chapter

5

# Operational Amplifiers

*He who will not reason is a bigot; he who cannot is a fool; and he who dares not is a slave.*

—Lord Byron

## Enhancing Your Career

### Career in Electronic Instrumentation

Engineering involves applying physical principles to design devices for the benefit of humanity. But physical principles cannot be understood without measurement. In fact, physicists often say that physics is the science that measures reality. Just as measurements are a tool for understanding the physical world, instruments are tools for measurement. The operational amplifier introduced in this chapter is a building block of modern electronic instrumentation. Therefore, mastery of operational amplifier fundamentals is paramount to any practical application of electronic circuits.

Electronic instruments are used in all fields of science and engineering. They have proliferated in science and technology to the extent that it would be ridiculous to have a scientific or technical education without exposure to electronic instruments. For example, physicists, physiologists, chemists, and biologists must learn to use electronic instruments. For electrical engineering students in particular, the skill in operating digital and analog electronic instruments is crucial. Such instruments include ammeters, voltmeters, ohmmeters, oscilloscopes, spectrum analyzers, and signal generators.

Beyond developing the skill for operating the instruments, some electrical engineers specialize in designing and constructing electronic instruments. These engineers derive pleasure in building their own instruments. Most of them invent and patent their inventions. Specialists in electronic instruments find employment in medical schools, hospitals, research laboratories, aircraft industries, and thousands of other industries where electronic instruments are routinely used.

Electronic Instrumentation used in medical research.

## 5.1 Introduction

Having learned the basic laws and theorems for circuit analysis, we are now ready to study an active circuit element of paramount importance: the *operational amplifier*, or *op amp* for short. The op amp is a versatile circuit building block.

> The term operational amplifier was introduced in 1947 by John Ragazzini and his colleagues, in their work on analog computers for the National Defense Research Council after World War II. The first op amps used vacuum tubes rather than transistors.

> An op amp may also be regarded as a voltage amplifier with very high gain.

> The **op amp** is an electronic unit that behaves like a voltage-controlled voltage source.

It can also be used in making a voltage- or current-controlled current source. An op amp can sum signals, amplify a signal, integrate it, or differentiate it. The ability of the op amp to perform these mathematical operations is the reason it is called an *operational amplifier*. It is also the reason for the widespread use of op amps in analog design. Op amps are popular in practical circuit designs because they are versatile, inexpensive, easy to use, and fun to work with.

We begin by discussing the ideal op amp and later consider the nonideal op amp. Using nodal analysis as a tool, we consider ideal op amp circuits such as the inverter, voltage follower, summer, and difference amplifier. We will also analyze op amp circuits with *PSpice*. Finally, we learn how an op amp is used in digital-to-analog converters and instrumentation amplifiers.

## 5.2 Operational Amplifiers

An operational amplifier is designed so that it performs some mathematical operations when external components, such as resistors and capacitors, are connected to its terminals. Thus,

> An **op amp** is an active circuit element designed to perform mathematical operations of addition, subtraction, multiplication, division, differentiation, and integration.

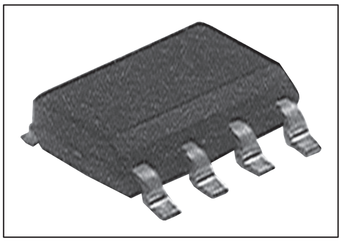

**Figure 5.1**
A typical operational amplifier.
Courtesy of Tech America.

The op amp is an electronic device consisting of a complex arrangement of resistors, transistors, capacitors, and diodes. A full discussion of what is inside the op amp is beyond the scope of this book. It will suffice to treat the op amp as a circuit building block and simply study what takes place at its terminals.

> The pin diagram in Fig. 5.2(a) corresponds to the 741 general-purpose op amp made by Fairchild Semiconductor.

Op amps are commercially available in integrated circuit packages in several forms. Figure 5.1 shows a typical op amp package. A typical one is the eight-pin dual in-line package (or DIP), shown in Fig. 5.2(a). Pin or terminal 8 is unused, and terminals 1 and 5 are of little concern to us. The five important terminals are:

1. The inverting input, pin 2.
2. The noninverting input, pin 3.
3. The output, pin 6.
4. The positive power supply $V^+$, pin 7.
5. The negative power supply $V^-$, pin 4.

The circuit symbol for the op amp is the triangle in Fig. 5.2(b); as shown, the op amp has two inputs and one output. The inputs are

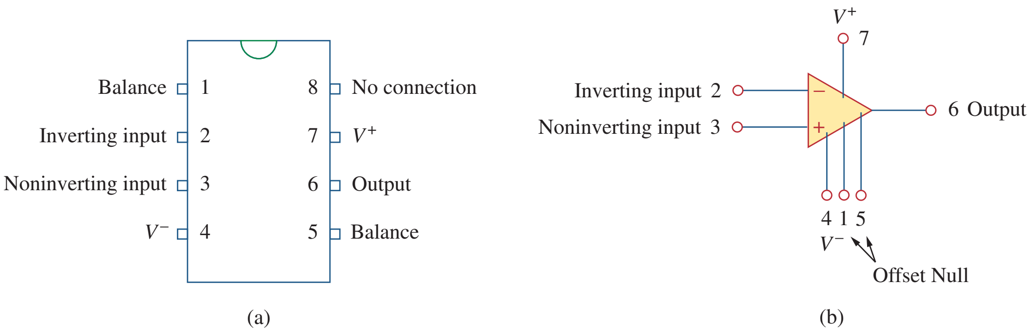


**Figure 5.2**
A typical op amp: (a) pin configuration, (b) circuit symbol.

marked with minus (−) and plus (+) to specify *inverting* and *noninverting* inputs, respectively. An input applied to the noninverting terminal will appear with the same polarity at the output, while an input applied to the inverting terminal will appear inverted at the output.

