CHAPTER 5

OPERATIONAL AMPLIFIERS

If A is success in life, then A equals X plus Y plus Z. Work is X, Y is play and Z is keeping your mouth shut.

—Albert Einstein

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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5.1 INTRODUCTION

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 during World War II. The first op amps used vacuum tubes rather than transistors.

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.

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

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 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.

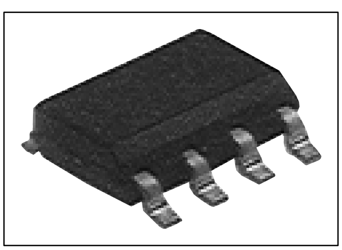


Figure 5.1 A typical operational amplifier. *(Courtesy of Tech America.)*

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 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.

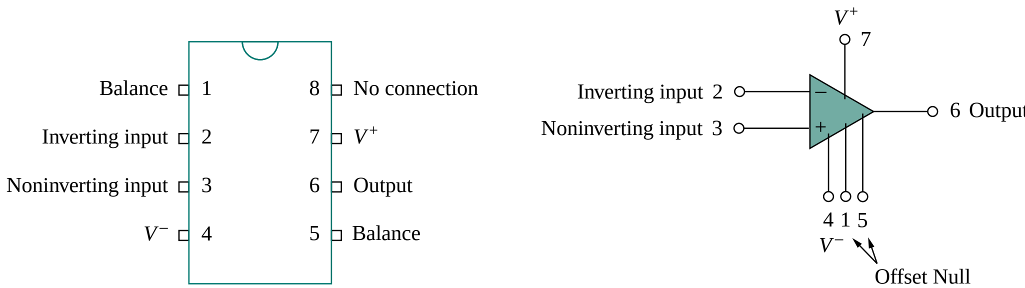


Figure 5.2 A typical op amp: (a) pin configuration, (b) circuit symbol.

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,

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

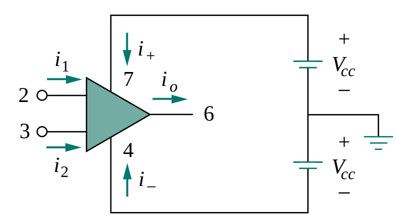


Figure 5.3 Powering the op amp.

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

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

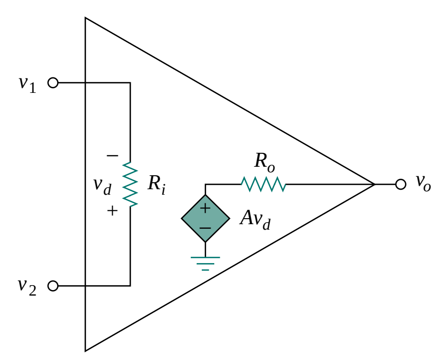


Figure 5.4 The equivalent circuit of the nonideal op amp.

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

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

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

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

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	10^6 to 10^{13} Ω	∞ Ω
Output resistance, R_o	10 to 100 Ω	0 Ω
Supply voltage, V_{cc}	5 to 24 V	

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:

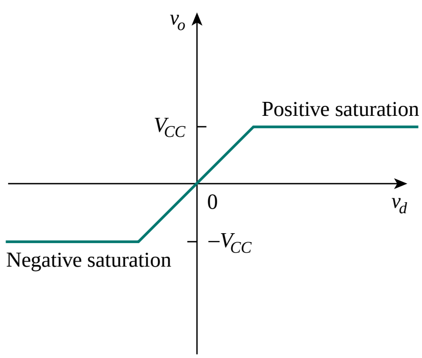


Figure 5.5 Op amp output voltage v_o as a function of the differential input voltage v_d.

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

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

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.

EXAMPLE 5.1

A 741 op amp has an open-loop voltage gain of 2×10^5, 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.

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

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

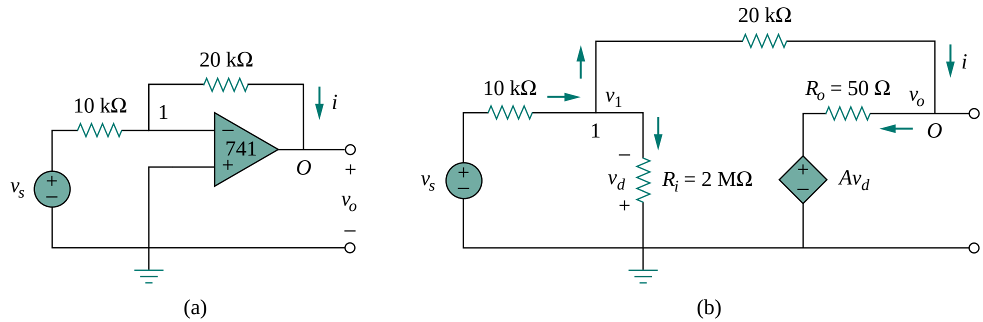


Figure 5.6 For Example 5.1: (a) original circuit, (b) the equivalent circuit.

Multiplying through by 2000×10^3, we obtain

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

or

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

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

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

This is closed-loop gain, because the 20-kΩ 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,

$$i = \frac{v_1 - v_o}{20 \times 10^3} = 0.1999 \text{ mA}$$

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: 9.0041, −362 mA.

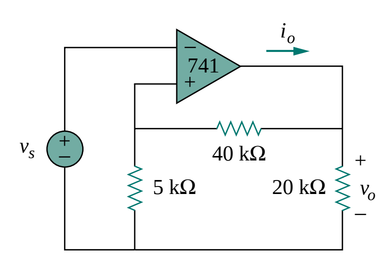


Figure 5.7 For Practice Prob. 5.1.

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, $R_o \simeq 0$.

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 characteristics of the ideal op amp are:

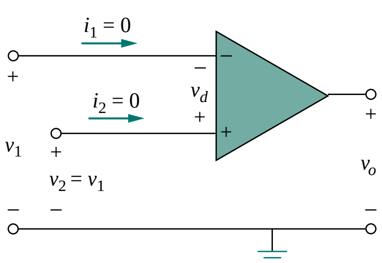


Figure 5.8 Ideal op amp model.

1. The currents into both input terminals are zero:

$$i_1 = 0, \qquad i_2 = 0 \tag{5.5}$$

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 negligibly small; i.e.,

$$v_d = v_2 - v_1 \simeq 0 \tag{5.6}$$

or

$$v_1 = v_2 \tag{5.7}$$

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

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.

EXAMPLE 5.2

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

$$v_2 = v_s \tag{5.2.1}$$

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

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

According to Eq. (5.7),

$$v_2 = v_1 \tag{5.2.3}$$

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

$$v_s = \frac{v_o}{9} \qquad \Longrightarrow \qquad \frac{v_o}{v_s} = 9 \tag{5.2.4}$$

which is very close to the value of 8.99955796 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,

$$i_o = \frac{v_o}{40+5} + \frac{v_o}{20} \text{ mA} \tag{5.2.5}$$

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

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

This, again, is close to the value of 0.649 mA obtained in Practice Prob. 5.1 with the nonideal model.

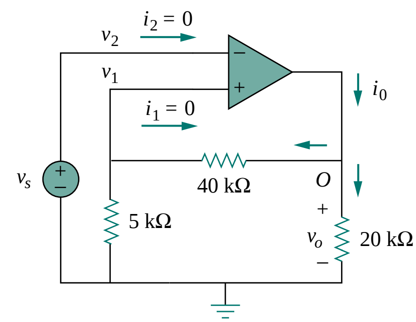


Figure 5.9 For Example 5.2.

PRACTICE PROBLEM 5.2

Repeat Example 5.1 using the ideal op amp model.

Answer: −2 , 0.2 mA.

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

$$i_1 = i_2 \qquad \Longrightarrow \qquad \frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_f} \tag{5.8}$$

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 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.

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

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

or

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

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.

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.

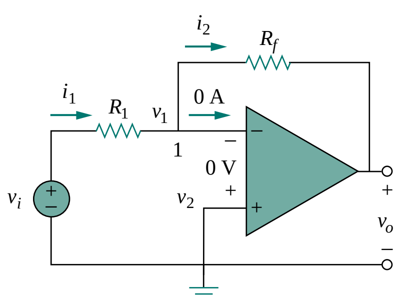


Figure 5.10 The inverting amplifier.

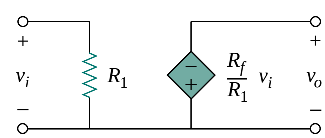


Figure 5.11 An equivalent circuit for the inverter in Fig. 5.10.

EXAMPLE 5.3

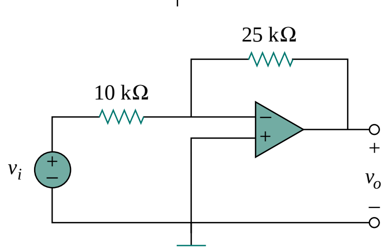


Figure 5.12 For Example 5.3.

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 kΩ resistor.

Solution:

(a) Using Eq. (5.9),

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

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

(b) The current through the 10-kΩ 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

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

Answer: -120 mV, 8 μA.

