Applied Electronics

Instructor:

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DAY#4
SUMMER 2016

Agenda

Op-Amp Parameters

Op-Amps with Negative Feedback

Bias Current and Offset Voltage

Basic Op-Amp Circuits

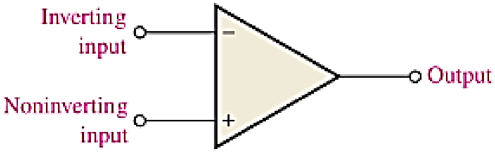
- Comparators
- Summing Amplifiers
- Integrators & Differentiators

Troubleshooting

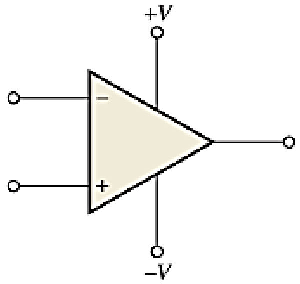
Practical Applications

Introduction to Op-Amps

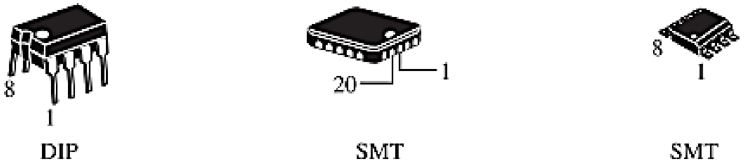
- Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation—thus the term **operational**.
- These early devices were constructed with vacuum tubes and worked with high voltages.
- Today's op-amps are linear integrated circuits (**ICs**) that use relatively low dc supply voltages and are reliable and inexpensive.



(a) Symbol

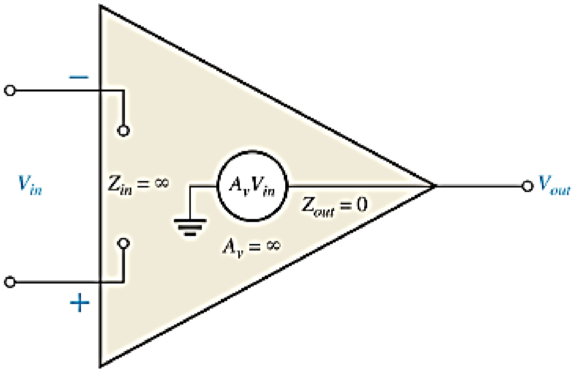


(b) Symbol with dc supply connections

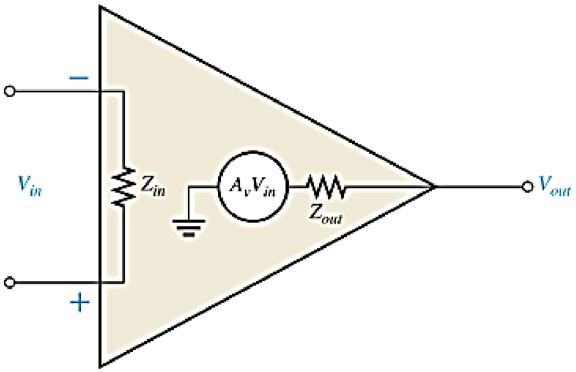


(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.

Ideal & Practical Op-Amp

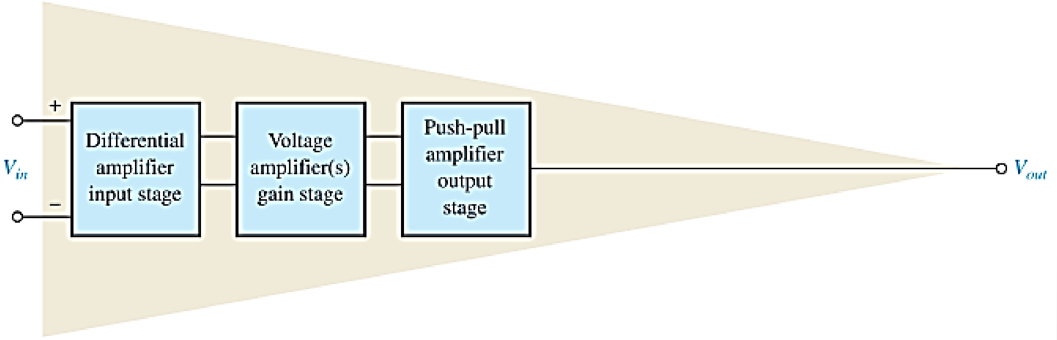


(a) Ideal op-amp representation



(b) Practical op-amp representation

- **Internal Block Diagram of an Op-Amp**

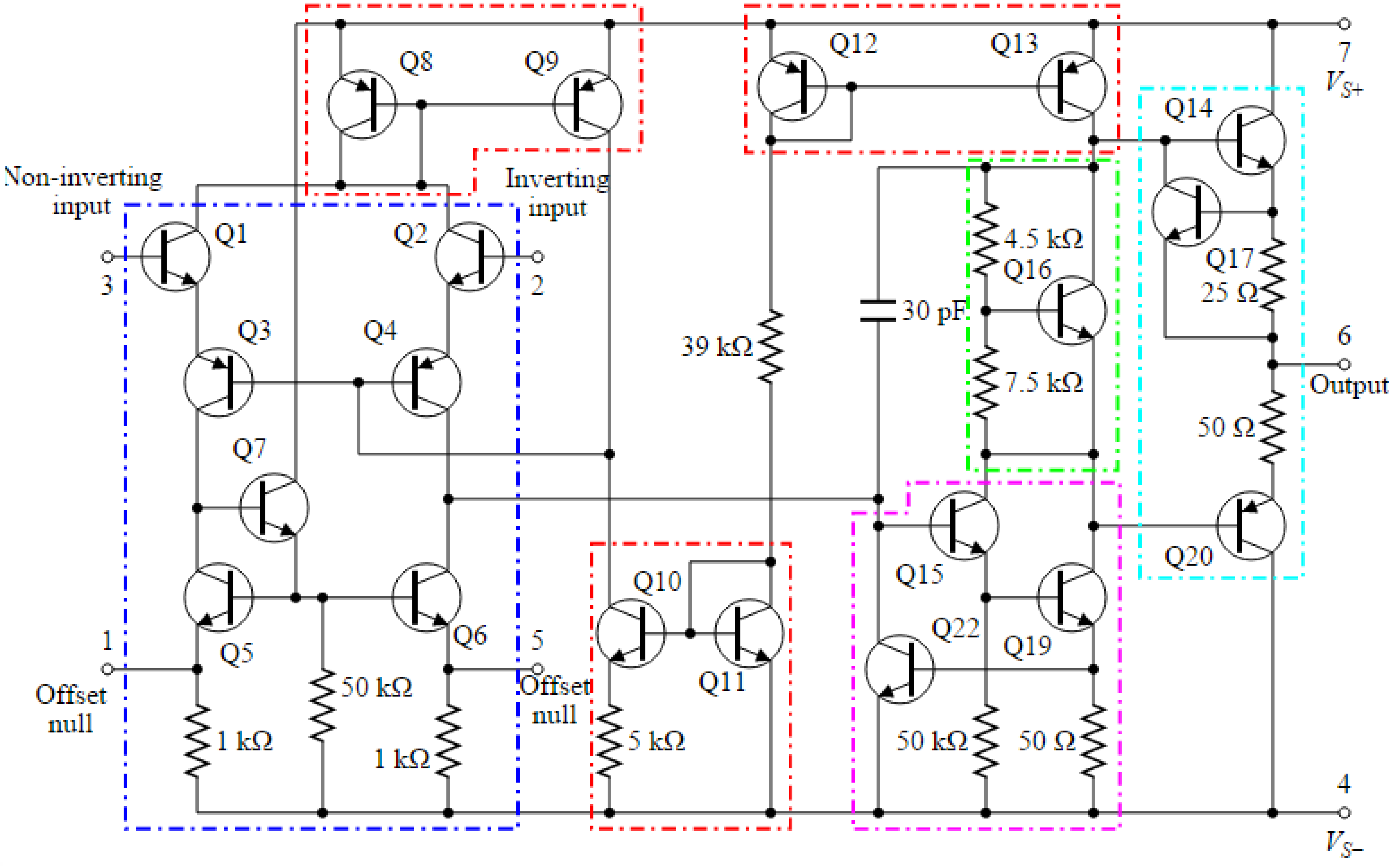


Differential amplifier input stage

Voltage amplifier(s) gain stage

Push-pull amplifier output stage

741 Op-Amp Internal Circuit



A component-level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

OP-AMPS PARAMETERS

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Op-Amp Parameters
Common-Mode Rejection Ratio

- The common-mode rejection ratio, **CMRR**:

It's the ratio of the open-loop differential voltage gain, $\mathbf{A_{ol}}$, to the common-mode gain, $\mathbf{A_{cm}}$.

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}} \qquad \text{CMRR} = 20\log\left(\frac{A_{ol}}{A_{cm}}\right)$$

- *Open-loop voltage gain* can range up to 200,000 (106 dB) and is not a well-controlled parameter.
- Datasheets often refer to the open-loop voltage gain as the *large-signal voltage gain*.
- A CMRR of 100,000, for example, means that the desired input signal (differential) is amplified 100,000 times more than the unwanted noise (common-mode).

Op-Amp Parameters..

Maximum Output Voltage Swing ($V_{O(p-p)}$)

- With no input signal, the output of an op-amp is ideally 0 V. This is called the quiescent output voltage.
- When an input signal is applied, the ideal limits of the peak-to-peak output signal are ±V_{cc}.
- In practice this ideal can be approached but never reached.
- Vo_{pp} varies with the load connected to the op-amp and increases directly with load resistance.

Example:
Fairchild KA741

$V_{O(p-p)}$ of ± 13 V for $V_{CC} = \pm 15$ V when $R_L = 2\,\mathrm{k}\Omega$

$V_{O(p-p)}$ increases to ± 14 V when $R_L = 10\,\mathrm{k}\Omega$

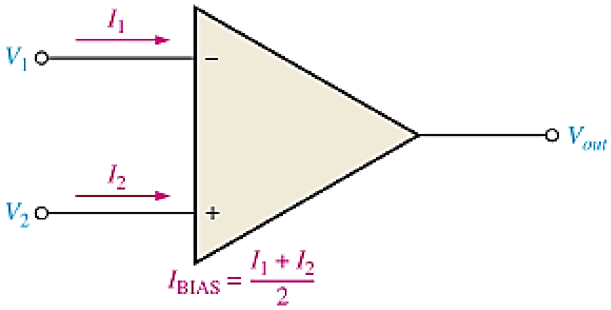
Input Offset Voltage:

- The ideal op-amp produces zero volts out for zero volts in.
- In a practical op-amp, a small dc voltage, $\mathbf{V_{OUT(error)}}$, appears at the output when no differential input voltage is applied.
- Its primary cause is a slight mismatch of the base-emitter voltages of the differential amplifier input stage of an op-amp.
- The input offset voltage, $\mathbf{V_{OS}}$, is the differential dc voltage required between the inputs to force the output to zero volts
- Typical values $\mathbf{V_{OS}}$, are in the range of 2 mV or less.

Op-Amp Parameters
Input Bias Current

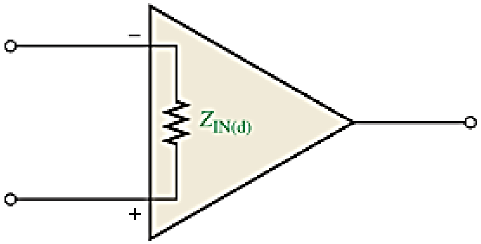
- The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage.
- Input bias current is the average of the two op-amp input currents

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$

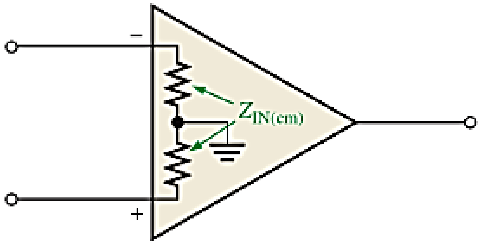


Input Impedance

- The differential input impedance is the total resistance between the inverting and the non-inverting inputs.
- The common-mode input impedance is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage.



