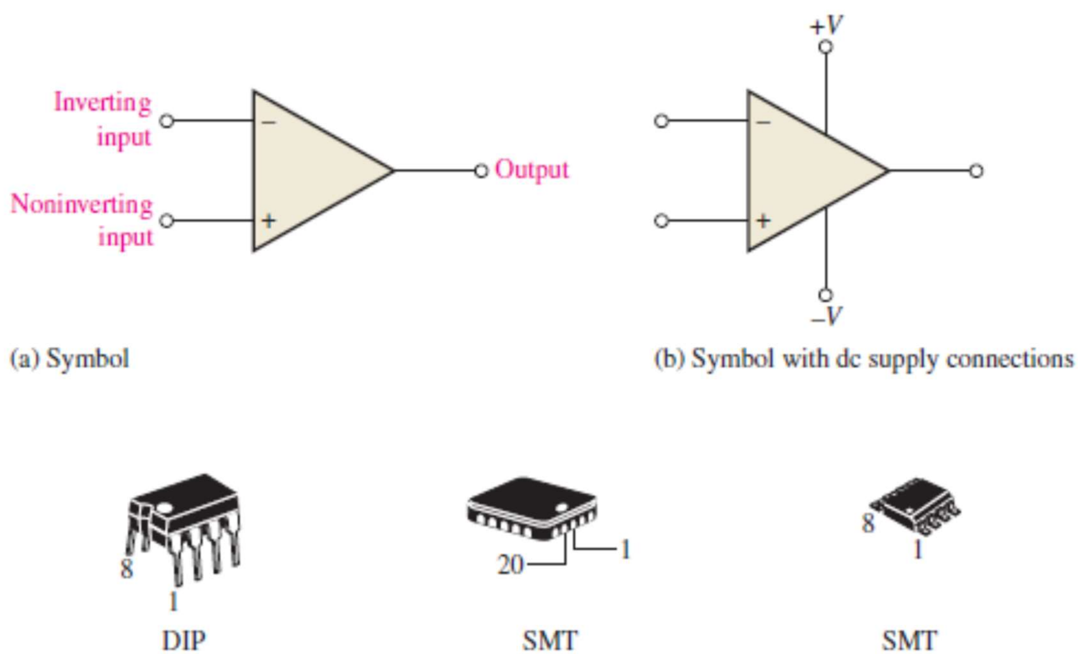
Operational Amplifier

The standard **operational amplifier (op-amp)** symbol is shown in Figure 1(a). It has two input terminals, the inverting (-) input and the noninverting (+) input, and one output terminal. Most op-amps operate with two dc supply voltages, one positive and the other negative, as shown in Figure 1(b), although some have a single dc supply. Usually these dc voltage terminals are left off the schematic symbol for simplicity but are understood to be there. Some typical op-amp IC packages are shown in Figure 1(c).