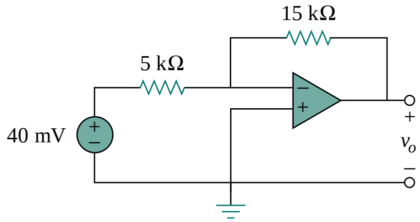


Figure 5.13 For Practice Prob. 5.3.

EXAMPLE 5.4

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

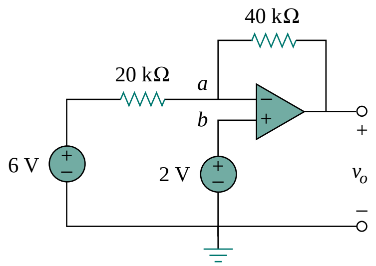


Figure 5.14 For Example 5.4.

Solution:

Applying KCL at node a,

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

$$v_a - v_o = 12 - 2v_a \qquad \Longrightarrow \qquad v_o = 3v_a - 12$$

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,

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

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

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),

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

(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.

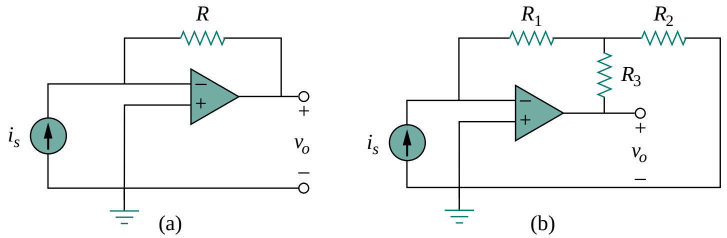


Figure 5.15 For Practice Prob. 5.4.

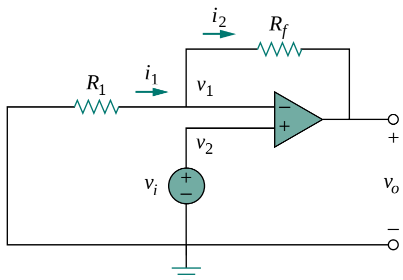


Figure 5.16 The noninverting amplifier.

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 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

$$i_1 = i_2 \quad \Longrightarrow \quad \frac{0 - v_1}{R_1} = \frac{v_1 - v_o}{R_f} \tag{5.10}$$

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

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

or

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

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.

Again we notice that the gain depends only on the external resistors.

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

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

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.

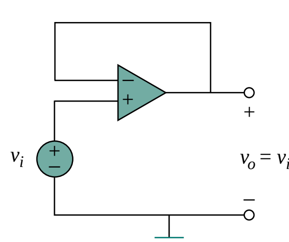


Figure 5.17 The voltage follower.

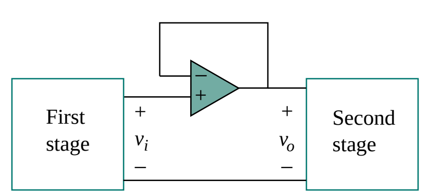


Figure 5.18 A voltage follower used to isolate two cascaded stages of a circuit.

EXAMPLE 5.5

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

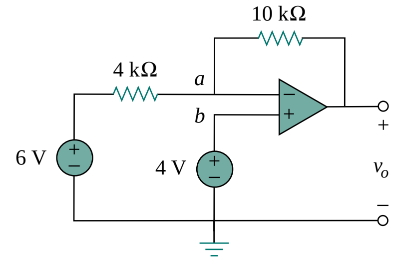


Figure 5.19 For Example 5.9.

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,

$$v_o = v_{o1} + v_{o2} = -15 + 14 = -1 \text{ V}$$

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

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

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

PRACTICE PROBLEM 5.5

Calculate v_o in the circuit in Fig. 5.20.

Answer: 7 V.

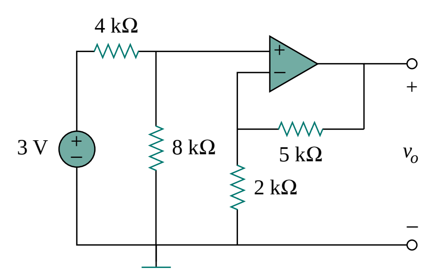


Figure 5.20 For Practice Prob. 5.5.

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.

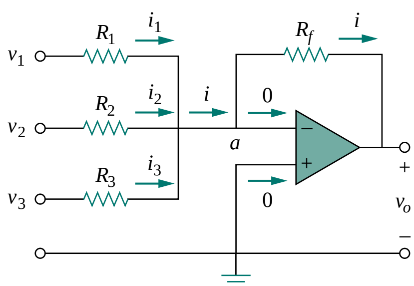


Figure 5.21 The summing amplifier.

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 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

$$\begin{aligned} i_1 &= \frac{v_1 - v_a}{R_1}, \qquad & i_2 &= \frac{v_2 - v_a}{R_2} \\ i_3 &= \frac{v_3 - v_a}{R_3}, \qquad & i &= \frac{v_a - v_o}{R_f} \end{aligned} \tag{5.14}$$

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

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

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.

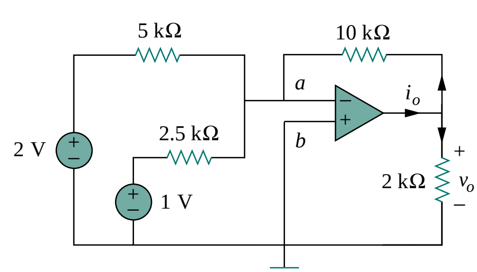


Figure 5.22 For Example 5.6.

Solution:

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

$$v_o = -\left[\frac{10}{5}(2) + \frac{10}{2.5}(1)\right] = -(4+4) = -8 \text{ V}$$

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

$$i_o = \frac{v_o - 0}{10} + \frac{v_o - 0}{2} \text{ mA} = -0.8 - 0.4 = -1.2 \text{ mA}$$

PRACTICE PROBLEM 5.6

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

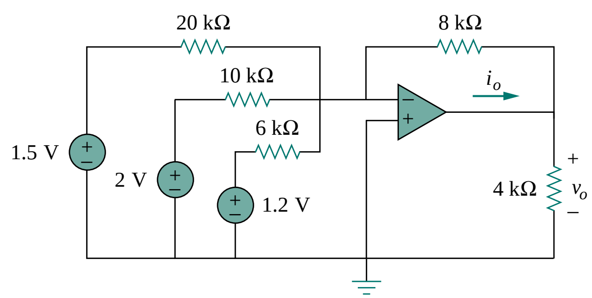


Figure 5.23 For Practice Prob. 5.6.

Answer: −3.8 V, −1.425 mA.

5.7 DIFFERENCE AMPLIFIER

Difference (or differential) amplifiers are used in various applications where there is 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.

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

> 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

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

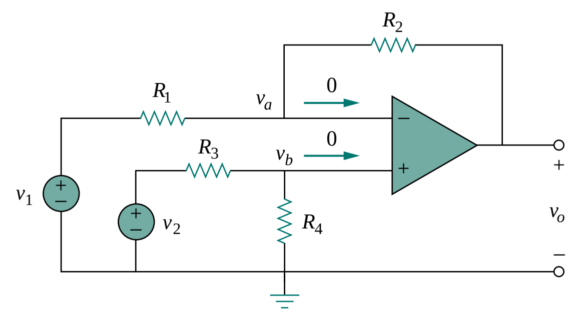


Figure 5.24 Difference amplifier.

Applying KCL to node b,

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

or

$$v_b = \frac{R_4}{R_3 + R_4} v_2 \qquad (5.17)$$

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

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

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

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \qquad (5.19)$$

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

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

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

$$v_o = v_2 - v_1 \qquad (5.21)$$

EXAMPLE 5.7

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

Solution:

The circuit requires that

$$v_o = 3v_2 - 5v_1 \qquad (5.7.1)$$

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),

$$\frac{R_2}{R_1} = 5 \qquad \Longrightarrow \qquad R_2 = 5R_1 \tag{5.7.2}$$

Also,

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

or

$$2 = 1 + \frac{R_3}{R_4} \qquad \Longrightarrow \qquad R_3 = R_4 \tag{5.7.3}$$

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

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,

$$v_o = -v_a - 5v_1 \tag{5.7.4}$$

and for the inverter,

$$v_a = -3v_2 \tag{5.7.5}$$

Combining Eqs. (5.7.4) and (5.7.5) gives

$$v_o = 3v_2 - 5v_1$$

which is the desired result. In Fig. 5.25, we may select $R_1 = 10\ \text{k}\Omega$ and $R_2 = 20\ \text{k}\Omega$ or $R_1 = R_2 = 10\ \text{k}\Omega$.

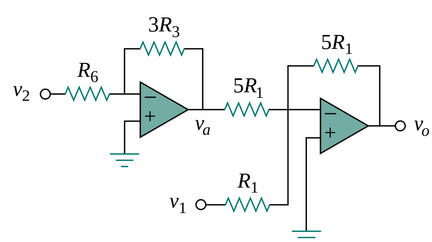


Figure 5.25 For Example 5.7.

PRACTICE PROBLEM 5.7

Design a difference amplifier with gain 4.

Answer: Typical: $R_1 = R_3 = 10\ \text{k}\Omega$, $R_2 = R_4 = 40\ \text{k}\Omega$.