(a) Differential input impedance



(b) Common-mode input impedance

Op-Amp Parameters…
Input Offset Current

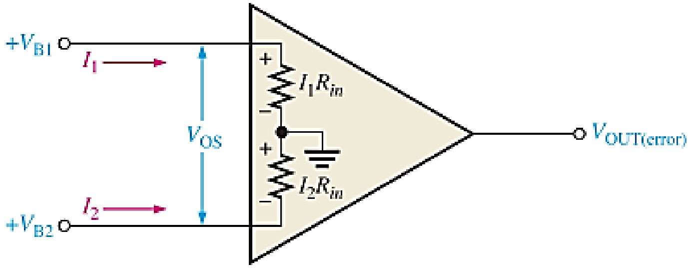
- Ideally, the two input bias currents are equal, and thus their difference is zero.
- In a practical op-amp, the bias currents are not exactly equal.
- The input offset current, IOS, is the difference of the input bias currents, expressed as an absolute value.

$$I_{OS} = |I_1 - I_2|$$

$$V_{OS} = I_1R_{in} - I_2R_{in} = (I_1 - I_2)R_{in}$$

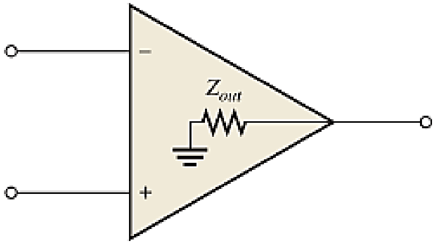
$$V_{OS} = I_{OS}R_{in}$$

$$V_{OUT(error)} = A_vI_{OS}R_{in}$$



Output Impedance

- The output impedance is the resistance viewed from the output terminal of the op-amp



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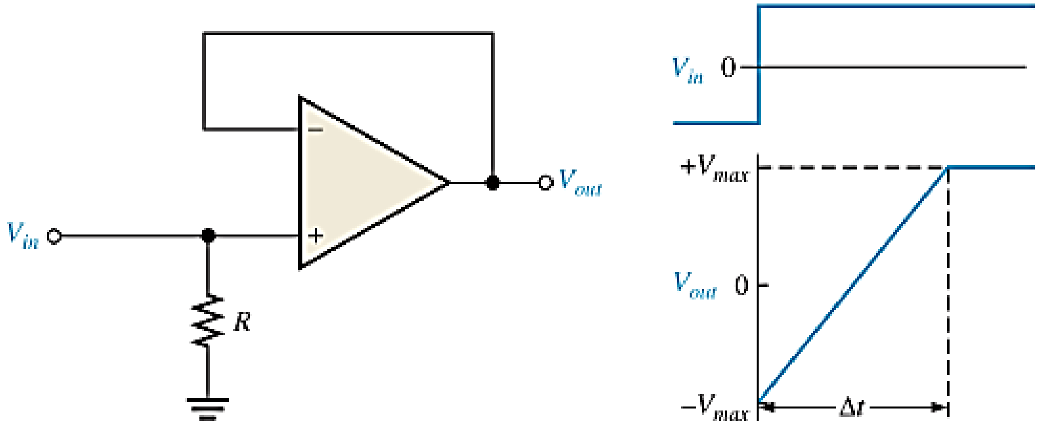
Op-Amp Parameters….
Slew Rate

- The maximum rate of change of the output voltage in response to a step input voltage is the slew rate of an op-amp.
- The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

- **Slew-rate measurement**



(a) Test circuit

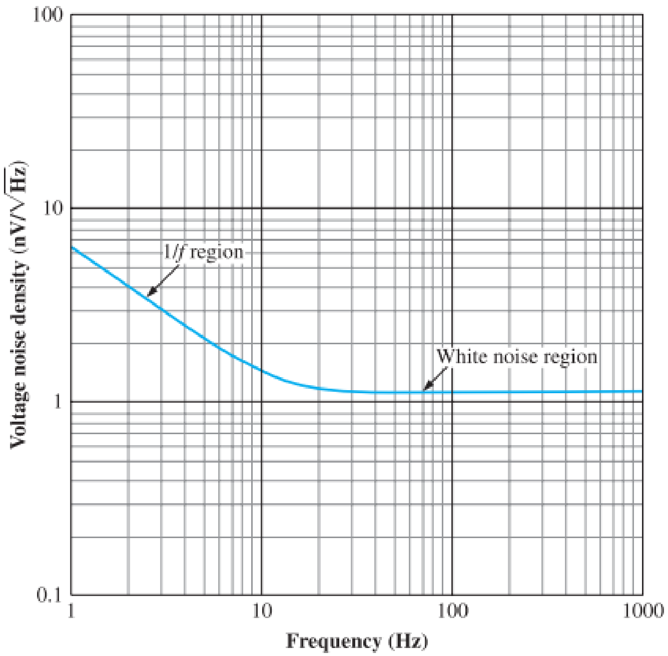
(b) Step input voltage and the resulting output voltage

Op-Amp Parameters….. Frequency Response

- The internal amplifier stages that make up an op-amp have voltage gains limited by junction capacitances.
- An op-amp has no internal coupling capacitors, however; therefore, the low-frequency response extends down to dc (0 Hz).

Noise Specification

- Noise has become a more important issue !
- Noise is defined as an unwanted signal that affects the quality of a desired signal.
- There are two basic forms of noise.
- At low frequencies, noise is inversely proportional to the frequency; this is called 1/f noise or "**pink noise**".
- Above a critical noise frequency, the noise becomes flat and is spread out equally across the frequency spectrum; this is called "**white noise**".
- The power distribution of noise is measured in watts per hertz (W/Hz).

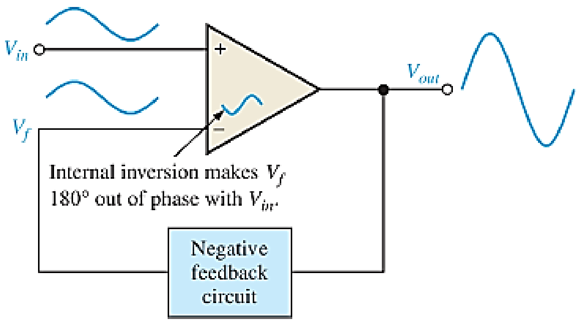


A Comparison of for some representative op-amps Parameters.
Check the reference !

OP-AMPS WITH NEGATIVE FEEDBACK

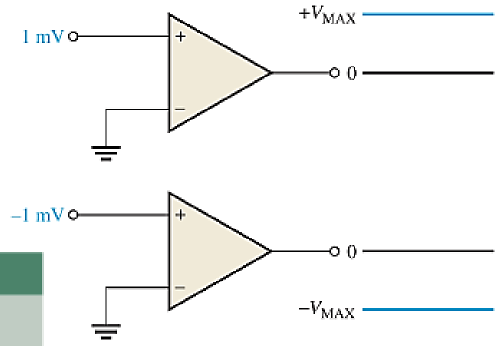
Why Use Negative Feedback?

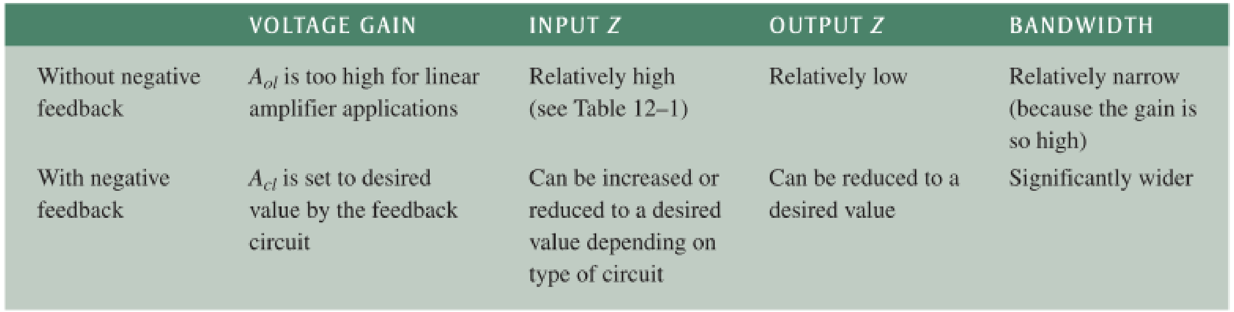
- **Negative feedback** is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes (or subtracts from) the input signal.



Internal inversion makes V_f 180° out of phase with V_{in}.

- Open-loop voltage gain of a typical op-amp is very high.
- Therefore, an extremely small input voltage drives the op-amp into its saturated output states.
- In fact, even the input offset voltage of the op-amp can drive it into saturation.





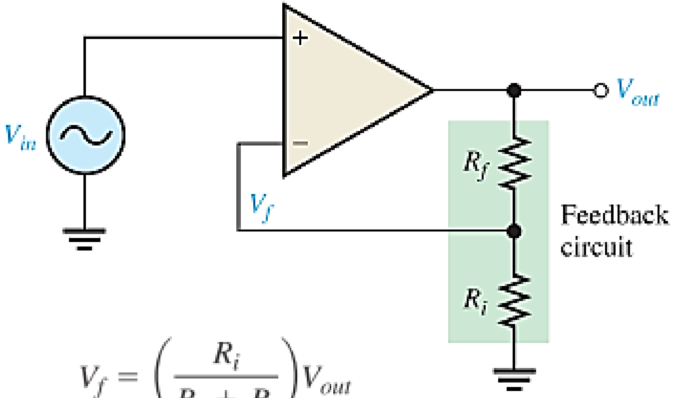
	VOLTAGE GAIN	INPUT Z	OUTPUT Z	BANDWIDTH
Without negative feedback	A_{ol} is too high for linear amplifier applications	Relatively high (see Table 12–1)	Relatively low	Relatively narrow (because the gain is so high)
With negative feedback	A_{cl} is set to desired value by the feedback circuit	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

OP-AMPS WITH NEGATIVE FEEDBACK

- An op-amp can be connected using negative feedback to stabilize the gain and increase frequency response.
- The closed-loop voltage gain is the voltage gain of an op-amp with external feedback.
- The closed-loop voltage gain is determined by the external component values and can be precisely controlled by them.

- **Non-inverting Amplifier**

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i}$$

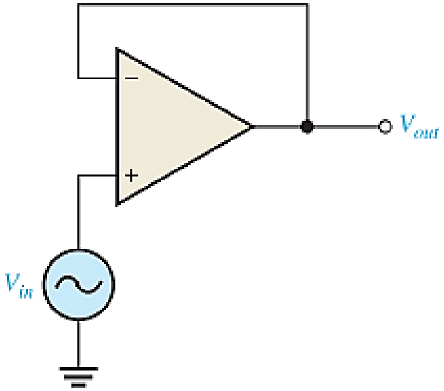


$$V_f = \left(\frac{R_i}{R_i + R_f}\right)V_{out}$$

OP-AMPS WITH NEGATIVE FEEDBACK..

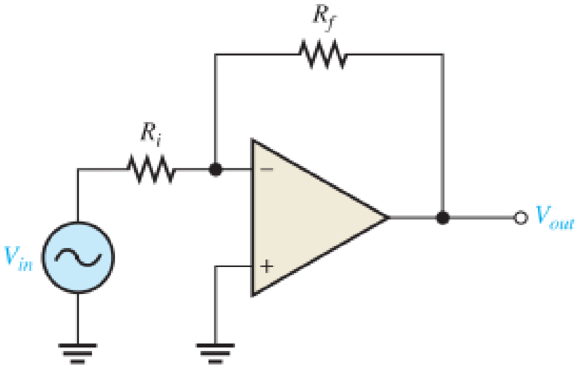
- **Voltage-Follower**

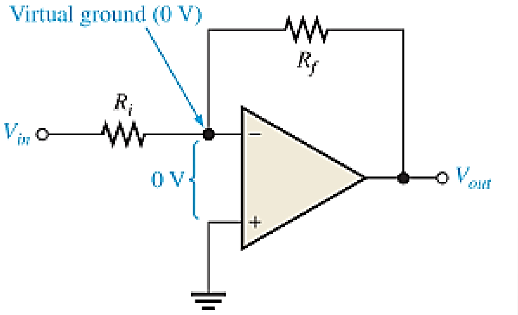
$$A_{cl(VF)} = 1$$



- **Inverting Amplifier**

$$A_{cl(I)} = -\frac{R_f}{R_i}$$



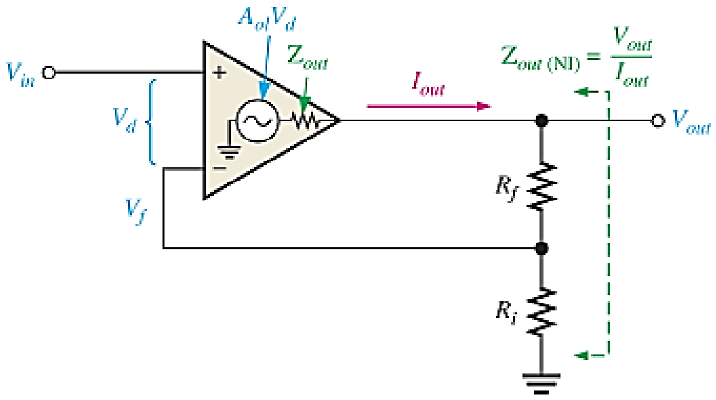


EFFECTS OF NEGATIVE FEEDBACK ON OP-AMP IMPEDANCES

- **Non-inverting Amplifier**

$$Z_{in(NI)} = (1 + A_{ol}B)Z_{in}$$

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B}$$



- **Voltage Follower**

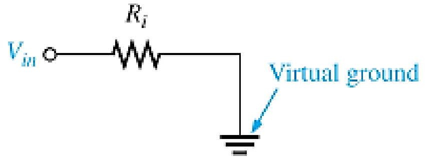
$$Z_{in(VF)} = (1 + A_{ol})Z_{in}$$

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{ol}}$$

- **Inverting Amplifier**

$$Z_{in(I)} \cong R_i$$

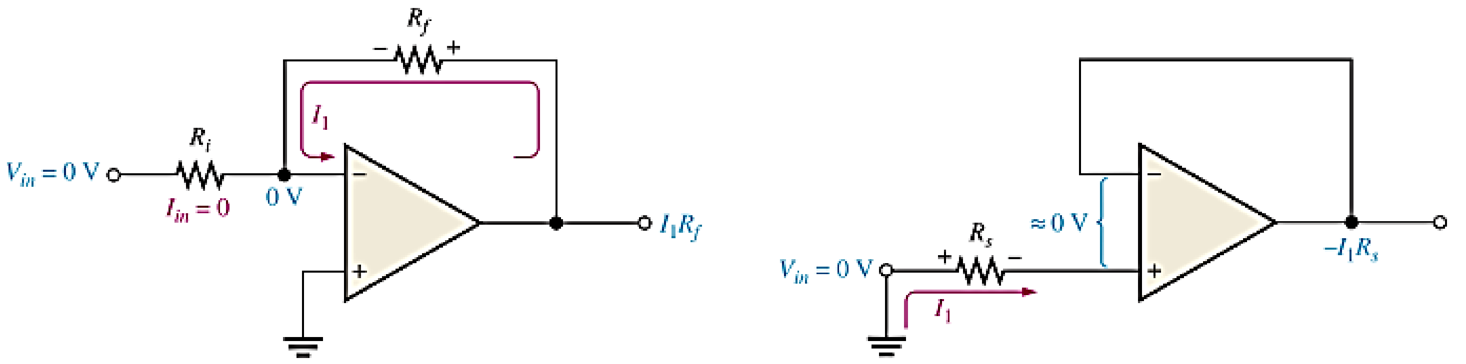
$$Z_{out(I)} = \frac{Z_{out}}{1 + A_{ol}B}$$



- Certain deviations from the ideal op-amp must be recognized because of their effects on its operation.
- Transistors within the op-amp must be biased so that they have the correct values of base and collector currents and collector-to-emitter voltages.
- The ideal op-amp has no input current at its terminals; but in fact, the practical op-amp has small input bias currents typically in the nA range.
- Also, small internal imbalances in the transistors effectively produce a small offset voltage between the inputs.

