

# 5

## SERIES CIRCUITS

### CHAPTER OUTLINE

- 5–1 Resistors in Series
  - 5–2 Total Series Resistance
  - 5–3 Current in a Series Circuit
  - 5–4 Application of Ohm’s Law
  - 5–5 Voltage Sources in Series
  - 5–6 Kirchhoff’s Voltage Law
  - 5–7 Voltage Dividers
  - 5–8 Power in Series Circuits
  - 5–9 Voltage Measurements
  - 5–10 Troubleshooting
- Application Activity

### CHAPTER OBJECTIVES

- ▶ Identify a series resistive circuit
- ▶ Determine total series resistance
- ▶ Determine the current throughout a series circuit
- ▶ Apply Ohm’s law in series circuits
- ▶ Determine the total effect of voltage sources connected in series
- ▶ Apply Kirchhoff’s voltage law
- ▶ Use a series circuit as a voltage divider
- ▶ Determine power in a series circuit
- ▶ Measure voltage with respect to ground
- ▶ Troubleshoot series circuits

### KEY TERMS

- ▶ Series
- ▶ Kirchhoff’s voltage law
- ▶ Voltage divider
- ▶ Open
- ▶ Short

### APPLICATION ACTIVITY PREVIEW

In this application activity, you will evaluate a voltage-divider circuit board connected to a 12 V battery to provide a selection of fixed reference voltages for use with an electronic instrument.

### VISIT THE COMPANION WEBSITE

Study aids for this chapter are available at  
<http://www.pearsonhighered.com/careersresources/>

### INTRODUCTION

In Chapter 3 you learned about Ohm’s law, and in Chapter 4 you learned about power in resistors. In this chapter, those concepts are applied to circuits in which resistors are connected in a series arrangement.

Resistive circuits can be of two basic forms: series and parallel. In this chapter, series circuits are studied. Parallel circuits are covered in Chapter 6, and combinations of series and parallel resistors are examined in Chapter 7. In this chapter, you will see how Ohm’s law is used in series circuits; and you will learn another important circuit law, Kirchhoff’s voltage law. Also, several applications of series circuits, including voltage dividers, are presented.

When resistors are connected in series and a voltage is applied across the series connection, there is only one path for current; therefore, each resistor in series has the same amount of current through it. All of the resistances in series add together to produce a total resistance. The voltage drops across each of the resistors add up to the voltage applied across the entire series connection.

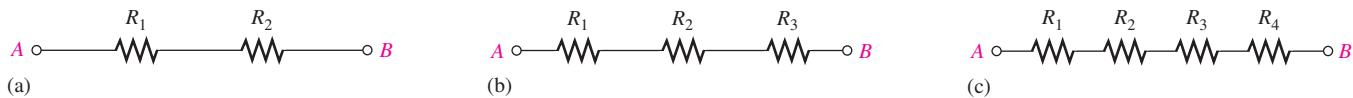
## 5-1 RESISTORS IN SERIES

When connected in series, resistors form a “string” in which there is only one path for current.

After completing this section, you should be able to

- ◆ Identify a series resistive circuit
- ◆ Translate a physical arrangement of resistors into a schematic

The schematic in Figure 5-1(a) shows two resistors connected in series between point *A* and point *B*. Part (b) shows three resistors in series, and part (c) shows four in series. Of course, there can be any number of resistors in a series circuit.



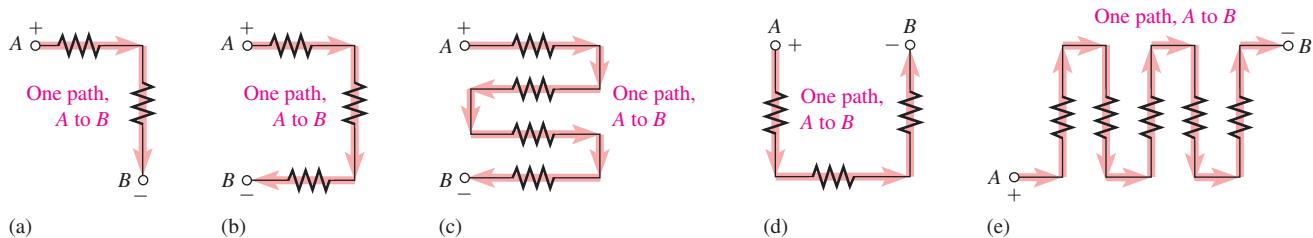
▲ FIGURE 5-1

Resistors in series.

When a voltage source is connected between point *A* and *B*, the only way for current to get from one point to the other in any of the connections of Figure 5-1 is to go through each of the resistors. The following statement describes a series circuit:

**A series circuit provides only one path for current between two points so that the current is the same through each series resistor.**

In an actual circuit diagram, a series circuit may not always be as easy to visually identify as those in Figure 5-1. For example, Figure 5-2 shows series resistors drawn in other ways with voltage applied. Remember, if there is only one current path between two points, the resistors between those two points are in series, no matter how they appear in a diagram.



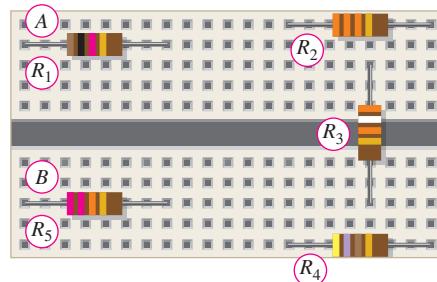
▲ FIGURE 5-2

Some examples of series circuits. Notice that the current is the same at all points because the current has only one path.

### EXAMPLE 5-1

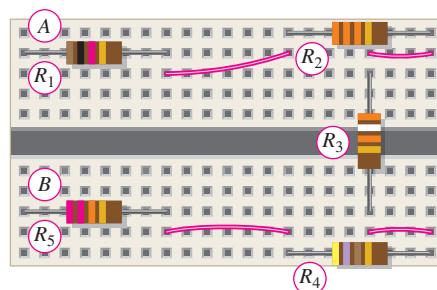
Suppose that there are five resistors positioned on a protoboard as shown in Figure 5-3. Wire them together in series so that, starting from the positive (+) terminal,  $R_1$  is first,  $R_2$  is second,  $R_3$  is third, and so on. Draw a schematic showing this connection.

► FIGURE 5-3

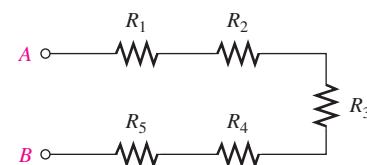
**Solution**

The wires are connected as shown in Figure 5-4(a), which is the assembly diagram. The schematic is shown in Figure 5-4(b). Note that the schematic does not necessarily show the actual physical arrangement of the resistors as does the assembly diagram. The schematic shows how components are connected electrically; the assembly diagram shows how components are arranged and interconnected physically.

► FIGURE 5-4



(a) Assembly diagram



(b) Schematic

**Related Problem\***

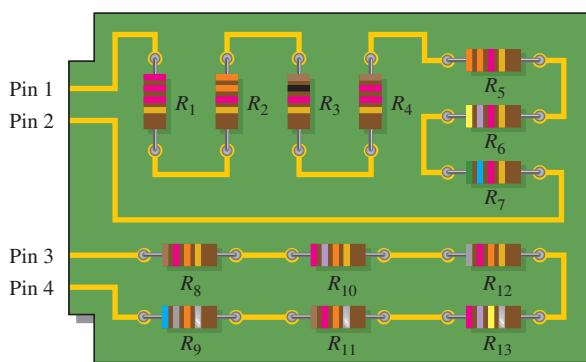
- (a) Show how you would rewire the protoboard in Figure 5-4(a) so that all the odd-numbered resistors come first followed by the even-numbered ones.  
 (b) Determine the resistance value of each resistor.

\*Answers are at the end of the chapter.

**EXAMPLE 5-2**

Describe how the resistors on the printed circuit (PC) board in Figure 5-5 are related electrically. Determine the resistance value of each resistor.

► FIGURE 5-5



**Solution** Resistors  $R_1$  through  $R_7$  are in series with each other. This series combination is connected between pins 1 and 2 on the PC board.

Resistors  $R_8$  through  $R_{13}$  are in series with each other. This series combination is connected between pins 3 and 4 on the PC board.

The values of the resistors are  $R_1 = 2.2\text{ k}\Omega$ ,  $R_2 = 3.3\text{ k}\Omega$ ,  $R_3 = 1.0\text{ k}\Omega$ ,  $R_4 = 1.2\text{ k}\Omega$ ,  $R_5 = 3.3\text{ k}\Omega$ ,  $R_6 = 4.7\text{ k}\Omega$ ,  $R_7 = 5.6\text{ k}\Omega$ ,  $R_8 = 12\text{ k}\Omega$ ,  $R_9 = 68\text{ k}\Omega$ ,  $R_{10} = 27\text{ k}\Omega$ ,  $R_{11} = 12\text{ k}\Omega$ ,  $R_{12} = 82\text{ k}\Omega$ , and  $R_{13} = 270\text{ k}\Omega$ .

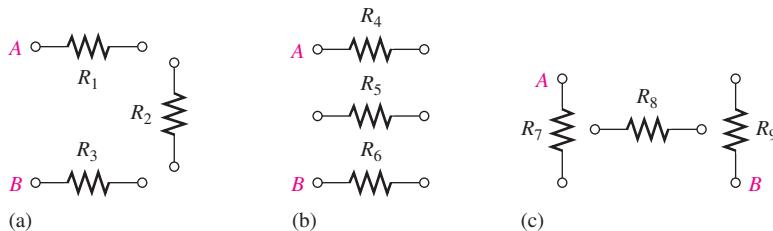
**Related Problem** How is the circuit changed when pin 2 and pin 3 in Figure 5–5 are connected?

### SECTION 5–1

#### CHECKUP

Answers are at the end of the chapter.

- How are the resistors connected in a series circuit?
- How can you identify a series circuit?
- Complete the schematics for the circuits in each part of Figure 5–6 by connecting each group of resistors in series in numerical order from terminal A to terminal B.
- Connect each group of series resistors in Figure 5–6 in series with each other.



▲ FIGURE 5–6

## 5–2 TOTAL SERIES RESISTANCE

The total resistance of a series circuit is equal to the sum of the resistances of each individual series resistor.

After completing this section, you should be able to

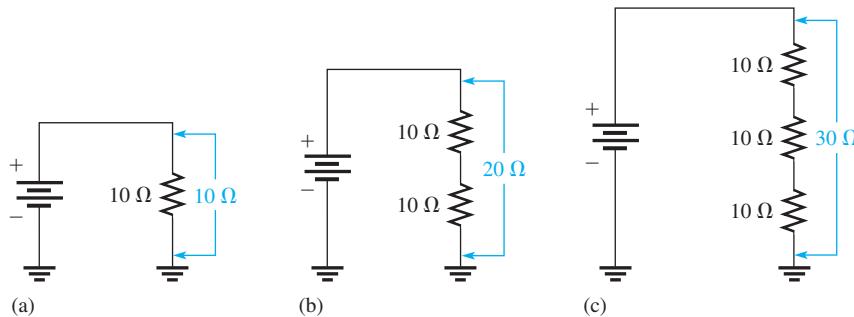
- ◆ **Determine total series resistance**
- ◆ Explain why resistance values add when resistors are connected in series
- ◆ Apply the series resistance formula

### Series Resistor Values Add

When resistors are connected in series, the resistor values add because each resistor offers opposition to the current in direct proportion to its resistance. A greater number of resistors connected in series creates more opposition to current. More opposition to current implies a higher value of resistance. Thus, every time a resistor is added in series, the total resistance increases.

Figure 5–7 illustrates how series resistances add to increase the total resistance. Part (a) has a single  $10\text{ }\Omega$  resistor. Part (b) shows another  $10\text{ }\Omega$  resistor connected

in series with the first one, making a total resistance of  $20\ \Omega$ . If a third  $10\ \Omega$  resistor is connected in series with the first two, as shown in part (c), the total resistance becomes  $30\ \Omega$ .



**▲ FIGURE 5-7**  
Total resistance increases with each additional series resistor.

## Series Resistance Formula

For any number of individual resistors connected in series, the total resistance is the sum of each of the individual values.

$$R_T = R_1 + R_2 + R_3 + \dots + R_n$$

**Equation 5-1**

where  $R_T$  is the total resistance and  $R_n$  is the last resistor in the series string ( $n$  can be any positive integer equal to the number of resistors in series). For example, if there are four resistors in series ( $n = 4$ ), the total resistance formula is

$$R_T = R_1 + R_2 + R_3 + R_4$$

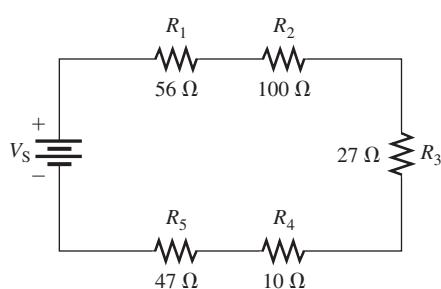
If there are six resistors in series ( $n = 6$ ), the total resistance formula is

$$R_T = R_1 + R_2 + R_3 + R_4 + R_5 + R_6$$

To illustrate the calculation of total series resistance, let's determine  $R_T$  in the circuit of Figure 5-8, where  $V_S$  is the source voltage. The circuit has five resistors in series. To get the total resistance, simply add the values.

$$R_T = 56\ \Omega + 100\ \Omega + 27\ \Omega + 10\ \Omega + 47\ \Omega = 240\ \Omega$$

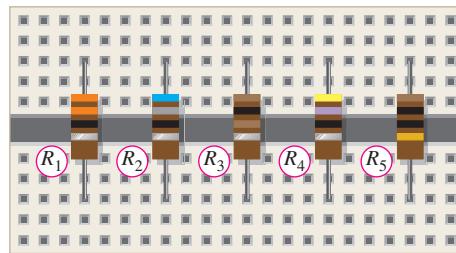
Note in Figure 5-8 that the order in which the resistances are added does not matter. You can physically change the positions of the resistors in the circuit without affecting the total resistance or the current.



