm 5\text{V} \text{ to } \pm 15\text{V} \]
\[ V_{\text{in}1} \quad \text{+} \quad 10K \quad \text{+} \quad V_{\text{in}2} \quad \text{+} \quad V_{\text{out}} \]

**TEST RESULT:**
\[ V_{\text{in}1} = 4.0\text{V} \]
\[ V_{\text{in}2} = 1.8\text{V} \]
\[ V_{\text{out}} = -4.8\text{V} \]

\[ V_{\text{out}} = -(V_{\text{in}1} + V_{\text{in}2}) \]

The output of the summing amplifier is the sum of the input voltages. The sum of the inputs should not exceed \( \pm 5\text{V} \). Allow two or three more inputs. (Use 10K resistor to Pin 2 for each input.) The circuit below preserves the polarity of \( V_{\text{in}1} \):

DIFERENCE AMPLIFIER

\[ R_1 \quad 100K \quad \text{V} = \pm 5\text{V} \text{ to } \pm 15\text{V} \]
\[ V_{\text{in}1} \quad \text{+} \quad 100K \quad \text{+} \quad V_{\text{in}2} \quad \text{+} \quad V_{\text{out}} \]

**TEST RESULT:**
\[ V_{\text{in}1} = 0.9\text{V} \]
\[ V_{\text{in}2} = 5.0\text{V} \]
\[ V_{\text{out}} = 4.1\text{V} \]

\[ V_{\text{out}} = V_{\text{in}2} - V_{\text{in}1} \]

The output of the difference amplifier is \( V_{\text{in}2} - V_{\text{in}1} \). The input voltages should not exceed \( \pm 5\text{V} \). The circuit below reverses the polarity of \( V_{\text{in}2} - V_{\text{in}1} \):
**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.

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

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

**DUAL-SUPPLY DIFFERENTIATOR**

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

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

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:

\[ f = 2,000 \text{ Hz}, \quad V = \pm 10 \text{ V} \]

\[ \text{IN} = \pm 0.5 \text{ V}, \quad \text{OUT} = \pm 7 \text{ V} \]

**SINGLE-SUPPLY INTEGRATOR**

\[ C_2 = 1 \mu F \]

\[ R_1 = 4.7K \]

\[ R_2 = 4.7K \]

\[ 20 \ell \]

\[ \text{IN} + V \]

\[ \text{OUT} \]

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

**SINGLE-SUPPLY DIFFERENTIATOR**

\[ C_2 = 1 \mu F \]

\[ R_1 = 4.7K \]

\[ R_2 = 4.7K \]

\[ \text{IN} + V \]

\[ \text{OUT} \]

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

$V = \pm 5 \text{ to } \pm 15 \text{ volts}$

This circuit follows an incoming voltage signal and stores the maximum voltage in $C_1$. Press $S_1$ to discharge $C_1$ and reset circuit. Connect a voltmeter from output to ground to measure the peak voltage stored in $C_1$. The circuit functions like this:

**NOTE:**
- How the output follows the preceding high (peak) input.
- Also note that the charge on $C_1$ will gradually leak away. $C_1$ in the test circuit fell 10 millivolts/second.

---

**INVERTING CLIPPER**

$V = \pm 5 \text{ to } \pm 15 \text{ volts}$

$D_1$ and $D_2$ 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 = $-R_2/R_1$

Values shown give $-10$ gain, $V_1 = D_2 = 5 \text{ volts}$.

---

**NON-INVERTING CLIPPER**

$V = \pm 5 \text{ to } \pm 15 \text{ volts}$

Gain = $1 + R_2/R_1$

Values shown give $\times 11$ gain.
BISTABLE RS FLIP-FLOP

\[ V = 3.5 \text{ to } 16 \text{ VOLS} \]

\[ R_3 = 10 \text{ k}\Omega \]
\[ R_1 = 4.7 \text{ k}\Omega \]
\[ R_0 = 4.7 \text{ k}\Omega \]
\[ S = 4.7 \text{ k}\Omega \]
\[ R_2 = 1 \text{ k}\Omega \]
\[ Q_1 = 2N2222 \]
\[ Q_2 = 2N2222 \]

DI AND D2 ARE OPTIONAL 5.1-VOLT ZENER DIODES. SEE BELOW.