BIAS CURRENT AND OFFSET VOLTAGE

Effect of Input Bias Current



(a) Input bias current creates output error voltage (I_1R_f) in an inverting amplifier.

(b) Input bias current creates output error voltage in a voltage-follower.

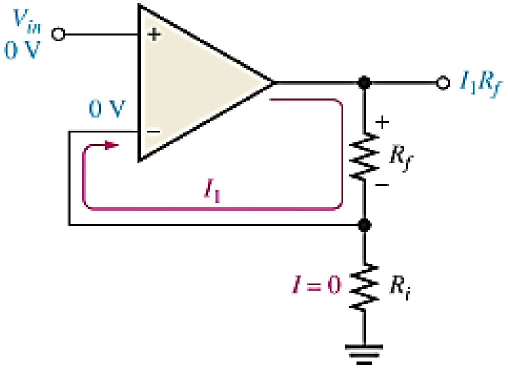
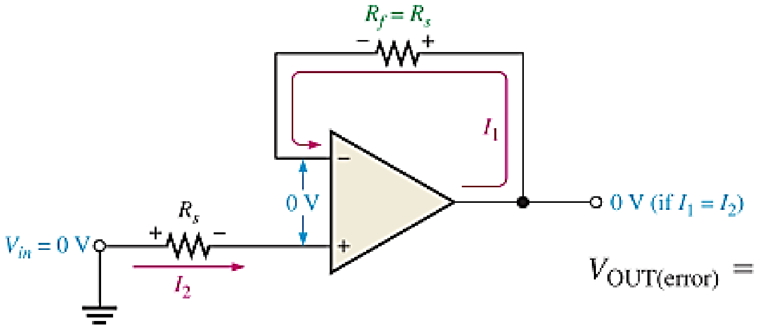


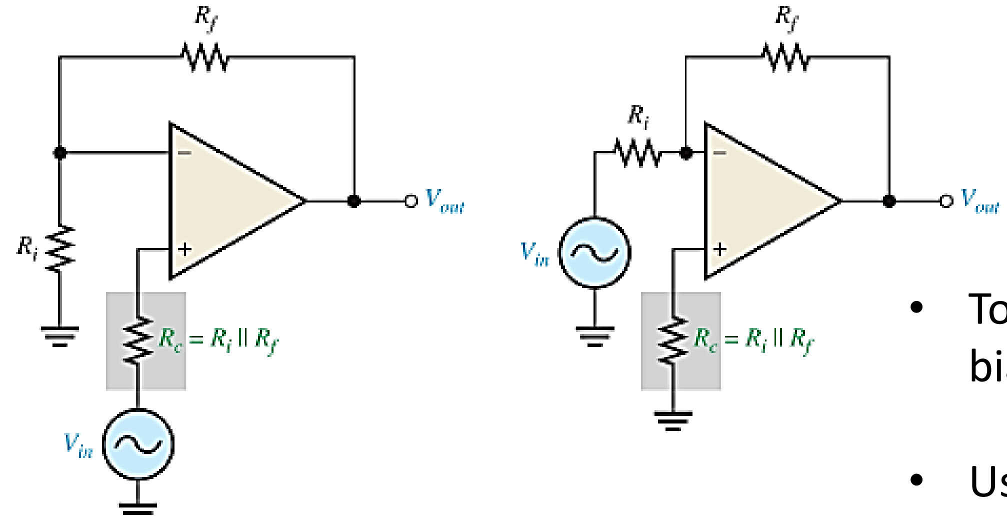
FIGURE 12–30

Input bias current creates output error voltage in a noninverting amplifier.

Bias Current Compensation



$$V_{OUT(error)} = |I_1 - I_2|R_s = I_{OS}R_s$$



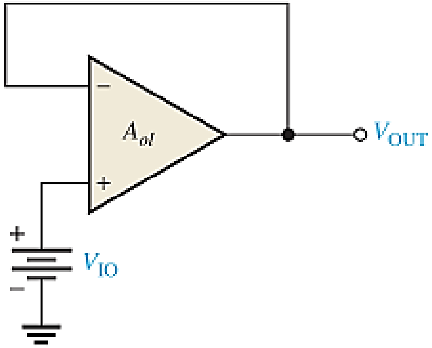
(a) Noninverting amplifier

(b) Inverting amplifier

- To compensate for the effect of bias , a resistor Rc is added.
- Use of a BIFET Op-Amp to Eliminate the Need for Bias Current Compensation

Effect of Input Offset Voltage

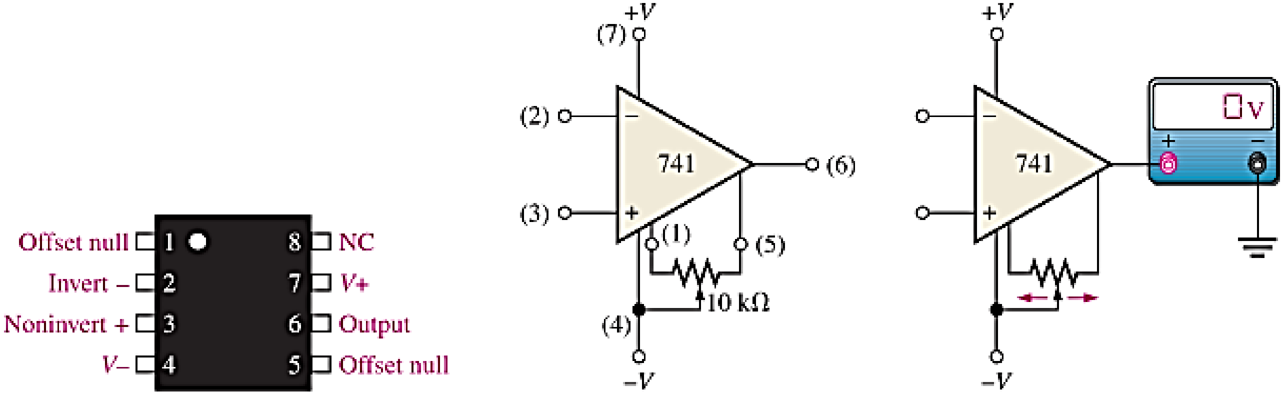
$$V_{OUT(error)} = A_{cl}V_{IO}$$



▲ **FIGURE 12–33**

Input offset voltage equivalent.

Input Offset Voltage Compensation



(a) 8-pin DIP or SMT package

(b) External potentiometer

(c) Adjust for zero output

▲ **FIGURE 12–34**

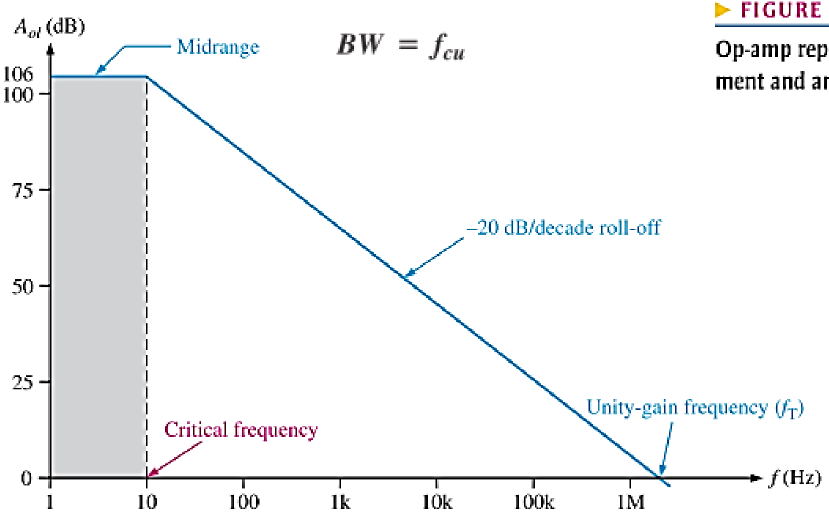
Input offset voltage compensation for a 741 op-amp.

OPEN & CLOSED LOOP FREQUENCY RESPONSES

Open-Loop Frequency & Phase Responses

$$BW = f_{cu} - f_{cl}$$

$$\boldsymbol{BW = f_{cu}}$$

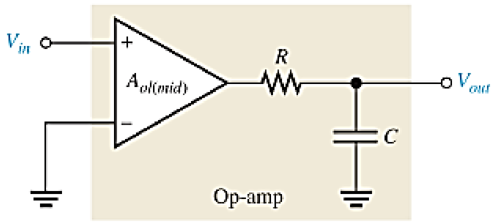


▲ **FIGURE 12–36**

Ideal plot of open-loop voltage gain versus frequency for a typical op-amp. The frequency scale is logarithmic.

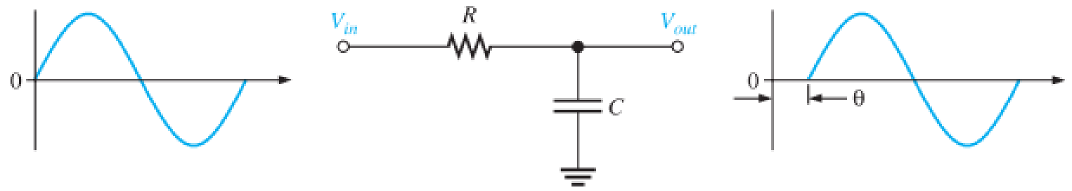
▶ **FIGURE 12–38**

Op-amp represented by a gain element and an internal *RC* circuit.

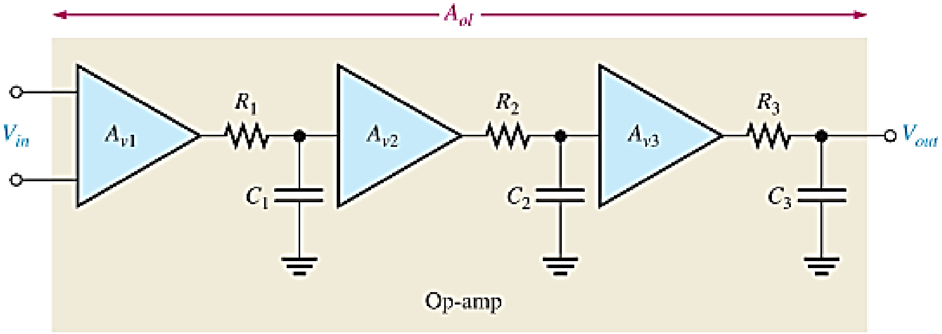


$$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1 + f^2/f_c^2}}$$

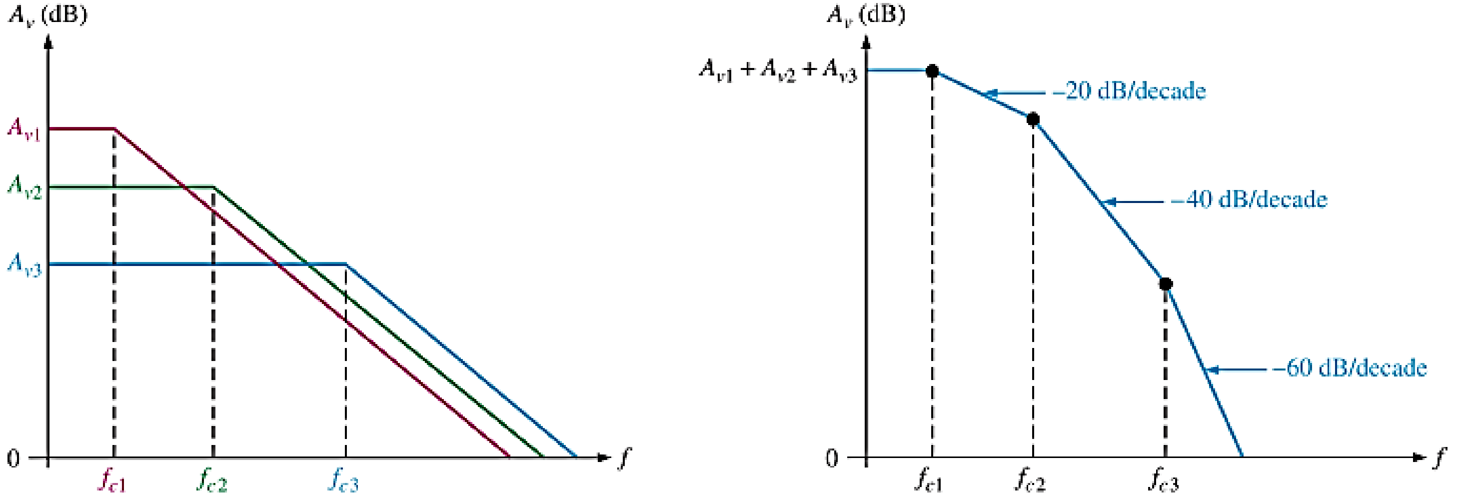
$$\theta = -\tan^{-1}\left(\frac{f}{f_c}\right)$$



Overall Frequency & Phase Responses (Open-Loop)



(a) Representation of an op-amp with three internal stages



(b) Individual responses

(c) Composite response

$$\theta_{tot} = -\tan^{-1}\left(\frac{f}{f_{c1}}\right) - \tan^{-1}\left(\frac{f}{f_{c2}}\right) - \tan^{-1}\left(\frac{f}{f_{c3}}\right)$$