**▲ FIGURE 5-8**  
Example of five resistors in series.

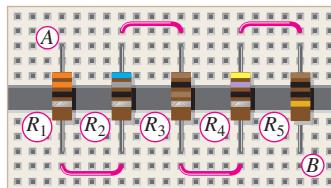
**EXAMPLE 5–3**

Connect the resistors in Figure 5–9 in series, and determine the total resistance,  $R_T$ , from the color codes.

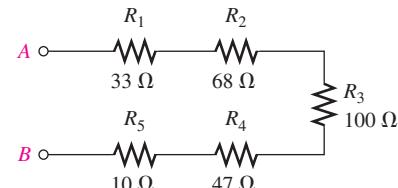
**► FIGURE 5–9**

**Solution** The resistors can be connected as shown in Figure 5–10. Find the total resistance by adding all the values.

$$R_T = R_1 + R_2 + R_3 + R_4 + R_5 = 33 \Omega + 68 \Omega + 100 \Omega + 47 \Omega + 10 \Omega = 258 \Omega$$



(a) Circuit assembly



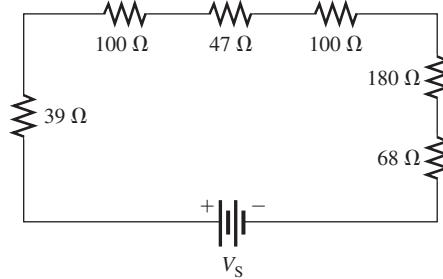
(b) Schematic

**▲ FIGURE 5–10****Related Problem**

Determine the total resistance in Figure 5–10(a) if the positions of  $R_2$  and  $R_4$  are interchanged.

**EXAMPLE 5–4**

What is the total resistance ( $R_T$ ) in the circuit of Figure 5–11?

**► FIGURE 5–11**

**Solution** Sum all the values.

$$R_T = 39 \Omega + 100 \Omega + 47 \Omega + 100 \Omega + 180 \Omega + 68 \Omega = 534 \Omega$$

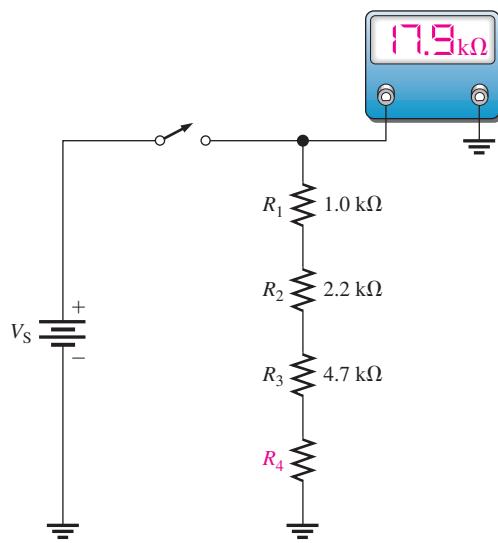
**Related Problem**

What is the total resistance for the following series resistors: 1.0 kΩ, 2.2 kΩ, 3.3 kΩ, and 5.6 kΩ?

**EXAMPLE 5–5**

Determine the value of  $R_4$  in the circuit of Figure 5–12.

► FIGURE 5–12



*Solution* From the ohmmeter reading,  $R_T = 17.9 \text{ k}\Omega$ .

$$R_T = R_1 + R_2 + R_3 + R_4$$

Solving for  $R_4$  yields

$$R_4 = R_T - (R_1 + R_2 + R_3) = 17.9 \text{ k}\Omega - (1.0 \text{ k}\Omega + 2.2 \text{ k}\Omega + 4.7 \text{ k}\Omega) = 10 \text{ k}\Omega$$

*Related Problem* Determine the value of  $R_4$  in Figure 5–12 if the ohmmeter reading is 14.7 kΩ.

**Equal-Value Series Resistors**

When a circuit has more than one resistor of the same value in series, there is a short-cut method to obtain the total resistance: Simply multiply the resistance value by the number of equal-value resistors that are in series. This method is essentially the same as adding the values. For example, five 100 Ω resistors in series have an  $R_T$  of  $5(100 \Omega) = 500 \Omega$ . In general, the formula is expressed as

$$R_T = nR \quad \text{Equation 5–2}$$

where  $n$  is the number of equal-value resistors and  $R$  is the resistance value.

**EXAMPLE 5–6**

Find the  $R_T$  of eight 22 Ω resistors in series.

*Solution* Find  $R_T$  by adding the values.

$$R_T = 22 \Omega + 22 \Omega = 176 \Omega$$

However, it is much easier to multiply to get the same result.

$$R_T = 8(22 \Omega) = 176 \Omega$$

*Related Problem* Find  $R_T$  for three 1.0 kΩ resistors and two 720 Ω resistors in series.

**SECTION 5-2  
CHECKUP**

- The following resistors (one each) are in series:  $1.0\ \Omega$ ,  $2.2\ \Omega$ ,  $3.3\ \Omega$ , and  $4.7\ \Omega$ . What is the total resistance?
- The following resistors are in series: one  $100\ \Omega$ , two  $56\ \Omega$ , four  $12\ \Omega$ , and one  $330\ \Omega$ . What is the total resistance?
- Suppose that you have one resistor each of the following values:  $1.0\ k\Omega$ ,  $2.7\ k\Omega$ ,  $5.6\ k\Omega$ , and  $560\ \Omega$ . To get a total resistance of approximately  $13.8\ k\Omega$ , you need one more resistor. What should its value be?
- What is the  $R_T$  for twelve  $56\ \Omega$  resistors in series?
- What is the  $R_T$  for twenty  $5.6\ k\Omega$  resistors and thirty  $8.2\ k\Omega$  resistors in series?

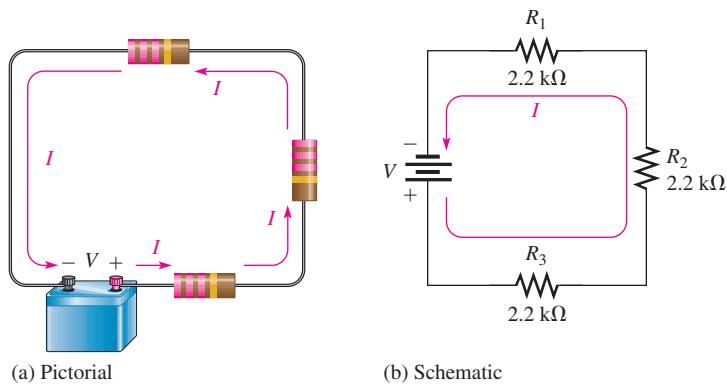
### 5-3 CURRENT IN A SERIES CIRCUIT

The current is the same through all points in a series circuit. The current through each resistor in a series circuit is the same as the current through all the other resistors that are in series with it.

After completing this section, you should be able to

- ◆ Determine the current throughout a series circuit
- ◆ Show that the current is the same at all points in a series circuit

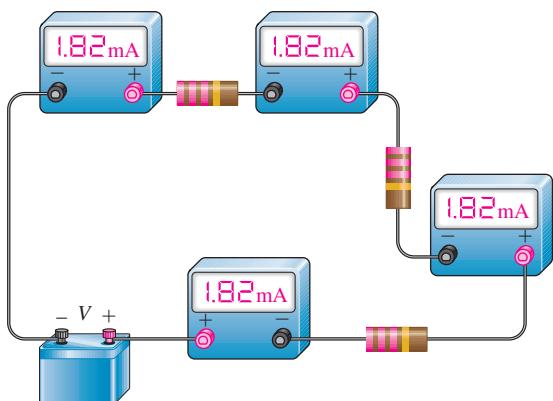
Figure 5–13 shows three resistors connected in series to a dc voltage source. *At any point in this circuit, the current into that point must equal the current out of that point*, as illustrated by the current directional arrows. Notice also that the current out of each resistor must equal the current into each resistor because there is no place where part of the current is diverted. Therefore, the current in each section of the circuit is the same as the current in all other sections. It has only one path going from the positive (+) side of the source to the negative (−) side.



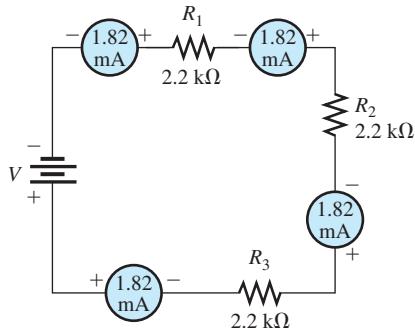
▲ FIGURE 5-13

Current into any point in a series circuit is the same as the current out of that point.

Let's assume that the battery in Figure 5–13 supplies  $1.82\text{ mA}$  of current to the series resistance. When ammeters are connected at several points in the circuit, as shown in Figure 5–14, each meter reads  $1.82\text{ mA}$ .



(a) Pictorial



(b) Schematic

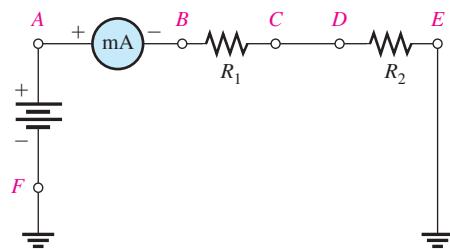
▲ FIGURE 5-14

Current is the same at all points in a series circuit.

### SECTION 5-3 CHECKUP

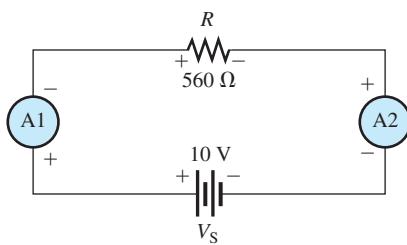
- In a circuit with a  $100\ \Omega$  resistor and a  $47\ \Omega$  resistor in series, there are  $20\text{ mA}$  of current through the  $100\ \Omega$  resistor. How much current is through the  $47\ \Omega$  resistor?
- A milliammeter is connected between points *A* and *B* in Figure 5-15. It measures  $50\text{ mA}$ . If you move the meter and connect it between points *C* and *D*, how much current will it indicate? Between *E* and *F*?

► FIGURE 5-15



- In Figure 5-16, how much current does ammeter 1 indicate? How much current does ammeter 2 indicate?
- Describe current in a series circuit.

► FIGURE 5-16



## 5-4 APPLICATION OF OHM'S LAW

The basic concepts of series circuits and Ohm's law can be applied to series circuit analysis.

After completing this section, you should be able to

- ◆ **Apply Ohm's law in series circuits**
  - ◆ Find the current in a series circuit
  - ◆ Find the voltage across each resistor in series

The following are key points to remember when you analyze series circuits:

1. Current through any of the series resistors is the same as the total current.
2. If you know the total applied voltage and the total resistance, you can determine the total current by Ohm's law.

$$I_T = \frac{V_T}{R_T}$$

3. If you know the voltage drop across one of the series resistors ( $R_x$ ), you can determine the total current by Ohm's law.

$$I_T = \frac{V_x}{R_x}$$

4. If you know the total current, you can find the voltage drop across any of the series resistors by Ohm's law.

$$V_x = I_T R_x$$

5. The polarity of a voltage drop across a resistor is positive at the end of the resistor that is closest to the positive terminal of the voltage source.

6. The current through a resistor is defined to be in a direction from the positive end of the resistor to the negative end.

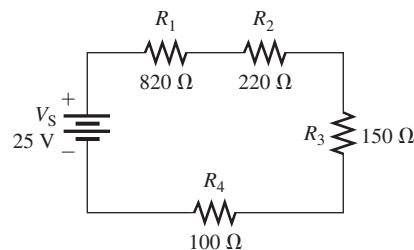
7. An open in a series circuit prevents current; therefore, there is zero voltage drop across each series resistor. The total voltage appears across the points between which there is an open.

Now let's look at several examples that use Ohm's law for series circuit analysis.

### EXAMPLE 5-7

Find the current in the circuit of Figure 5-17.

► FIGURE 5-17



**Solution** The current is determined by the source voltage  $V_S$  and the total resistance  $R_T$ . First, calculate the total resistance.

$$R_T = R_1 + R_2 + R_3 + R_4 = 820 \Omega + 220 \Omega + 150 \Omega + 100 \Omega = 1.29 \text{ k}\Omega$$

Next, use Ohm's law to calculate the current.

$$I = \frac{V_S}{R_T} = \frac{25 \text{ V}}{1.29 \text{ k}\Omega} = 0.0194 \text{ A} = 19.4 \text{ mA}$$

where  $V_S$  is the total voltage and  $I$  is the total current. Remember, the same current exists at all points in the circuit. Thus, each resistor has 19.4 mA through it.

*Related Problem*



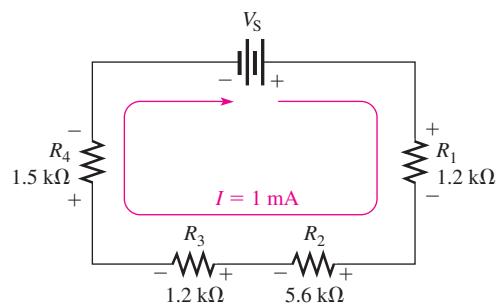
What is the current in the circuit of Figure 5–17 if  $R_4$  is changed to 200  $\Omega$ ?

Use Multisim file E05-07 to verify the calculated results in this example and to confirm your calculation for the related problem.

### EXAMPLE 5–8

The current in the circuit of Figure 5–18 is 1 mA. For this amount of current, what must the source voltage  $V_S$  be?

► FIGURE 5–18



*Solution* In order to calculate  $V_S$ , first determine  $R_T$ .

$$R_T = R_1 + R_2 + R_3 + R_4 = 1.2 \text{ k}\Omega + 5.6 \text{ k}\Omega + 1.2 \text{ k}\Omega + 1.5 \text{ k}\Omega = 9.5 \text{ k}\Omega$$

Next, use Ohm's law to determine  $V_S$ .

$$V_S = IR_T = (1 \text{ mA})(9.5 \text{ k}\Omega) = 9.5 \text{ V}$$

*Related Problem*



Calculate  $V_S$  if the 5.6 k $\Omega$  resistor is changed to 3.9 k $\Omega$  with the same current.

Use Multisim file E05-08 to verify the calculated results in this example and to confirm your calculation for the related problem.