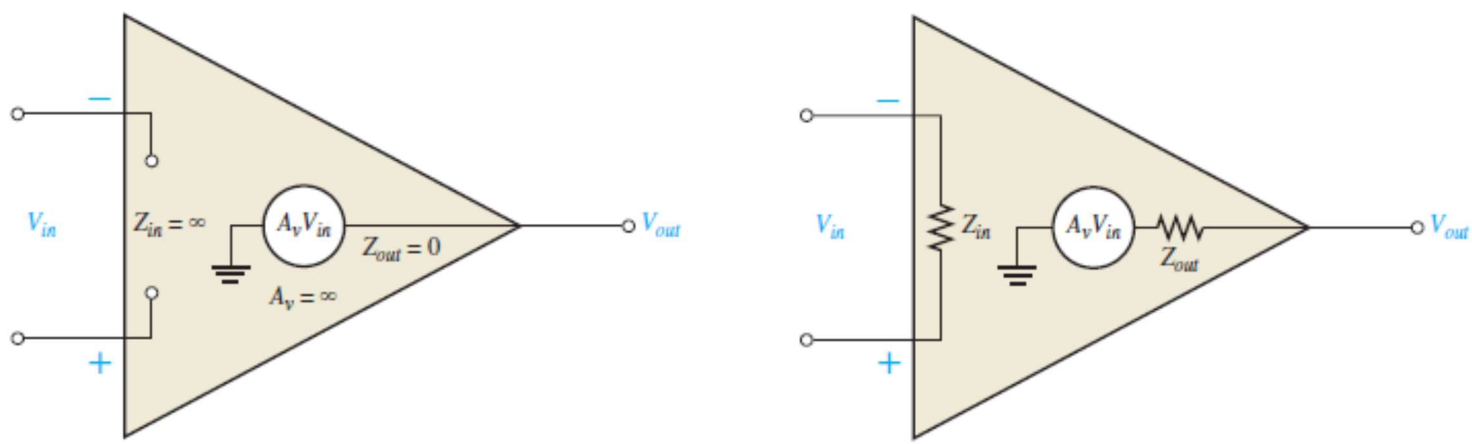


(a) Symbol

(b) Symbol with dc supply connections

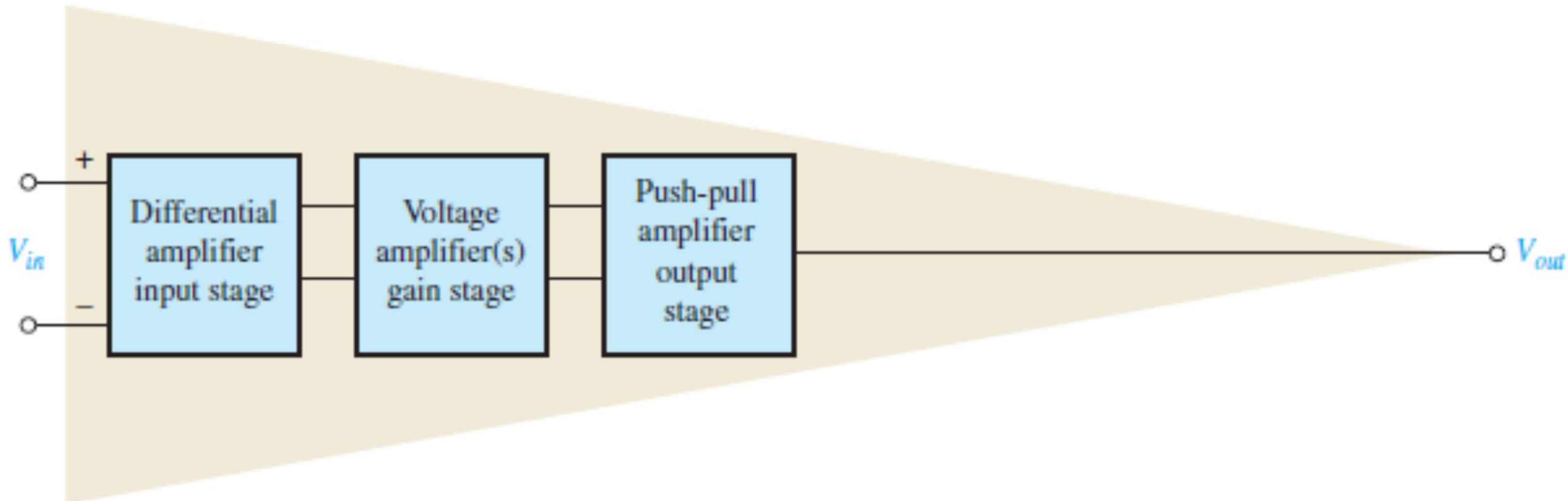
(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.

the ideal op-amp has *infinite voltage gain* and *infinite bandwidth.* Also, it has an *infinite input impedance* (open) so that it does not load the driving source. Finally, it has a *zero output impedance.* Op-amp characteristics are illustrated in Figure (a). The input voltage, *Vin*, appears between the two input terminals, and the output voltage is *AvVin*, as indicated by the internal voltage source symbol.



(a) Ideal op-amp representation

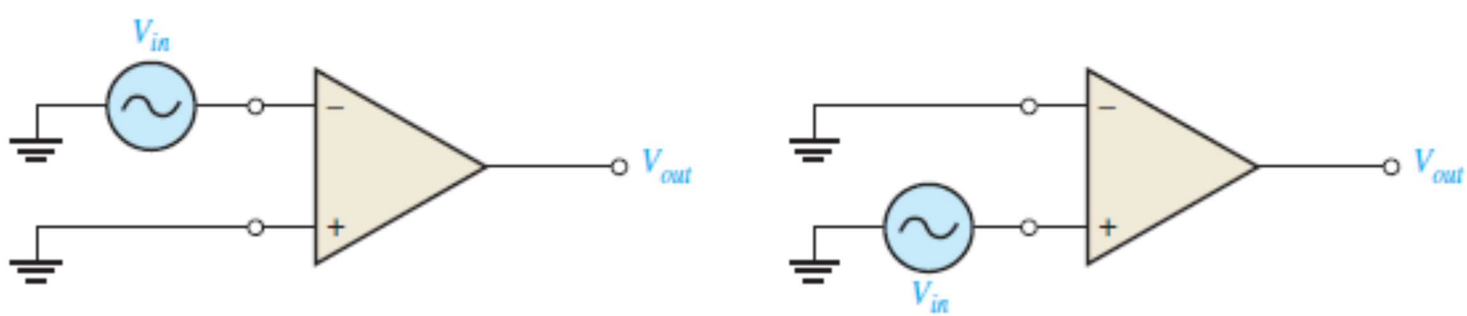
(b) Practical op-amp representation



Characteristics of a practical op-amp are *very high voltage gain, very high input impedance, and very low output impedance.* These are labelled in Figure (b). Another practical consideration is that there is always noise generated within the op-amp. **Noise** is an undesired signal that affects the quality of a desired signal. Today, circuit designers are using smaller voltages that require high accuracy, so low-noise components are in greater demand. All circuits generate noise; op-amps are no exception, but the amount can be minimized.

