If a circuit such as this is implemented in reality, it would be helpful to understand the effect of finite op-amp gain on the circuit's overall gain to ensure that the circuit operates as intended. To do so, we can turn back to the previous derivation of op-amp gain. Instead of dividing the equation by $A = \infty$ early in the derivation, the input and output terms are immediately separated and re-expressed as follows:

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

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

This relationship is more complex than the ideal case, but it can be seen that, as A approaches infinity, the expression simplifies to that which has already been presented. A wide variety of op-amps are manufactured with differing gains and electrical characteristics. One of the most common op-amps is the LM741, a device that has been around for decades. The LM741 has a minimum voltage gain of 20 V/mV, or A = 20,000 V/V.* For small circuit gains where $R2 \div R1$ is much less than A, the LM741 will provide an overall circuit gain that is extremely close to the ideal. Using the previous example, the gain expression becomes

$$v_O = v_I \frac{20000\left[1 + \dfrac{2.2}{3.3}\right]}{1 + \dfrac{2.2}{3.3} + 20000} = v_I \frac{33333}{20001.67} = v_I 1.6665$$

It can be observed that, for a real-world op-amp gain of much less than infinity, the ideal gain expression for an op-amp provides a very accurate calculation. As the gain desired from the circuit is increased, the denominator of the nonideal gain expression will increase as well, causing greater divergence between ideal and nonideal calculations for a given op-amp gain specification. Of course, the LM741 is not the only op-amp available. Newer and more advanced designs are readily available with gains an order of magnitude higher than that of the LM741.

The minimum gain achievable by the noninverting op-amp circuit is 1, or *unity gain*, when R2 = 0 Ω. There are instances in which a unity-gain buffer stage is desired. An example is the need to isolate a weak driver from a heavy load. While an ideal op-amp has infinite input impedance, a real op-amp has very high input impedance. Consequently, even a nonideal op-amp will present a light load to a driver. And while a real op-amp has nonzero output impedance, it will be much lower than the weak driver being isolated. As shown in Fig. 14.4, a unity-gain buffer is constructed by directly feeding the output back to the negative input. It can be observed from the previous circuit that when R2 = 0 Ω, R1 becomes superfluous.

A limitation of the noninverting op-amp circuit is that the minimum gain achievable is 1. When a gain of less than 1 is desired, a slightly different circuit topology is used: the inverting configuration. As shown in Fig. 14.5, the noninverting input is grounded, and the signal is injected into the negative input through R1. As before, R2 forms the feedback loop that stabilizes the circuit's overall gain.

* LM741 Single Operational Amplifier, Fairchild Semiconductor Corporation, 2001, p. 3.

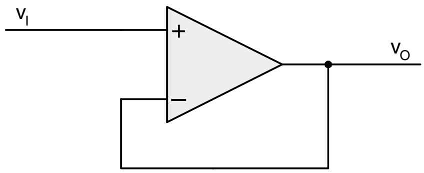

FIGURE 14.4 Unity-gain buffer.

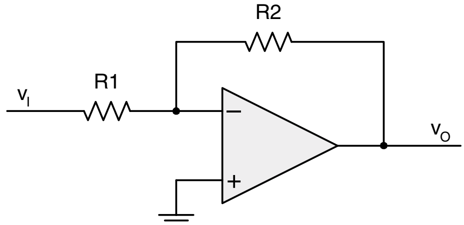

FIGURE 14.5 Op-amp inverting closed-loop circuit.

The inverting configuration's relationship between v_I and v_O can be derived using the resistor divider method shown previously for the noninverting circuit. Op-amp circuits can also be analyzed with an alternative method that provides a slightly different view of their operation. In some cases, mathematical analysis is made somewhat easier using one of the two methods. The alternative method uses the assumption of infinite gain to declare that the differential input voltage, v_D, equals zero. If $A = \infty$ and $v_O = Av_D$, it follows that $v_D = 0$ for a finite v_O. This assumption leads to an implied *virtual short circuit* between the op-amp's two input terminals. If $v_D = 0$, $v_+ = v_-$. The virtual short circuit tells us that if a voltage is applied at the positive terminal, it will appear at the negative terminal as well, and vice versa. Therefore, rather than expressing v_- as a resistor divider between v_O and v_I, each portion of the circuit can be analyzed separately. In such a simple circuit, this concept may not seem to have much advantage. However, the analysis of more complex op-amp circuits can benefit from this approach.

To demonstrate circuit analysis using the virtual short circuit approach, we begin by knowing that $v_- = 0$ V, because the positive terminal is grounded. Therefore, the voltage drop across R1 is known by inspection, and its current, i_1, is simply $v_I \div \mathrm{R1}$. We know from basic circuit theory that current cannot just disappear. Assuming that the op-amp has infinite input impedance, all of i_1 must flow toward v_O. Hence, $i_2 = -i_1$. The output voltage can now be determined using Ohm's law to show that the overall gain is controlled by the resistors when an ideal op-amp is used.

$$v_O = v_- + i_2R2 = 0 - i_1R2 = -v_I\frac{R2}{R1}$$

The inverting circuit can be designed with arbitrary gains of less than 1. However, both a positive and negative voltage supply are required to enable the op-amp to drive both positive and negative voltages. If a signal with a voltage range from 0 to 3 V is applied to an inverting circuit with a gain of 0.8, the op-amp will generate an output signal from –2.4 to 0 V. In some situations, this may be undesirable because of the requirement imposed by processing negative voltages. Fortunately, op-amps are very flexible, and the inverting configuration can be biased to center the output signal about a nonzero DC level. Consider the circuit in Fig. 14.6. Rather than grounding the positive input, a bias voltage is applied.

Using the virtual short circuit approach, an expression relating v_O, v_I, and V_{BIAS} can be derived in the same basic manner as done just before for the basic inverting configuration.

$$v_O = v_- + i_2R2 = V_{BIAS} - i_1R2 = V_{BIAS} - \frac{(v_I - V_{BIAS})R2}{R1} = -v_I\frac{R2}{R1} + V_{BIAS}\left[1 + \frac{R2}{R1}\right]$$

For a given gain controlled by R1 and R2, a bias voltage can be selected such that v_O sits at a nonzero DC voltage when $v_I = 0$ V. Assuming a desired gain of 0.8 and an output level of –2.4 V to com-