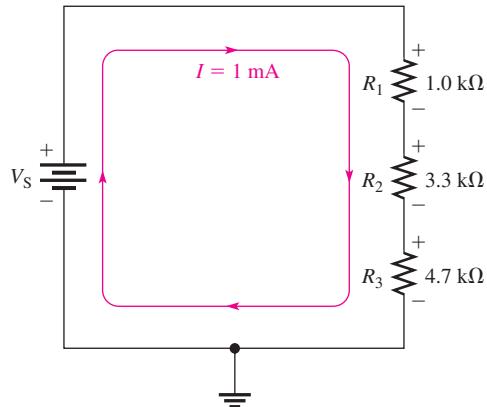
### EXAMPLE 5–9

Calculate the voltage across each resistor in Figure 5–19, and find the value of  $V_S$ . To what maximum value can  $V_S$  be raised if the current is to be limited to 5 mA?

*Solution*

By Ohm's law, the voltage across each resistor is equal to its resistance multiplied by the current through it. Use the Ohm's law formula  $V = IR$  to determine the

► FIGURE 5–19



voltage across each of the resistors. Keep in mind that there is the same current through each series resistor. The voltage across  $R_1$  (designated  $V_1$ ) is

$$V_1 = IR_1 = (1 \text{ mA})(1.0 \text{ k}\Omega) = 1 \text{ V}$$

The voltage across  $R_2$  is

$$V_2 = IR_2 = (1 \text{ mA})(3.3 \text{ k}\Omega) = 3.3 \text{ V}$$

The voltage across  $R_3$  is

$$V_3 = IR_3 = (1 \text{ mA})(4.7 \text{ k}\Omega) = 4.7 \text{ V}$$

To find the value of  $V_S$ , first determine  $R_T$ .

$$R_T = 1.0 \text{ k}\Omega + 3.3 \text{ k}\Omega + 4.7 \text{ k}\Omega = 9 \text{ k}\Omega$$

The source voltage  $V_S$  is equal to the current times the total resistance.

$$V_S = IR_T = (1 \text{ mA})(9 \text{ k}\Omega) = 9 \text{ V}$$

Notice that if you add the voltage drops of the resistors, they total 9 V, which is the same as the source voltage.

$V_S$  can be increased to a value where  $I = 5 \text{ mA}$ . Calculate the maximum value of  $V_S$  as follows:

$$V_{S(\max)} = IR_T = (5 \text{ mA})(9 \text{ k}\Omega) = 45 \text{ V}$$

#### Related Problem

Repeat the calculations for  $V_1$ ,  $V_2$ ,  $V_3$ ,  $V_S$ , and  $V_{S(\max)}$  if  $R_3 = 2.2 \text{ k}\Omega$  and  $I$  is maintained at 1 mA.

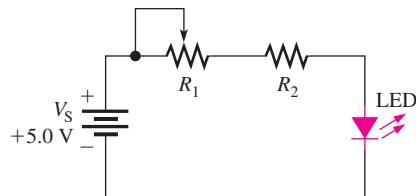


Use Multisim files E05-09A, E05-09B, and E05-09C to verify the calculated results in this example and to confirm your calculations for the related problem.

#### EXAMPLE 5–10

Series connections often involve using resistance to limit current to some level. For example, it is necessary to limit current to a light-emitting diode (LED) to prevent the LED from burning out. The circuit in Figure 5–20 shows a basic application, where a red LED is used as an indicator as part of a more complicated circuit. The rheostat is included to dim the LED depending on ambient conditions. We will focus on these two current-limiting resistors.

► FIGURE 5-20



A red LED will always have a voltage across it of about +1.7 V when it is on and working within its normal operating range. The remaining voltage from the power supply will be across the two series resistors. Together, the rheostat and the fixed resistor will have a total of 3.3 V across them.

Assume you want current in the LED to range from a minimum of 2.5 mA (dim) to a maximum of 10 mA (bright). What values of  $R_1$  and  $R_2$  would you choose to accomplish this?

**Solution** Start with the brightest condition when the resistance of the rheostat is adjusted for  $0\ \Omega$ . In this case, there will be no voltage across  $R_1$  and 3.3 V will be across  $R_2$ . Because it is a series circuit, the same current is in  $R_2$  as the LED. Therefore,

$$R_2 = \frac{V}{I} = \frac{3.3\text{ V}}{10\text{ mA}} = 330\ \Omega$$

Now determine the total resistance required to limit the current to 2.5 mA. The total resistance is  $R_T = R_1 + R_2$ , and the voltage drop across  $R_T$  is 3.3 V. From Ohm's law,

$$R_T = \frac{V}{I} = \frac{3.3\text{ V}}{2.5\text{ mA}} = 1.32\text{ k}\Omega$$

To find  $R_1$ , subtract the value of  $R_2$  from the total resistance.

$$R_1 = R_T - R_2 = 1.32\text{ k}\Omega - 330\ \Omega = 990\ \Omega$$

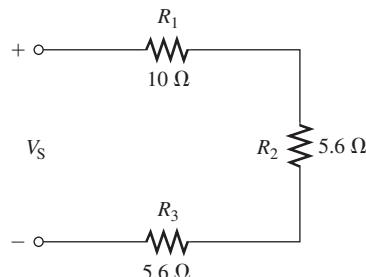
Choose a **1.0 kΩ** rheostat as the nearest standard value.

**Related Problem** What is the value of  $R_2$  if the highest current is 12 mA?

## SECTION 5-4 CHECKUP

1. A 6 V battery is connected across three  $100\ \Omega$  resistors in series. What is the current through each resistor?
2. How much voltage is required to produce 50 mA through the circuit of Figure 5-21?

► FIGURE 5-21



3. How much voltage is dropped across each resistor in Figure 5–21 when the current is 50 mA?
4. There are four equal-value resistors connected in series with a 5 V source. A current of 4.63 mA is measured. What is the value of each resistor?
5. What value should a series current-limiting resistor be to limit the current in a red LED to 10 mA if the source is 3 V and the LED drops 1.7 V?

## 5–5 VOLTAGE SOURCES IN SERIES

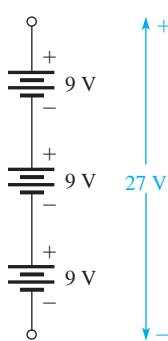
Recall that an ideal voltage source is an energy source that provides a constant voltage to a load. Electronic power supplies, batteries, and solar cells are practical examples of dc voltage sources.

After completing this section, you should be able to

- ◆ Determine the total effect of voltage sources connected in series
  - ◆ Determine the total voltage of series sources with the same polarities
  - ◆ Determine the total voltage of series sources with opposite polarities

### TECH NOTE

When replacing batteries in a portable electronic device, it is best to use all of the same type of battery and not mix old batteries with new batteries. In particular, do not mix alkaline with nonalkaline batteries. Incorrect use of batteries can cause hydrogen gas to build inside the battery and cause the casing to rupture. Worse, the mixing of hydrogen gas with oxygen can be an explosion hazard.



▲ FIGURE 5–23

Connection of three 9 V batteries to obtain 27 V.

When two or more voltage sources are in series, the total voltage is equal to the algebraic sum of the individual source voltages. The algebraic sum means that the polarities of the sources must be included when the sources are combined in series. Sources with opposite polarities have voltages with opposite signs.

$$V_{S(\text{tot})} = V_{S1} + V_{S2} + \dots + V_{Sn}$$

When the voltage sources are all in the same direction in terms of their polarities, as in Figure 5–22(a), all of the voltages have the same sign when added; there is a total of 4.5 V from terminal *A* to terminal *B* with *A* more positive than *B*.

$$V_{AB} = 1.5 \text{ V} + 1.5 \text{ V} + 1.5 \text{ V} = +4.5 \text{ V}$$

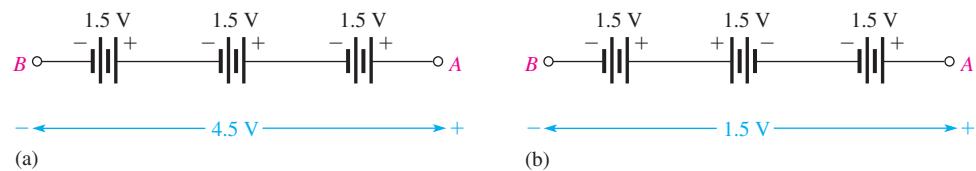
The voltage has a double subscript, *AB*, to indicate that it is the voltage at point *A* with respect to point *B*.

In Figure 5–22(b), the middle voltage source is opposite to the other two; so its voltage has an opposite sign when added to the others. For this case the total voltage from *A* to *B* is

$$V_{AB} = +1.5 \text{ V} - 1.5 \text{ V} + 1.5 \text{ V} = +1.5 \text{ V}$$

Terminal *A* is 1.5 V more positive than terminal *B*.

A familiar example of voltage sources in series is the flashlight. When you put two 1.5 V batteries in your flashlight, they are connected in series, giving a total of 3 V. When connecting batteries or other voltage sources in series to increase the total voltage, always connect from the positive (+) terminal of one to the negative (–) terminal of another. Such a connection is illustrated in Figure 5–23.



▲ FIGURE 5–22

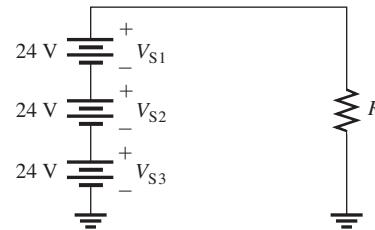
Voltage sources in series add algebraically. If a source is reversed, it subtracts from the total voltage as shown in part (b). This is not a normal configuration for batteries.

Another practical case is the wiring of solar panels to increase the voltage. Solar panels come in various voltages. Small panels are available that provide 12 Vdc under standard conditions. To increase the voltage, connect the panels in series. For example, to obtain 48 Vdc from series wired 12 V panels, you need to connect four panels in series.

### EXAMPLE 5–11

Assume three 24 V solar panels are connected together in series as shown in Figure 5–24. What is the total source voltage ( $V_{S(\text{tot})}$ ) in Figure 5–24?

► FIGURE 5–24

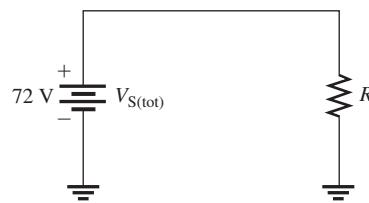


**Solution** The polarity of each source is the same (the sources are connected in the same direction in the circuit). Add the three voltages to get the total.

$$V_{S(\text{tot})} = V_{S1} + V_{S2} + V_{S3} = 24 \text{ V} + 24 \text{ V} + 24 \text{ V} = 72 \text{ V}$$

The three individual sources can be replaced by a single equivalent source of 72 V with its polarity as shown in Figure 5–25.

► FIGURE 5–25



#### Related Problem

If  $V_{S3}$  in Figure 5–24 is accidentally installed backwards, what is the total source voltage?

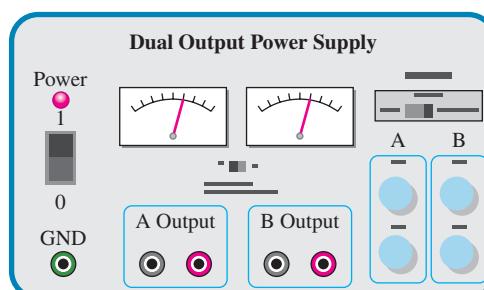
Use Multisim file E05-11 to verify the calculated results in this example and to confirm your calculation for the related problem.



### EXAMPLE 5–12

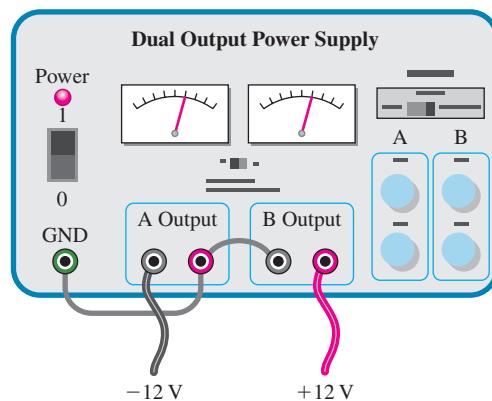
Many circuits use positive and negative supply voltages. A dual-power supply will normally have two independent outputs such as those shown in Figure 5–26. Show how to connect the two 12 V outputs from the power supply so that there is both a positive and a negative output. Assume the A and B outputs are “floating”—that is they are not referenced to ground.

► FIGURE 5–26



**Solution** See Figure 5–27. The positive output of one supply is connected to the negative output of the second supply. The ground terminal is connected to this same point, forcing the A output to be negative and the B output to be positive. (Note that this procedure only works for supplies that are not referenced internally to ground.)

► FIGURE 5–27

**Related Problem**

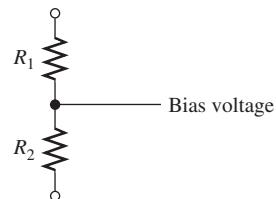
Draw the schematic of the setup in Figure 5–27.

Open Multisim file E05-12. Verify that the connection for the dual power supply will result in negative and positive voltages on the A and B outputs.

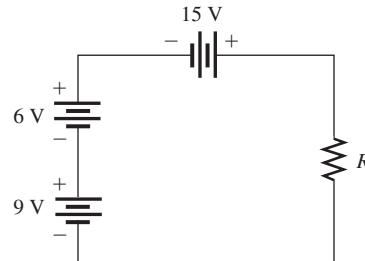
**SECTION 5–5  
CHECKUP**

- Four 1.5 V flashlight batteries are connected in series plus to minus. What is the total voltage of all four cells?
- How many 12 V batteries must be connected in series to produce 60 V? Draw a schematic that shows the battery connections.
- The resistive circuit in Figure 5–28 is used to bias a transistor amplifier. Show how to connect two 15 V power supplies in order to get 30 V across the two resistors.
- Determine the total source voltage for the circuit of Figure 5–29.
- One of four 1.5 V batteries was accidentally installed in the wrong direction in a flashlight. What is the voltage across the bulb?

