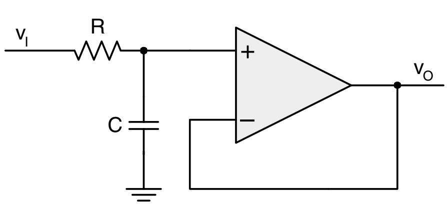

FIGURE 14.25 First-order active filters.

pass and highpass active filters implemented with op-amps. These simple filters buffer a passive filter with a noninverting op-amp stage. In this example, the configurations are for unity gain, although higher gains are possible. Because of the high input resistance of an op-amp, there is little signal loss through the series elements while operating in the passband. Unlike a passive filter whose characteristics are influenced by the load being driven, the op-amp isolates the load from the filter elements.

Filter design is a topic in electrical engineering that can get quite complex when very specific and demanding frequency response characteristics are necessary. Active filters add to this complexity as a result of nonideal op-amp characteristics. Although a complete discussion of filter design is outside the scope of this text, certain filtering tasks can be accomplished by drawing on a basic familiarity with common circuits. A common second-order topology used to implement active filters is the Sallen-Key filter. Sallen-Key lowpass and highpass filters are implemented with two resistors and two capacitors each for unity gain in the passband, as shown in Fig. 14.26. If higher gains are desired, two resistors can be added per the standard noninverting amplifier circuit topology. As with a passive second-order filter, the frequency response curve falls off at 40 dB per decade beyond the cut-off frequency.

The Sallen-Key lowpass filter operates by shunting the op-amp's input path to low-impedance sources at high frequencies. C1 shunts the signal to ground as in a passive filter, and C2 shunts the signal to the op-amp's output. The highpass filter operates in the reverse manner. At low frequencies, C1 blocks the incoming signal and allows R2 to feed the output back to the input. Simultaneously, C2 blocks the signal, which pulls the input to ground. The general expression for the cut-off frequency, f_C, is

$$f_C = \frac{1}{2\pi\sqrt{R1R2C1C2}}$$

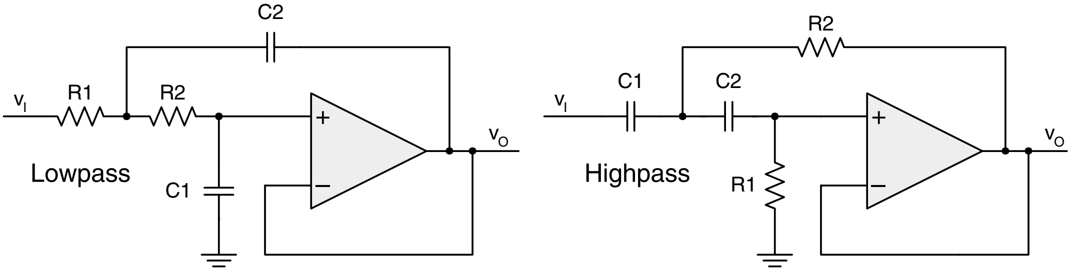

FIGURE 14.26 Sallen-Key second-order active filters.

In many cases, it is convenient to set $R1 = R2$ and $C1 = C2$, in which case f_C is given by

$$f_C = \frac{1}{2\pi RC}$$

Aside from providing amplification, a benefit of using op-amps to build filter stages is that multiple stages can be cascaded to implement more advanced filters. The presence of the op-amp in each stage isolates one stage's filter components from the other, thereby preserving the desired response of each filter circuit. Higher-order lowpass and highpass filters with sharper roll-off responses can be constructed in this manner. Alternatively, bandpass or band-reject filters can be designed by cascading lowpass and highpass stages as needed.

14.7 COMPARATORS AND HYSTERESIS

Each op-amp circuit discussed so far is closed loop because of the need to moderate the op-amp's large open-loop gain and, simultaneously, to increase the circuit's bandwidth to a practical frequency range. Analog electronics begins to turn digital when the concern is no longer about maintaining a linear relationship between a circuit's input and output signals. *Comparators* are a key crossover function between the analog and digital worlds. The job of a comparator is to assert its output when the input rises above a certain threshold and deassert its output when the input falls below a threshold. A comparator implements a binary step function as shown in Fig. 14.27. This transfer function is decidedly nonlinear and is produced using a differential amplifier with very large gain.

If an op-amp is operated in an open-loop topology, it can be adapted to serve as a comparator. Figure 14.28 shows an op-amp or comparator with its negative input connected to a fixed threshold voltage, V_{REF}, and its positive input being driven by the circuit's input signal. As long as the input signal remains below V_{REF}, the differential voltage is negative, and the output is driven to the lower voltage rail (ground, in this case). As the input signal rises above V_{REF}, a minute differential voltage is amplified by the tremendous open-loop gain, resulting in a nearly perfect step function.

Op-amps can be used as comparators, but dedicated comparator ICs have long been available. Comparators and op-amps share various internal similarities. Their common heritage is obvious

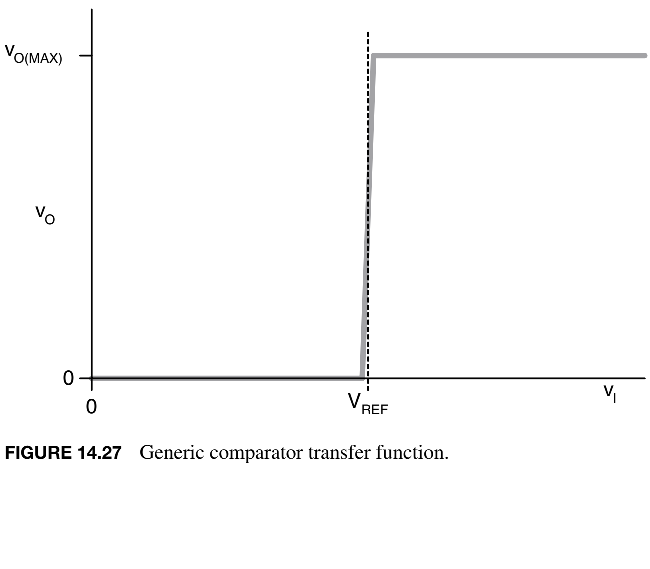

FIGURE 14.27 Generic comparator transfer function.