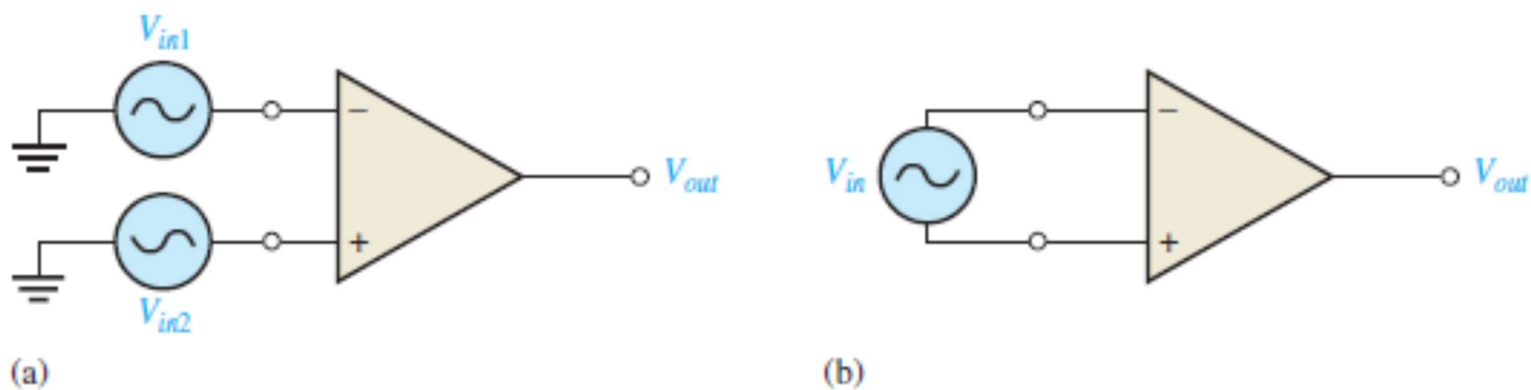
Input Signal Modes

Differential Mode , either one signal is applied to an input with the other input grounded or two opposite-polarity signals are applied to the inputs. When an op-amp is operated in the single-ended differential mode, one input is grounded and a signal voltage is applied to the other input, as shown in Figure 4. In the case where the signal voltage is applied to the inverting input as in part (a), an inverted, amplified signal voltage appears at the output. In the case where the signal is applied to the noninverting input with the inverting input grounded, as in Figure (b), a non-inverted, amplified signal voltage appears at the output.

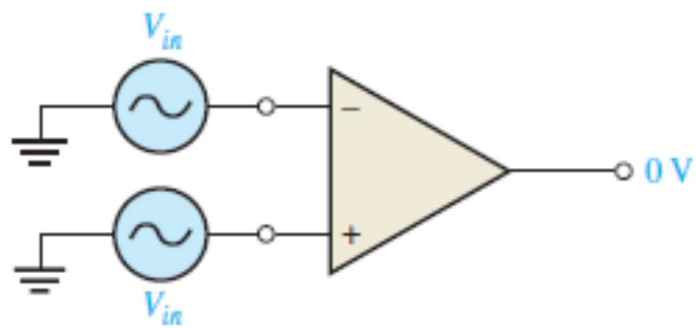


(a) (b)

In the *double-ended* differential mode, two opposite-polarity (out-of-phase) signals are applied to the inputs, as shown in Figure 2(a). The amplified difference between the two inputs appears on the output. Equivalently, the double-ended differential mode can be represented by a single source connected between the two inputs, as shown in
Figure 2(b).



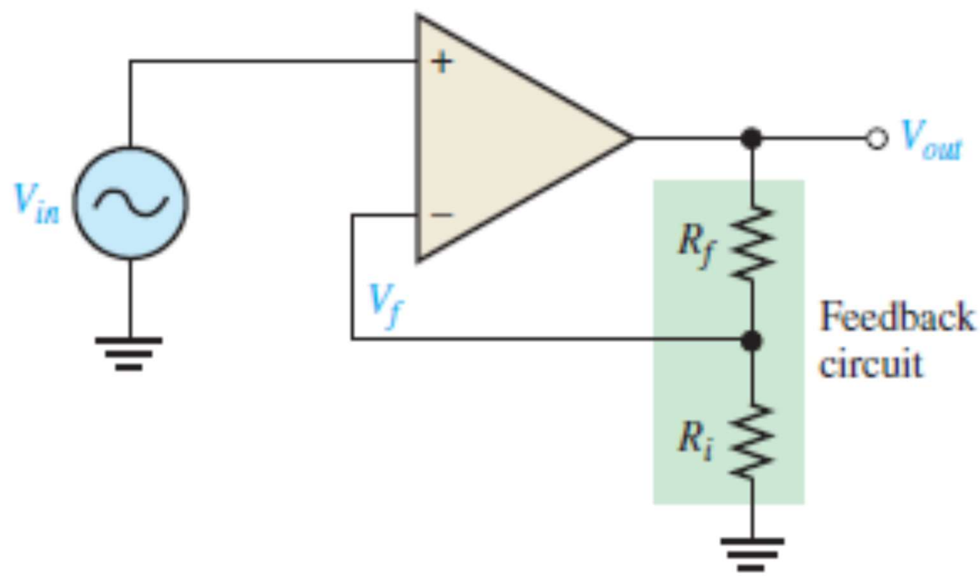
Common Mode, two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown in Figure 3. When equal input signals are applied to both inputs, they tend to cancel, resulting in a zero output voltage.



Noninverting Amplifier

An op-amp connected in a **closed-loop** configuration as a **noninverting amplifier** with a controlled amount of voltage gain is shown in Figure 4. The input signal is applied to the noninverting (+) input. The output is applied back to the inverting input through the feedback circuit (closed loop) formed by the input resistor *Ri* and the feedback resistor *Rf.* This creates negative feedback as follows. Resistors *Ri* and *Rf* form a voltage-divider circuit, which reduces *Vout* and connects the reduced voltage *Vf* to the inverting input. The feedback voltage is expressed as

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

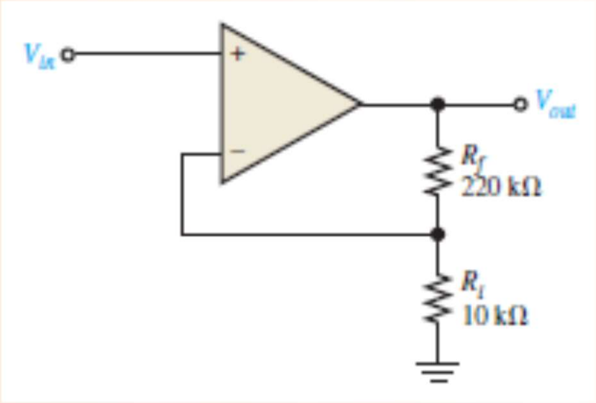


EXAMPLE 12–5

(a) Determine the input and output impedances of the amplifier in Figure 12–25. The op-amp datasheet gives $Z_{in} = 2\ \text{M}\Omega$, $Z_{out} = 75\ \Omega$, and $A_{ol} = 200{,}000$.