As an active element, the op amp must be powered by a voltage supply as typically shown in Fig. 5.3. Although the power supplies are often ignored in op amp circuit diagrams for the sake of simplicity, the power supply currents must not be overlooked. By KCL,

$$i_o = i_1 + i_2 + i_+ + i_- \tag{5.1}$$

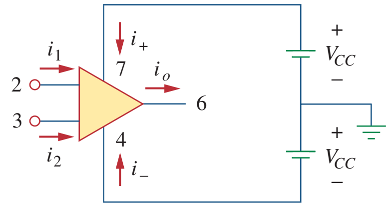


**Figure 5.3**
Powering the op amp.

The equivalent circuit model of an op amp is shown in Fig. 5.4. The output section consists of a voltage-controlled source in series with the output resistance $R_o$. It is evident from Fig. 5.4 that the input resistance $R_i$ is the Thevenin equivalent resistance seen at the input terminals, while the output resistance $R_o$ is the Thevenin equivalent resistance seen at the output. The differential input voltage $v_d$ is given by

$$v_d = v_2 - v_1 \tag{5.2}$$

where $v_1$ is the voltage between the inverting terminal and ground and $v_2$ is the voltage between the noninverting terminal and ground. The op amp senses the difference between the two inputs, multiplies it by the gain $A$, and causes the resulting voltage to appear at the output. Thus, the output $v_o$ is given by

$$\boxed{v_o = Av_d = A(v_2 - v_1)} \tag{5.3}$$

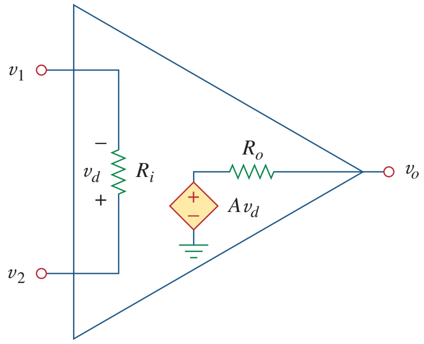


**Figure 5.4**
The equivalent circuit of the nonideal op amp.

$A$ is called the *open-loop voltage gain* because it is the gain of the op amp without any external feedback from output to input. Table 5.1

Sometimes, voltage gain is expressed in decibels (dB), as discussed in Chapter 14.

$$A \text{ dB} = 20 \log_{10} A$$

**TABLE 5.1**

Typical ranges for op amp parameters.

| Parameter | Typical range | Ideal values |
|---|---|---|
| Open-loop gain, $A$ | $10^5$ to $10^8$ | $\infty$ |
| Input resistance, $R_i$ | $10^5$ to $10^{13}$ Ω | $\infty$ Ω |
| Output resistance, $R_o$ | 10 to 100 Ω | 0 Ω |
| Supply voltage, $V_{CC}$ | 5 to 24 V | |

shows typical values of voltage gain $A$, input resistance $R_i$, output resistance $R_o$, and supply voltage $V_{CC}$.

The concept of feedback is crucial to our understanding of op amp circuits. A negative feedback is achieved when the output is fed back to the inverting terminal of the op amp. As Example 5.1 shows, when there is a feedback path from output to input, the ratio of the output voltage to the input voltage is called the *closed-loop gain*. As a result of the negative feedback, it can be shown that the closed-loop gain is almost insensitive to the open-loop gain $A$ of the op amp. For this reason, op amps are used in circuits with feedback paths.

A practical limitation of the op amp is that the magnitude of its output voltage cannot exceed $|V_{CC}|$. In other words, the output voltage is dependent on and is limited by the power supply voltage. Figure 5.5 illustrates that the op amp can operate in three modes, depending on the differential input voltage $v_d$:

1. Positive saturation, $v_o = V_{CC}$.
2. Linear region, $-V_{CC} \le v_o = Av_d \le V_{CC}$.
3. Negative saturation, $v_o = -V_{CC}$.

If we attempt to increase $v_d$ beyond the linear range, the op amp becomes saturated and yields $v_o = V_{CC}$ or $v_o = -V_{CC}$. Throughout this book, we will assume that our op amps operate in the linear mode. This means that the output voltage is restricted by

$$-V_{CC} \le v_o \le V_{CC} \tag{5.4}$$

Although we shall always operate the op amp in the linear region, the possibility of saturation must be borne in mind when one designs with op amps, to avoid designing op amp circuits that will not work in the laboratory.