EXAMPLE 5.8

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),

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

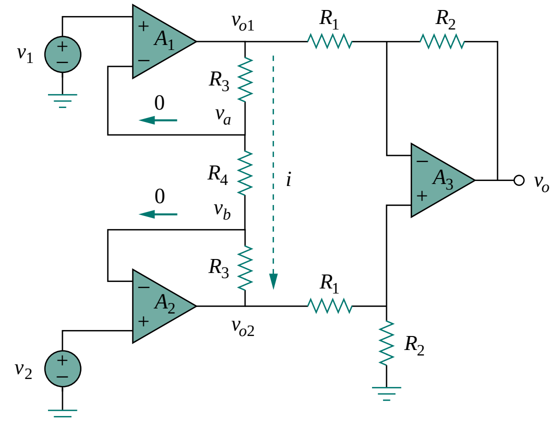


Figure 5.26 Instrumentation amplifier; for Example 5.8.

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,

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

But

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

and $v_a = v_1, \quad v_b = v_2$. 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.

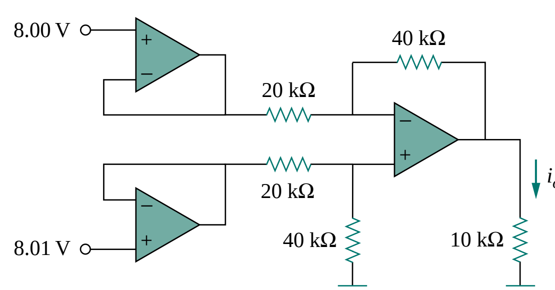


Figure 5.27 Instrumentation amplifier; for Practice Prob. 5.8.

Answer: 2 μA.

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

$$A = A_1 A_2 A_3 \tag{5.22}$$

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.

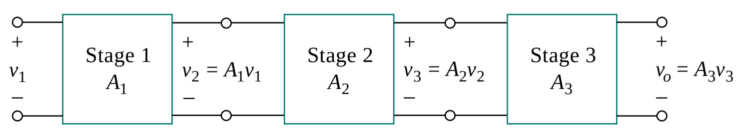


Figure 5.28 A three-stage cascaded connection.

EXAMPLE 5.9

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,

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

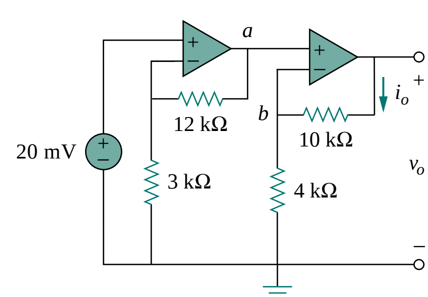


Figure 5.29 For Example 5.9.

The required current i_o is the current through the 10-kΩ resistor.

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

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: 10 V, 1 mA.

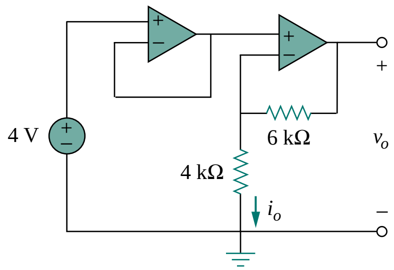


Figure 5.30 For Practice Prob. 5.9.

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.

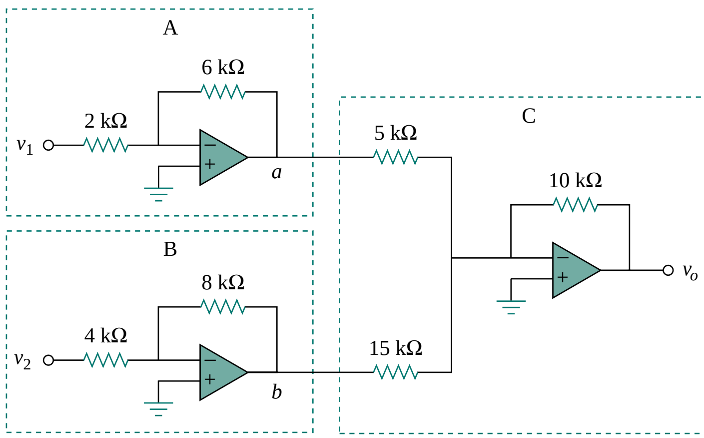


Figure 5.31 For Example 5.10.

Solution:

The circuit consists of two inverters A and B and a summer C as shown in Fig. 5.31. We first find the outputs of the inverters.

$$v_a = -\frac{6}{2}(v_1) = -3(1) = -3\text{ V}, \qquad v_b = -\frac{8}{4}(v_2) = -2(2) = -4\text{ V}$$

These become the inputs to the summer so that the output is obtained as

$$v_o = -\left(\frac{10}{5}v_a + \frac{10}{15}v_b\right) = -\left[2(-3) + \frac{2}{3}(-4)\right] = 8.333 \text{ V}$$

PRACTICE PROBLEM 5.10

If $v_1 = 2$ V and $v_2 = 1.5$ V, find v_o in the op amp circuit of Fig. 5.32.

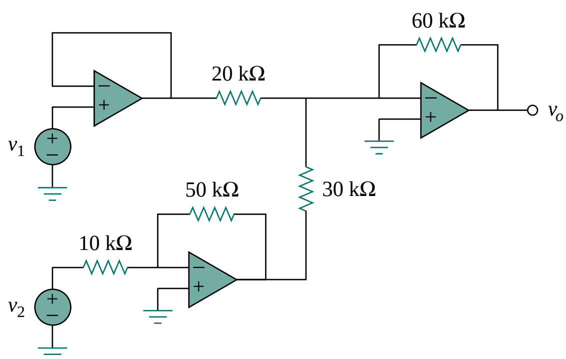
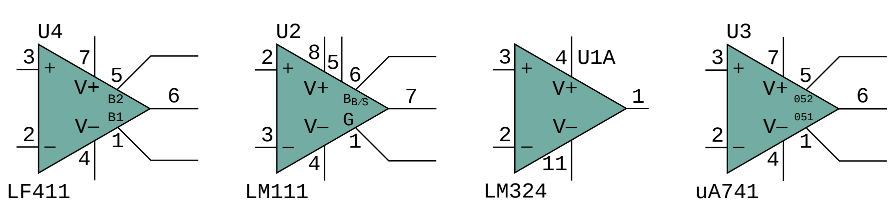


Figure 5.32 Practice Prob. 5.10.

Answer: 9 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 uA471, as shown in Fig. 5.33. 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.



(a) JFET–input op amp subcircuit (b) Op amp subcircuit (c) Five–connection op amp subcircuit (d) Five–connection op amp subcircuit

Figure 5.33 Nonideal op amp model available in *PSpice*.

EXAMPLE 5.11

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

Solution:

Using Schematics, we draw the circuit in Fig. 5.6(a) as shown in Fig. 5.34. Notice that the positive terminal of the voltage source v_s is connected to the inverting terminal (pin 2) via the 10-kΩ 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-kΩ resistor.

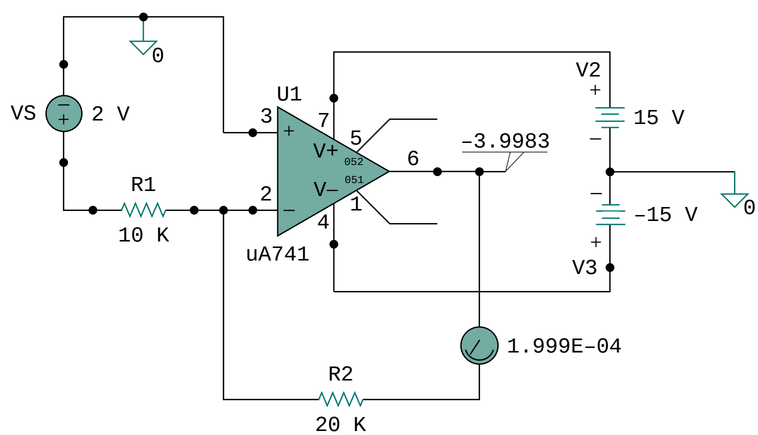


Figure 5.34 Schematic for Example 5.11.

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.

PRACTICE PROBLEM 5.11

Rework Practice Prob. 5.1 using *PSpice*.

Answer: 9.0027, 0.6502 mA.

†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. 5.35(a). The four-bit DAC can be realized in many ways. A simple realization is the *binary weighted ladder*, shown in Fig. 5.35(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,

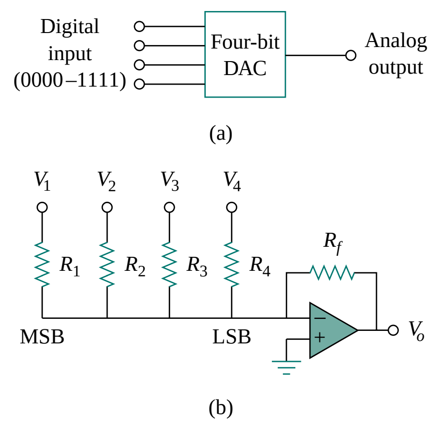


Figure 5.35 Four-bit DAC: (a) block diagram, (b) binary weighted ladder type.