CLOSED-LOOP FREQUENCY RESPONSE

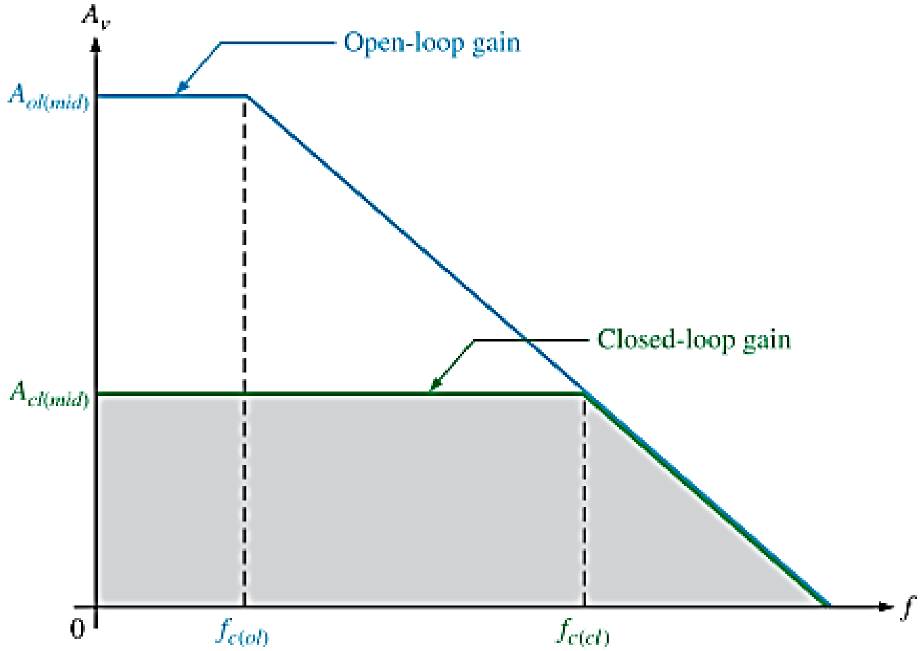


FIGURE 12–42

Closed-loop gain compared to open-loop gain.

$$f_{c(cl)} = f_{c(ol)}(1 + BA_{ol(mid)})$$

$$BW_{cl} = BW_{ol}(1 + BA_{ol(mid)})$$

- The **gain-bandwidth product** is always equal to the frequency at which the op-amp's open-loop gain is unity or 0 dB (unity-gain bandwidth, f_T).

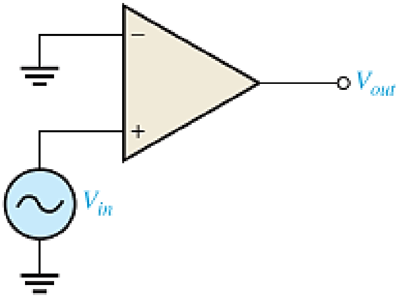
$$f_T = A_{cl}f_{c(cl)}$$

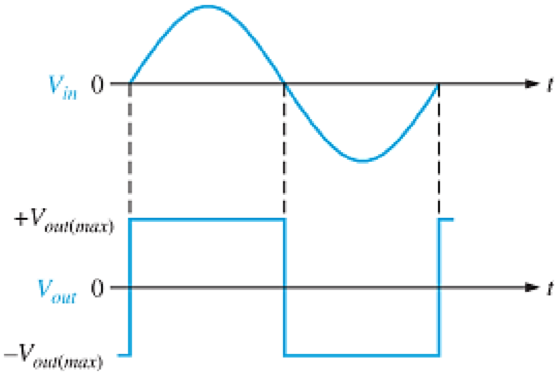
COMPARATORS

Zero Level Detection

- Operational amplifiers are often used as **comparators** to compare the **amplitude** of one voltage with another.
- In this application, the op-amp is used in the **open-loop** configuration, with the input voltage on one input and a **reference** voltage on the other.
- The **output** is always at either one of **two states**, indicating the greater or less than **relationship** between the inputs.
- Comparators provide very **fast switching times**.
- Comparators are often used to **interface** between an analog and digital circuit (output is in one of two states).

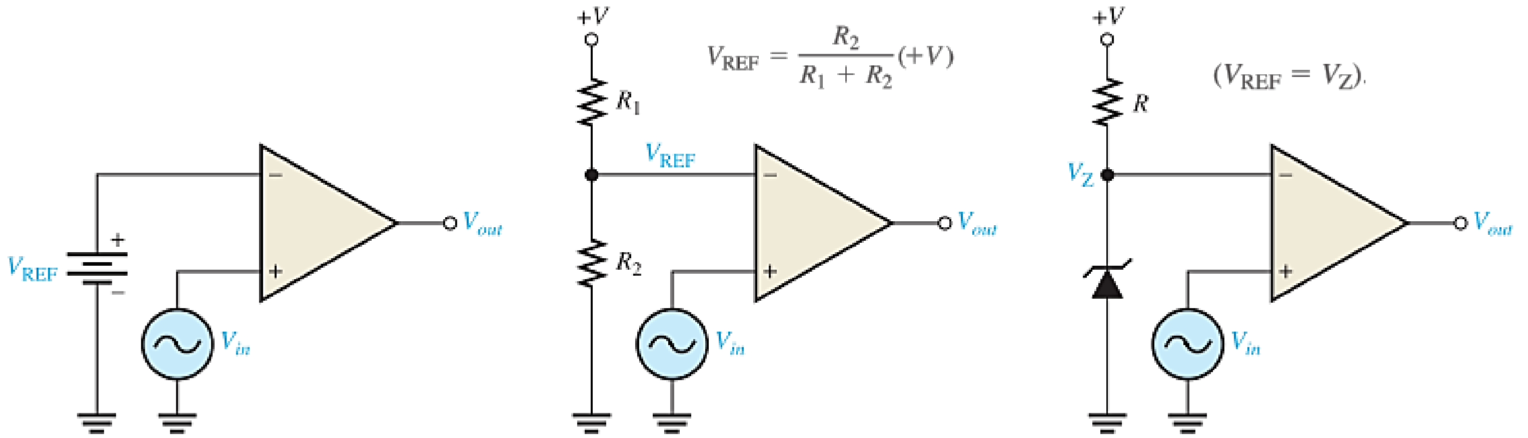
- One **application** of a comparator is to determine when an input voltage **exceeds** a certain **level**.





- If the level is Zero (Ground) → Zero Level Detection

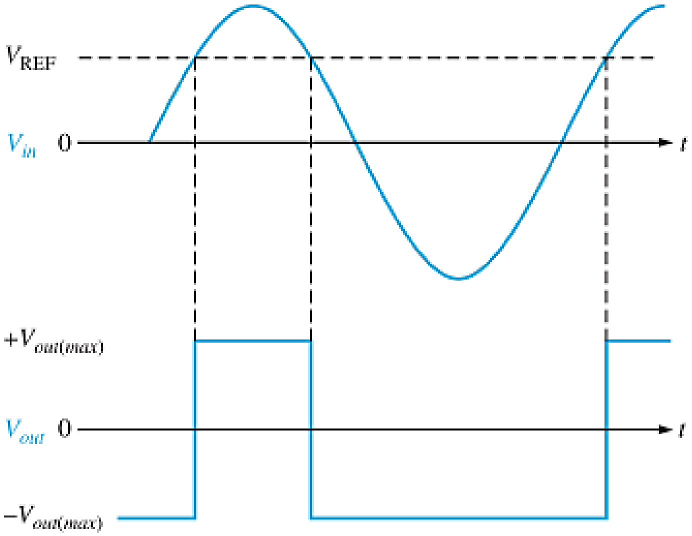
Nonzero-Level Detection



(a) Battery reference

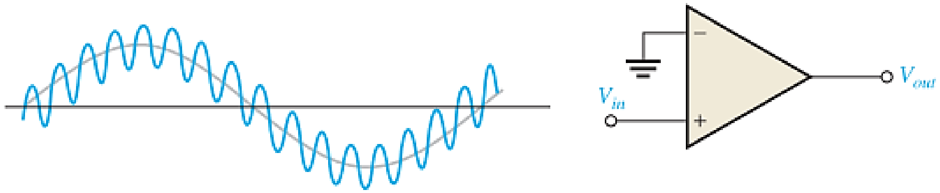
(b) Voltage-divider reference

(c) Zener diode sets reference voltage

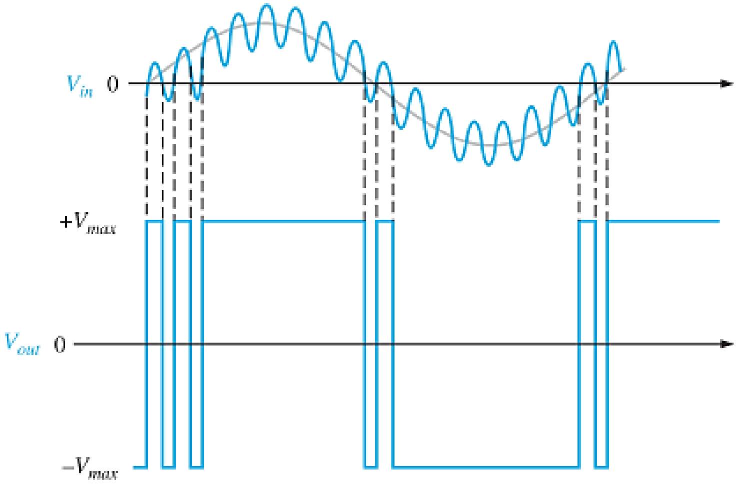


(d) Waveforms

Effects of Input Noise on Comparator Operation



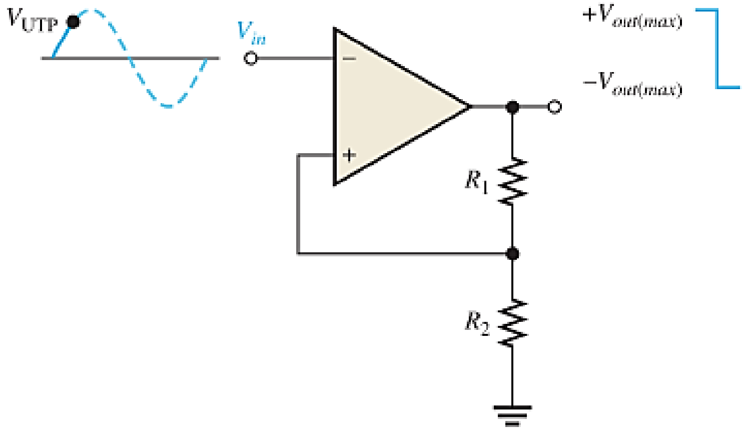
(a)



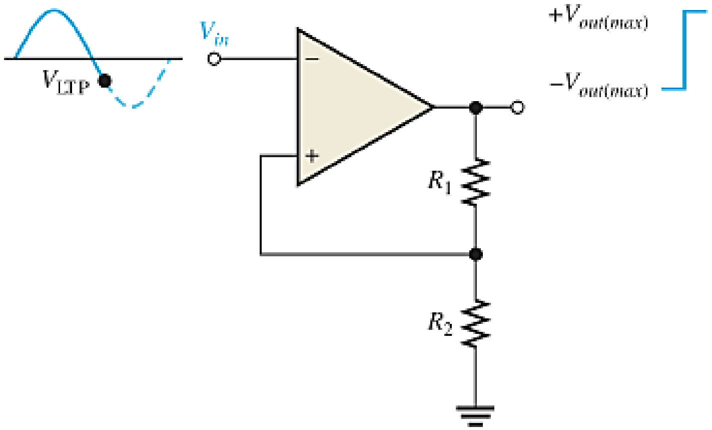
(b)

- To make the comparator less sensitive to noise, a technique uses positive feedback, called **hysteresis**, can be used.
- **Hysteresis** means that there is a higher reference level when the input voltage goes from a lower to higher value than when it goes from a higher to a lower value.
- A good **example** of hysteresis is a common house-hold thermostat that turns the furnace on at one temperature and off at another.

Reducing Noise Effects with Hysteresis



(a) When the output is at the maximum positive voltage and the input exceeds UTP, the output switches to the maximum negative voltage.

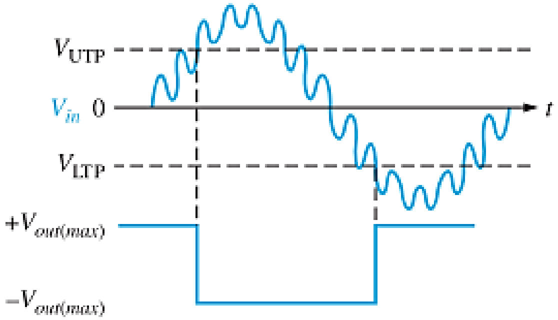


(b) When the output is at the maximum negative voltage and the input goes below LTP, the output switches back to the maximum positive voltage.

$$V_{UTP} = \frac{R_2}{R_1 + R_2}(+V_{out(max)})$$

$$V_{LTP} = \frac{R_2}{R_1 + R_2}(-V_{out(max)})$$

$$V_{HYS} = V_{UTP} - V_{LTP}$$

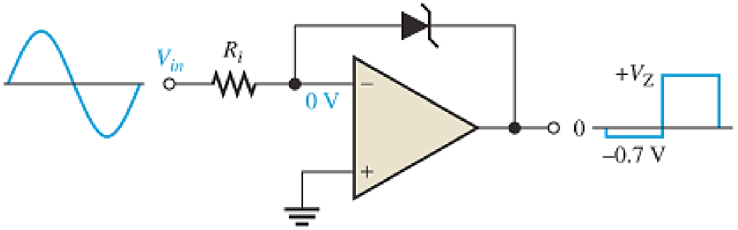


(c) Device triggers only once when UTP or LTP is reached; thus, there is immunity to noise that is riding on the input signal.

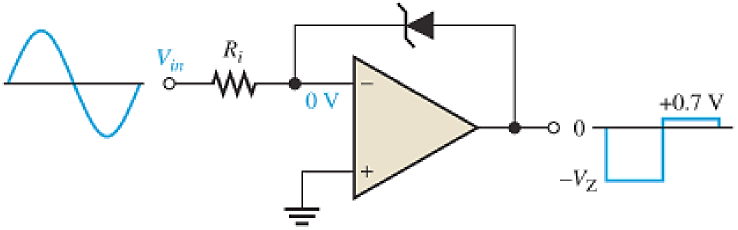
- A comparator with built-in hysteresis is sometimes known as a **Schmitt trigger**.
- The amount of hysteresis is defined by the difference of the two trigger levels.