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

<table>
<thead>
<tr>
<th>INPUT</th>
<th>LED</th>
<th>THESE OUTPUTS HAVE MEMORY AND HOLD THEIR STATE EVEN WHEN S INPUT FLOATS. USE D1 AND D2 TO LIMIT OUTPUT LEVEL.</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>S</td>
<td>1</td>
</tr>
<tr>
<td>GND</td>
<td>+V</td>
<td>ON</td>
</tr>
<tr>
<td>GND</td>
<td>-V</td>
<td>OFF</td>
</tr>
<tr>
<td>+V GND</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>-V GND</td>
<td>ON</td>
<td>OFF</td>
</tr>
</tbody>
</table>

MONOSTABLE MULTIVIBRATOR

\[ V = 3.5 \text{ to } 16 \text{ VOLS} \]

\[ C_1 = .01 \mu F \]
\[ R_1 = 22 \text{ k}\Omega \]
\[ R_2 = 50 \text{ k}\Omega \]
\[ R_3 = 1 \text{ k}\Omega \]
\[ C_2 = 1 \mu F \]
\[ R_4 = 2.2 \text{ k}\Omega \]
\[ R_5 = 47 \text{ k}\Omega \]

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:

<table>
<thead>
<tr>
<th>TRIGGER PULSES</th>
<th>V = 3.9 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5</td>
<td>-5</td>
</tr>
<tr>
<td>+1.1 mSEC</td>
<td>25 \mu SEC</td>
</tr>
</tbody>
</table>

\[ \text{DIVIDE-BY-1 OUTPUT} \]
\[ C_2 = .001 \mu F \]
\[ R_2 = 25 \text{ k}\Omega \]
\[ C_2 = 1 \mu F \]
\[ R_2 = 18.2 \text{ k}\Omega \]

NOTE: USE THE 555 FOR MORE VERSATILITY.
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 741) 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.

When \(V_{\text{in}}\) exceeds \(V_{\text{ref}}\), output switches from low to high.

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 \(V_{\text{ref}} = 4.5\) Volts \((9V/2 = 4.5\) Volts\). R1 then controls \(V_{\text{in}}\).

**LED OFF**

\[ V_{\text{out}} = 0.2V \]

\[ V_{\text{in}} = 0 \]

\[ V_{\text{ref}} = 6.8V \]

\[ V_{\text{in}} = 1.9V \]

**LED ON**

\[ V_{\text{out}} = 4.2V \]

\[ V_{\text{in}} = 4.5V \]

\[ V_{\text{ref}} = 6.8V \]
BASIC WINDOW COMPARATOR

+V = 5 TO 15 V
OK TO USE 791, 339, etc.

Vref (High)

Vref (Low)

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:

VREF (LOW) — WINDOW — (VREF (HIGH))

V_in (volts)

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

Vref = +V (R2)
(R1 + R2)

Vref Varies =
2B

WINDOW COMPARATOR (CONT.)

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 +9V use to start an automatic 3-step sequence

R1 4.7K R2 24
1M 1/4W8 6V
S1 R5 IN914
3.3V 1/4W8
D1 IN914
R6 1K
4.7K
C1 100nF

Q1 2N2222
R8 470

OK to drive external circuit.

Delay in seconds:

Delay 1 2 3
R4 1K 10K 1
10K 1 2
1K 1

Output I = 0

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.

R1 100K
5 3 2
4 339
1 2
7 339
6 339
1

R2 1K
9 14
8 14
10 13
12 13

R3 1K
11

R4 1K
10

R5 1K

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

PHOTOTRANSISTOR:

ILLUMINATE Q1 TO ACTIVATE RELAY.

