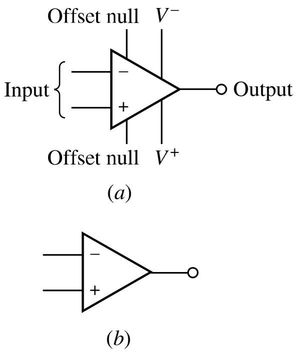

(*a*) (*b*) (*c*)

■ **FIGURE 6.1** (*a*) A Philbrick K2-W op amp, based on a matched pair of 12AX7A vacuum tubes. (*b*) LMV321 op amp, used in a variety of phone and game applications. (*c*) LMC6035 operational amplifier, which packs 114 transistors into a package so small that it fits on the head of a pin.


■ **FIGURE 6.2** (*a*) Electrical symbol for the op amp. (*b*) Minimum required connections to be shown on a circuit schematic.

much lower dc supply voltages (±18 V, for example, as opposed to ±300 V for the K2-W), are more reliable, and considerably smaller (Fig. 6.1*b*,*c*). In some cases, the IC may contain several op amps. In addition to the output pin and the two inputs, other pins enable power to be supplied to run the transistors, and for external adjustments to be made to balance and compensate the op amp. The symbol commonly used for an op amp is shown in Fig. 6.2*a*. At this point, we are not concerned with the internal circuitry of the op amp or the IC, but only with the voltage and current relationships that exist between the input and output terminals. Thus, for the time being we will use a simpler electrical symbol, shown in Fig. 6.2*b*. Two input terminals are shown on the left, and a single output terminal appears at the right. The terminal marked by a "+" is referred to as the ***noninverting input,*** and the "−" marked terminal is called the ***inverting input.***

## 6.2 THE IDEAL OP AMP: A CORDIAL INTRODUCTION

In practice, we find that most op amps perform so well that we can often make the assumption that we are dealing with an "ideal" op amp. The characteristics of an ***ideal op amp*** form the basis for two fundamental rules that at first may seem somewhat unusual:

### Ideal Op Amp Rules

1. No current ever flows into either input terminal.
2. There is no voltage difference between the two input terminals.

In a real op amp, a very small leakage current will flow into the input (sometimes as low as 40 femtoamperes). It is also possible to obtain a very small voltage across the two input terminals. However, compared to other voltages and currents in most circuits, such values are so small that including them in the analysis does not typically affect our calculations.

When analyzing op amp circuits, we should keep one other point in mind. As opposed to the circuits that we have studied so far, an op amp circuit always has an *output* that depends on some type of *input*. Therefore, we will analyze op amp circuits with the goal of obtaining an expression for the output in terms of the input quantities. *We will find that it is usually a good idea to begin the analysis of an op amp circuit at the input, and proceed from there.*

The circuit shown in Fig. 6.3 is known as an ***inverting amplifier.*** We choose to analyze this circuit using KVL, beginning with the input voltage source. The current labeled $i$ flows only through the two resistors $R_1$ and $R_f$; ideal op amp rule 1 states that no current flows into the inverting input terminal. Thus, we can write

$$-v_{\text{in}} + R_1 i + R_f i + v_{\text{out}} = 0$$

which can be rearranged to obtain an equation that relates the output to the input:

$$v_{\text{out}} = v_{\text{in}} - (R_1 + R_f)i \qquad [1]$$

Given $v_{\text{in}} = 5 \sin 3t$ mV, $R_1 = 4.7$ kΩ, and $R_f = 47$ kΩ, we require one additional equation that expresses $i$ only in terms of $v_{\text{out}}$, $v_{\text{in}}$, $R_1$, and/or $R_f$.

This is a good time to mention that we have not yet made use of ideal op amp rule 2. Since the noninverting input is grounded, it is at zero volts. By ideal op amp rule 2, the inverting input is therefore also at zero volts! *This does not mean that the two inputs are physically shorted together, and we should be careful not to make such an assumption*. Rather, the two input voltages simply track each other: if we try to change the voltage at one pin, the other pin will be driven by internal circuitry to the same value. Thus, we can write one more KVL equation:

$$-v_{\text{in}} + R_1 i + 0 = 0$$

or

$$i = \frac{v_{\text{in}}}{R_1} \qquad [2]$$

Combining Eq. [2] with Eq. [1], we obtain an expression for $v_{\text{out}}$ in terms of $v_{\text{in}}$:

$$v_{\text{out}} = -\frac{R_f}{R_1} v_{\text{in}} \qquad [3]$$

Substituting $v_{\text{in}} = 5 \sin 3t$ mV, $R_1 = 4.7$ kΩ, and $R_f = 47$ kΩ,

$$v_{\text{out}} = -50 \sin 3t \qquad \text{mV}$$

Since $R_f > R_1$, this circuit amplifies the input voltage signal $v_{\text{in}}$. If we choose $R_f < R_1$, the signal will be attenuated instead. We also note that the output voltage has the opposite sign of the input voltage,[1] hence the name "inverting amplifier." The output is sketched in Fig. 6.4, along with the input waveform for comparison.

At this point, it is worth mentioning that the ideal op amp seems to be violating KCL. Specifically, in the above circuit no current flows into or out of either input terminal, but somehow current is able to flow into the output pin! This would imply that the op amp is somehow able to either create electrons out of nowhere or store them forever (depending on the direction of current flow). Obviously, this is not possible. The conflict arises because we have been treating the op amp the same way we treated passive elements

(1) Or, "*the output is 180° out of phase with the input*," which sounds more impressive.

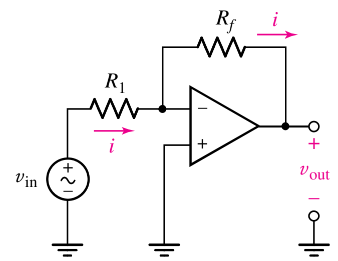



**FIGURE 6.3** An op amp used to construct an inverting amplifier circuit. The current $i$ flows to ground through the output pin of the op amp.

The fact that the inverting input terminal finds itself at zero volts in this type of circuit configuration leads to what is often referred to as a "virtual ground." This does not mean that the pin is actually grounded, which is sometimes a source of confusion for students. The op amp makes whatever internal adjustments are necessary to prevent a voltage difference between the input terminals. The input terminals are not shorted together.

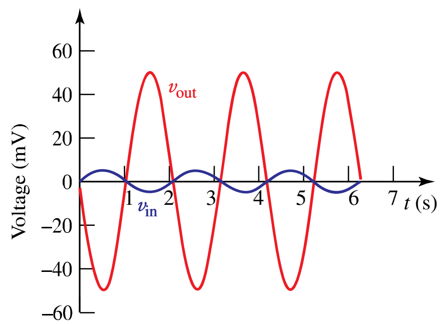



**FIGURE 6.4** Input and output waveforms of the inverting amplifier circuit.