► FIGURE 5–28



► FIGURE 5–29



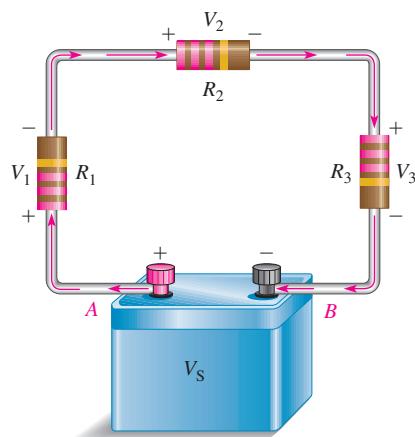
## 5–6 KIRCHHOFF'S VOLTAGE LAW

Kirchhoff's voltage law is a fundamental circuit law that states that the algebraic sum of all the voltages around a single closed path is zero or, in other words, the sum of the voltage drops equals the total source voltage.

After completing this section, you should be able to

- ◆ **Apply Kirchhoff's voltage law**
- ◆ State Kirchhoff's voltage law
- ◆ Determine the source voltage by adding the voltage drops
- ◆ Determine an unknown voltage drop

In an electric circuit, the voltages across the resistors (voltage drops) *always* have polarities opposite to the source voltage polarity. For example, in Figure 5–30, follow a clockwise loop around the circuit. Note that the source polarity is minus-to-plus and each voltage drop is plus-to-minus. The voltage drops across resistors are designated as  $V_1$ ,  $V_2$ , and so on.



◀ FIGURE 5–30  
Illustration of voltage polarities in a closed-loop circuit.

In Figure 5–30, by definition, the current is out of the positive side of the source and through the resistors as the arrows indicate. The current is into the positive side of each resistor and out the negative side. The drop in energy across a resistor creates a potential difference, or voltage drop, with a plus-to-minus polarity in the direction of the current.

The voltage from point *A* to point *B* in the circuit of Figure 5–30 is the source voltage,  $V_s$ . Also, the voltage from *A* to *B* is the sum of the series resistor voltage drops. Therefore, the source voltage is equal to the sum of the three voltage drops, as stated by **Kirchhoff's voltage law**.

**The sum of all the voltage drops around a single closed path in a circuit is equal to the total source voltage in that loop.**

Kirchhoff's voltage law applied to a series circuit is illustrated in Figure 5–31. For this case, Kirchhoff's voltage law can be expressed by Equation 5–3.

$$V_s = V_1 + V_2 + V_3 + \dots + V_n$$

Equation 5–3

where the subscript *n* represents the number of voltage drops.

If all the voltage drops around a closed path are added and then this total is subtracted from the source voltage, the result is zero. This result occurs because the sum of the voltage drops always equals the source voltage.

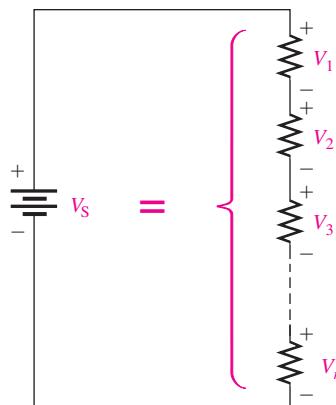
**HISTORY NOTE**

Gustav  
Robert  
Kirchhoff  
(1824–1887)

Kirchhoff was a German physicist who contributed to the fundamental understanding of electrical circuits, spectroscopy, and the emission of black-body radiation by heated objects. Concepts in both circuit theory and thermal emission are named Kirchhoff's laws in his honor. Kirchhoff formulated his circuit laws, which are now commonly used in electrical engineering and technology, in 1845 while still a student. He completed this study as a seminar exercise; it later became his doctoral dissertation. (Photo credit: Photographic Gesellschaft, Berlin, courtesy AIP Emilio Segre Visual Archives, W. F. Meggers Collection, Brittle Books Collection, Harvard University Collection.)

**► FIGURE 5-31**

Sum of  $n$  voltage drops equals the source voltage.



The algebraic sum of all the voltages (both source and drops) around a single closed path is zero.

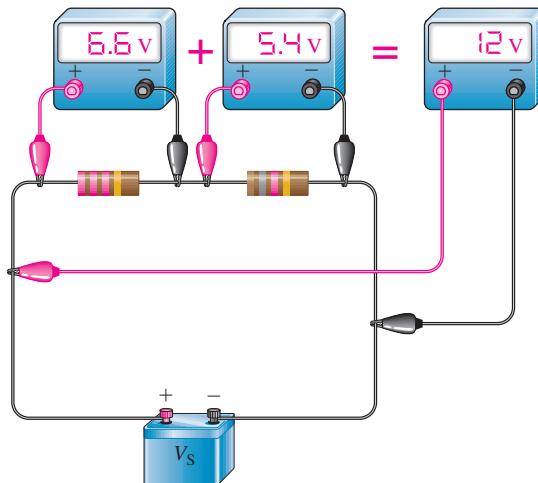
Therefore, another way of expressing Kirchhoff's voltage law in equation form is

$$V_s - V_1 - V_2 - V_3 - \cdots - V_n = 0$$

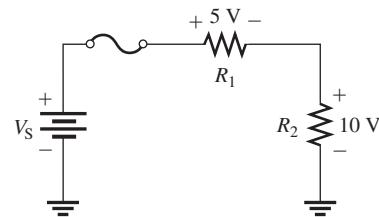
You can verify Kirchhoff's voltage law by connecting a circuit and measuring each resistor voltage and the source voltage as illustrated in Figure 5-32. When the resistor voltages are added together, their sum will equal the source voltage. Any number of resistors can be added.

**► FIGURE 5-32**

Illustration of an experimental verification of Kirchhoff's voltage law.

**EXAMPLE 5-13**

Determine the source voltage  $V_s$  in Figure 5-33 where the two voltage drops are given. There is no voltage drop across the fuse.

**► FIGURE 5-33**

**Solution** By Kirchhoff's voltage law (Eq. 5–3), the source voltage (applied voltage) must equal the sum of the voltage drops. Adding the voltage drops gives the value of the source voltage.

$$V_S = 5 \text{ V} + 10 \text{ V} = 15 \text{ V}$$

**Related Problem**

If  $V_S$  is increased to 30 V, determine the two voltage drops. What is the voltage across each component (including the fuse) if the fuse is blown?

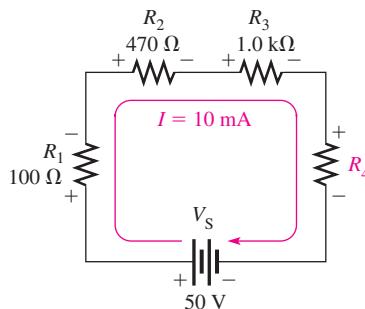


Open Multisim files E05-13A and E05-13B to verify the calculated results in the example and to confirm your calculations for the related problem.

### EXAMPLE 5–14

Find the value of  $R_4$  in Figure 5–34.

► FIGURE 5–34



**Solution** In this problem you will use both Ohm's law and Kirchhoff's voltage law. First, use Ohm's law to find the voltage drop across each of the known resistors.

$$V_1 = IR_1 = (10 \text{ mA})(100 \Omega) = 1.0 \text{ V}$$

$$V_2 = IR_2 = (10 \text{ mA})(470 \Omega) = 4.7 \text{ V}$$

$$V_3 = IR_3 = (10 \text{ mA})(1.0 \text{ k}\Omega) = 10 \text{ V}$$

Next, use Kirchhoff's voltage law to find  $V_4$ , the voltage drop across the unknown resistor.

$$\begin{aligned} V_S - V_1 - V_2 - V_3 - V_4 &= 0 \text{ V} \\ 50 \text{ V} - 1.0 \text{ V} - 4.7 \text{ V} - 10 \text{ V} - V_4 &= 0 \text{ V} \\ 34.3 \text{ V} - V_4 &= 0 \text{ V} \\ V_4 &= 34.3 \text{ V} \end{aligned}$$

Now that you know  $V_4$ , use Ohm's law to calculate  $R_4$ .

$$R_4 = \frac{V_4}{I} = \frac{34.3 \text{ V}}{10 \text{ mA}} = 3.43 \text{ k}\Omega$$

$R_4$  is most likely color-coded as a 3.3 kΩ resistor because 3.43 kΩ is within a standard tolerance range ( $\pm 5\%$ ) of 3.3 kΩ.

**Related Problem**

Determine  $R_4$  in Figure 5–34 for  $V_S = 25 \text{ V}$  and  $I = 10 \text{ mA}$ .



Use Multisim file E05-14 to verify the calculated results in the example and to confirm your calculation for the related problem.

So far, you have seen how Kirchhoff's voltage law can be applied to a series circuit with a voltage source, but it can also be applied to other types of circuits. For example, there are cases where there is no source voltage in a given closed loop. Even so, Kirchhoff's voltage law still applies. This leads to a more-general form of Equation 5–3.

#### Equation 5–4

$$V_1 + V_2 + V_3 + \cdots + V_n = 0$$

If a voltage source is present, it is simply treated as one of the terms in Equation 5–4.

In applying Equation 5–4, an algebraic sign is given to each voltage in the path depending on whether it is voltage rise (+) or a voltage drop (−). A voltage across a resistor can appear as either a rise or a drop depending on the path direction chosen, so you will need to assign algebraic signs to voltage rises and voltage drops in a consistent manner. A practical example of writing Kirchhoff's voltage law around a loop with no source is given in the Application Activity in Chapter 6.

Sometimes you will see an equation such as Equation 5–4 expressed in shorthand notation using the Greek letter sigma ( $\Sigma$ ) to denote summation, as follows:

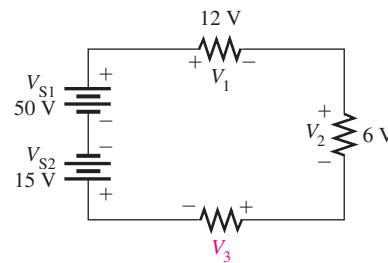
$$\sum_{i=1}^n V_i = 0$$

This mathematical expression is equivalent to Equation 5–4 and means that you add the voltages from the first ( $i = 1$ ) to the last ( $i = n$ ).

#### EXAMPLE 5–15

Determine the unknown voltage drop,  $V_3$ , in Figure 5–35.

► FIGURE 5–35



#### Solution

By Kirchhoff's voltage law (Eq. 5–4), the algebraic sum of all the voltages around the circuit is zero. The value of each voltage drop except  $V_3$  is known. Substitute these values into the equation.

$$\begin{aligned} V_{S1} + V_{S2} + V_3 + V_2 + V_1 &= 0 \\ 50 \text{ V} - 15 \text{ V} - V_3 - 6 \text{ V} - 12 \text{ V} &= 0 \end{aligned}$$

Next, combine the known values, transpose 17 V to the right side of the equation, and cancel the minus signs.

$$\begin{aligned} 17 \text{ V} - V_3 &= 0 \text{ V} \\ -V_3 &= -17 \text{ V} \\ V_3 &= 17 \text{ V} \end{aligned}$$

The voltage drop across  $R_3$  is 17 V, and its polarity is as shown in Figure 5–35.

#### Related Problem

Determine  $V_3$  if the polarity of  $V_{S2}$  is reversed in Figure 5–35.

#### SECTION 5–6 CHECKUP

- State Kirchhoff's voltage law in two ways.
- A 50 V source is connected to a series resistive circuit. What is the sum of the voltage drops in this circuit?
- A series light string has an open bulb and is plugged into a 120 V source. What is the voltage across the open bulb?
- In a series circuit with a 25 V source, there are three resistors. One voltage drop is 5 V, and the other is 10 V. What is the value of the third voltage drop?
- The individual voltage drops in a series string are as follows: 1 V, 3 V, 5 V, 8 V, and 7 V. What is the total voltage applied across the series string?

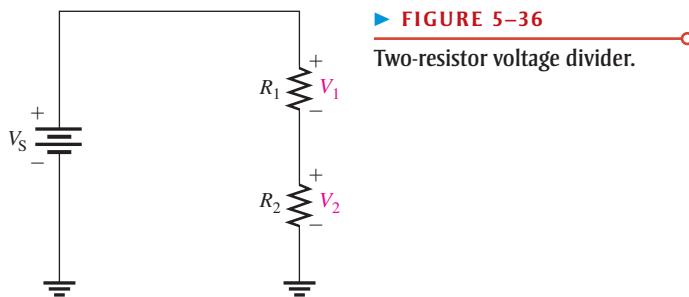
## 5–7 VOLTAGE DIVIDERS

A series circuit acts as a voltage divider. The voltage divider is an important application of series circuits. With the voltage divider formula, you can find voltage drops across resistors without calculating the current.

After completing this section, you should be able to

- ◆ Use a series circuit as a voltage divider
  - ◆ Apply the voltage-divider formula
  - ◆ Use a potentiometer as an adjustable voltage divider
  - ◆ Describe some voltage-divider applications

A circuit consisting of a series string of resistors connected to a voltage source acts as a **voltage divider**. Figure 5–36 shows a circuit with two resistors in series, although there can be any number. There are two voltage drops across the resistors: one across  $R_1$  and one across  $R_2$ . These voltage drops are  $V_1$  and  $V_2$ , respectively, as indicated in the schematic. Since each resistor has the same current, the voltage drops are proportional to the resistance values. For example, if the value of  $R_2$  is twice that of  $R_1$ , then the value of  $V_2$  is twice that of  $V_1$ .



The total voltage drop around a single closed path divides among the series resistors in amounts directly proportional to the resistance values. For example, in Figure 5–36, if  $V_s$  is 10 V,  $R_1$  is 50 Ω, and  $R_2$  is 100 Ω, then  $V_1$  is one-third the total voltage, or 3.33 V, because  $R_1$  is one-third the total resistance of 150 Ω. Likewise,  $V_2$  is two-thirds  $V_s$ , or 6.67 V.

### Voltage-Divider Formula

With a few calculations, you can develop a formula for determining how the voltages divide among series resistors. Assume a circuit with  $n$  resistors in series as shown in Figure 5–37, where  $n$  can be any number.