Output Bounding

- The process of **limiting the output range** is called **bounding**.



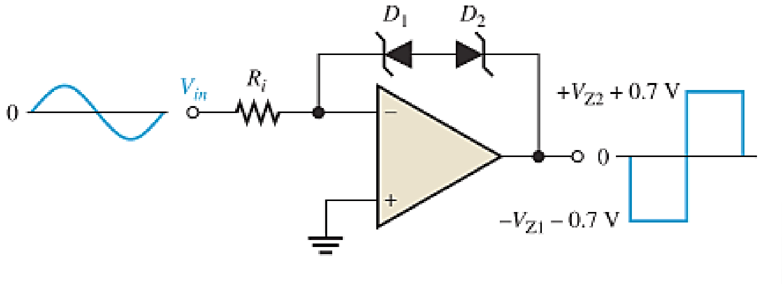
(a) Bounded at a positive value



(b) Bounded at a negative value

FIGURE 13–12

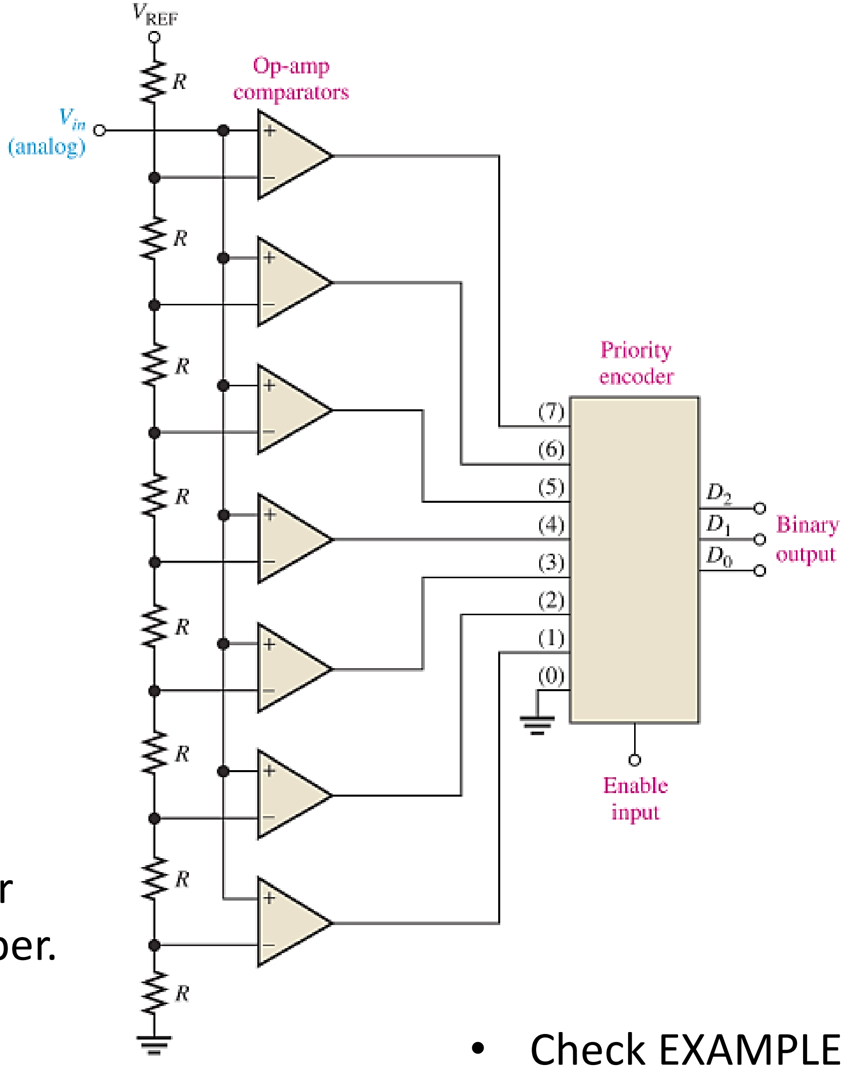
Double-bounded comparator.



Comparator Applications
Analog-to-Digital (A/D) Conversion

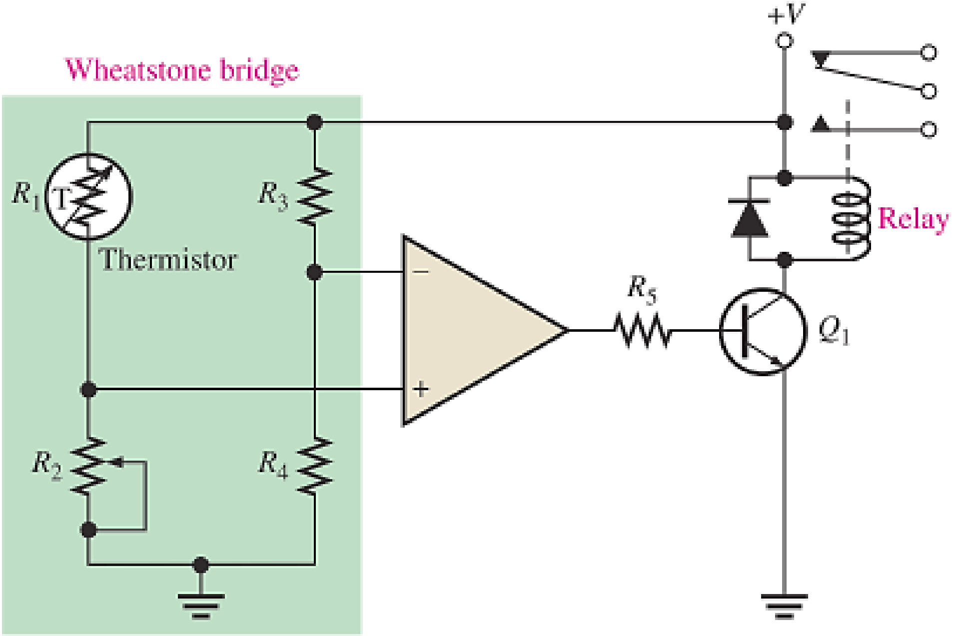
- The **simultaneous**, or **flash**, method of A/D conversion uses **parallel comparators** to compare the linear input signal with **various reference** voltages developed by a voltage divider.
- When the **input** voltage **exceeds the reference** voltage for a given comparator, a **high level is produced** on that comparator's output.

→**2ⁿ- 1** comparators are required for conversion to an **n-digit** binary number.



- Check EXAMPLE 13–4 !

Comparator Applications
Over-Temperature Sensing Circuit



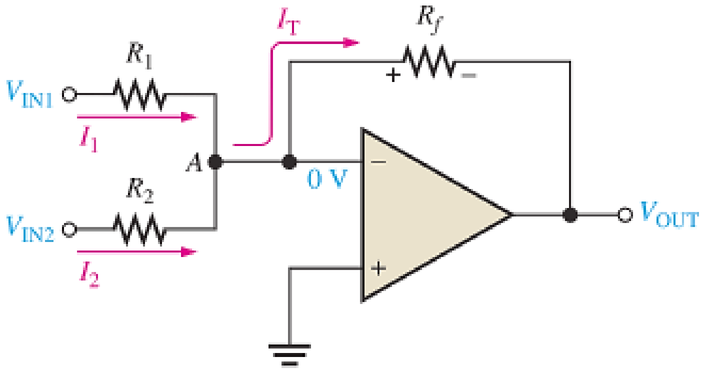
Specific Comparators

- The **LM111** and **LM311** are examples of specific comparators that exhibit high switching speeds and other features not normally found on the general type of op-amp.

SUMMING AMPLIFIERS

Summing Amplifier with Unity/ Non Unity Gain

- The summing amplifier is an **application of the inverting op-amp** configuration.
- A summing amplifier has **two or more inputs**, and its **output** voltage is proportional to the negative of the **algebraic sum** of its input voltages.

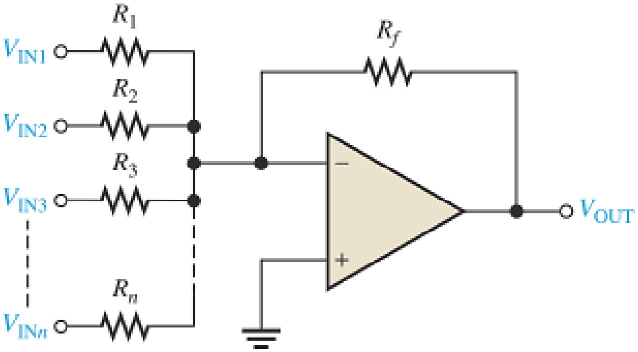


$$I_T = I_1 + I_2$$

$$V_{OUT} = -(I_1 + I_2)R_f = -\left(\frac{V_{IN1}}{R_1} + \frac{V_{IN2}}{R_2}\right)R_f$$

$R_1 = R_2 = R_f = R$ → **Unity Gain**

$$V_{OUT} = -\left(\frac{V_{IN1}}{R} + \frac{V_{IN2}}{R}\right)R = -(V_{IN1} + V_{IN2})$$



$$V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3} + \cdots + V_{INn})$$

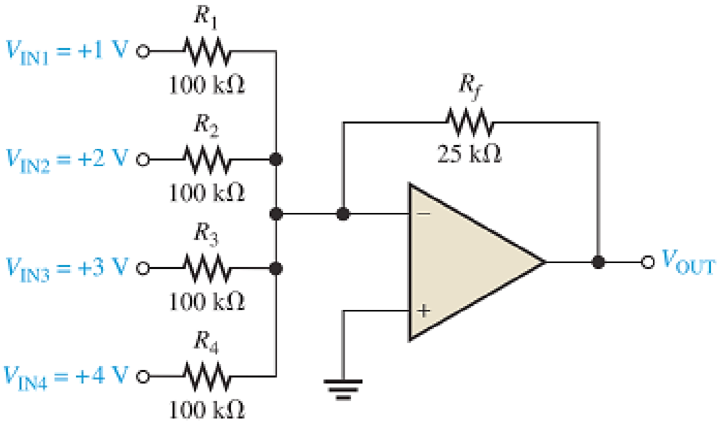
→ **Gain greater than Unity**

$$V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2} + \cdots + V_{INn})$$

Averaging & Scaling Amplifiers

- **Averaging:**

$$\frac{R_f}{R} = \frac{1}{n}$$



V_{out}= ?

- **Scaling:**

A **different weight** can be assigned to each input by adjusting the values of the input resistors.

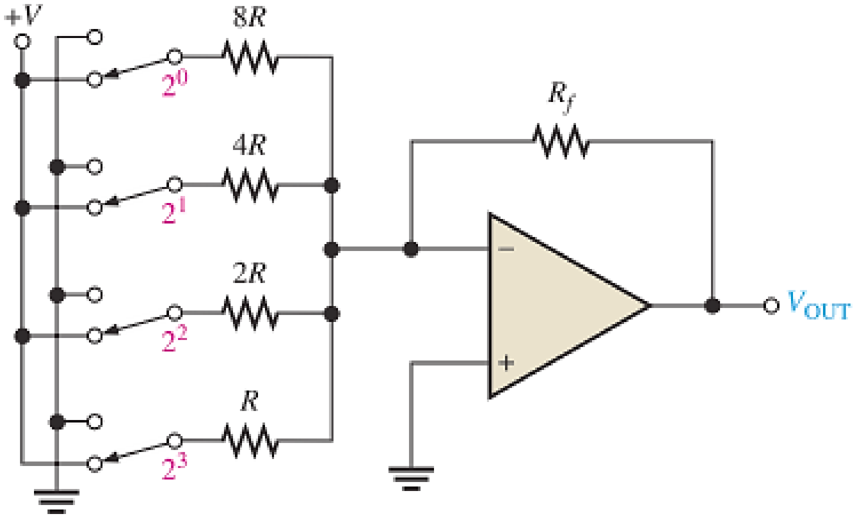
$$V_{OUT} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \cdots + \frac{R_f}{R_n}V_{INn}\right)$$

<u>Example</u>:

V_{out}= - ($3V_{IN1}$+ $0.5V_{IN2}$)