PHOTORESISTOR:

ILLUMINATE Cds CELL TO ACTIVATE RELAY.

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 wake-up 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

- **Cds PHOTOCELL**
  - Frequency increases as light level at Cds cell rises.
  - R1 = 1K
  - C1 = 4.7uF
  - R2 = 10K
  - R3 = 10K
  - R4 = 1K
  - OK to connect Cds to Piezo speaker amplifier.

- **Silicon Solar Cell**
  - Illuminate Cds 1 to increase tone frequency and Cds 2 to reduce.
  - R1 = 1K
  - R2 = 10K
  - R3 = 10K
  - R4 = 1K
  - Cds 1
  - ADJUST RS FOR BALANCE. RS 50K
  - PIEZO SPEAKER

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. 0-10mA
    - 2. 0.1mA
    - 3. 0.01mA

- **Silicon Solar Cell**
  - R4
  - S1
  - 6V

- **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 (RS) until meter reads 0. Then disconnect pin 2 from ground. R4 is an optional control for altering sensitivity of the circuit.**

- **Ck = 0.02uF**
  - R1 = 1M
  - C2 = 2.2uF
  - R2 = 100K
  - C3 = 2uF
  - R3 = 10K
  - R4 = 5K
  - 0-1mA meter
  - -9V (Panel or VOM)
SOUND-LEVEL METER

+9V

CAUTION: USE EAR PROTECTION WHEN MEASURING LOUD SOUNDS.

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 6-8 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 2 mA. AT 12" THE OUTPUT FELL TO 0.4 mA. NORMAL SPEECH AT 12" GAVE FLUCTUATING SIGNAL UP TO 10 mA.

SOUND-ACTIVATED RELAY

+9V

RS CONTROLS SENSITIVITY.

MICROPHONE (RADIO SHACK 270-092 OR SIMILAR).

THIS CIRCUIT TRIPS RELAY IN RESPONSE TO LOUD SOUND (VOICE, CLAP, ETC.). R5 AND C3 CONTROL THE RELAY STAYS PULLED IN (VALUES SHOWN GIVE 2-3 SECONDS). IMPORTANT: USE 0.1 uF CAPACITOR ACROSS POWER SUPPLY PINS OF BOTH THE 741 AND 555. REDUCE RESISTANCE OF R3 TO REDUCE SENSITIVITY.
PIEZO ELEMENT DRIVERS

GATED:

V± 9 V TO 12 VOLS

+V

PIEZO ELEMENT

R2
4.7K

R3
100K

R4
22K

HIGH

LOW

IN

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

+V

R1
4.7K

R3
1M

C1
1μF

R2
4.7K

R4
22K

PIEZO ELEMENT

ADJUST R3 TO ALTER FREQUENCY OF TONE FROM PIEZO ELEMENT.

PERCUSSION SYNTHESIZER

C1
2.2μF

+V

R5
10K

R7
10K

R6
100K

R4
22K

R1
1M

R2
1M

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

R5 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. R1 AND R4 CONTROL PITCH.
LOW-PASS FILTER

IN

\[ R_1 \quad C_1 \quad V = \pm 5 \text{ to } \pm 15 \text{ VOLTS} \]

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

CUT-OFF

FREQUENCY (\( f_c \))

15 \(
\times \sqrt{2} \)

MAXIMUM

OUTPUT.

\[ f_c = \frac{1}{2\pi R C} \]

GAIN = \( R_4 / R_3 \)

(ABOUT 1.59)

\[ R_3 = 33 \text{ K} \]
\[ R_4 = 56 \text{ K} \]

THIS IS AN EQUAL COMPONENT SALLEN-KEY FILTER. \( R_3 \) SHOULD BE \( 0.586 \times R_4 \). SHOWN BELOW IS RESPONSE OF FILTER WHEN INPUT WAS A 1-VOLT SINE WAVE:

\[ R = 4.7 \text{ K} \]
\[ C = 0.01 \text{ \mu F} \]
MEASURED \( f_c = 3,000 \text{ Hz} \)