(b) Find the closed-loop voltage gain.

► FIGURE 12–25



Solution **(a)** The attenuation, B, of the feedback circuit is

$$B = \frac{R_i}{R_i + R_f} = \frac{10\ \text{k}\Omega}{230\ \text{k}\Omega} = 0.0435$$

$$Z_{in(NI)} = (1 + A_{ol}B)Z_{in} = [1 + (200{,}000)(0.0435)](2\ \text{M}\Omega)$$

$$= (1 + 8700)(2\ \text{M}\Omega) = \mathbf{17.4\ G\Omega}$$

This is such a large number that, for all practical purposes, it can be assumed to be infinite as in the ideal case.

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{75\ \Omega}{1 + 8700} = \mathbf{8.6\ m\Omega}$$

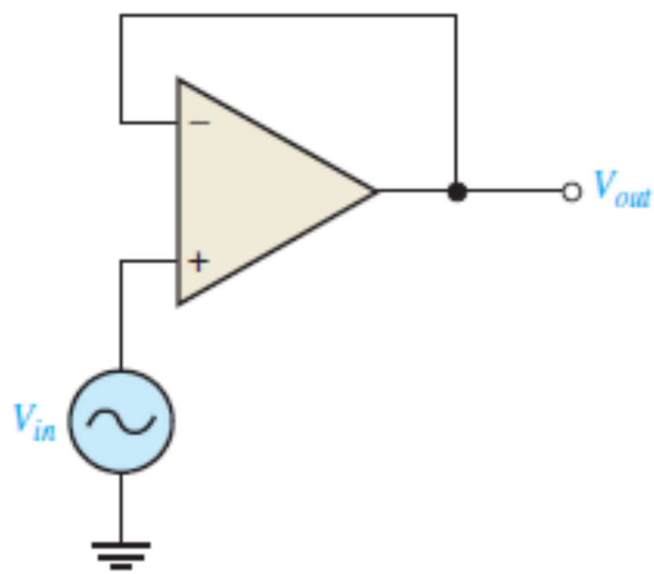
This is such a small number that, for all practical purposes, it can be assumed to be zero as in the ideal case.

(b) $A_{cl(NI)} = 1 + \dfrac{R_f}{R_i} = 1 + \dfrac{220\ \text{k}\Omega}{10\ \text{k}\Omega} = \mathbf{23.0}$

Voltage-Follower

The **voltage-follower** configuration is a special case of the noninverting amplifier where all of the output voltage is fed back to the inverting input by a straight connection, as shown in Figure 6. As you can see, the straight feedback connection has a voltage gain of 1 (which means there is no gain). The closed-loop voltage gain of a noninverting amplifier is as previously derived. Since *B* 1 for a voltage-follower, the closed-loop voltage gain of the voltage-follower is

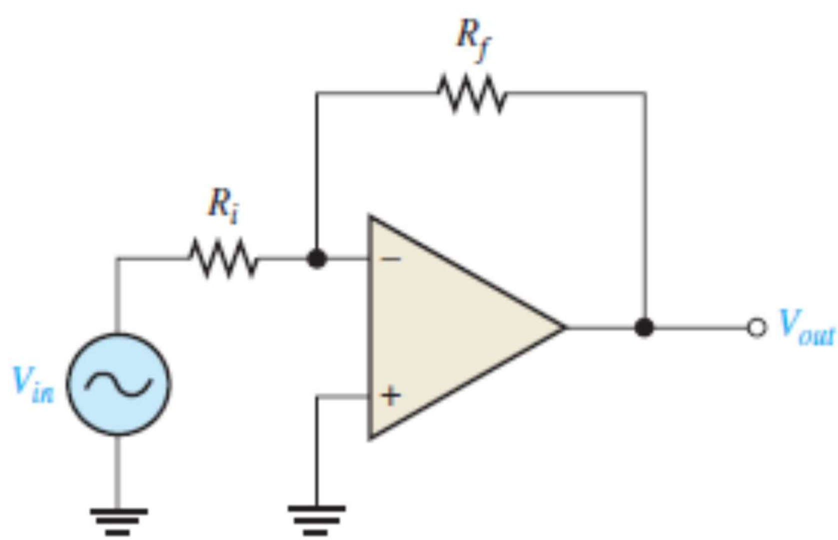
$$A_{cl(\mathrm{VF})} = 1$$



Inverting Amplifier

An op-amp connected as an **inverting amplifier** with a controlled amount of voltage gain is shown in Figure 7. The input signal is applied through a series input resistor *Ri* to the inverting input. Also, the output is fed back through *Rf* to the same input. The noninverting (+) input is grounded.

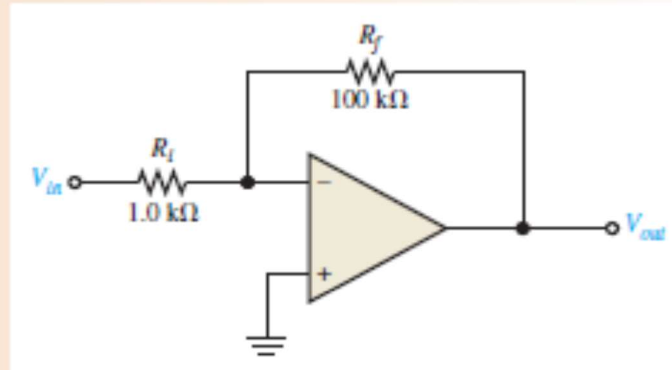
$$A_{cl(I)} = -\frac{R_f}{R_i}$$



EXAMPLE 12–7

Find the values of the input and output impedances in Figure 12–28. Also, determine the closed-loop voltage gain. The op-amp has the following parameters: $A_{ol} = 50{,}000$; $Z_{in} = 4\ \text{M}\Omega$; and $Z_{out} = 50\ \Omega$.

▶ FIGURE 12–28



Solution

$$Z_{in(I)} \cong R_i = \mathbf{1.0\ k\Omega}$$

The feedback attenuation, B, is

$$B = \frac{R_i}{R_i + R_f} = \frac{1.0\ \text{k}\Omega}{101\ \text{k}\Omega} = 0.001$$

Then

$$Z_{out(I)} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{50\ \Omega}{1 + (50{,}000)(0.001)}$$

$$= \mathbf{980\ m\Omega}\ \text{(zero for all practical purposes)}$$

The closed-loop voltage gain is

$$A_{cl(I)} = -\frac{R_f}{R_i} = -\frac{100\ \text{k}\Omega}{1.0\ \text{k}\Omega} = \mathbf{-100}$$

Comparators

A **comparator** is a specialized op-amp circuit that compares two input voltages and produces an output that is always at either one of two states, indicating the greater or less than relationship between the inputs. Comparators provide very fast switching times, and many have additional capabilities *(such as fast propagation delay or internal reference voltages)* to optimize the comparison function. For example, some ultra-high-speed comparators can have propagation delays of as little as 500 ps. Because the output is always in one of two states, comparators are often used to interface between an analog and digital circuit.

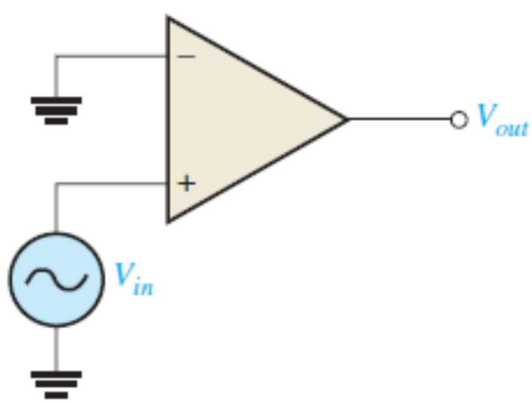
For less critical applications, an op-amp running without negative feedback *(open-loop)* is often used as a comparator. Although op-amps are much slower and lack other special features, they have very high open-loop gain, which enables them to detect very tiny differences in the inputs. In general, comparators cannot be used as op-amps, but op-amps can be used as comparators in noncritical applications. Because an op-amp without negative feedback is essentially a comparator, we will look at the comparison function using a typical op-amp.

Zero-Level Detection

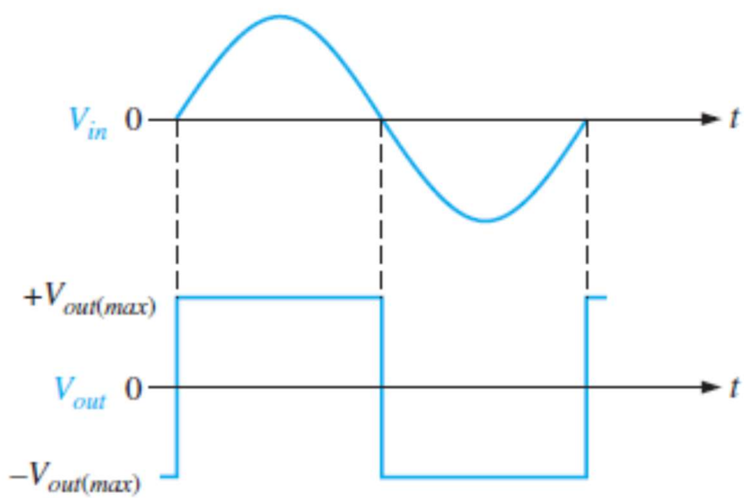
One application of an op-amp used as a comparator is to determine when an input voltage exceeds a certain level. Figure 13–1(a) shows a zero-level detector. Notice that the inverting input is grounded to produce a zero level and that the input signal voltage is applied to the noninverting input. Because of the high open-loop voltage gain, a very small difference voltage between the two inputs drives the amplifier into saturation, causing the output voltage to go to its limit. For example, consider an op-amp having *Aol* 100,000. A voltage difference of only 0.25 mV between the inputs could produce an output voltage of (0.25 mV)(100,000) 25 V *if* the op-amp were capable. However, since most op-amps have maximum output voltage limitations near the value of their dc supply voltages, the device would be driven into saturation.

Zero-Level Detection

Figure (b) shows the result of a sinusoidal input voltage applied to the noninverting input of the zero-level detector. When the sine wave is positive, the output is at its maximum positive level. When the sine wave crosses 0, the amplifier is driven to its opposite state and the output goes to its maximum negative level, as shown. As you can see, the zero level detector can be used as a squaring circuit to produce a square wave from a sine wave.