Let  $V_x$  represent the voltage drop across any one of the resistors and  $R_x$  represent the number of a particular resistor or combination of resistors. By Ohm's law, you can express the voltage drop across  $R_x$  as follows:

$$V_x = IR_x$$

The current through the circuit is equal to the source voltage divided by the total resistance ( $I = V_s/R_T$ ). In the circuit of Figure 5–37, the total resistance is  $R_1 + R_2 + R_3 + \dots + R_n$ . By substitution of  $V_s/R_T$  for  $I$  in the expression for  $V_x$ ,

$$V_x = \left( \frac{V_s}{R_T} \right) R_x$$

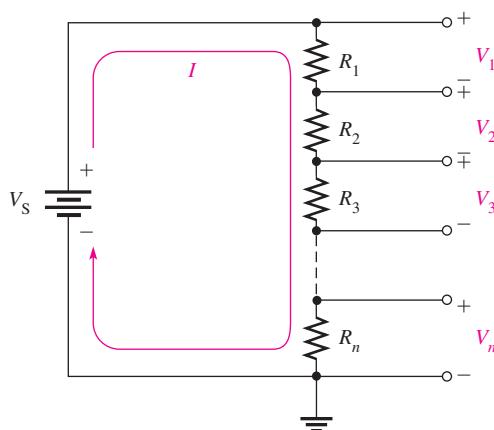
Rearranging the terms you get

$$V_x = \left( \frac{R_x}{R_T} \right) V_s$$

**Equation 5–5**

► FIGURE 5-37

Generalized voltage divider with  $n$  resistors.



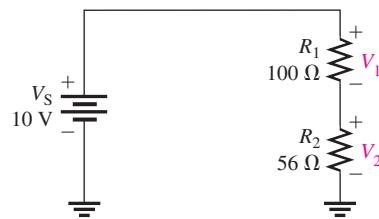
Equation 5–5 is the general voltage-divider formula, which can be stated as follows:

**The voltage drop across any resistor or combination of resistors in a series circuit is equal to the ratio of that resistance value to the total resistance, multiplied by the source voltage.**

### EXAMPLE 5-16

Determine  $V_1$  (the voltage across  $R_1$ ) and  $V_2$  (the voltage across  $R_2$ ) in the voltage divider in Figure 5–38.

► FIGURE 5-38



#### Solution

To determine  $V_1$ , use the voltage-divider formula,  $V_x = (R_x/R_T)V_S$ , where  $x = 1$ . The total resistance is

$$R_T = R_1 + R_2 = 100 \Omega + 56 \Omega = 156 \Omega$$

$R_1$  is 100  $\Omega$  and  $V_S$  is 10 V. Substitute these values into the voltage-divider formula.

$$V_1 = \left( \frac{R_1}{R_T} \right) V_S = \left( \frac{100 \Omega}{156 \Omega} \right) 10 V = 6.41 V$$

There are two ways to find the value of  $V_2$ : Kirchhoff's voltage law or the voltage-divider formula. If you use Kirchhoff's voltage law ( $V_S = V_1 + V_2$ ), substitute the values for  $V_S$  and  $V_1$  as follows:

$$V_2 = V_S - V_1 = 10 V - 6.41 V = 3.59 V$$

To determine  $V_2$ , use the voltage-divider formula where  $x = 2$ .

$$V_2 = \left( \frac{R_2}{R_T} \right) V_S = \left( \frac{56 \Omega}{156 \Omega} \right) 10 V = 3.59 V$$

#### Related Problem

Find the voltages across  $R_1$  and  $R_2$  in Figure 5–38 if  $R_2$  is changed to 180  $\Omega$ .

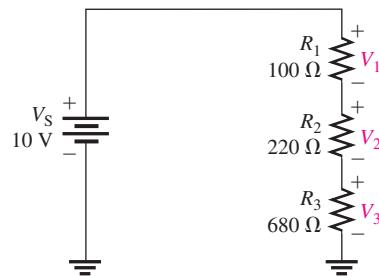
Use Multisim file E05-16 to verify the calculated results in this example and to confirm your calculations for the related problem.



**EXAMPLE 5-17**

Calculate the voltage drop across each resistor in the voltage divider of Figure 5-39.

► FIGURE 5-39

*Solution*

Look at the circuit for a moment and consider the following: The total resistance is  $1000\ \Omega$ . Ten percent of the total voltage is across  $R_1$  because it is 10% of the total resistance ( $100\ \Omega$  is 10% of  $1,000\ \Omega$ ). Likewise, 22% of the total voltage is dropped across  $R_2$  because it is 22% of the total resistance ( $220\ \Omega$  is 22% of  $1,000\ \Omega$ ). Finally,  $R_3$  drops 68% of the total voltage because  $680\ \Omega$  is 68% of  $1,000\ \Omega$ .

Because of the convenient values in this problem, it is easy to figure the voltages mentally. ( $V_1 = 0.10 \times 10\text{ V} = 1\text{ V}$ ,  $V_2 = 0.22 \times 10\text{ V} = 2.2\text{ V}$ , and  $V_3 = 0.68 \times 10\text{ V} = 6.8\text{ V}$ .) Such is usually not the case, but sometimes a little thinking will produce a result more efficiently and eliminate some calculating. This is also a good way to estimate what your results should be so that you will recognize an unreasonable answer as a result of a calculation error.

Although you have already reasoned through this problem, the calculations will verify your results.

$$V_1 = \left( \frac{R_1}{R_T} \right) V_S = \left( \frac{100\ \Omega}{1000\ \Omega} \right) 10\text{ V} = 1.0\text{ V}$$

$$V_2 = \left( \frac{R_2}{R_T} \right) V_S = \left( \frac{220\ \Omega}{1000\ \Omega} \right) 10\text{ V} = 2.2\text{ V}$$

$$V_3 = \left( \frac{R_3}{R_T} \right) V_S = \left( \frac{680\ \Omega}{1000\ \Omega} \right) 10\text{ V} = 6.8\text{ V}$$

Notice that the sum of the voltage drops is equal to the source voltage, in accordance with Kirchhoff's voltage law. This check is a good way to verify your results.

*Related Problem*

If  $R_1$  and  $R_2$  in Figure 5-39 are changed to  $680\ \Omega$ , what are the voltage drops?

Use Multisim file E05-17 to verify the calculated results in this example and to confirm your calculations for the related problem.

**EXAMPLE 5-18**

Determine the voltages between the following points in the voltage divider of Figure 5-40:

- (a)  $A$  to  $B$       (b)  $A$  to  $C$       (c)  $B$  to  $C$       (d)  $B$  to  $D$       (e)  $C$  to  $D$

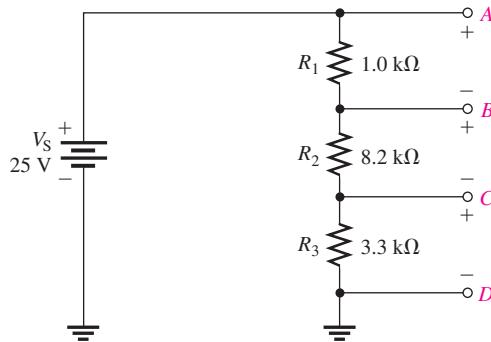
*Solution*

First, determine  $R_T$ .

$$R_T = R_1 + R_2 + R_3 = 1.0\text{ k}\Omega + 8.2\text{ k}\Omega + 3.3\text{ k}\Omega = 12.5\text{ k}\Omega$$

Next, apply the voltage-divider formula to obtain each required voltage.

► FIGURE 5–40



(a) The voltage *A* to *B* is the voltage drop across  $R_1$ .

$$V_{AB} = \left( \frac{R_1}{R_T} \right) V_S = \left( \frac{1.0 \text{ k}\Omega}{12.5 \text{ k}\Omega} \right) 25 \text{ V} = 2.0 \text{ V}$$

(b) The voltage from *A* to *C* is the combined voltage drop across both  $R_1$  and  $R_2$ .

In this case,  $R_x$  in the general formula given in Equation 5–5 is  $R_1 + R_2$ .

$$V_{AC} = \left( \frac{R_1 + R_2}{R_T} \right) V_S = \left( \frac{9.2 \text{ k}\Omega}{12.5 \text{ k}\Omega} \right) 25 \text{ V} = 18.4 \text{ V}$$

(c) The voltage from *B* to *C* is the voltage drop across  $R_2$ .

$$V_{BC} = \left( \frac{R_2}{R_T} \right) V_S = \left( \frac{8.2 \text{ k}\Omega}{12.5 \text{ k}\Omega} \right) 25 \text{ V} = 16.4 \text{ V}$$

(d) The voltage from *B* to *D* is the combined voltage drop across both  $R_2$  and  $R_3$ .

In this case,  $R_x$  in the general formula is  $R_2 + R_3$ .

$$V_{BD} = \left( \frac{R_2 + R_3}{R_T} \right) V_S = \left( \frac{11.5 \text{ k}\Omega}{12.5 \text{ k}\Omega} \right) 25 \text{ V} = 23 \text{ V}$$

(e) Finally, the voltage from *C* to *D* is the voltage drop across  $R_3$ .

$$V_{CD} = \left( \frac{R_3}{R_T} \right) V_S = \left( \frac{3.3 \text{ k}\Omega}{12.5 \text{ k}\Omega} \right) 25 \text{ V} = 6.6 \text{ V}$$

If you connect this voltage divider, you can verify each of the calculated voltages by connecting a voltmeter between the appropriate points in each case.

#### Related Problem

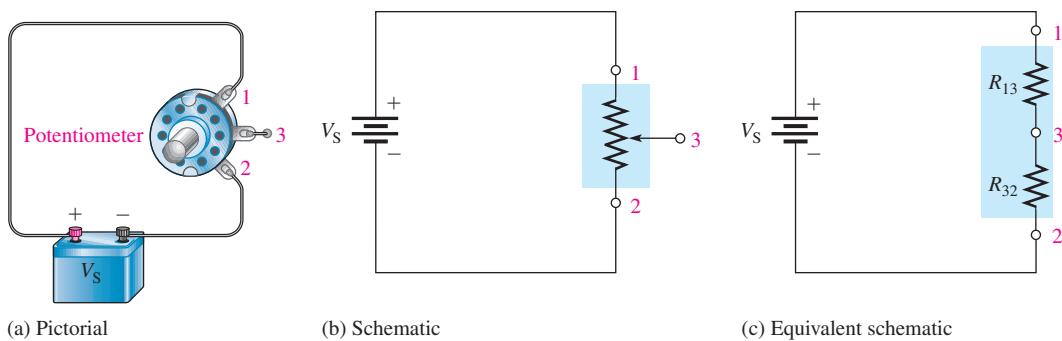


Determine each of the previously calculated voltages if  $V_S$  is doubled.

Use Multisim file E05-18 to verify the calculated results in this example and to confirm your calculations for the related problem.

## A Potentiometer as an Adjustable Voltage Divider

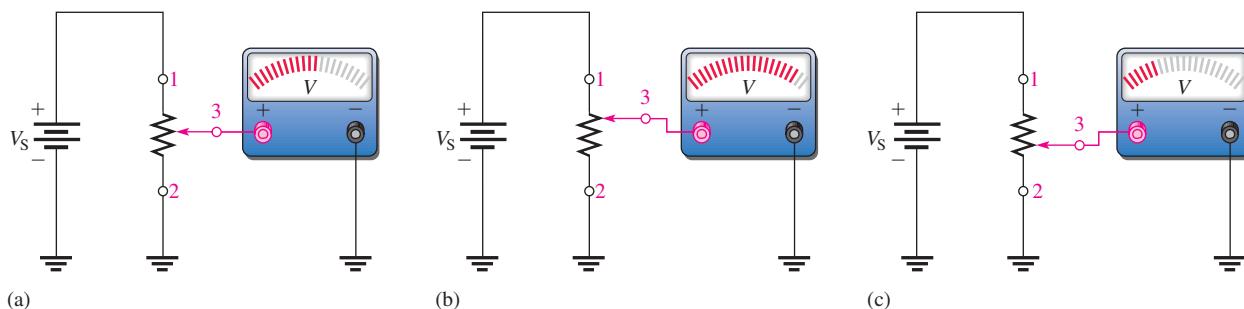
Recall from Chapter 2 that a potentiometer is a variable resistor with three terminals. A linear potentiometer connected to a voltage source is shown in Figure 5–41(a) with the schematic shown in part (b). Notice that the two end terminals are labeled 1 and 2. The adjustable terminal or wiper is labeled 3. The potentiometer functions as a voltage divider, which can be illustrated by separating the total resistance into two parts, as shown in Figure 5–41(c). The resistance between terminal 1 and terminal 3 ( $R_{13}$ ) is

**▲ FIGURE 5-41**

The potentiometer used as a voltage divider.

one part, and the resistance between terminal 3 and terminal 2 ( $R_{32}$ ) is the other part. So this potentiometer is equivalent to a two-resistor voltage divider that can be manually adjusted for any output voltage from 0 V to  $V_S$ .

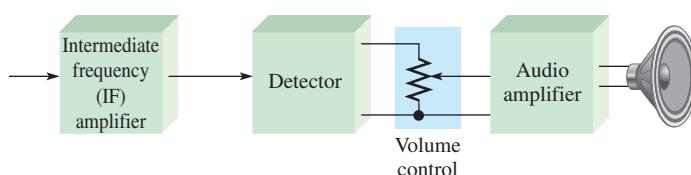
Figure 5-42 shows what happens when the wiper contact (3) is moved. In part (a), the wiper is exactly centered, making the two resistances equal. If you measure the voltage across terminals 3 to 2 as indicated by the voltmeter symbol, you have one-half of the total source voltage. When the wiper is moved up, as in part (b), the resistance between terminals 3 and 2 increases, and the voltage across it increases proportionally. When the wiper is moved down, as in part (c), the resistance between terminals 3 and 2 decreases, and the voltage decreases proportionally.

**▲ FIGURE 5-42**

Adjusting the voltage divider.

## Applications

The volume control of some radio receivers is a common application of a potentiometer used as a voltage divider. Since the loudness of the sound is dependent on the amount of voltage associated with the audio signal, you can increase or decrease the volume by adjusting the potentiometer, that is, by turning the knob of the volume control on the set. The block diagram in Figure 5-43 shows how a potentiometer can be used for volume control in a typical receiver.

**▲ FIGURE 5-43**

A variable voltage divider used for volume control in a radio receiver.

Voltage dividers are commonly used in operational amplifier circuits to control gain among other things. An **operational amplifier** is a widely used high-gain amplifier that is a basic building block for many analog circuits. It has two inputs that are non-inverting (+) and inverting (-) and a single output as shown in Figure 5–44(a). In a basic non-inverting amplifier shown in (b), a voltage divider returns a fraction of the output voltage ( $V_{out}$ ) to the inverting input. This is called negative feedback and the feedback voltage,  $V_f$ , is the voltage developed across  $R_2$ . As you will learn in a study of devices, the amount of feedback determines the gain. In the case of the amplifier in Figure 5–44(b), you can apply the voltage divider rule to obtain  $V_f$ :

$$V_x = \left( \frac{R_x}{R_T} \right) V_s$$

$$V_f = \left( \frac{R_2}{R_1 + R_2} \right) V_{out}$$

**► FIGURE 5–44**

A voltage divider used in an operational amplifier circuit.

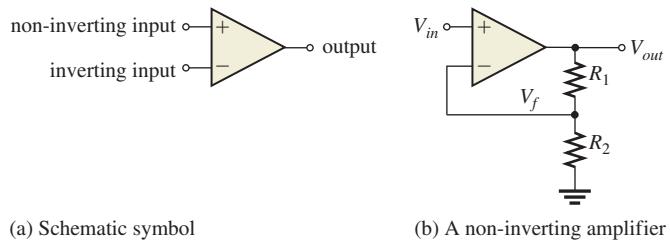
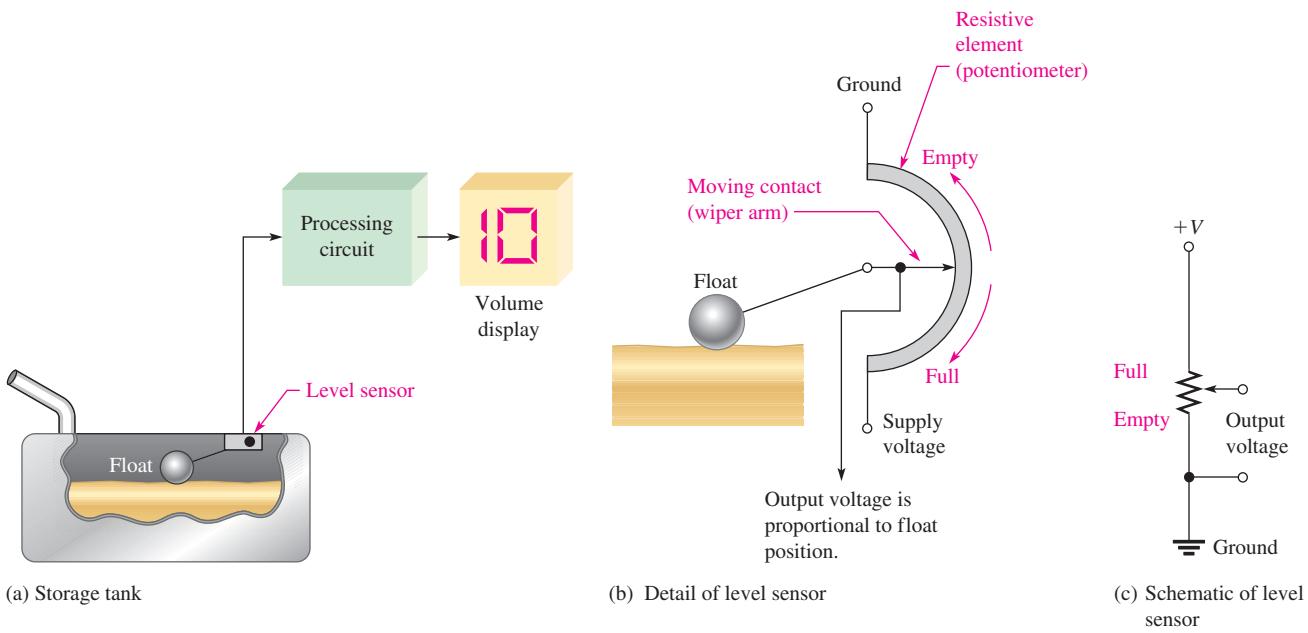


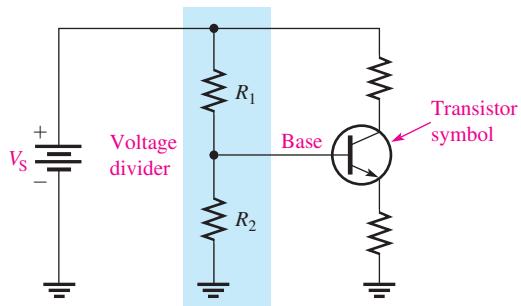
Figure 5–45 illustrates another application in which a potentiometer voltage divider can be used as a level sensor in a liquid storage tank. As shown in part (a), the float moves up as the tank is filled and moves down as the tank empties. The float is mechanically linked to the wiper arm of a potentiometer, as shown in part (b). The output voltage varies proportionally with the position of the wiper arm. As the liquid

**▲ FIGURE 5–45**

A potentiometer voltage divider used in a level sensor.

in the tank decreases, the sensor output voltage also decreases. The output voltage goes to the indicator circuitry, which controls a digital readout to show the amount of liquid in the tank. The schematic of this system is shown in part (c).

Voltage dividers are also commonly used in setting the dc operating voltage (bias) in transistor amplifiers. Figure 5–46 shows a voltage divider used for this purpose. You will study transistor amplifiers and biasing in a later course, so it is important that you understand the basics of voltage dividers at this point.



◀ FIGURE 5–46

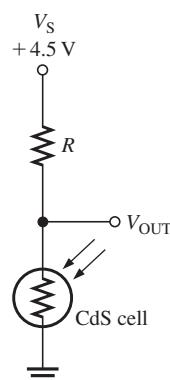
The voltage divider used as a bias circuit for a transistor amplifier, where the voltage at the base terminal of the transistor is determined by the voltage divider as  $V_{\text{base}} = (R_2/(R_1 + R_2))V_s$ .

A voltage divider is useful for converting a resistance sensor output to a voltage. Resistance sensors were described in Chapter 2 and include thermistors, CdS cells, and strain gauges. To convert a change in resistance to an output voltage, the resistance sensor can replace one of the resistors in a voltage divider.

### EXAMPLE 5–19

Assume you have a CdS cell configured as shown in Figure 5–47 that uses three AA batteries for a voltage source (4.5 V). At dusk, the resistance of the cell rises from a low resistance to above  $90 \text{ k}\Omega$ . The cell is used to trigger a logic circuit that will turn on lights if  $V_{\text{OUT}}$  is greater than approximately 1.5 V. What value of  $R$  will produce an output voltage of 1.5 V when the cell resistance is  $90 \text{ k}\Omega$ ?

► FIGURE 5–47



**Solution** Notice that the threshold voltage (1.5 V) is one-third of the supply voltage. You know that  $90 \text{ k}\Omega$  represents one-third of the total resistance at this point. Therefore, the total resistance is

$$R_T = 3(90 \text{ k}\Omega) = 270 \text{ k}\Omega$$

The resistance value needed to produce  $V_{\text{OUT}} = 1.5 \text{ V}$  is

$$R = R_T - 90 \text{ k}\Omega = 270 \text{ k}\Omega - 90 \text{ k}\Omega = 180 \text{ k}\Omega$$

**Related Problem** Starting with Equation 5–5, prove that the required resistance needed to produce an output voltage of 1.5 V is  $180 \text{ k}\Omega$  when the cell resistance is  $90 \text{ k}\Omega$ .

Another application for series circuits is to share power dissipation. When testing high power transmitters it is sometimes necessary to dissipate the power in a resistive load (called a *dummy load*) rather than allow the power to radiate from the antenna. A dummy load can consist of multiple series resistors, to enable its construction with lower power rated resistors.

### SECTION 5-7 CHECKUP

1. What is a voltage divider?
2. Write the general formula for voltage dividers.
3. If two series resistors of equal value are connected across a 10 V source, how much voltage is there across each resistor?
4. A 47 kΩ resistor and an 82 kΩ resistor are connected as a voltage divider. The source voltage is 10 V. Draw the circuit, and determine the voltage across each of the resistors.
5. Refer to Figure 5-44(b). Assume  $R_1 = 10 \text{ k}\Omega$  and  $R_2 = 680 \Omega$ . What fraction of  $V_{out}$  is  $V_f$ ?
6. You have a 10 V source, and need to design a voltage divider to obtain 0 to 5 V out. Show how you can connect a 10 kΩ resistor and a 10 kΩ potentiometer to achieve this.

## 5-8 POWER IN SERIES CIRCUITS

The power dissipated by each individual resistor in a series circuit contributes to the total power in the circuit. The individual powers are additive.

After completing this section, you should be able to

- ◆ Determine power in a series circuit
- ◆ Apply one of the power formulas

The total amount of power in a series resistive circuit is equal to the sum of the powers in each resistor in series.

### Equation 5-6

$$P_T = P_1 + P_2 + P_3 + \dots + P_n$$

where  $P_T$  is the total power and  $P_n$  is the power in the last resistor in series.

The power formulas that you learned in Chapter 4 are applicable to series circuits. Since there is the same current through each resistor in series, the following formulas are used to calculate the total power:

$$P_T = V_S I$$

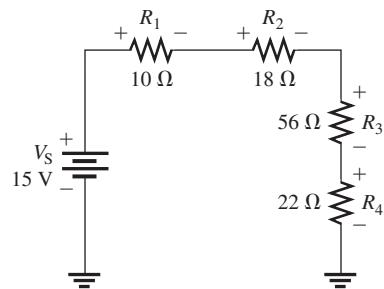
$$P_T = I^2 R_T$$

$$P_T = \frac{V_S^2}{R_T}$$

where  $I$  is the current through the circuit,  $V_S$  is the total source voltage across the series connection, and  $R_T$  is the total resistance.

**EXAMPLE 5-20**

Determine the total amount of power in the series circuit in Figure 5-48.

**► FIGURE 5-48**

**Solution** The source voltage is 15 V. The total resistance is

$$R_T = R_1 + R_2 + R_3 + R_4 = 10 \Omega + 18 \Omega + 56 \Omega + 22 \Omega = 106 \Omega$$

The easiest formula to use is  $P_T = V_S^2/R_T$  since you know both  $V_S$  and  $R_T$ .

$$P_T = \frac{V_S^2}{R_T} = \frac{(15 \text{ V})^2}{106 \Omega} = \frac{225 \text{ V}^2}{106 \Omega} = 2.12 \text{ W}$$

If you determine the power in each resistor separately and all of these powers are added, you obtain the same result. First, find the current.

$$I = \frac{V_S}{R_T} = \frac{15 \text{ V}}{106 \Omega} = 142 \text{ mA}$$

Next, calculate the power for each resistor using  $P = I^2R$ .

$$P_1 = I^2R_1 = (142 \text{ mA})^2(10 \Omega) = 200 \text{ mW}$$

$$P_2 = I^2R_2 = (142 \text{ mA})^2(18 \Omega) = 360 \text{ mW}$$

$$P_3 = I^2R_3 = (142 \text{ mA})^2(56 \Omega) = 1.12 \text{ W}$$

$$P_4 = I^2R_4 = (142 \text{ mA})^2(22 \Omega) = 441 \text{ mW}$$

Then, add these powers to get the total power.

$$P_T = P_1 + P_2 + P_3 + P_4 = 200 \text{ mW} + 360 \text{ mW} + 1.12 \text{ W} + 441 \text{ mW} = 2.12 \text{ W}$$

This result is the same as the total power as determined previously by the formula  $P_T = V_S^2/R_T$ .

**Related Problem** What is the power in the circuit of Figure 5-48 if  $V_S$  is increased to 30 V?

The amount of power in a resistor is important because the power rating of the resistors must be high enough to handle the expected power in the circuit. The following example illustrates practical considerations relating to power in a series circuit.

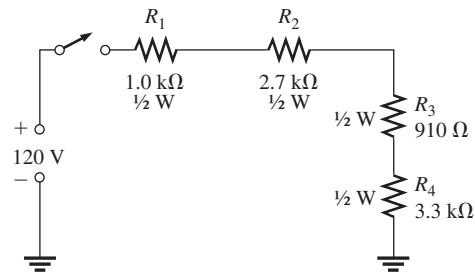
**EXAMPLE 5-21**

Determine if the indicated power rating ( $\frac{1}{2} \text{ W}$ ) of each resistor in Figure 5-49 is sufficient to handle the actual power when the switch is closed. If a rating is not adequate, specify the required minimum rating.

**Solution** First, determine the total resistance.

$$R_T = R_1 + R_2 + R_3 + R_4 = 1.0 \text{ k}\Omega + 2.7 \text{ k}\Omega + 910 \Omega + 3.3 \text{ k}\Omega = 7.91 \text{ k}\Omega$$

► FIGURE 5–49



Next, calculate the current.

$$I = \frac{V_S}{R_T} = \frac{120 \text{ V}}{7.91 \text{ k}\Omega} = 15 \text{ mA}$$

Then calculate the power in each resistor.

$$P_1 = I^2 R_1 = (15 \text{ mA})^2 (1.0 \text{ k}\Omega) = 225 \text{ mW}$$

$$P_2 = I^2 R_2 = (15 \text{ mA})^2 (2.7 \text{ k}\Omega) = 608 \text{ mW}$$

$$P_3 = I^2 R_3 = (15 \text{ mA})^2 (910 \Omega) = 205 \text{ mW}$$

$$P_4 = I^2 R_4 = (15 \text{ mA})^2 (3.3 \text{ k}\Omega) = 743 \text{ mW}$$

$R_2$  and  $R_4$  do not have a rating sufficient to handle the actual power, which exceeds  $\frac{1}{2} \text{ W}$  in each of these two resistors, and they may burn out if the switch is closed. These resistors should be replaced by 1 W resistors.

**Related Problem** Determine the minimum power rating required for each resistor in Figure 5–49 if the source voltage is increased to 240 V.

### SECTION 5–8 CHECKUP

1. If you know the power in each resistor in a series circuit, how can you find the total power?
2. The resistors in a series circuit dissipate the following powers: 2 W, 5 W, 1 W, and 8 W. What is the total power in the circuit?
3. A circuit has a  $100 \Omega$ , a  $330 \Omega$ , and a  $680 \Omega$  resistor in series. There is a current of 1 A through the circuit. What is the total power?

## 5–9 VOLTAGE MEASUREMENTS

The concept of *reference ground* was introduced in Chapter 2 and designated as the 0 V reference point for a circuit. Voltage is always measured with respect to another point in the circuit. In this section, ground is discussed in more detail.

After completing this section, you should be able to

- ◆ **Measure voltage with respect to ground**
  - ◆ Define the term *reference ground*
  - ◆ Explain the use of single and double subscripts for indicating voltages
  - ◆ Identify ground in a circuit

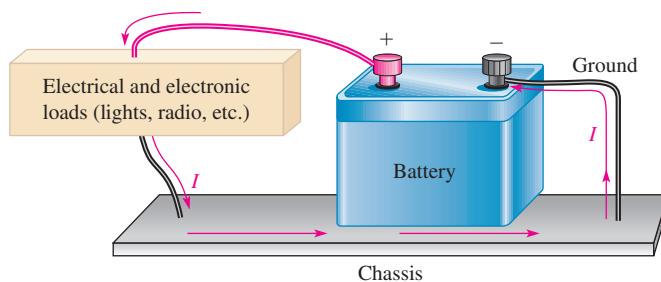
The term *ground* has its origin in telephone systems in which one of the conductors was the earth itself. The term was also used in early radio receiving antennas (called *aerials*) where one part of the system was connected to a metal pipe driven into the earth. Today, *ground* can mean different things and is not necessarily at the same potential as the earth. Recall that reference ground was defined in Section 2–8 as a common point in a circuit from which voltages are typically measured. Frequently, the reference ground is the conductor that carries the power supply return current. Most electronic circuit boards have a larger conducting surface area for ground. For many multilayer circuit boards, the ground surface area is a separate internal layer, which is referred to as a *ground plane*.

Basic concepts of standard electrical wiring in North America were discussed in Chapter 2 (Section 2–8). Recall that the neutral conductor is connected to earth ground *only* at the entrance to a building. Neutral is part of the live circuit and carries return current from the load but ground is for safety purposes and connects metal boxes, cases, and the like to the building ground. In normal operation, ground and neutral are at the same potential and neutral can serve as a reference ground.

The concept of *reference ground* is also used in automotive electrical systems. In most automotive systems, the chassis of the automobile is the ground reference. In nearly all modern automobiles, the negative post of the battery is connected to the chassis with a solid low-resistance connection. This makes the chassis of the vehicle serve as the return path for all of the electrical circuits in the vehicle, as illustrated in the simplified drawing in Figure 5–50. In some vintage cars, the positive terminal was connected to the chassis in an arrangement called *positive ground*. In both cases, the chassis represents the reference ground point.

### SAFETY NOTE

When removing a battery from an automobile, remove the reference ground wire first. If a tool should then accidentally come in contact with the chassis and the positive terminal, a spark will be avoided; there is no current because there is no return path. When installing a battery, always install the ground connection last.



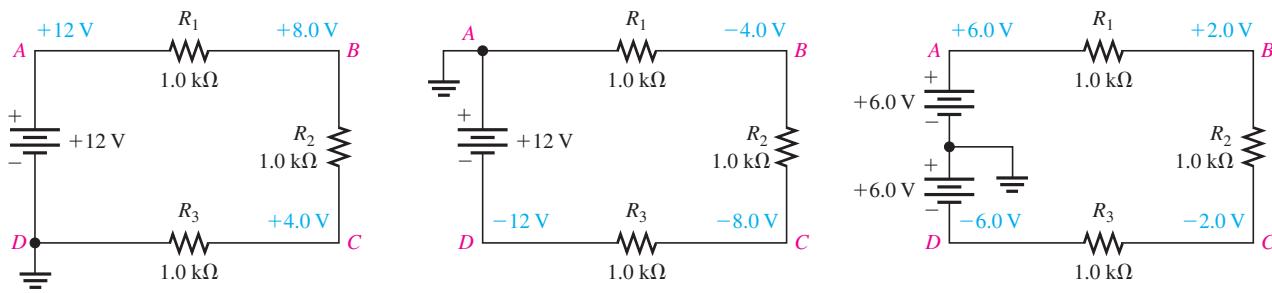
◀ FIGURE 5–50

The chassis serves as a return current path for the electrical circuits in a vehicle.

## Measuring Voltages with Respect to Ground

When voltages are measured with respect to ground, they are indicated with a single letter subscript. For example,  $V_A$  is voltage at point *A* with respect to ground. The circuits in Figure 5–51 consist of three  $1.0\text{ k}\Omega$  series resistors and four lettered reference points. Reference ground represents a potential of  $0\text{ V}$  with respect to all other points in the circuit as illustrated. In part (a), the reference point is *D* and all voltages are positive with respect to *D*. In part (b), the reference point is *A* in the circuit, and all other points have a negative voltage.

Many circuits use both positive and negative voltages and as mentioned, the return path for these supplies is designated as reference ground. Figure 5–51(c) shows the same circuit but with two  $6\text{ V}$  sources replacing the  $12\text{ V}$  source. In this case, the reference point is arbitrarily designated between the two voltage sources. There is exactly the same current in all three circuits, but now voltages are referenced to the



(a) Positive voltages with respect to ground

(b) Negative voltages with respect to ground

(c) Positive and negative voltages with respect to ground

**▲ FIGURE 5-51**

The ground point does not affect the current in the circuit or the voltage drops across the resistors.

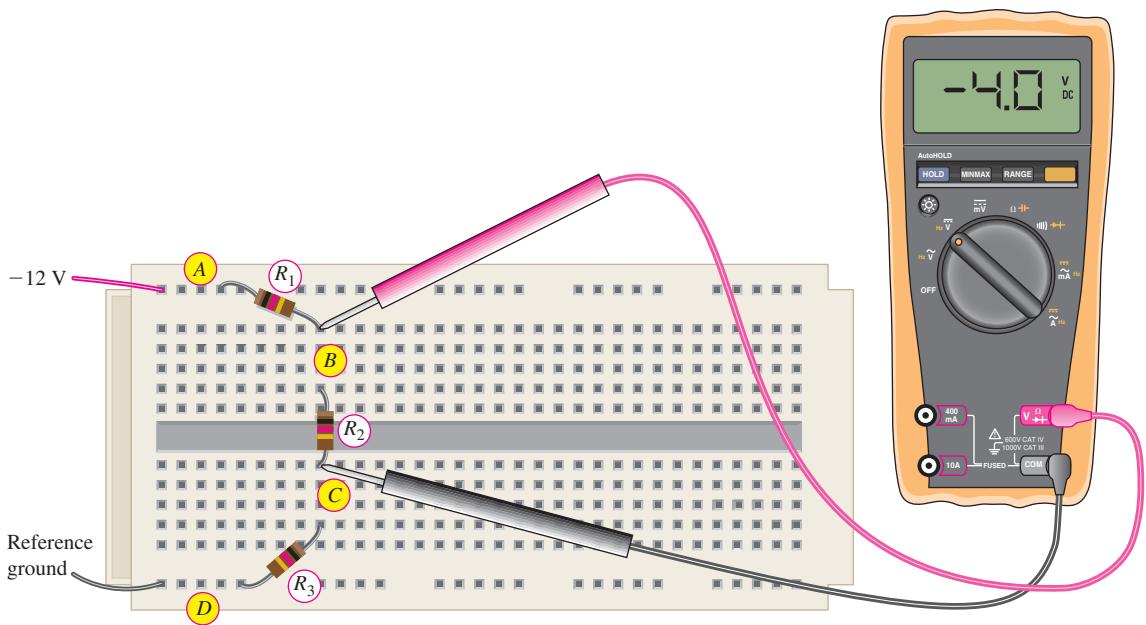
new ground point. As you can see from these examples, the reference ground point is arbitrary and does not change the current.

Not all voltages are measured with respect to ground. If you wish to specify the voltage drop across an ungrounded resistor, you can name the resistor in the subscript or use two subscripts. When two subscripts are used, the voltage represents the difference between the points. For example,  $V_{BC}$  means  $V_B - V_C$ . In Figure 5-51,  $V_{BC}$  is the same in all three circuits (+4.0 V) as you can confirm by performing the subtraction in each case. Another way of designating  $V_{BC}$  is to write simply  $V_{R2}$ .

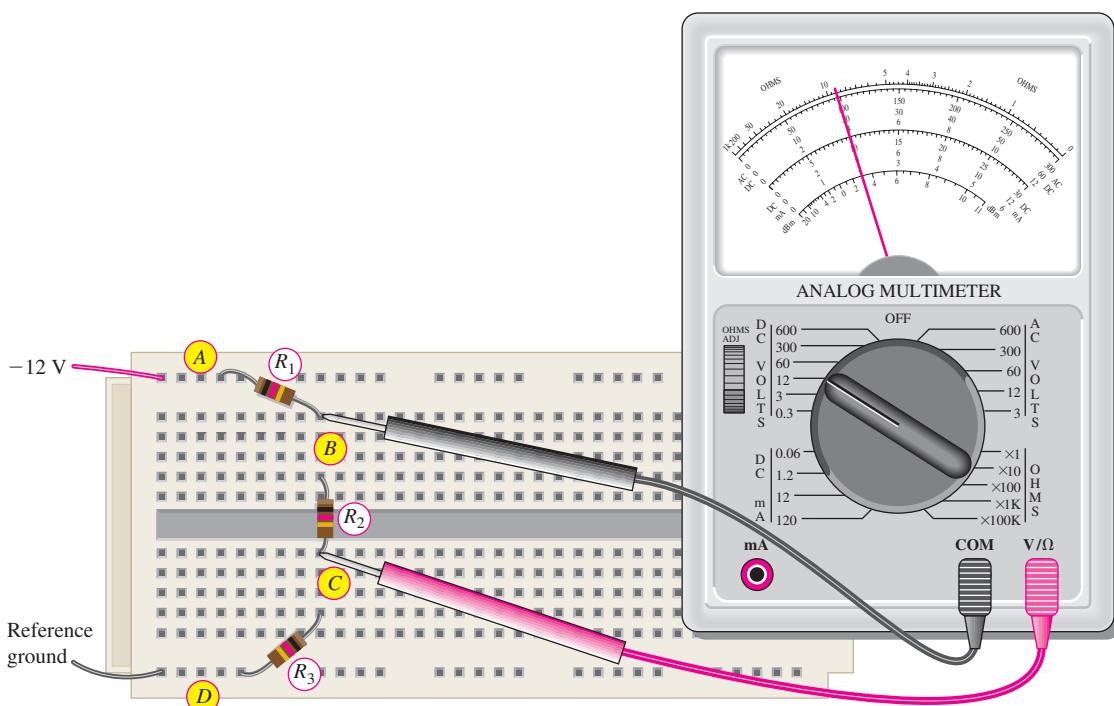
There is one more convention commonly used to express voltages using subscripts. Power supply voltages are usually given with a double-letter subscript. The reference point is ground or common. For example, a voltage written as  $V_{CC}$  is a positive power supply voltage with respect to ground. Other common power supply voltages are  $V_{SS}$  (positive),  $V_{EE}$  (negative), and  $V_{SS}$  (negative).

To measure voltages with a digital meter, the meter leads can be connected across any two points and the meter will indicate the voltage, either positive or negative. The meter reference jack is labeled “COM” (normally black). This is common only to the meter, not to the circuit. Figure 5-52 shows measuring a floating voltage using a DMM to measure the voltage across the ungrounded resistor  $R_2$ . The circuit is the same one given in Figure 5-51(b), which has a negative power supply. It is shown as it might be constructed in a lab. Notice that the meter indicates a negative voltage, which means that the meter’s COM lead is the more positive lead. If you wanted to measure voltages with respect to the circuit’s reference ground, you would connect the COM on the meter to the circuit’s reference ground. The voltage with respect to the reference ground will be indicated.

If you are using an analog meter to make circuit measurements, you must connect the meter so that its common lead is connected to the most negative point in the circuit; otherwise, the meter movement will try to move backward. (An exception is when the meter has a switch for reversing the polarity.) If you are uncertain as to the polarity of the voltage, set the meter for the highest range and note which direction the meter deflects. Then choose a scale that produces reasonable deflection and zero the meter on that scale prior to making a measurement. Figure 5-53 shows an analog meter connected to the same circuit as before; notice that the meter leads are reversed. To measure voltage across  $R_2$ , the leads must be connected so that the meter will deflect in the positive direction. Notice that the positive lead on the meter is connected to the more positive point in the circuit, which in this case is the circuit’s ground. The user appends a minus sign to the reading when recording the reading.

**▲ FIGURE 5–52**

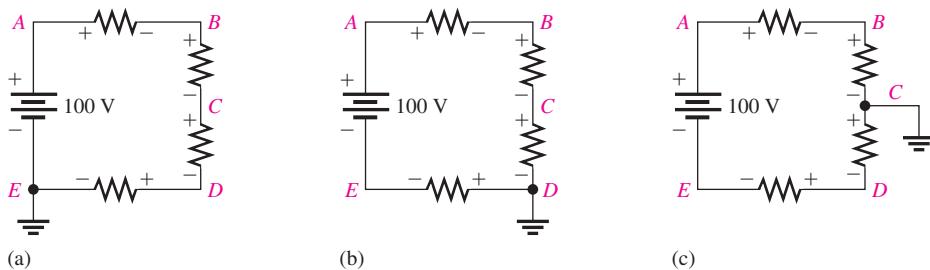
A DMM has a “floating” common, so it can be connected to any point in the circuit and read the correct voltage between the two leads.

**▲ FIGURE 5–53**

An analog meter needs to be connected so that the positive lead goes to the more positive point in the circuit.

**EXAMPLE 5–22**

Determine the voltages with respect to ground of each of the indicated points in each circuit of Figure 5–54. Assume that the resistors have equal values and that 25 V are dropped across each resistor.