Applications

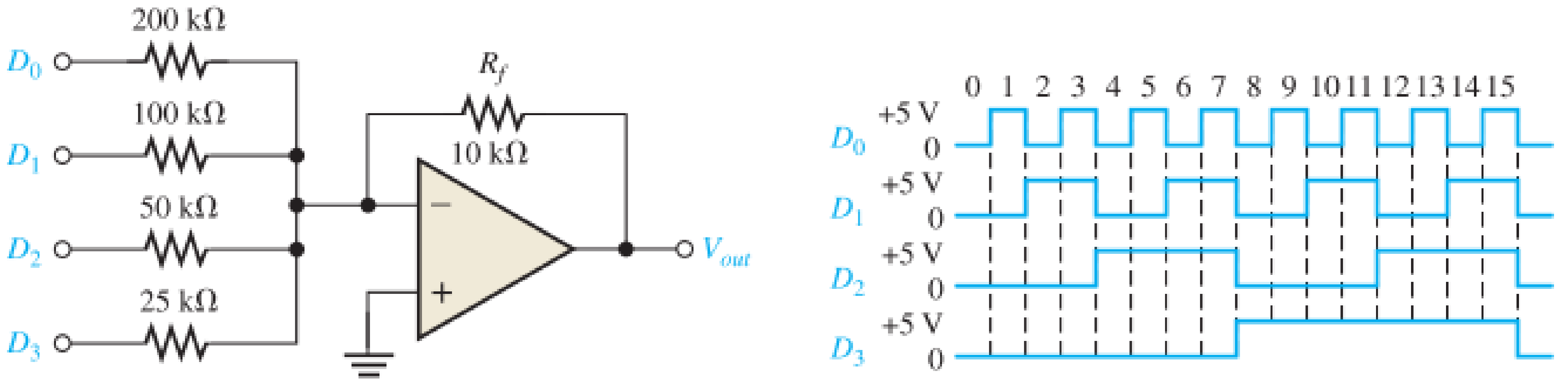
DAC, Scaling Adder as a four-digit DAC



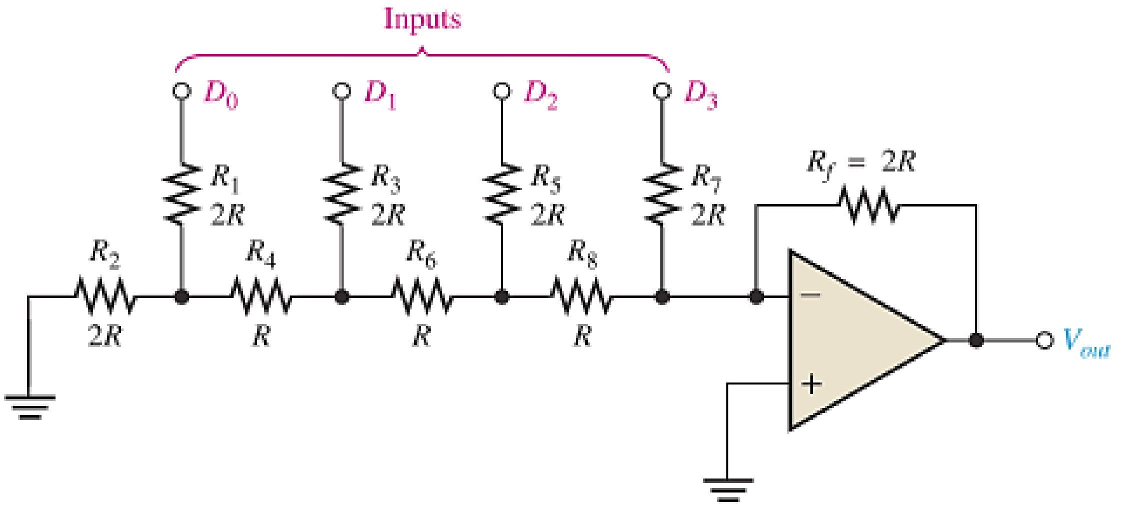
$I_0=+V/8R$
$I_1=+V/4R$
$I_2=+V/2R$
$I_3=+V/R$

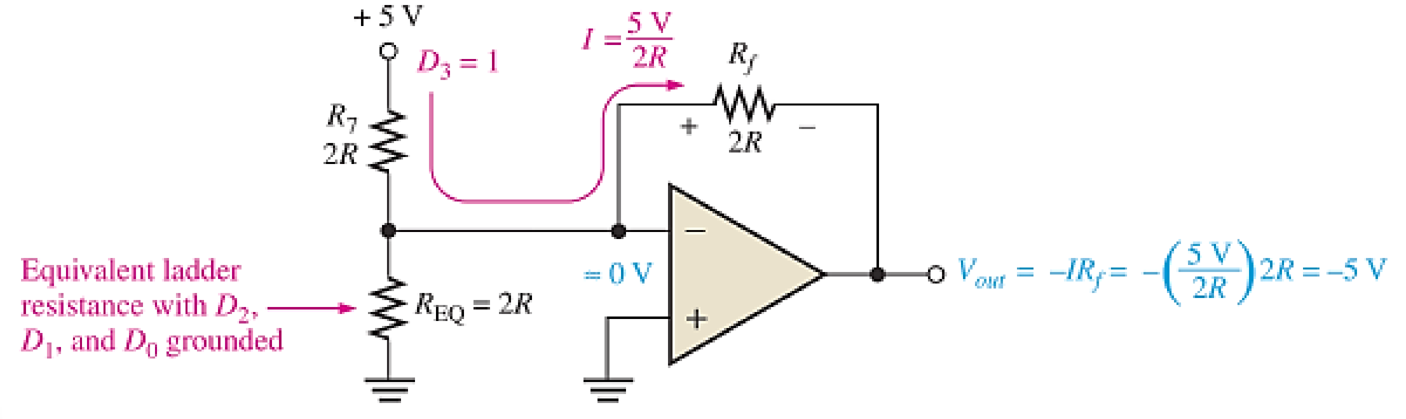
$V_{out(D0)}=-R_f\ I_0$
$V_{out(D1)}=-R_f\ I_1$
$V_{out(D2)}=-R_f\ I_2$
$V_{out(D3)}=-R_f\ I_3$

- Example 13-9



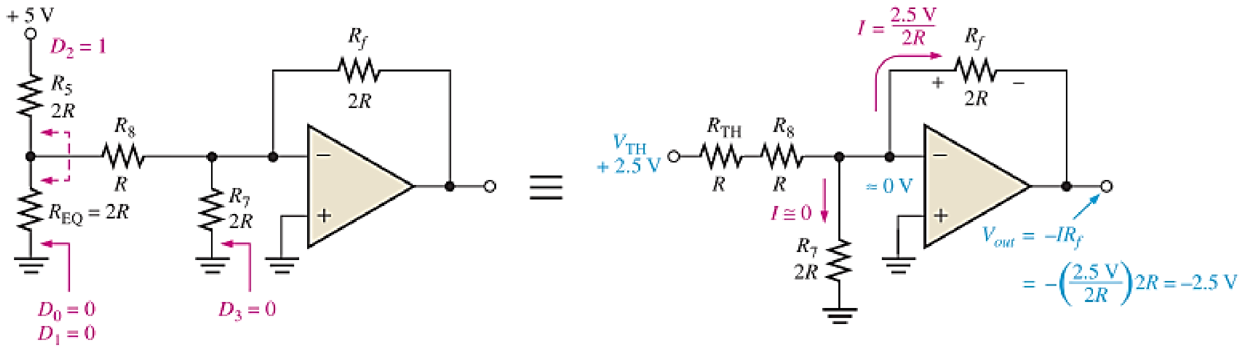
Applications
DAC, An R/2R ladder DAC



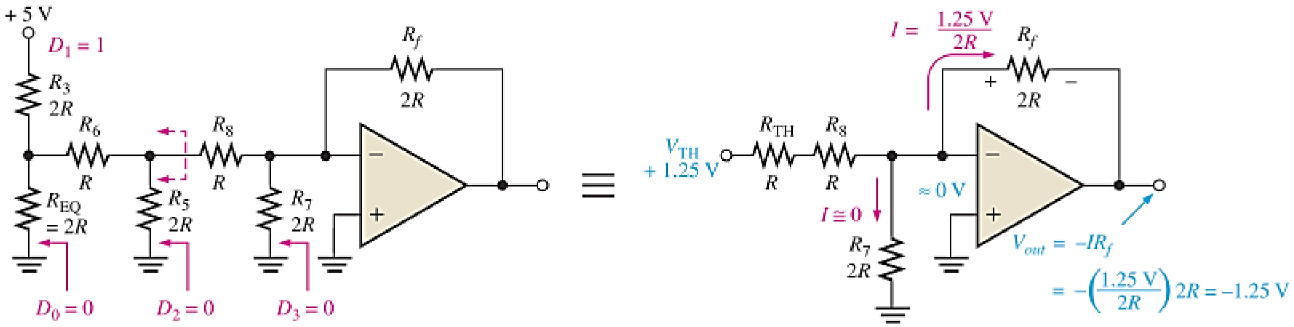


(a) Equivalent circuit for $D_3 = 1$, $D_2 = 0$, $D_1 = 0$, $D_0 = 0$

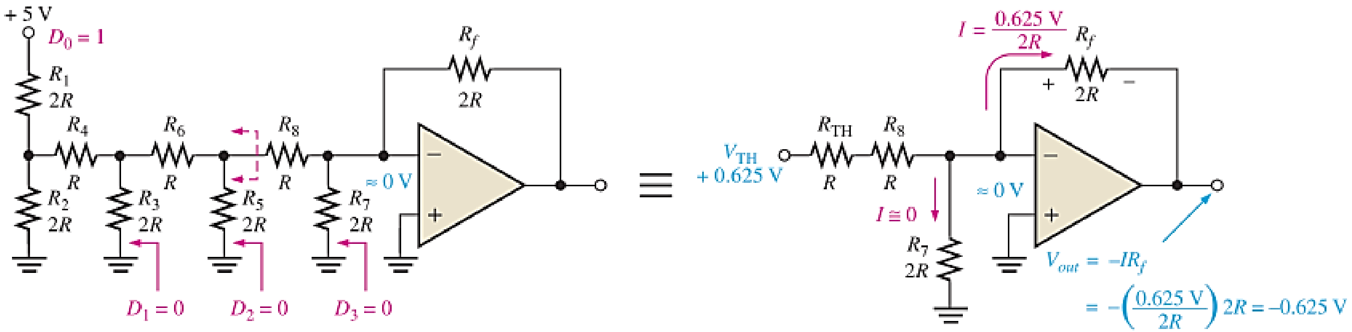
An R/2R ladder DAC ..



(b) Equivalent circuit for $D_3 = 0$, $D_2 = 1$, $D_1 = 0$, $D_0 = 0$



(c) Equivalent circuit for $D_3 = 0$, $D_2 = 0$, $D_1 = 1$, $D_0 = 0$



(d) Equivalent circuit for $D_3 = 0$, $D_2 = 0$, $D_1 = 0$, $D_0 = 1$

▲ **FIGURE 13–30**

Analysis of the *R*/2*R* ladder DAC.

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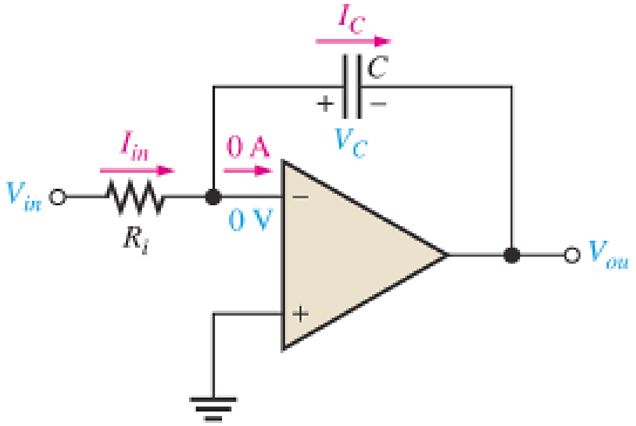
- An op-amp **integrator** simulates mathematical integration, which is basically a **summing** process that determines **the total area under the curve** of a function.
- An op-amp **differentiator** simulates mathematical differentiation, which is a process of determining the **instantaneous rate of change** of a function.

INTEGRATORS & DIFFERENTIATORS

The Op-Amp Integrator Ideal

$$Q = I_C t$$

$$Q = CV_C \longrightarrow V_C = \left(\frac{I_C}{C}\right)t$$

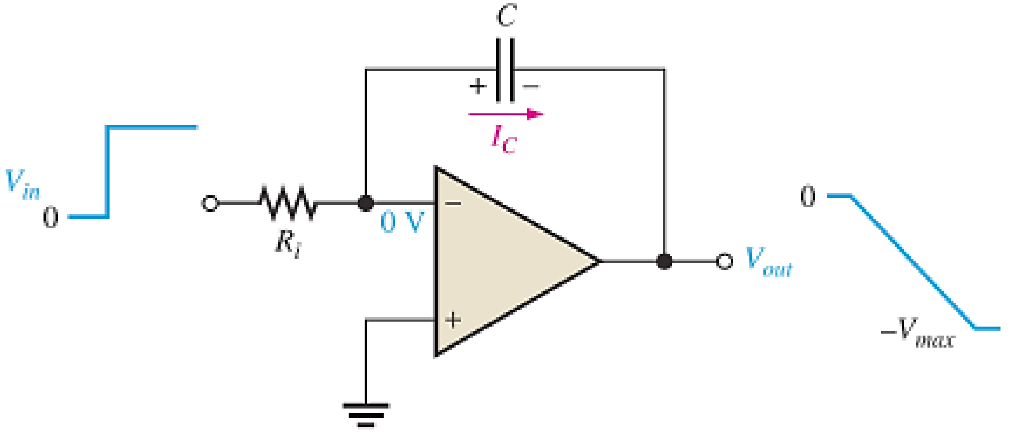


$$I_{in} = \frac{V_{in}}{R_i}$$

$$I_C = I_{in} \qquad I_C = V_{in}/R_i,$$

rate of change or slope of the integrator’s output voltage:

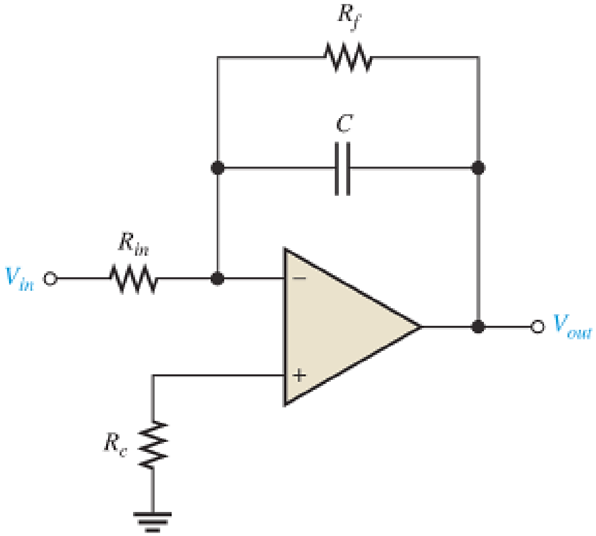
$$\frac{\Delta V_{out}}{\Delta t} = -\frac{V_{in}}{R_i C}$$



The Op-Amp Integrator Practical

- The ideal integrator uses a **capacitor** in the feedback path, which is **open to dc**.
- The gain at dc is the **open-loop gain** of the op-amp.
- In a practical integrator, any **dc error voltage due to offset error** will cause the output to produce a **ramp** that moves toward either positive or negative saturation (depending on the offset), even when no signal is present.