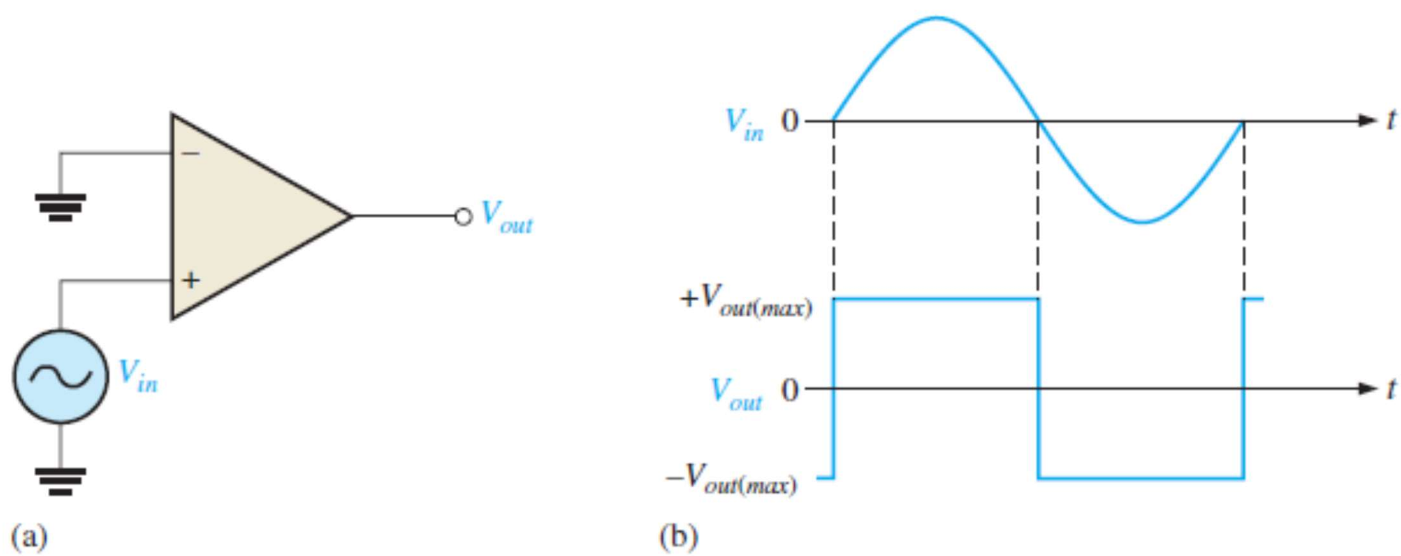
(a)



(b)

Nonzero-Level Detection

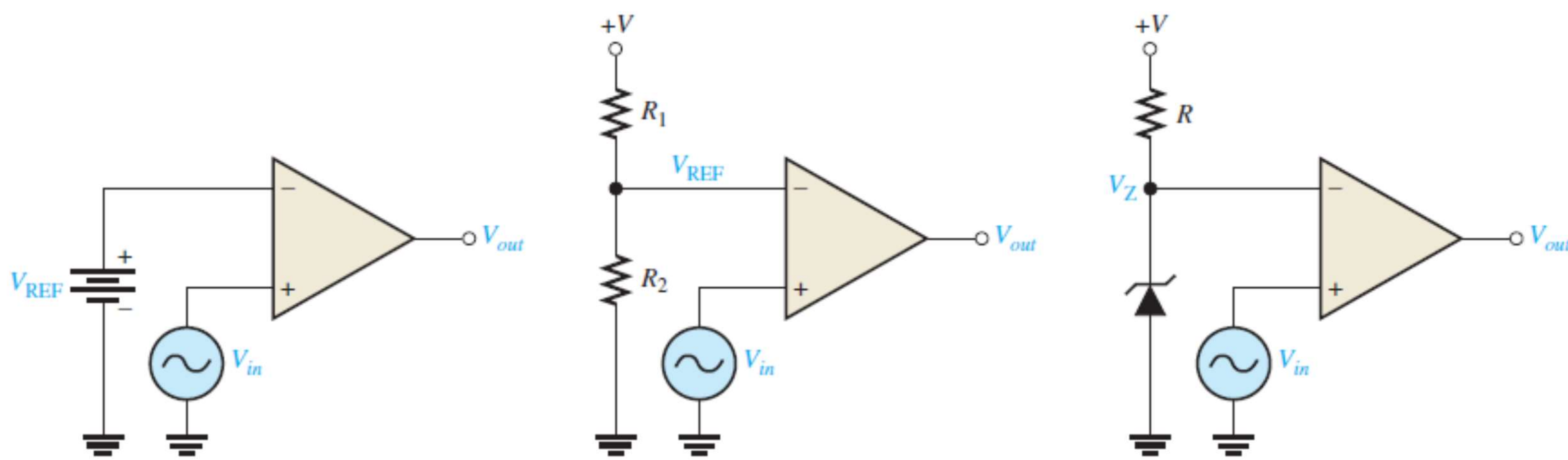
The zero-level detector in Figure can be modified to detect positive and negative voltages by connecting a fixed reference voltage source to the inverting input, as shown in Figure (a). A more practical arrangement is shown in Figure (b) using a voltage divider to set the reference voltage, *V*REF, as follows:



Nonzero-Level Detection

where +*V* is the positive op-amp dc supply voltage. The circuit in Figure 13–2(c) uses a zener diode to set the reference voltage (*V*REF *V*Z). As long as *Vin* is less than *V*REF, the output remains at the maximum negative level. When the input voltage exceeds the reference voltage, the output goes to its maximum positive voltage, as shown in Figure (d) with a sinusoidal input voltage.

$$V_{\mathrm{REF}} = \frac{R_2}{R_1 + R_2}(+V)$$

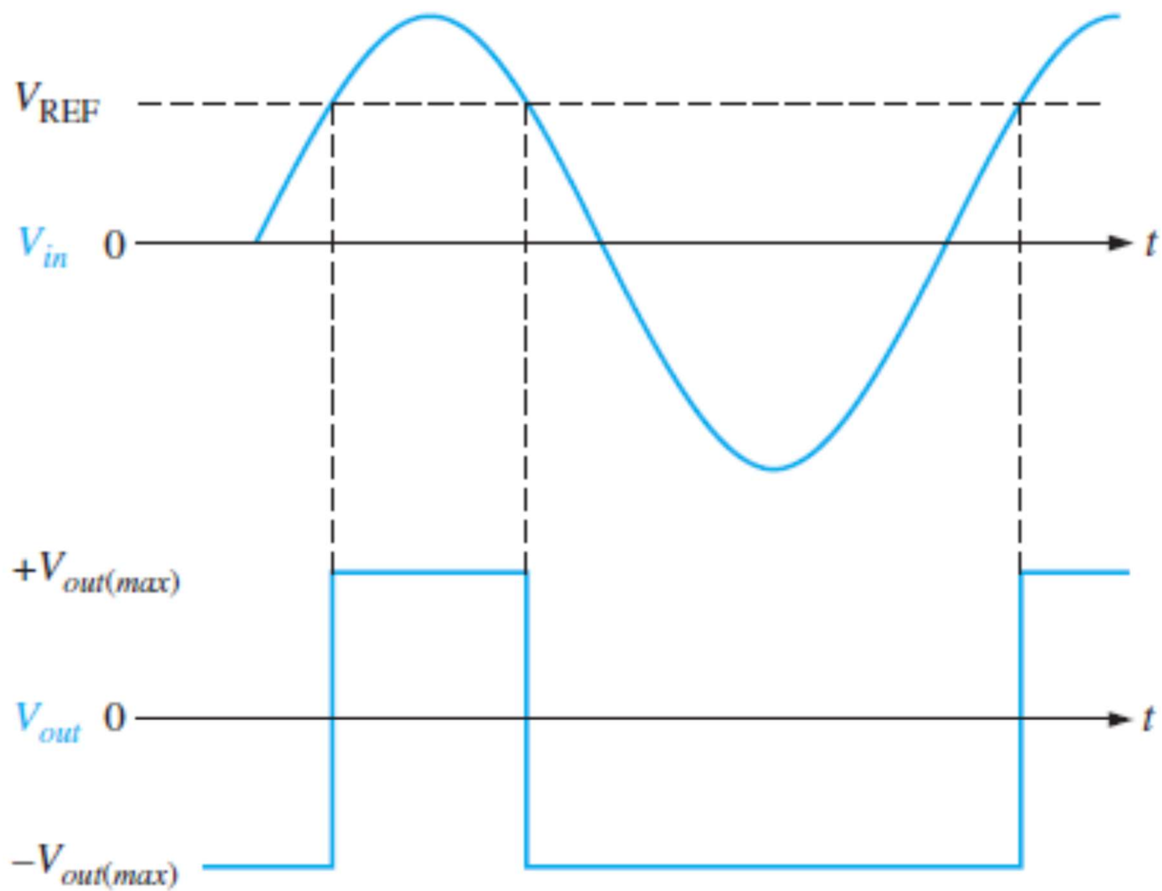


(a) Battery reference

(b) Voltage-divider reference

(c) Zener diode sets reference voltage

Nonzero-Level Detection

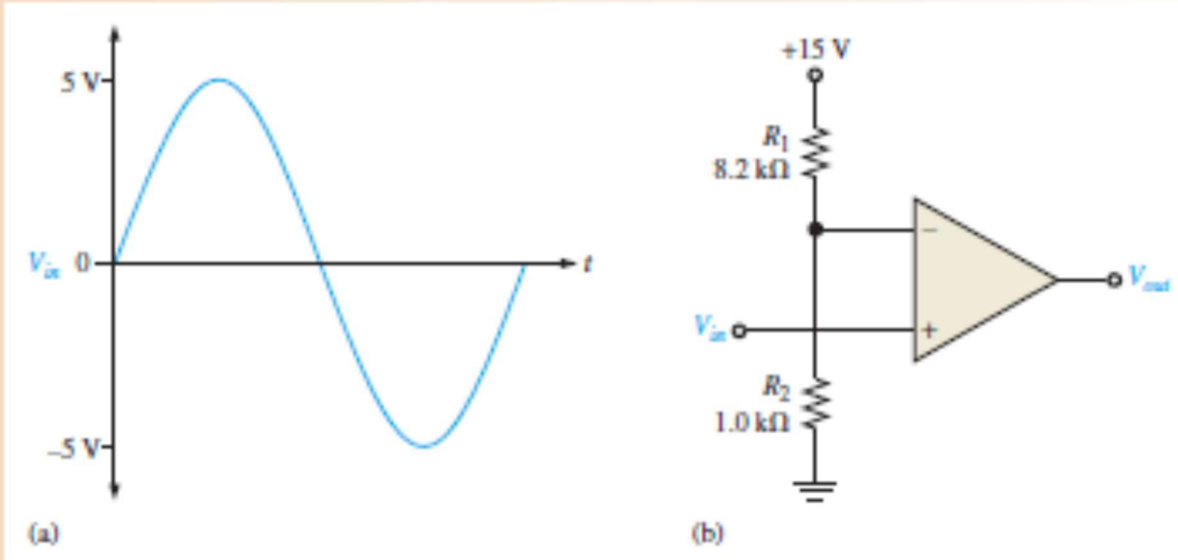


(d) Waveforms

EXAMPLE 13–1

The input signal in Figure 13–3(a) is applied to the comparator in Figure 13–3(b). Draw the output showing its proper relationship to the input signal. Assume the maximum output levels of the comparator are ±14 V.