HIGH-PASS FILTER

IN

\[ R_1 \quad C_1 \quad V = \pm 5 \text{ to } \pm 15 \text{ VOLTS} \]

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

CUT-OFF

FREQUENCY (\( f_c \))

15 \(
\times \sqrt{2} \)

MAXIMUM

OUTPUT.

\[ f_c = \frac{1}{2\pi R C} \]

GAIN = \( R_4 / R_3 \)

(ABOUT 1.59)

\[ R_3 = 33 \text{ K} \]
\[ R_4 = 56 \text{ K} \]

THIS CIRCUIT IS IDENTICAL TO THE EQUAL COMPONENT Sallen-Key FILTER ON FACING PAGE EXCEPT \( R_1 \) AND \( R_2 \) AND \( C_1 \) AND \( C_2 \) HAVE BEEN INTERCHANGED. BELOW IS RESPONSE WHEN INPUT WAS A 1-VOLT SINE WAVE:

\[ R = 4.7 \text{ K} \]
\[ C = 0.01 \text{ \mu F} \]
MEASURED \( f_c = 3,000 \text{ Hz} \)
60-Hz Notch Filter

Wien Bridge

R1 = R2 = R3 = R4 = R5 = 27k
R2 = 27k
C2 = 1μF

R3
27k

R5
27k

Twin Tee

R = R1 = R2 = 2k
C + C1 + C2 = C3 / 2

R3 = 220k
C1 = 0.01μF
C2 = 0.005μF

Use these filters to block power line hum.

Wien Bridge, Twin Tee

Graph shows results for test versions of both filters. Input was 2-volt peak-to-peak sine wave, 60 Hz.

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:
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.

R4 5.7K
C7 1uF
C8 1µF
R5 220K
R6 1K
R7 10K
C9 .122µF

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

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

<table>
<thead>
<tr>
<th>FREQUENCY (Hz)</th>
<th>BRIGHTNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>LOW (LOW)</td>
</tr>
<tr>
<td>1</td>
<td>MID</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td></td>
</tr>
</tbody>
</table>

REDUCE R10 AND R11 TO INCREASE RED AND YELLOW BRIGHTNESS. INCREASE R12 TO INCREASE GREEN BRIGHTNESS.

MINI-COLOR ORGAN (CONT.)
SQUARE WAVE GENERATOR

PLACE C2 CLOSE TO 741.

R1 10K
R2 10K
R3 10K
R4 1K
R5 100K
R6 1K
R7 1M
R8

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 GND THEREBY ELIMINATING R1 AND R3. TYPICAL RESULTS:

<table>
<thead>
<tr>
<th>C1 FREQUENCY</th>
<th>FOR THESE RESULTS,</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.001</td>
<td>R1-R2-R3 REPLACED BY</td>
</tr>
<tr>
<td>1.047</td>
<td>3.884 K FROM PIN 3 TO</td>
</tr>
<tr>
<td>.001</td>
<td>+V AND 4.7 K FROM</td>
</tr>
<tr>
<td>.01</td>
<td>3.156 K FROM</td>
</tr>
<tr>
<td>.047</td>
<td>2.42 K</td>
</tr>
<tr>
<td>.1</td>
<td>287 HZ</td>
</tr>
<tr>
<td>.47</td>
<td>43 HZ</td>
</tr>
<tr>
<td>1.10</td>
<td>24 HZ</td>
</tr>
</tbody>
</table>

OK TO ADD FOLLOWER STAGE TO BUFFER OUTPUT.

SINE WAVE OSCILLATOR

R1 1K
R2 10K
R3 1K
R4 1K
R5 100K
R6
R7

SEE BELOW

C1 .01
C2 .01
C3 .01
C4 .01

R3 = R4 = C1 = C2

ADJUST R5 UNTIL CIRCUIT OSCILLATES.


TYPICAL RESULTS

| R3 = R4 FREQUENCY |
| FROM TEST |
| 47 K |
| 10 K |
| 15 K |

CIRCUIT: