considered to be basic building blocks in analog circuit design. An op-amp may contain dozens of transistors, but its external interface consists of two differential inputs and an amplified output as shown in Fig. 14.1. The positive, or *noninverting*, and the negative, or *inverting*, inputs form a differential voltage, $v_D = v_+ - v_-$, that is amplified by a certain gain, A, at the output so that $v_O = Av_D = A(v_+ - v_-)$. When discussing the AC signals on which amplifiers operate, lower-case letters are used to indicate voltages and currents by convention to distinguish them from DC voltages and currents that have already been shown to use capital letters.

Many of the implementation details of how an AC signal is amplified within the op-amp are hidden from the circuit designer, requiring only an understanding of how the op-amp behaves from an external perspective. It is best to first explore an ideal op-amp's operation and then take into account the real-world deviations from the ideal model as necessary when designing a real circuit. An ideal op-amp has the following characteristics:

- *Infinite input impedance.* No current flows into or out of the inputs
- *Infinite open-loop gain.* This may sound confusing, but most op-amp circuits employ feedback that reduces the infinite gain to the desired level. $A = \infty$ simplifies op-amp circuit analysis, as will soon be shown.
- *Infinite bandwidth.* The op-amp's gain is constant across frequency from zero to infinity.
- *Zero output impedance.* The op-amp's output will always be equal to Av_D regardless of the load being driven.

These fundamental assumptions provide the engineer with a very flexible amplifier component that can be customized by surrounding circuitry to suit a wide range of applications. Perhaps the first question that comes to mind is how an amplifier with infinite gain can be made useful. The trick is in creating a *closed-loop* circuit that provides feedback from output to input to control the gain of the overall circuit. Without a feedback path, an *open-loop* op-amp circuit would, in fact, exhibit very high gain to the point of grossly distorting most types of signals. Consider the basic *noninverting* closed-loop op-amp circuit in Fig. 14.2. While the signal is injected into the positive input, the op-amp's output feeds back to the negative input through the resistor network formed by R1 and R2.

Based on the assumption of infinite input impedance, a basic resistor divider expression for v_- can be written based solely on the output voltage, v_O, and the two resistors.

$$v_- = v_O \frac{R1}{R1 + R2}$$

Knowing that $v_O = Av_D = A(v_+ - v_-)$, this expression can be used to reveal a relationship between the input voltage, v_I, and v_O.

$$v_O = A(v_+ - v_-) = Av_I - A\left[v_O \frac{R1}{R1 + R2}\right]$$

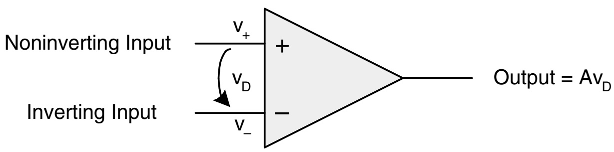

FIGURE 14.1 Op-amp graphical representation.

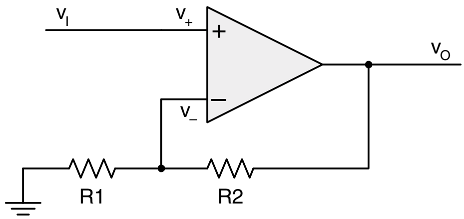

FIGURE 14.2 Noninverting op-amp circuit.

This relationship can be simplified based on the assumption of infinite gain. Dividing both sides of the equation by $A = \infty$ causes the lone v_O term on the left-hand side to disappear because $v_O \div \infty = 0$.

$$0 = v_I - \frac{v_O R1}{R1 + R2}$$

Finally, the input and output terms of the equation can be separated onto separate sides of the equality to yield a final simplified relationship between v_I and v_O as follows:

$$v_I = v_O \frac{R1}{R1 + R2}$$

$$v_O = v_I\left(\frac{R1 + R2}{R1}\right) = v_I\left[1 + \frac{R2}{R1}\right]$$

This shows that, despite the ideal op-amp's infinite gain, the circuit's overall gain is easily quantifiable and controllable based on the two resistor values. A noninverting op-amp circuit can be used to scale up an incoming signal for a purpose such as that already mentioned: using all of the available resolution of an analog-to-digital converter. In this example, a transducer of some kind (e.g., temperature sensor or audio input device) creates a signal that ranges from 0 to 3 V, and the analog-to-digital converter that is sensing it has a fixed sampling range from 0 to 5 V. To take full advantage of the sampling range, it is desirable to apply a gain of 1.667 to the input signal so that it swings from 0 to 5 V. This is accomplished using the noninverting circuit shown in Fig. 14.3. R1 and R2 are chosen arbitrarily as long as they satisfy the ratio R2:R1 = 2:3. Values of 2.2 and 3.3 kΩ provide feedback in the desired ratio with relatively low maximum current draw on the order of 1 mA.

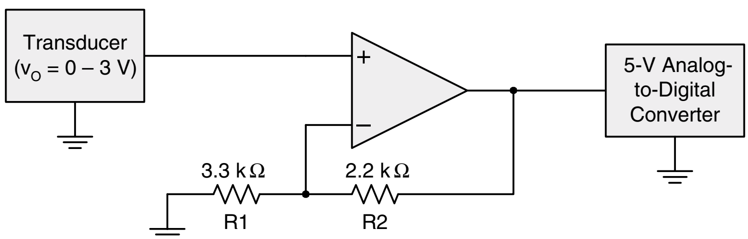

FIGURE 14.3 Scaling up an analog-to-digital converter input signal.