▶ FIGURE 13–3

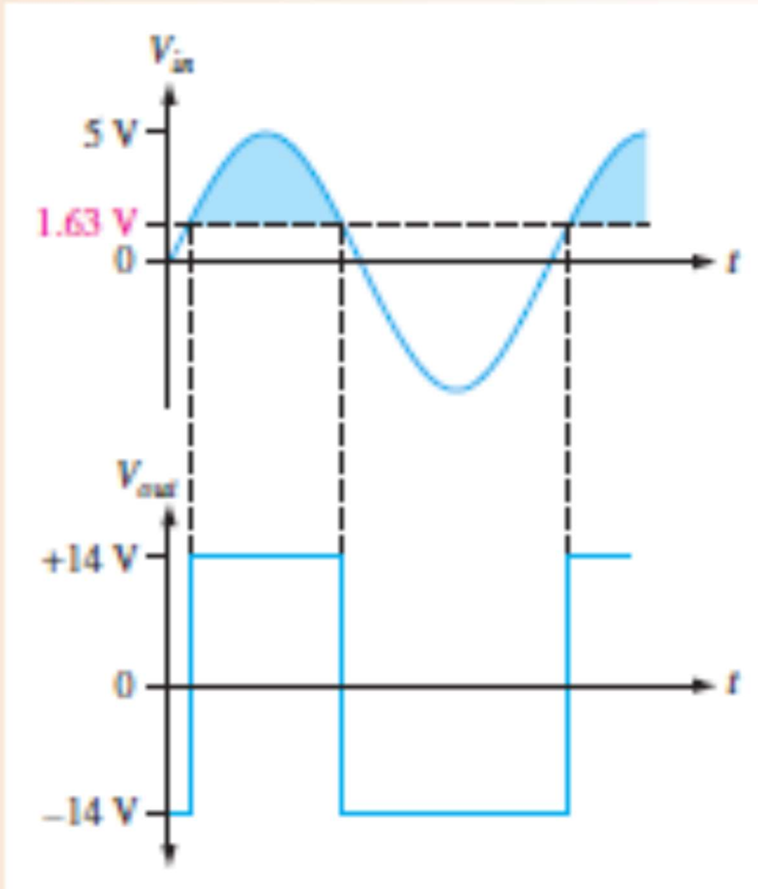


Solution The reference voltage is set by R_1 and R_2 as follows:

$$V_{REF} = \frac{R_2}{R_1 + R_2}(+V) = \frac{1.0\,k\Omega}{8.2\,k\Omega + 1.0\,k\Omega}(+15\,V) = 1.63\,V$$

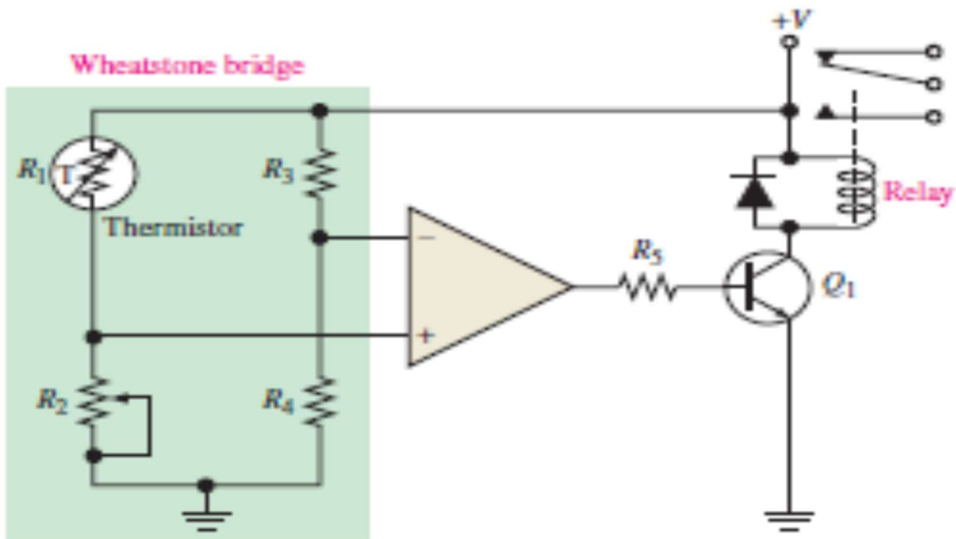
As shown in Figure 13–4, each time the input exceeds +1.63 V, the output voltage switches to its +14 V level, and each time the input goes below +1.63 V, the output switches back to its −14 V level.

▶ FIGURE 13–4



Comparator Applications

Over-Temperature Sensing Circuit Figure 13–15 shows an op-amp comparator used in a precision over-temperature sensing circuit to determine when the temperature reaches a certain critical value. The circuit consists of a Wheatstone bridge with the op-amp used to detect when the bridge is balanced. One leg of the bridge contains a thermistor (R_1), which is a temperature-sensing resistor with a negative temperature coefficient (its resistance decreases as temperature increases). The potentiometer (R_2) is set at a value equal to the resistance of the thermistor at the critical temperature. At normal temperatures (below critical), R_1 is greater than R_2, thus creating an unbalanced condition that drives the op-amp to its low saturated output level and keeps transistor Q_1 off.



As the temperature increases, the resistance of the thermistor decreases. When the temperature reaches the critical value, R_1 becomes equal to R_2, and the bridge becomes balanced (since $R_3 = R_4$). At this point the op-amp switches to its high saturated output level, turning Q_1 on. This energizes the relay, which can be used to activate an alarm or initiate an appropriate response to the over-temperature condition.