- Practical integrators must overcome the effects of offset and bias current.
- Various **solutions** are available, such as **chopper stabilized amplifiers**.
- The **simplest** solution is to **use a resistor in parallel** with the capacitor in the feedback path.

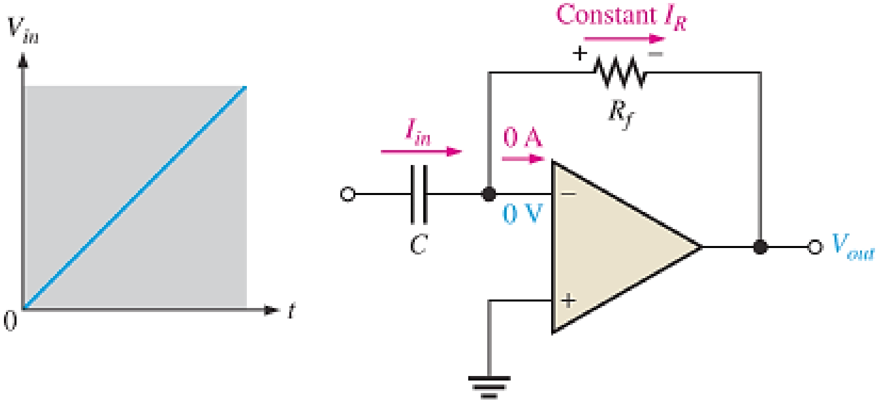


The Op-Amp Differentiator Ideal

$$I_C = \left(\frac{V_C}{t}\right)C$$

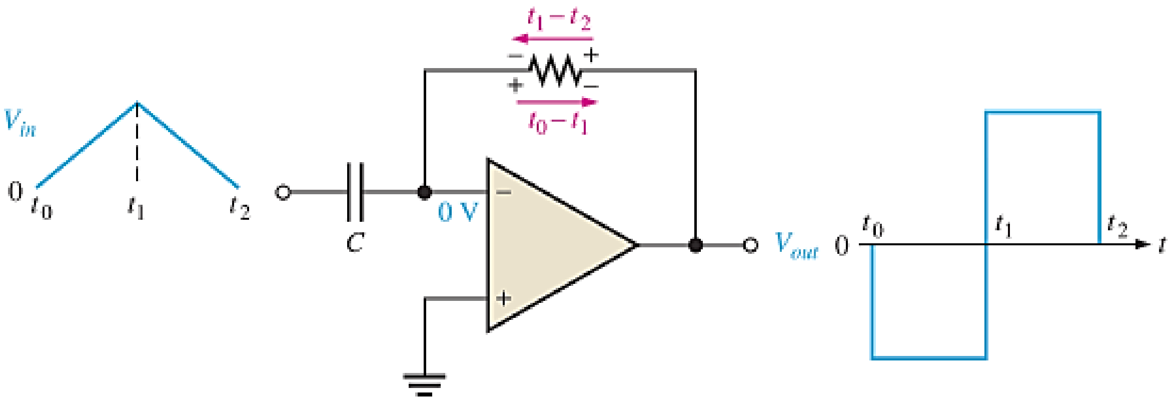
$$V_{out} = I_R R_f = I_C R_f$$

$$V_{out} = -\left(\frac{V_C}{t}\right)R_f C$$



► FIGURE 13–39

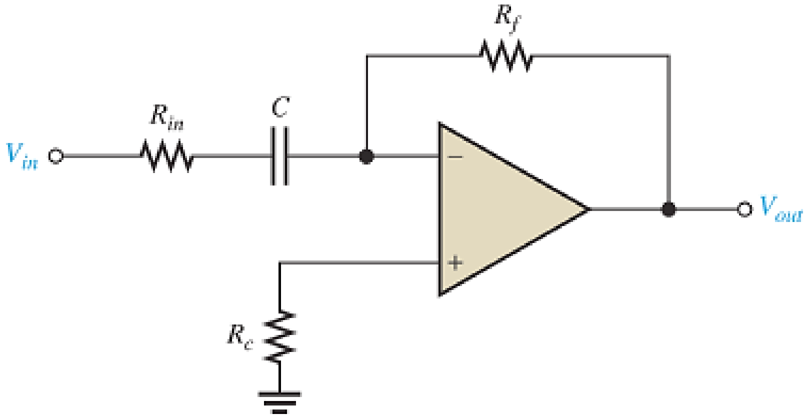
Output of a differentiator with a series of positive and negative ramps (triangle wave) on the input.



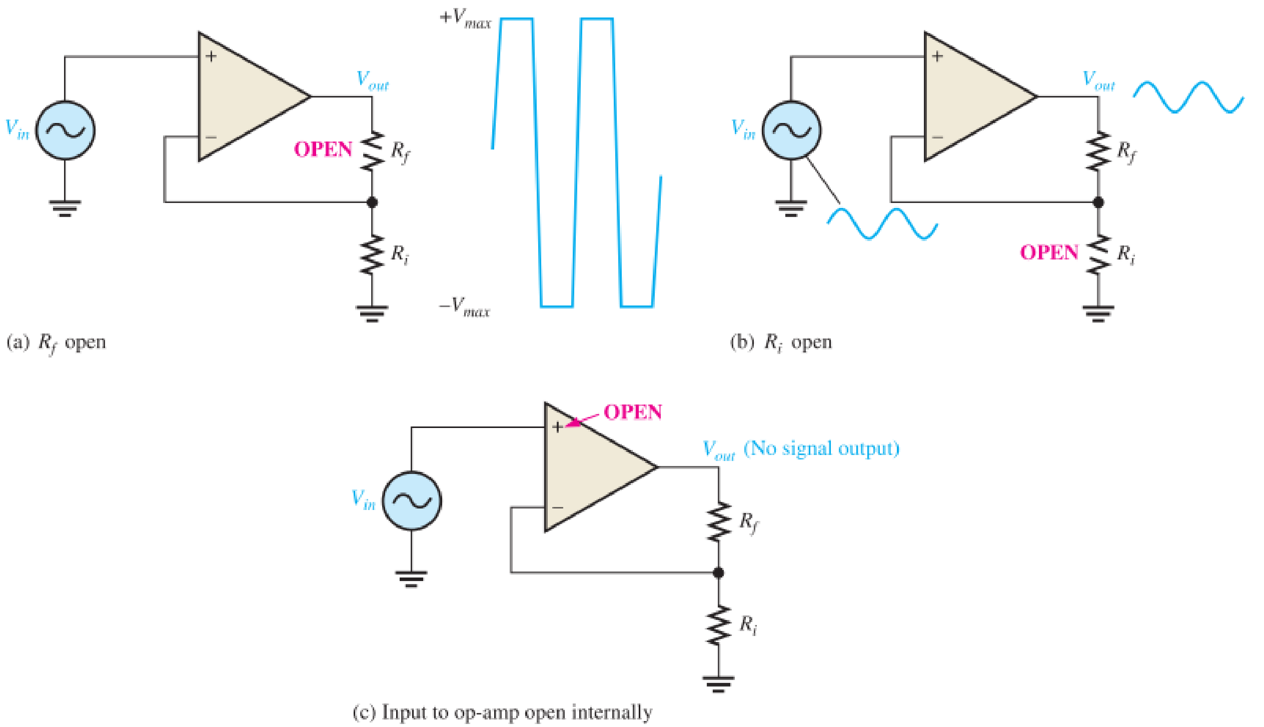
The Op-Amp Differentiator Practical

- The ideal differentiator uses a **capacitor** in series with the inverting input.
- Because a capacitor has very **low impedance** at high frequencies, the combination of R_f and C form a **very high gain amplifier** at high frequencies.
- This means that a differentiator circuit tends to be **noisy** because electrical noise mainly consists of high frequencies.

- The solution to this problem is simply to **add** a resistor, $\mathbf{R_{in}}$, in series with the capacitor to act as a **LPF** and reduce the gain at high frequencies.
- The resistor should be **small** compared to the feedback resistor in order to have a **negligible effect** on the desired signal.



TROUBLESHOOTING



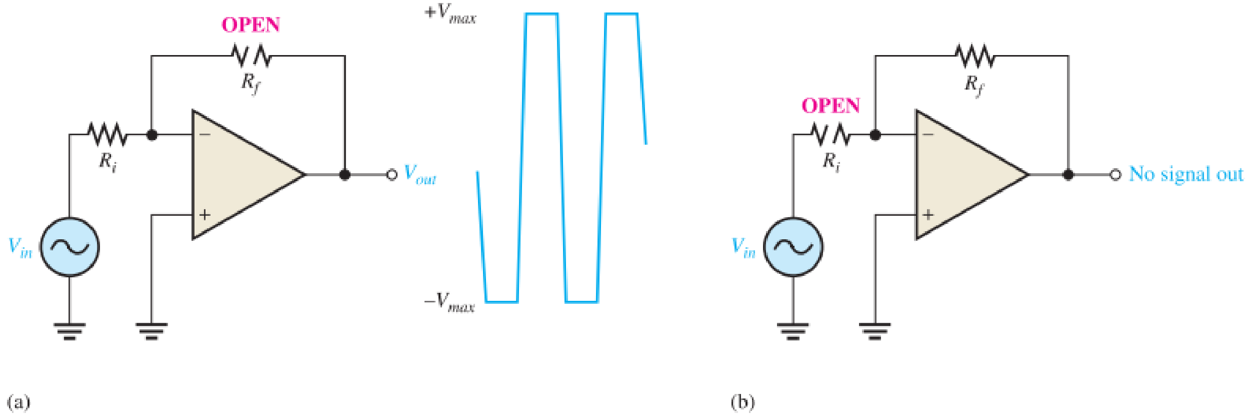
(a) R_f open

(b) R_i open

(c) Input to op-amp open internally

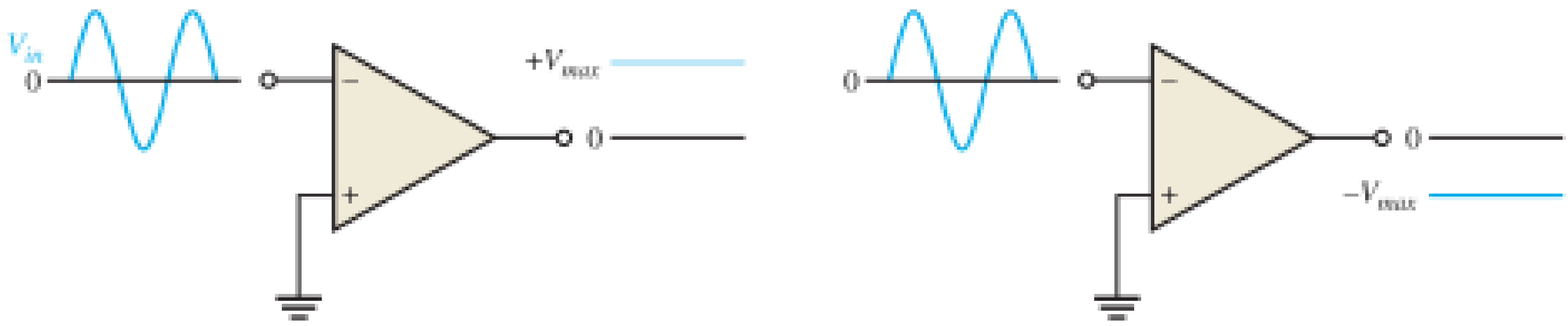
▲ FIGURE 12–44

Faults in the noninverting amplifier.



▲ FIGURE 12–45

Faults in the inverting amplifier.

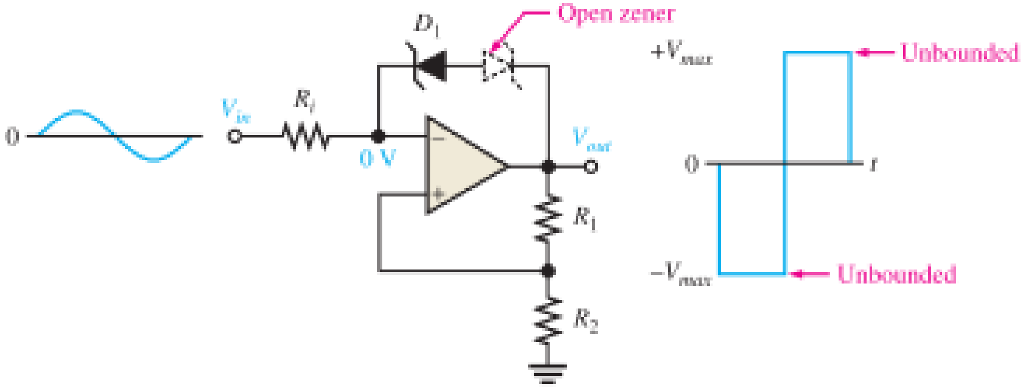


(a) Output failed in the HIGH state

(b) Output failed in the LOW state

FIGURE 13–43

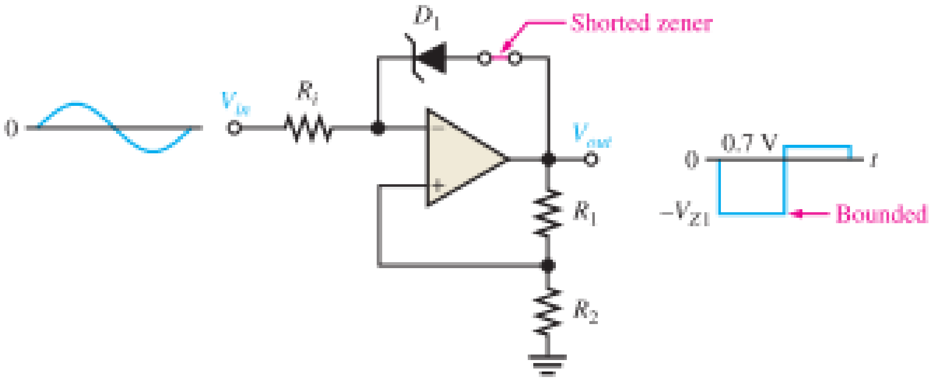
Internal comparator failures typically result in the output being "stuck" in the HIGH or LOW state.



