In circuit analysis terms, a single input voltage can be isolated from the others by tying each other input to ground and then evaluating the circuit as if that single input voltage were the only input present. This analysis method can be applied to each input in succession, and then the partial results can be summed to yield a final output expression. Superposition is applied to analyze the noninverting summer as follows. First, v_2 and v_3 are grounded, yielding a basic voltage divider expression for the op-amp input voltage that translates to a partial output voltage.

$$v_{O1} = Av_1\left[\frac{R_{IN2} \parallel R_{IN3}}{R_{IN1} + R_{IN2} \parallel R_{IN3}}\right] = \left[1 + \frac{R2}{R1}\right]v_1\left[\frac{R_{IN2}R_{IN3}}{R_{IN1}R_{IN2} + R_{IN1}R_{IN3} + R_{IN2}R_{IN3}}\right]$$

To ease calculation for the sake of discussion, assume that $R1 = R2 = R_{IN1} = R_{IN2} = R_{IN3} = 10\ \text{k}\Omega$. Under these conditions,

$$v_{O1} = 2v_1\frac{1}{3} = v_1\frac{2}{3}$$

This same treatment is performed separately for v_2 and v_3, and then each partial output voltage is summed.

$$v_O = \frac{2}{3}[v_1 + v_2 + v_3]$$

It can be observed that the noninverting summer is really just amplifying the average input voltage by setting $v_{IN} = v_1 = v_2 = v_3$. This results in an output voltage of $2v_{IN}$, which is exactly how the noninverting circuit behaves in the absence of input resistors with a single input signal.

Inverting and noninverting summer circuits can be combined by feeding input signals into both op-amp terminals with multiple resistors. This results in addition of the signals at the positive input and subtraction of the signals at the negative input. Analysis of these more complex circuits can be started using superposition to determine the voltage at the positive input. This reveals an expression for the voltage at the negative input, which enables computation of the currents flowing through the negative-side input resistors. With the current through the feedback resistor known along with the voltage at the negative terminal, a final expression for the op-amp output may be determined.

Analog addition and subtraction functions can be combined to form a difference amplifier. As its name implies, a difference amplifier emits a voltage that is proportional to the magnitude of the voltage difference between its two inputs. A simple difference amplifier can be constructed using a single op-amp as shown in Fig. 14.24.

This circuit can be analyzed in a couple of ways. The direct approach is to derive the voltage at the op-amp's two input terminals, find the current through the feedback resistor, and obtain a final expression for v_O. Alternatively, superposition can be used to isolate each input and then add the two partial results for a final answer. To provide a second example of analysis by superposition, this technique is used. Grounding v_{IN-} turns the circuit into a noninverting amplifier.

$$v_{O+} = v_+\left[1 + \frac{R2}{R1}\right] = v_{IN+}\frac{R2}{R1 + R2}\left[1 + \frac{R2}{R1}\right] = v_{IN+}\frac{R2}{R1 + R2}\left[\frac{R1 + R2}{R1}\right] = v_{IN+}\frac{R2}{R1}$$

Next, v_{IN+} is grounded, yielding an inverting amplifier.

$$v_{O-} = -v_{IN-}\frac{R2}{R1}$$

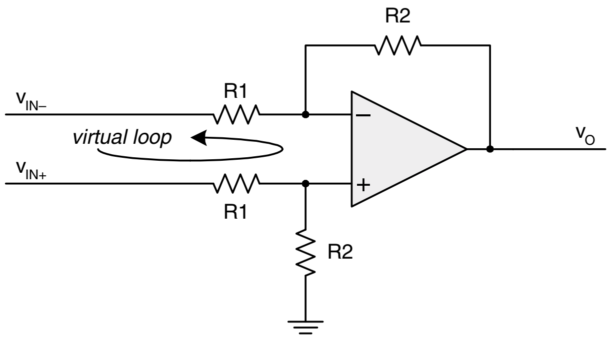

FIGURE 14.24 Single op-amp difference amplifier.

By superposition, the linear partial terms, v_{O+} and v_{O-}, are summed to yield a final output expression that clearly shows that this circuit is a difference amplifier.

$$v_O = v_{O+} + v_{O-} = v_{IN+}\frac{R2}{R1} - v_{IN-}\frac{R2}{R1} = \frac{R2}{R1}(v_{IN+} - v_{IN-})$$

A drawback of the single op-amp difference amplifier is that it has a relatively low input resistance. Using the virtual short concept, the two op-amp terminals are at the same voltage, thereby creating a virtual loop circuit consisting of the differential voltage input and the two input resistors, R1. Because this virtual circuit consists only of the input voltage source and the two resistors, the input resistance is observed to be equal to 2R1 by inspection. As with the basic inverting op-amp circuit, there is a practical ceiling imposed on input resistance caused by the circuit's gain and the range of resistances that are practical to use in a real circuit.

Many applications in which a difference amplifier is necessary involve weak signal sources such as an unbuffered transducer. To solve this problem, a more complex difference amplifier can be constructed with multiple op-amps to present a much higher input resistance. Usually called *instrumentation amplifiers*, these circuits commonly consist of three op-amps, two of which are configured in the noninverting topology for very high input resistance. The third op-amp is configured in the just-mentioned difference amplification topology. As with the example in Fig. 14.18, the noninverting op-amps buffer each half of the differential input signal, and the second op-amp stage performs the final difference function. If such a circuit is required in a digital system, it may be most practical to use an integrated instrumentation amplifier as manufactured by such companies as Linear Technology (e.g., LT1167) and Texas Instruments (e.g., INA332) rather than constructing one from discrete op-amps.

14.6 ACTIVE FILTERS

Active filters perform the same basic frequency passing and blocking function as passive filters, but they can simultaneously amplify the signal to form a filter that has unity or higher gain. This is in contrast to passive filters that achieve less than unity gain because of finite losses inherent in the components from which they are constructed. Op-amps can be used to implement active filters as long as their gain-bandwidth product is not exceeded. Figure 14.25 shows familiar first-order low-