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

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.

In practice, the voltage levels may be typically 0 and ± 5 V.

EXAMPLE 5.12

In the op amp circuit of Fig. 5.35(b), let $R_f = 10$ kΩ, $R_1 = 10$ kΩ, $R_2 = 20$ kΩ, $R_3 = 40$ kΩ, and $R_4 = 80$ kΩ. 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

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

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,

$$[V_1V_2V_3V_4] = [0010] \implies -V_o = 0.25 \text{ V}$$
$$[V_1V_2V_3V_4] = [0011] \implies -V_o = 0.25 + 0.125 = 0.375 \text{ V}$$
$$[V_1V_2V_3V_4] = [0100] \implies -V_o = 0.5 \text{ V}$$
$$\vdots$$
$$[V_1V_2V_3V_4] = [1111] \implies -V_o = 1 + 0.5 + 0.25 + 0.125 = 1.875 \text{ V}$$

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	0.125
1010	10	0.25
1011	11	1.375
1011	12	1.5
1100	13	1.625
1101	14	1.75
1111	15	1.875

PRACTICE PROBLEM 5.12

A three-bit DAC is shown in Fig. 5.36.

(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 $[V_1 V_2 V_3]$?

(d) To get $|V_o| = 1.75$ V, what should be $[V_1 V_2 V_3]$?

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

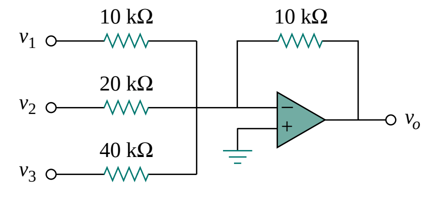


Figure 5.36 Three-bit DAC; for Practice Prob. 5.12.

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. 5.37(a), where the resistors are made equal except for the external gain-setting resistor R_G, connected between the gain set terminals. Figure 5.37(b) shows its schematic symbol. Example 5.8 showed that

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

where the voltage gain is

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

As shown in Fig. 5.38, the instrumentation amplifier amplifies small differential signal voltages superimposed on larger common-mode voltages. Since the common-mode voltages are equal, they cancel each other.

The IA has three major characteristics:

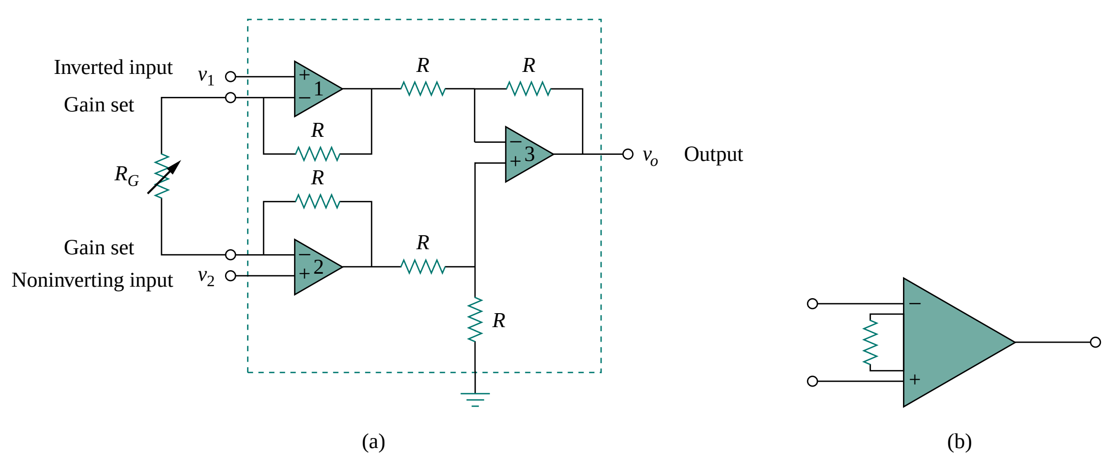


Figure 5.37 (a) The instrumentation amplifier with an external resistance to adjust the gain, (b) schematic diagram.

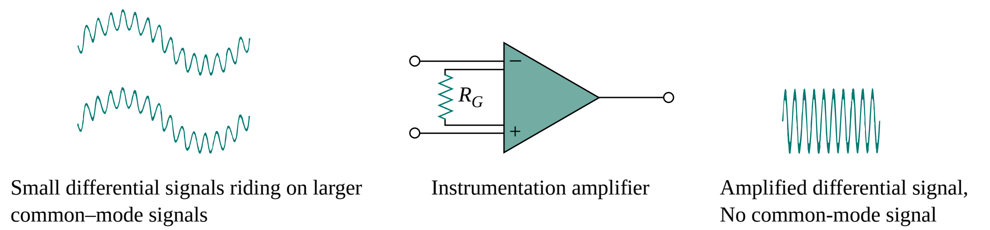


Figure 5.38 The IA rejects common voltages but amplifies small signal voltages.
(Source: T. L. Floyd, Electronic Devices, 2nd ed., Englewood Cliffs, NJ: Prentice Hall, 1996, p. 795.)

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 Ω to 10 kΩ.

EXAMPLE 5.13

In Fig. 5.37, let $R = 10$ kΩ, $v_1 = 2.011$ V, and $v_2 = 2.017$ V. If R_G is adjusted to 500 Ω, determine: (a) the voltage gain, (b) the output voltage v_o.

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

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

PRACTICE PROBLEM 5.13

Determine the value of the external gain-setting resistor R_G required for the IA in Fig. 5.37 to produce a gain of 142 when $R = 25$ kΩ.

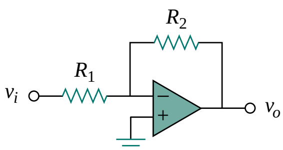
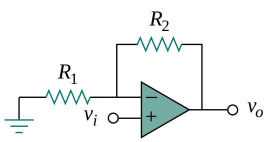
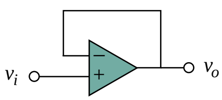
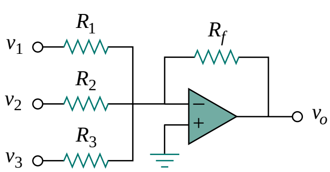
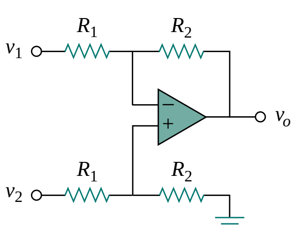
Answer: 354.6 Ω.

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.
4. 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.
10. Op amp circuits may be cascaded without changing their input-output 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. 5.39, voltage v_o is:
(a) −6 V (b) −5 V
(c) −1.2 V (d) −0.2 V

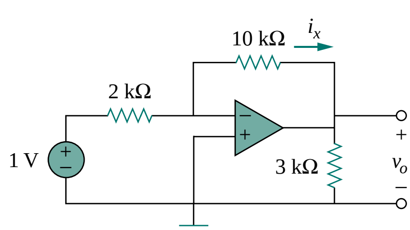


Figure 5.39 For Reivew Questions 5.3 and 5.4.

5.4 For the circuit in Fig. 5.39, current i_x is:
(a) 0.6 A (b) 0.5 A
(c) 0.2 A (d) 1/12 A

5.5 If $v_s = 0$ in the circuit of Fig. 5.40, current i_o is:
(a) −10 A (b) −2.5 A
(c) 10/12 A (d) 10/14 A

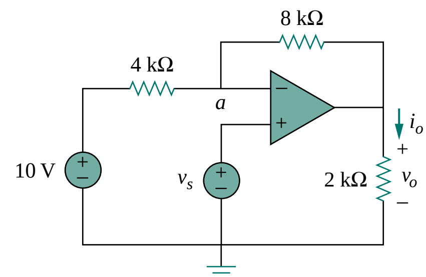


Figure 5.40 For Review Questions 5.5 to 5.7.

5.6 If $v_s = 8$ V in the circuit of Fig. 5.40, the output voltage is:
(a) −44 V (b) −8 V
(c) 4 V (d) 7 V

5.7 Refer to Fig. 5.40. If $v_s = 8$ V, voltage v_a is:
(a) −8 V (b) 0 V
(c) 10/3 V (d) 8 V

5.8 The power absorbed by the 4-kΩ resistor in Fig. 5.41 is:
(a) 9 mW (b) 4 mW
(c) 2 mW (d) 1 mW

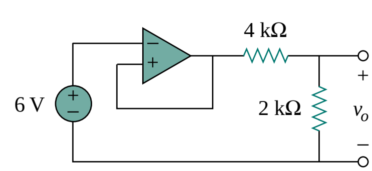


Figure 5.41 For Review Question 5.8.

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:
(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. 5.42. Determine:
(a) the input resistance
(b) the output resistance
(c) the voltage gain in dB.

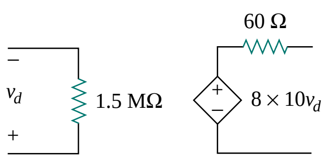


Figure 5.42 For Prob. 5.1.

5.2 The open-loop gain of an op amp is 100,000. Calculate the output voltage when there are inputs of $+10\ \mu$V on the inverting terminal and $+20\ \mu$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 2×10^6, what is the inverting input?

5.5 For the op amp circuit of Fig. 5.43, the op amp has an open-loop gain of 100,000, an input resistance of 10 kΩ, and an output resistance of 100 Ω. Find the voltage gain v_o/v_i using the nonideal model of the op amp.

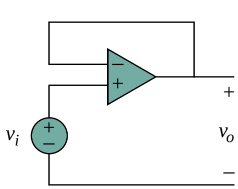


Figure 5.43 For Prob. 5.5.

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. 5.44.

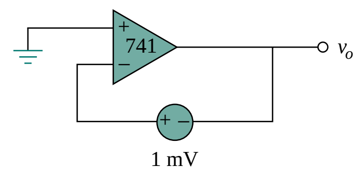


Figure 5.44 For Prob. 5.6.

5.7 The op amp in Fig. 5.45 has $R_i = 100$ kΩ, $R_o = 100\ \Omega$, $A = 100{,}000$. Find the differential voltage v_d and the output voltage v_o.

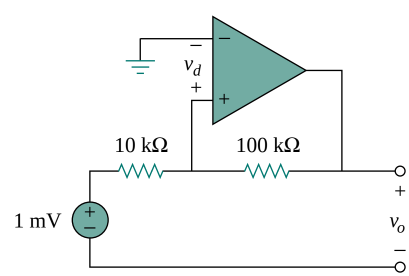


Figure 5.45 For Prob. 5.7.

Section 5.3 Ideal Op Amp

5.8 Obtain v_o for each of the op amp circuits in Fig. 5.46.

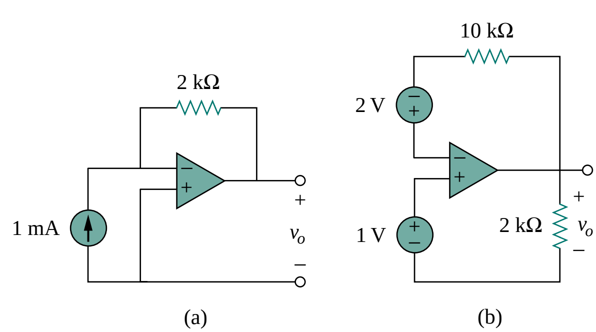


Figure 5.46 For Prob. 5.8.

5.9 Determine v_o for each of the op amp circuits in Fig. 5.47.

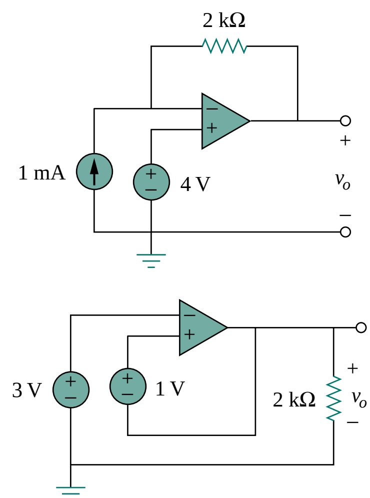


Figure 5.47 For Prob. 5.9.

5.10 Find the gain v_o/v_s of the circuit in Fig. 5.48.

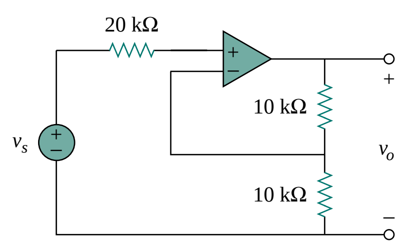


Figure 5.48 For Prob. 5.10.

5.11 Find v_o and i_o in the circuit in Fig. 5.49.

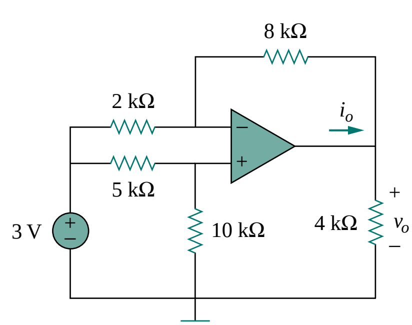


Figure 5.49 For Prob. 5.11.

5.12 Refer to the op amp circuit in Fig. 5.50. Determine the power supplied by the voltage source.

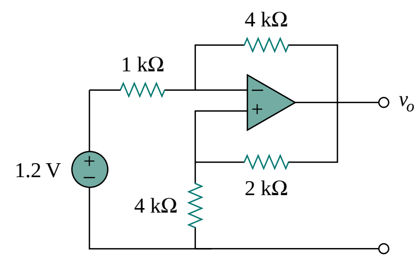


Figure 5.50 For Prob. 5.12.

5.13 Find v_o and i_o in the circuit of Fig. 5.51.

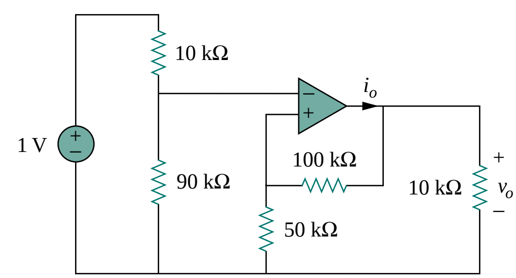


Figure 5.51 For Prob. 5.13.

5.14 Determine the output voltage v_o in the circuit of Fig. 5.52.

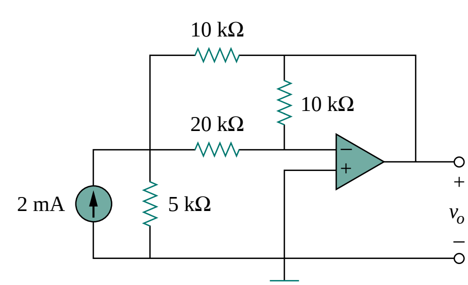


Figure 5.52 For Prob. 5.14.

Section 5.4 Inverting Amplifier

5.15 (a) For the circuit shown in Fig. 5.53, show that the gain is

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

(b) Evaluate the gain when $R = 10\ \text{k}\Omega$, $R_1 = 100\ \text{k}\Omega$, $R_2 = 50\ \text{k}\Omega$, $R_3 = 25\ \text{k}\Omega$.

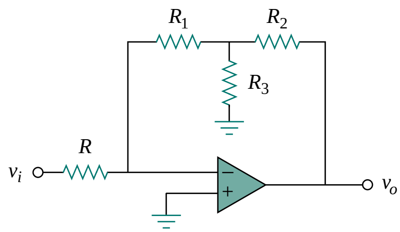


Figure 5.53 For Prob. 5.15.

5.16 Calculate the gain v_o/v_i when the switch in Fig. 5.54 is in:
(a) position 1 (b) position 2 (c) position 3

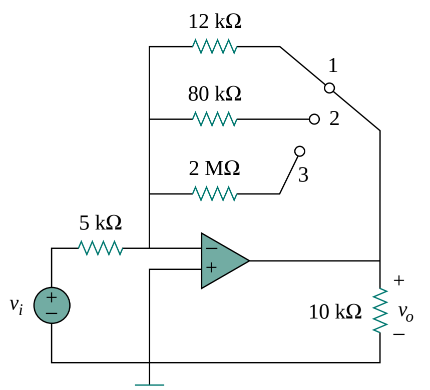


Figure 5.54 For Prob. 5.16.

5.17 Calculate the gain v_o/v_i of the op amp circuit in Fig. 5.55.

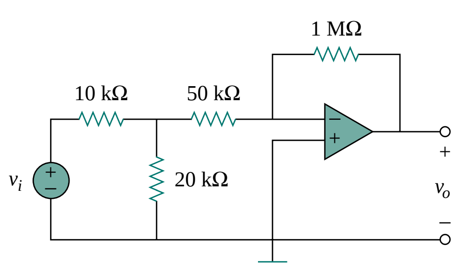


Figure 5.55 For Prob. 5.17.

5.18 Determine i_o in the circuit of Fig. 5.56.

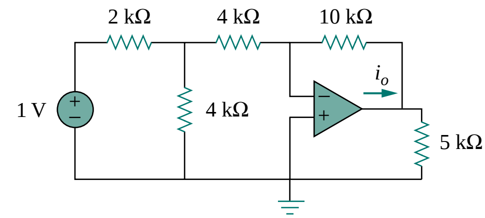


Figure 5.56 For Prob. 5.18.

5.19 In the circuit in Fig. 5.57, calculate v_o if $v_s = 0$.

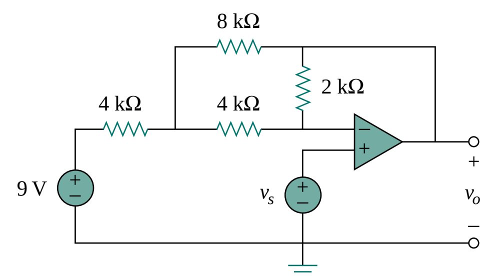


Figure 5.57 For Prob. 5.19.

5.20 Repeat the previous problem if $v_s = 3$ V.

5.21 Design an inverting amplifier with a gain of -15.

Section 5.5 Noninverting Amplifier

5.22 Find v_a and v_o in the op amp circuit of Fig. 5.58.

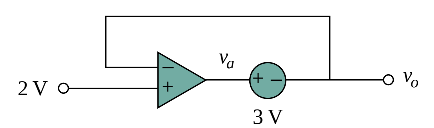


Figure 5.58 For Prob. 5.22.

5.23 Refer to Fig. 5.59.
(a) Determine the overall gain v_o/v_i of the circuit.
(b) What value of v_i will result in $v_o = 15 \cos 120\pi t$?

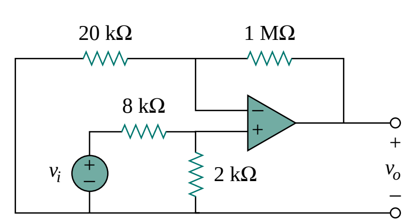


Figure 5.59 For Prob. 5.23.

5.24 Find i_o in the op amp circuit of Fig. 5.60.

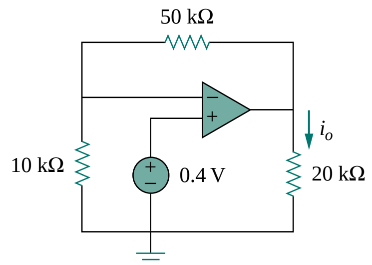


Figure 5.60 For Prob. 5.24.

5.25 In the circuit shown in Fig. 5.61, find i_x and the power absorbed by the 20-Ω resistor.

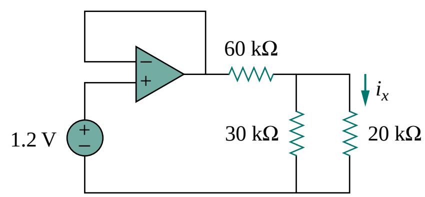


Figure 5.61 For Prob. 5.25.

5.26 For the circuit in Fig. 5.62, find i_x.

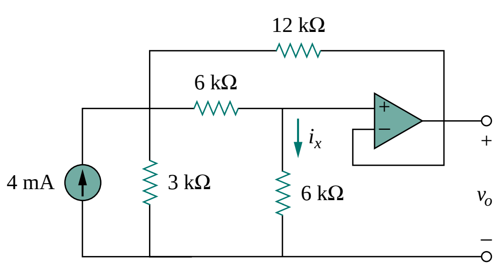


Figure 5.62 For Prob. 5.26.

5.27 Calculate i_x and v_o in the circuit of Fig. 5.63. Find the power dissipated by the 60-kΩ resistor.

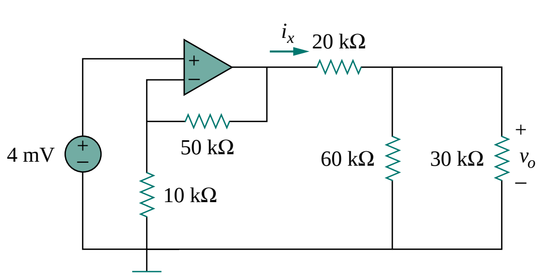


Figure 5.63 For Prob. 5.27.

5.28 Refer to the op amp circuit in Fig. 5.64. Calculate i_x and the power dissipated by the 3-kΩ resistor.

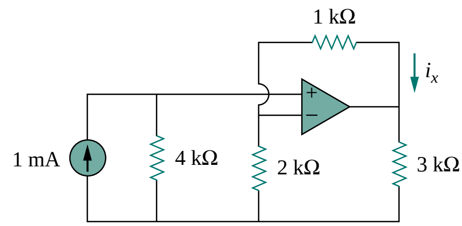


Figure 5.64 For Prob. 5.28.

5.29 Design a noninverting amplifier with a gain of 10.

Section 5.6 Summing Amplifier

5.30 Determine the output of the summing amplifier in Fig. 5.65.

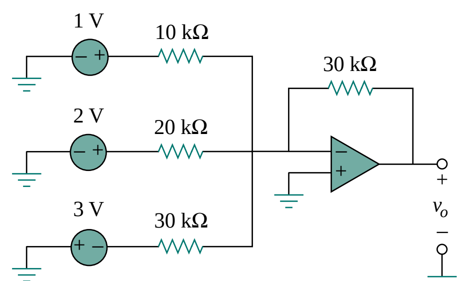


Figure 5.65 For Prob. 5.30.

5.31 Calculate the output voltage due to the summing amplifier shown in Fig. 5.66.

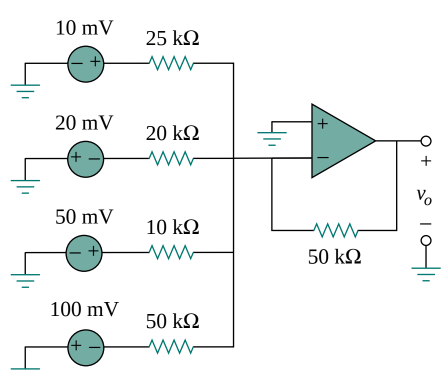


Figure 5.66 For Prob. 5.31.

5.32 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 kΩ, design an averaging amplifier with four inputs.

5.33 A four-input summing amplifier has $R_1 = R_2 = R_3 = R_4 = 12$ kΩ. What value of feedback resistor is needed to make it an averaging amplifier?

5.34 Show that the output voltage v_o of the circuit in Fig. 5.67 is

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

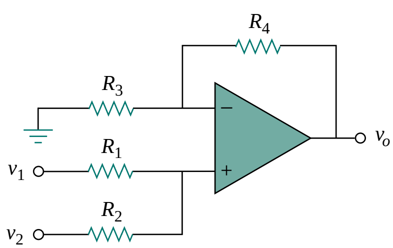


Figure 5.67 For Prob. 5.34.

5.35 Design an op amp circuit to perform the following operation:

$$v_o = 3v_1 - 2v_2$$

All resistances must be ≤ 100 kΩ.

5.36 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

5.37 Find v_o and i_o in the differential amplifier of Fig. 5.68.

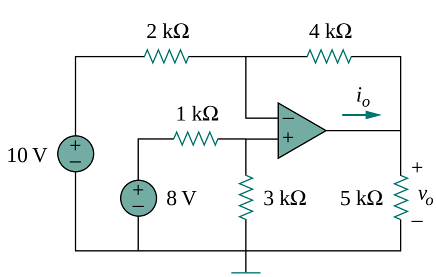


Figure 5.68 For Prob. 5.37.

5.38 The circuit in Fig. 5.69 is a differential amplifier driven by a bridge. Find v_o.

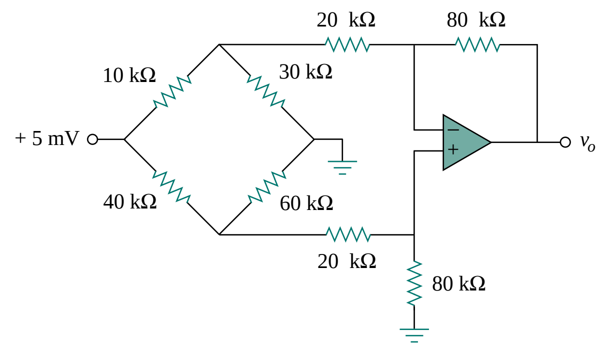


Figure 5.69 For Prob. 5.38.

5.39 Design a difference amplifier to have a gain of 2 and a common mode input resistance of 10 kΩ at each input.

5.40 Design a circuit to amplify the difference between two inputs by 2.

(a) Use only one op amp.

(b) Use two op amps.

5.41 Using two op amps, design a subtractor.

***5.42** The ordinary difference amplifier for fixed-gain operation is shown in Fig. 5.70(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. 5.70(b). Another way is to use the circuit in Fig. 5.70(c). Show that:

(a) for the circuit in Fig. 5.70(a),

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

Fg5_70b

(b) for the circuit in Fig. 5.70(b),

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

Fg5_70c

(c) for the circuit in Fig. 5.70(c),

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

*An asterisk indicates a challenging problem.

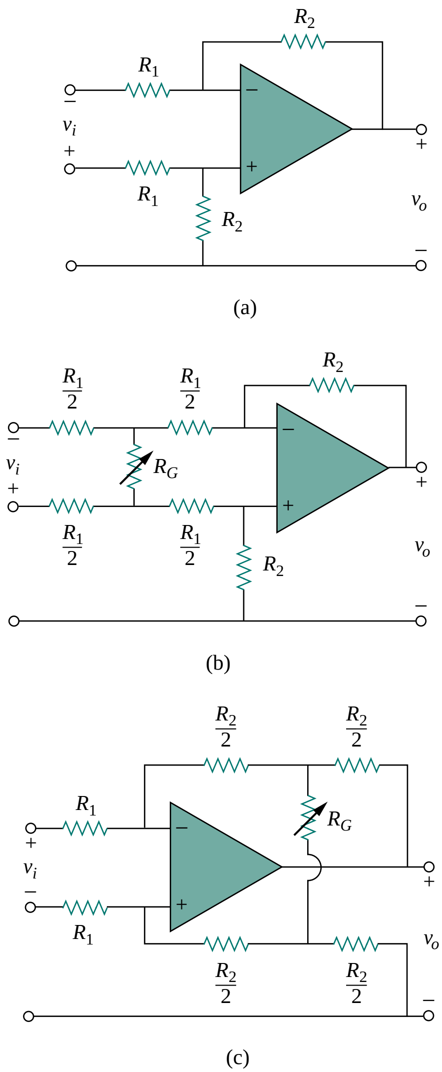


Figure 5.70 For Prob. 5.42.

Section 5.8 Cascaded Op Amp Circuits

5.43 The individual gains of the stages in a multistage amplifier are shown in Fig. 5.71.

(a) Calculate the overall voltage gain v_o/v_i.

(b) Find the voltage gain that would be needed in a fourth stage which would make the overall gain to be 60 dB when added.

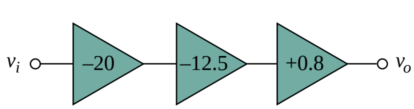


Figure 5.71 For Prob. 5.43.

5.44 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.

5.45 Refer to the circuit in Fig. 5.72. Calculate i_o if:
(a) $v_s = 12$ mV (b) $v_s = 10 \cos 377t$ mV.

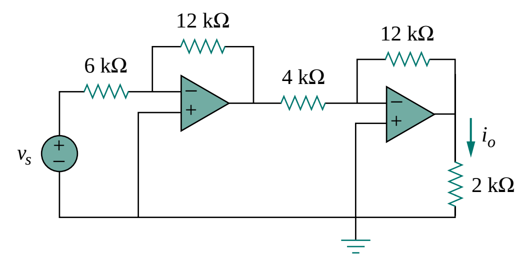


Figure 5.72 For Prob. 5.45.

5.46 Calculate i_o in the op amp circuit of Fig. 5.73.

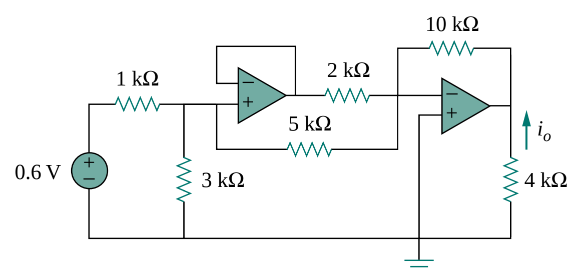


Figure 5.73 For Prob. 5.46.

5.47 Find the voltage gain v_o/v_s of the circuit in Fig. 5.74.

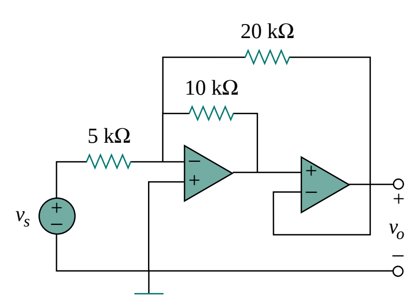


Figure 5.74 For Prob. 5.47.

5.48 Calculate the current gain i_o/i_s of the op amp circuit in Fig. 5.75.

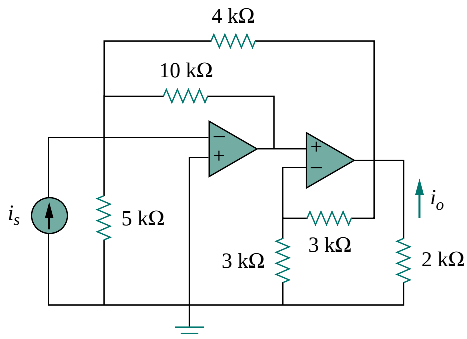


Figure 5.75 For Prob. 5.48.

5.49 Find v_o in terms of v_1 and v_2 in the circuit in Fig. 5.76.

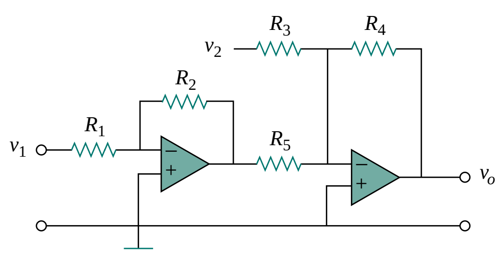


Figure 5.76 For Prob. 5.49.

5.50 Obtain the closed-loop voltage gain v_o/v_i of the circuit in Fig. 5.77.

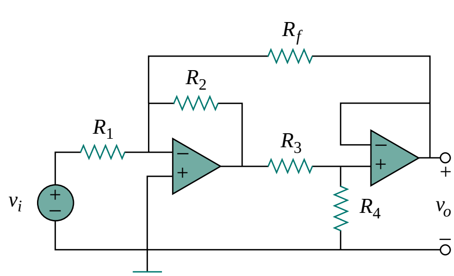


Figure 5.77 For Prob. 5.50.

5.51 Determine the gain v_o/v_i of the circuit in Fig. 5.78.

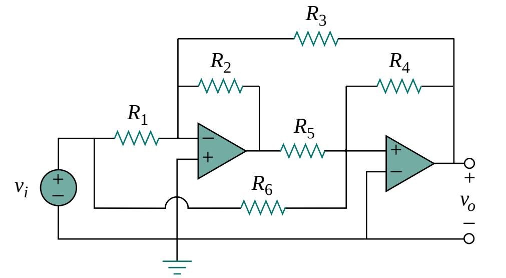


Figure 5.78 For Prob. 5.51.

5.52 For the circuit in Fig. 5.79, find v_o.

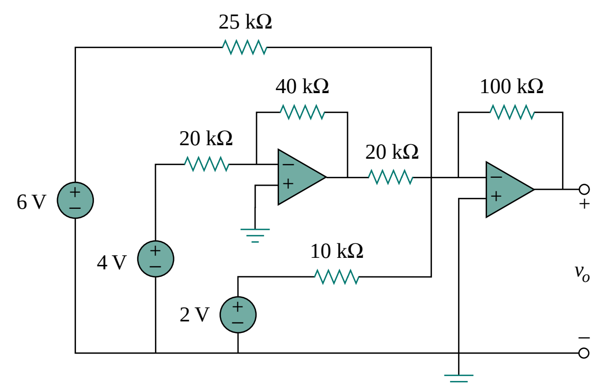


Figure 5.79 For Prob. 5.52.

5.53 Obtain the output v_o in the circuit of Fig. 5.80.

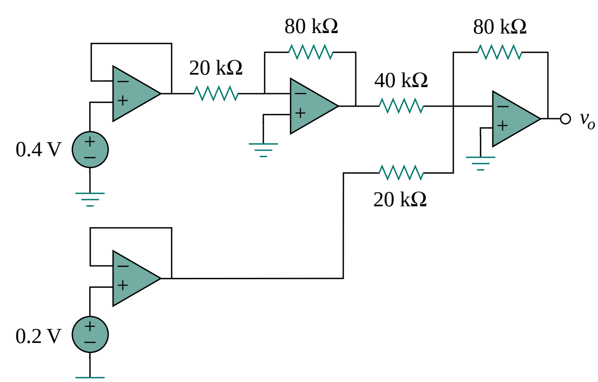


Figure 5.80 For Prob. 5.53.

5.54 Find v_o in the circuit in Fig. 5.81, assuming that $R_f = \infty$ (open circuit).

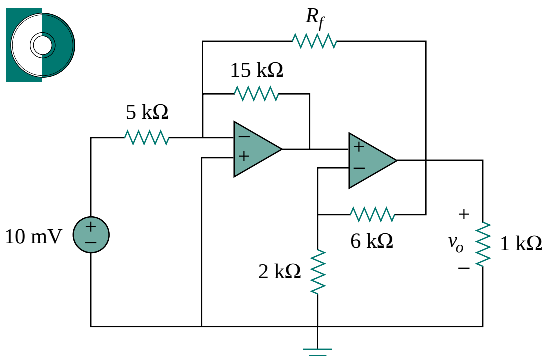


Figure 5.81 For Probs. 5.54 and 5.55.

5.55 Repeat the previous problem if $R_f = 10$ kΩ.

5.56 Determine v_o in the op amp circuit of Fig. 5.82.

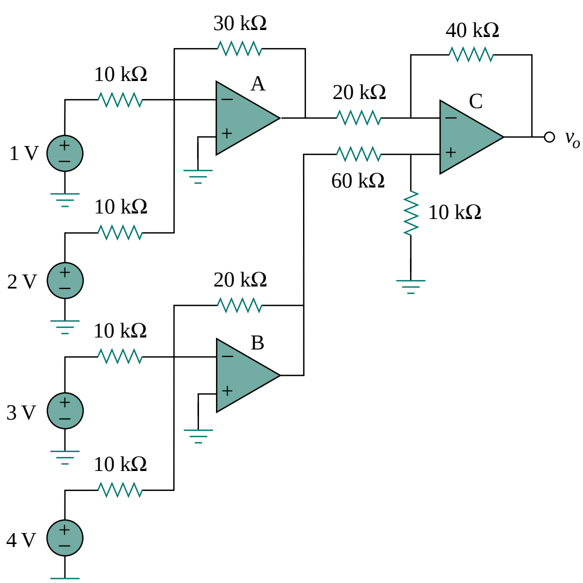


Figure 5.82 For Prob. 5.56.