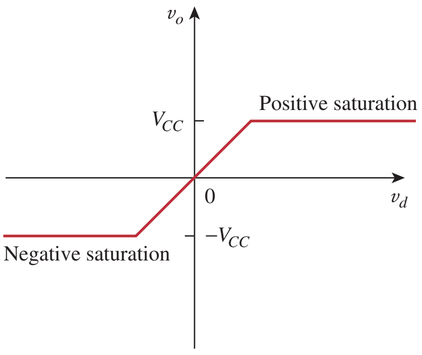


**Figure 5.5**
Op amp output voltage $v_o$ as a function of the differential input voltage $v_d$.

Throughout this book, we assume that an op amp operates in the linear range. Keep in mind the voltage constraint on the op amp in this mode.

## Example 5.1

A 741 op amp has an open-loop voltage gain of $2 \times 10^5$, input resistance of 2 MΩ, and output resistance of 50 Ω. The op amp is used in the circuit of Fig. 5.6(a). Find the closed-loop gain $v_o/v_s$. Determine current $i$ when $v_s = 2$ V.

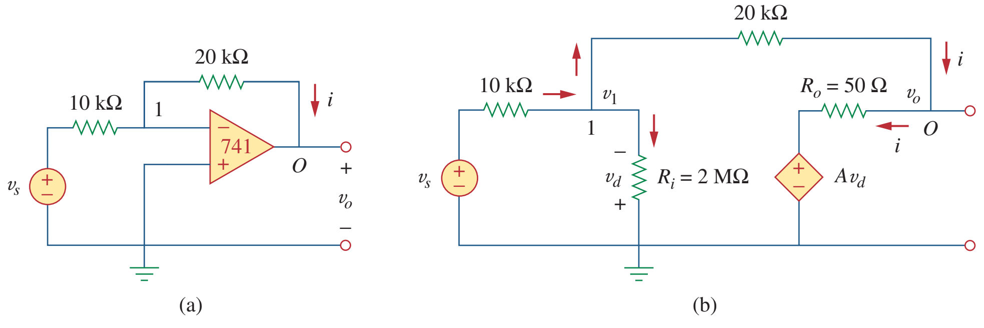


**Figure 5.6**
For Example 5.1: (a) original circuit, (b) the equivalent circuit.

**Solution:**

Using the op amp model in Fig. 5.4, we obtain the equivalent circuit of Fig. 5.6(a) as shown in Fig. 5.6(b). We now solve the circuit in Fig. 5.6(b) by using nodal analysis. At node 1, KCL gives

$$\frac{v_s - v_1}{10 \times 10^3} = \frac{v_1}{2000 \times 10^3} + \frac{v_1 - v_o}{20 \times 10^3}$$

Multiplying through by $2000 \times 10^3$, we obtain

$$200v_s = 301v_1 - 100v_o$$

or

$$2v_s \simeq 3v_1 - v_o \quad \Rightarrow \quad v_1 = \frac{2v_s + v_o}{3} \tag{5.1.1}$$

At node $O$,

$$\frac{v_1 - v_o}{20 \times 10^3} = \frac{v_o - Av_d}{50}$$

But $v_d = -v_1$ and $A = 200{,}000$. Then

$$v_1 - v_o = 400(v_o + 200{,}000v_1) \tag{5.1.2}$$

Substituting $v_1$ from Eq. (5.1.1) into Eq. (5.1.2) gives

$$0 \simeq 26{,}667{,}067v_o + 53{,}333{,}333v_s \quad \Rightarrow \quad \frac{v_o}{v_s} = -1.9999699$$

This is closed-loop gain, because the 20-k$\Omega$ feedback resistor closes the loop between the output and input terminals. When $v_s = 2$ V, $v_o = -3.9999398$ V. From Eq. (5.1.1), we obtain $v_1 = 20.066667\ \mu$V. Thus,

$$i = \frac{v_1 - v_o}{20 \times 10^3} = 0.19999 \text{ mA}$$

It is evident that working with a nonideal op amp is tedious, as we are dealing with very large numbers.

## Practice Problem 5.1

If the same 741 op amp in Example 5.1 is used in the circuit of Fig. 5.7, calculate the closed-loop gain $v_o/v_s$. Find $i_o$ when $v_s = 1$ V.

**Answer:** 9.00041, 657 $\mu$A.

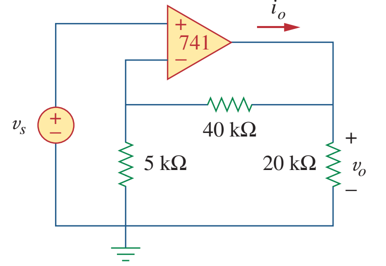


**Figure 5.7**
For Practice Prob. 5.1.

## 5.3 Ideal Op Amp

To facilitate the understanding of op amp circuits, we will assume ideal op amps. An op amp is ideal if it has the following characteristics:

1. Infinite open-loop gain, $A \simeq \infty$.
2. Infinite input resistance, $R_i \simeq \infty$.
3. Zero output resistance, $R_o \simeq 0$.