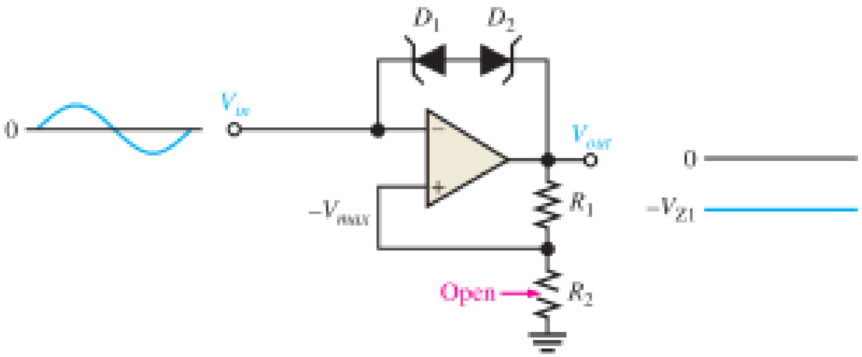
(a) The effect of an open zener

FIGURE 13–45

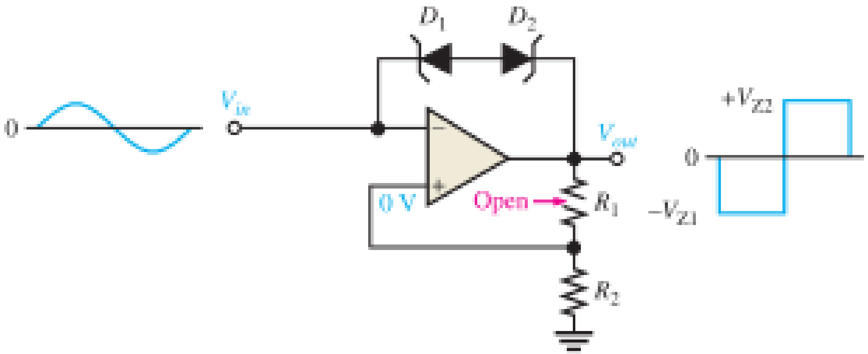
Examples of comparator circuit failures and their effects.



(b) The effect of a shorted zener



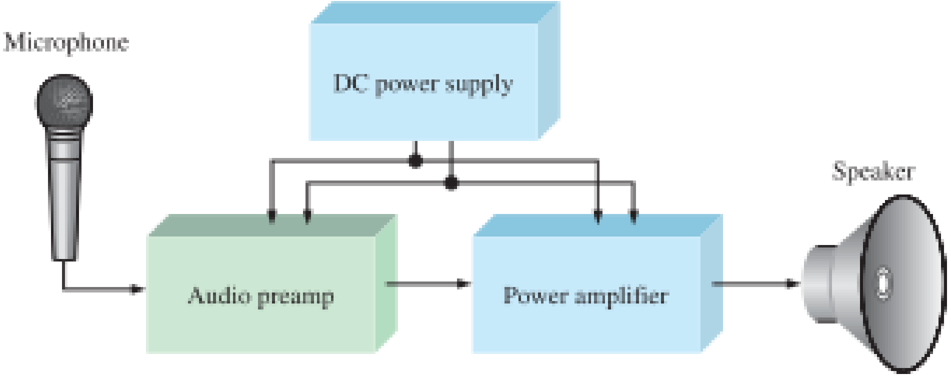
(c) Open R_2 causes output to "stick" in one state

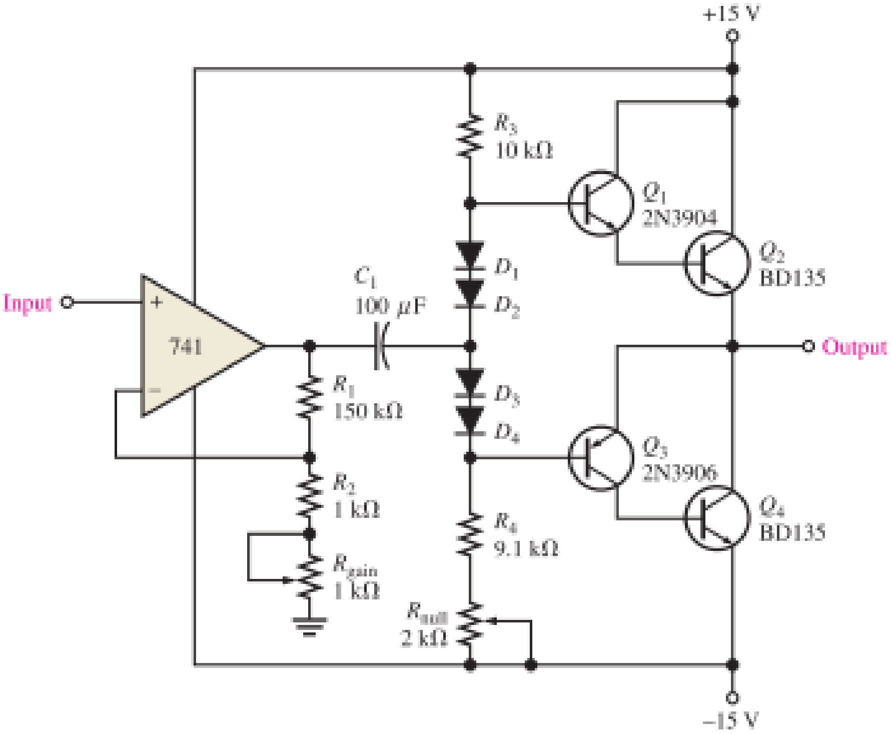


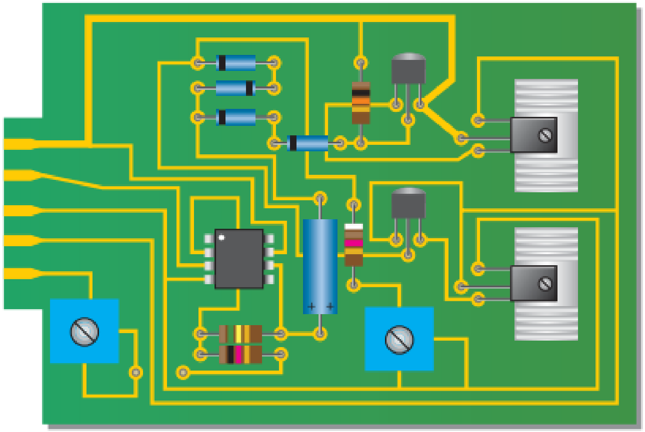
(d) Open R_1 forces the circuit to operate as a zero-level detector

PRACTICAL APPLICATIONS

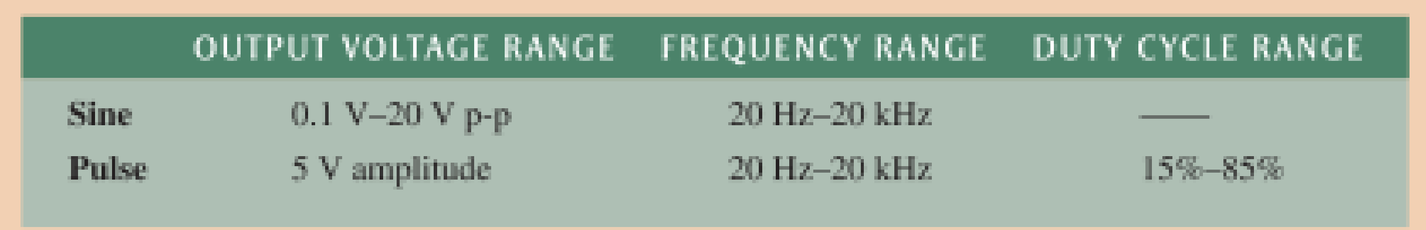
Op-Amp Audio Amplifier



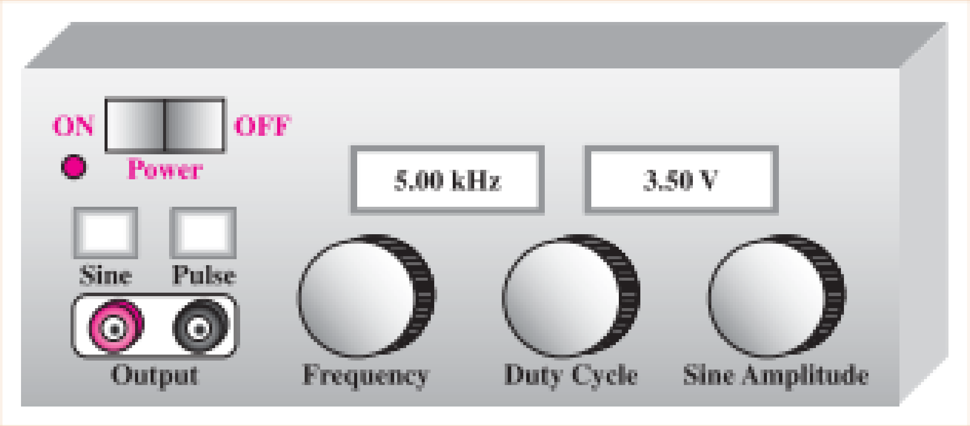




Sine/Pulse Waveform Generator



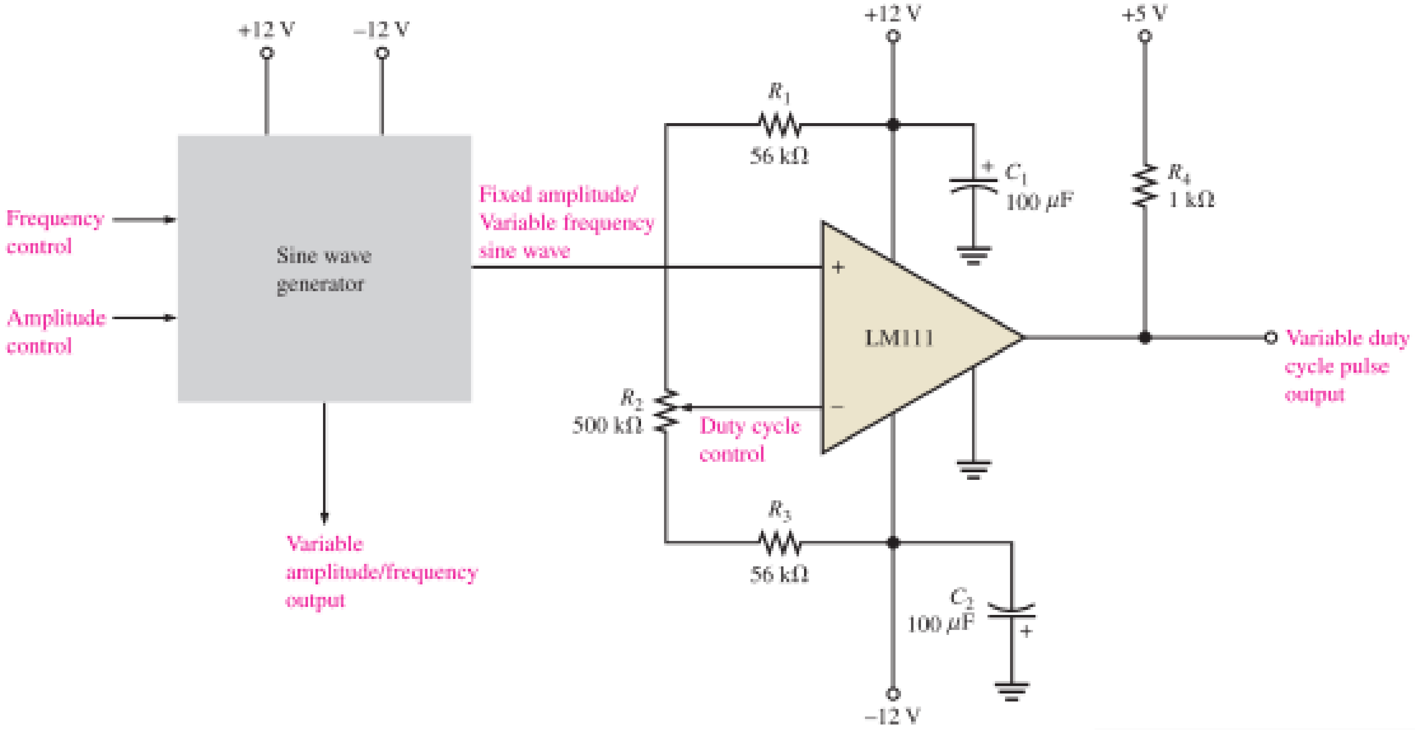
	OUTPUT VOLTAGE RANGE	FREQUENCY RANGE	DUTY CYCLE RANGE
Sine	0.1 V–20 V p-p	20 Hz–20 kHz	——
Pulse	5 V amplitude	20 Hz–20 kHz	15%–85%

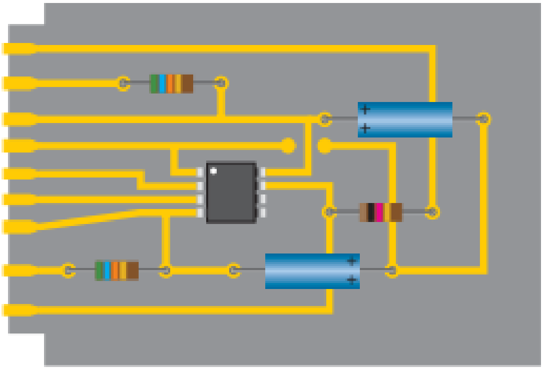


▲ FIGURE 13–49

Front panel of the sine/pulse generator.

Sine/Pulse Waveform Generator..





References

- Floyd, chapters: 12,13
- Boylestad, chapters: 10,11

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