5.57 Find the load voltage v_L in the circuit of Fig. 5.83.

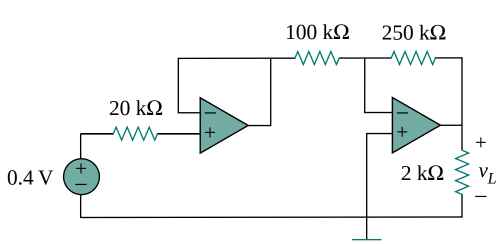


Figure 5.83 For Prob. 5.57.

5.58 Determine the load voltage v_L in the circuit of Fig. 5.84.

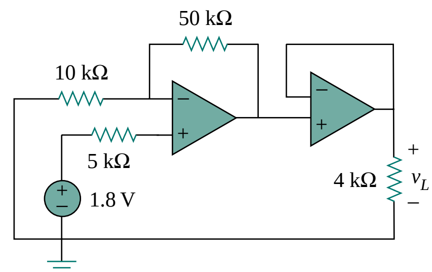


Figure 5.84 For Prob. 5.58.

5.59 Find i_o in the op amp circuit of Fig. 5.85.

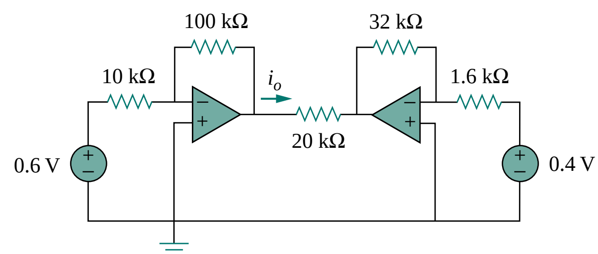


Figure 5.85 For Prob. 5.59.

Section 5.9 Op Amp Circuit Analysis with *PSpice*

5.60 Rework Example 5.11 using the nonideal op amp LM324 instead of uA741.

5.61 Solve Prob. 5.18 using *PSpice* and op amp uA741.

5.62 Solve Prob. 5.38 using *PSpice* and op amp LM324.

5.63 Use *PSpice* to obtain v_o in the circuit of Fig. 5.86.

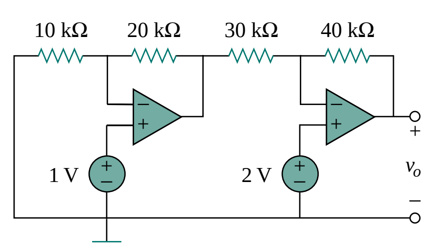


Figure 5.86 For Prob. 5.63.

5.64 Determine v_o in the op amp circuit of Fig. 5.87 using *PSpice*.

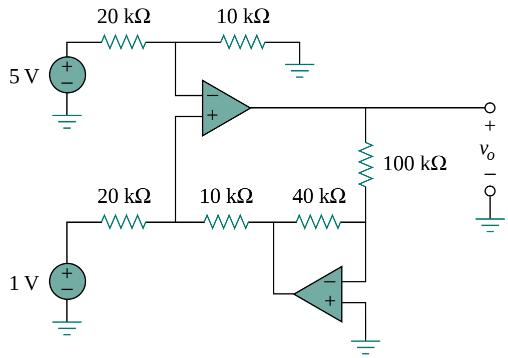


Figure 5.87 For Prob. 5.64.

5.65 Use *PSpice* to solve Prob. 5.56, assuming that the op amps are uA741.

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

Section 5.10 Applications

5.67 A five-bit DAC covers a voltage range of 0 to 7.75 V. Calculate how much voltage each bit is worth.

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

(a) If $|V_o| = 1.1875$ V is desired, what should $[V_1 V_2 V_3 V_4 V_5 V_6]$ be?

(b) Calculate $|V_o|$ if $[V_1 V_2 V_3 V_4 V_5 V_6] = [011011]$.

(c) What is the maximum value $|V_o|$ can assume?

***5.69** A four-bit *R-2R ladder* DAC is presented in Fig. 5.88.

(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 $R_f = 12$ kΩ and $R = 10$ kΩ, find $|V_o|$ for $[V_1 V_2 V_3 V_4] = [1011]$ and $[V_1 V_2 V_3 V_4] = [0101]$.

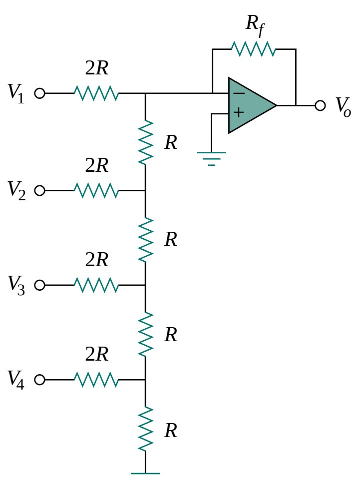


Figure 5.88 For Prob. 5.69.

5.70 If $R_G = 100\ \Omega$ and $R = 20$ kΩ, calculate the voltage gain of the IA in Fig. 5.37.

5.71 Assuming a gain of 200 for an IA, find its output voltage for:

(a) $v_1 = 0.402$ V and $v_2 = 0.386$ V

(b) $v_1 = 1.002$ V and $v_2 = 1.011$ V.

5.72 Figure 5.89 displays a two-op-amp instrumentation amplifier. Derive an expression for v_o in terms of v_1 and v_2. How can this amplifier be used as a subtractor?

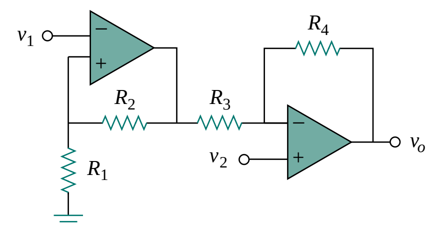


Figure 5.89 For Prob. 5.72.

***5.73** Figure 5.90 shows an instrumentation amplifier driven by a bridge. Obtain the gain v_o/v_i of the amplifier.

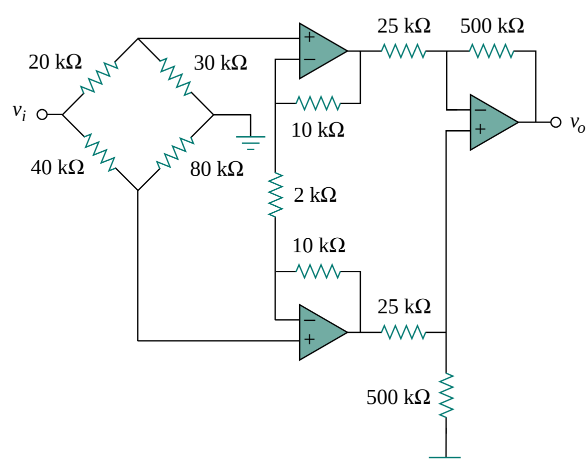


Figure 5.90 For Prob. 5.73.

COMPREHENSIVE PROBLEMS

5.74 A gain of 6 (+ or −, it does not matter) is required in an audio system. Design an op amp circuit to provide the gain with an input resistance of 2 kΩ.

5.75 The op amp circuit in Fig. 5.91 is a *current amplifier.* Find the current gain i_o/i_s of the amplifier.

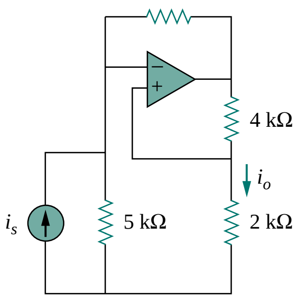


Figure 5.91 For Prob. 5.75.

5.76 A noninverting current amplifier is portrayed in Fig. 5.92. Calculate the gain i_o/i_s. Take $R_1 = 8$ kΩ and $R_2 = 1$ kΩ.

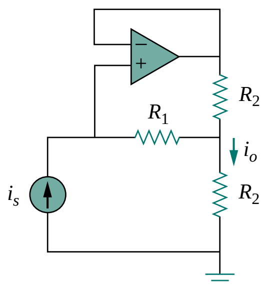


Figure 5.92 For Prob. 5.76.

5.77 Refer to the *bridge amplifier* shown in Fig. 5.93. Determine the voltage gain v_o/v_i.

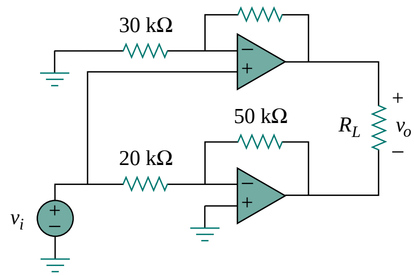


Figure 5.93 For Prob. 5.77.

***5.78** A voltage-to-current converter is shown in Fig. 5.94, which means that $i_L = Av_i$ if $R_1R_2 = R_3R_4$. Find the constant term A.

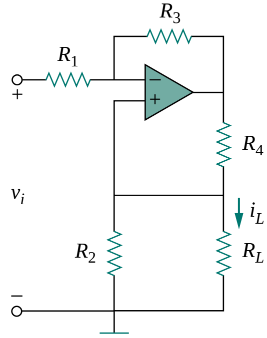


Figure 5.94 For Prob. 5.78.