**▲ FIGURE 5–54****Solution**

In circuit (a), the voltage polarities are as shown. Point  $E$  is ground. Single-letter subscripts denote voltage at a point with respect to ground. The voltages with respect to ground are as follows:

$$V_E = 0 \text{ V}, V_D = +25 \text{ V}, V_C = +50 \text{ V}, V_B = +75 \text{ V}, V_A = +100 \text{ V}$$

In circuit (b), the voltage polarities are as shown. Point  $D$  is ground. The voltages with respect to ground are as follows:

$$V_E = -25 \text{ V}, V_D = 0 \text{ V}, V_C = +25 \text{ V}, V_B = +50 \text{ V}, V_A = +75 \text{ V}$$

In circuit (c), the voltage polarities are as shown. Point  $C$  is ground. The voltages with respect to ground are as follows:

$$V_E = -50 \text{ V}, V_D = -25 \text{ V}, V_C = 0 \text{ V}, V_B = +25 \text{ V}, V_A = +50 \text{ V}$$

**Related Problem**

If the ground is at point  $A$  in the circuit in Figure 5–54, what are the voltages at each of the points with respect to ground?



Use Multisim file E05-22 to verify the calculated results in this example and to confirm your calculation for the related problem.

**SECTION 5–9  
CHECKUP**

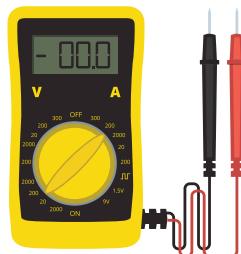
1. What is the reference point in a circuit called?
2. Voltages in a circuit are generally referenced with respect to ground. (T or F)
3. The housing or chassis is often used as reference ground. (T or F)
4. If  $V_{AB}$  in a circuit is +5.0 V, what is  $V_{BA}$ ?

## 5–10 TROUBLESHOOTING

Open resistors or contacts and one point shorted to another are common problems in all circuits including series circuits.

After completing this section, you should be able to

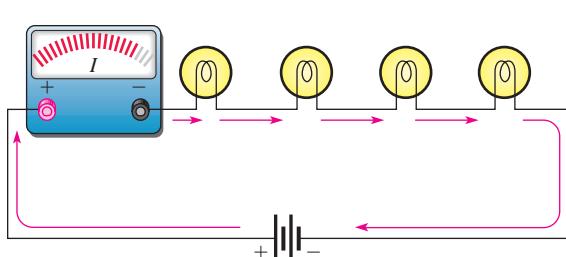
- ◆ Troubleshoot series circuits
  - ◆ Check for an open circuit
  - ◆ Check for a short circuit
  - ◆ Identify primary causes of opens and shorts



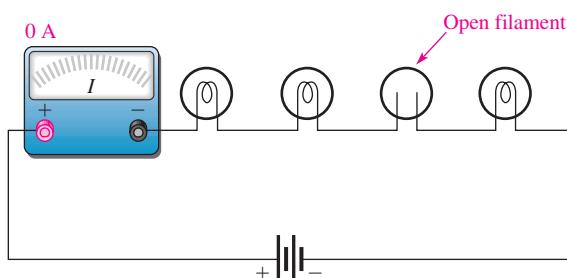
### Open Circuit

The most common failure in a series circuit is an **open**. For example, when a resistor or a lamp burns out, it causes a break in the current path and creates an open circuit, as illustrated in Figure 5–55. An open circuit can also be created by a switch, circuit breaker or fuse; any of these can interrupt current when open.

**An open in a series circuit prevents current.**



(a) A complete series circuit has current.



(b) An open series circuit has no current.

▲ FIGURE 5–55

Current ceases when an open occurs.

**Troubleshooting an Open** In Chapter 3, you were introduced to the analysis, planning, and measurement (APM) approach to troubleshooting. You also learned about the half-splitting method and saw an example using an ohmmeter. Now, the same principles will be applied using voltage measurements instead of resistance measurements. As you know, voltage measurements are generally the easiest to make because you do not have to disconnect anything.

As a beginning step, prior to analysis, it is a good idea to make a visual check of the faulty circuit. Occasionally, you can find a charred resistor, a broken lamp filament, a loose wire, or a loose connection this way. However, it is possible (and probably more common) for a resistor or other component to open without showing visible signs of damage. When a visual check reveals nothing, then proceed with the APM approach.

*When an open occurs in a series circuit, all of the source voltage appears across the open.* The reason for this is that the open condition prevents current through the series circuit. With no current, there can be no voltage drop across any of the other resistors (or other component). Since  $IR = (0\text{ A})R = 0\text{ V}$ , the voltage on each end of a good resistor is the same. Therefore, the voltage applied across a series string also appears across the open component because there are no other voltage drops in the

### TECH NOTE

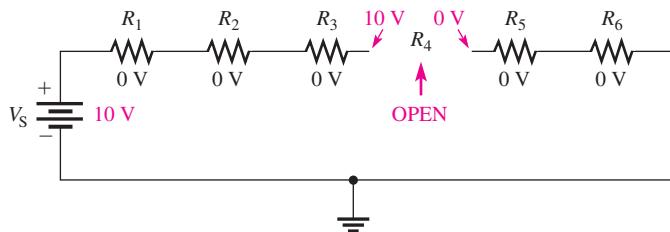
When measuring a resistance, make sure that you do not touch the meter leads or the resistor leads with your fingers. If you hold both ends of a high-value resistor in your fingers along with the meter probes, the measurement will be inaccurate because your body resistance can affect the measured value. When body resistance is placed in parallel with a high-value resistor, the measured value will be less than the actual value of the resistor.

circuit, as illustrated in Figure 5–56. The source voltage will appear across the open resistor in accordance with Kirchhoff's voltage law as follows:

$$\begin{aligned}V_S &= V_1 + V_2 + V_3 + V_4 + V_5 + V_6 \\V_4 &= V_S - V_1 - V_2 - V_3 - V_5 - V_6 \\&= 10 \text{ V} - 0 \text{ V} = 0 \text{ V} \\V_4 &= V_S = 10 \text{ V}\end{aligned}$$

► FIGURE 5–56

The source voltage appears across the open series resistor.

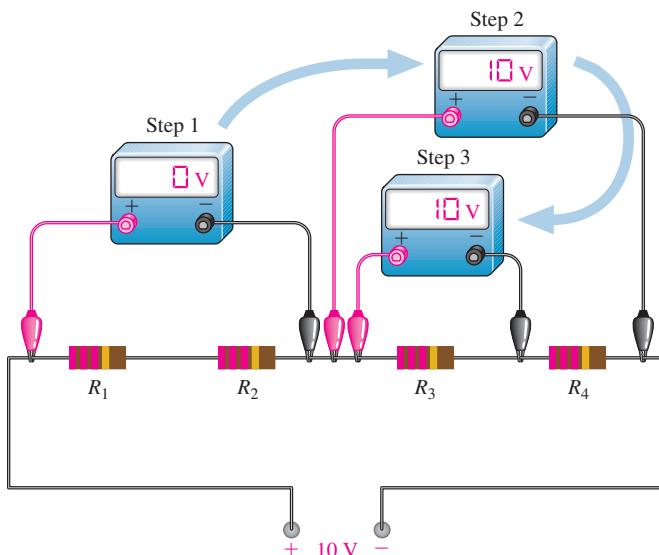


**Example of Half-Splitting Using Voltage Measurements** Suppose a circuit has four resistors in series. You have determined by *analyzing* the symptoms (there is voltage at the source but no current) that one of the resistors is open, and you are *planning* to find the open resistor using a voltmeter for *measuring* by the half-splitting method. A sequence of measurements for this particular case is illustrated in Figure 5–57.

**Step 1:** Measure across  $R_1$  and  $R_2$  (the left half of the circuit). A 0 V reading indicates that neither of these resistors is open.

**Step 2:** Move the meter to measure across  $R_3$  and  $R_4$ ; the reading is 10 V. This indicates there is an open in the right half of the circuit, so either  $R_3$  or  $R_4$  is the faulty resistor (assume no bad connections).

**Step 3:** Move the meter to measure across  $R_3$ . A measurement of 10 V across  $R_3$  identifies it as the open resistor. If you had measured across  $R_4$ , it would have indicated 0 V. This would have also identified  $R_3$  as the faulty component because it would have been the only one left that could have 10 V across it.

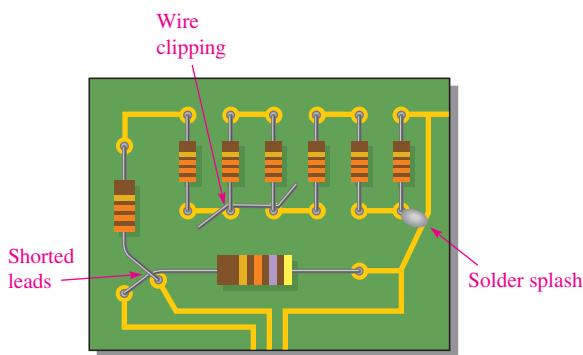


▲ FIGURE 5–57

Troubleshooting a series circuit for an open using half-splitting.

## Short Circuit

Sometimes an unwanted short circuit occurs when two conductors touch or a foreign object such as solder or a wire clipping accidentally connects two sections of a circuit together. This situation can occur in circuits with a high component density. Several potential causes of short circuits are illustrated on the PC board in Figure 5–58.

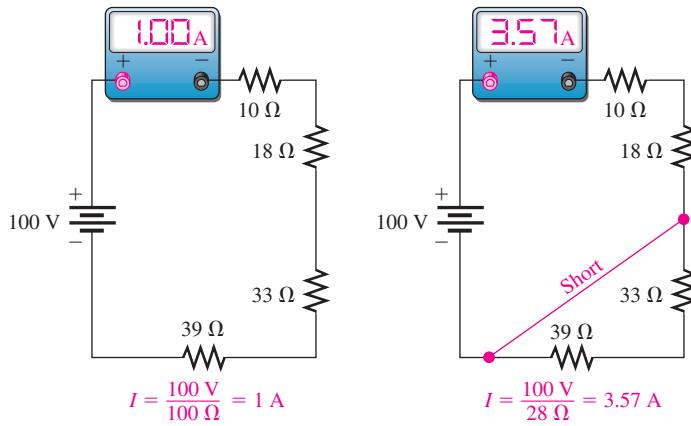


◀ FIGURE 5–58

Examples of shorts on a PC board.

When there is a **short**, a portion of the series resistance is bypassed (all of the current goes through the short), thus reducing the total resistance as illustrated in Figure 5–59. Notice that the current increases as a result of the short.

**A short in a series circuit causes more current than normal.**



◀ FIGURE 5–59

Example of the effect of a short in a series circuit.

**Troubleshooting a Short** A short is very difficult to troubleshoot. As in any troubleshooting situation, it is a good idea to make a visual check of the faulty circuit. In the case of a short in the circuit, a wire clipping, solder splash, or touching leads is often found to be the culprit. In terms of component failure, shorts are less common than opens in many types of components. Furthermore, a short in one part of a circuit can cause overheating in another part due to the higher current caused by the short. As a result two failures, an open and a short, may occur together.

*When a short occurs in a series circuit, there is essentially no voltage across the shorted part.* A short has zero or near zero resistance, although shorts with significant resistance values can occur from time to time. These are called *resistive shorts*. For purposes of illustration, zero resistance is assumed for all shorts.

In order to troubleshoot a short, measure the voltage across each resistor until you get a reading of 0 V. This is the straightforward approach and does not use half-splitting.

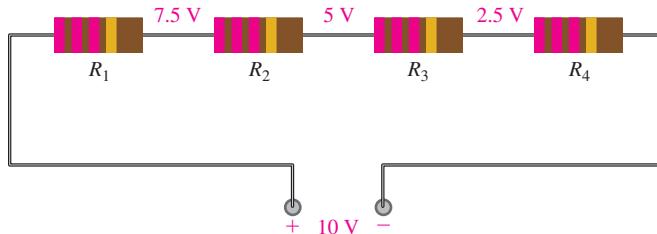
In order to apply the half-splitting method, you must know the correct voltage at each point in the circuit and compare it to measured voltages. Example 5–23 illustrates using half-splitting to find a short.

### EXAMPLE 5–23

Assume you have determined that there is a short in a circuit with four series resistors because the current is higher than it should be. You know that the voltage at each point in the circuit should be as shown in Figure 5–60 if the circuit is working properly. The voltages are shown relative to the negative terminal of the source. Find the location of the short.

► FIGURE 5–60

Series circuit (without a short) with correct voltages indicated.

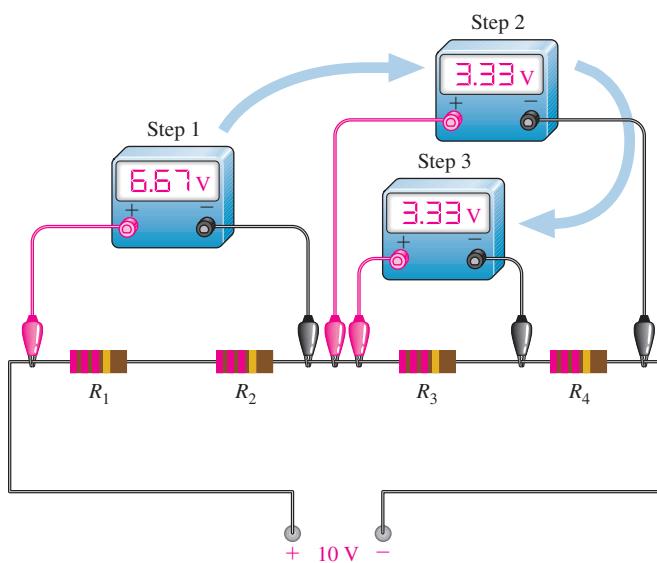


**Solution** Use the half-splitting method to troubleshoot the short.

- Step 1:** Measure across  $R_1$  and  $R_2$ . The meter shows a reading of 6.67 V, which is higher than the normal voltage (it should be 5 V). Look for a voltage that is lower than normal because a short will make the voltage less across that part of the circuit.
- Step 2:** Move the meter and measure across  $R_3$  and  $R_4$ ; the reading of 3.33 V is incorrect and lower than normal (it should be 5 V). This shows that the short is in the right half of the circuit and that either  $R_3$  or  $R_4$  is shorted.
- Step 3:** Again move the meter and measure across  $R_3$ . A reading of 3.3 V across  $R_3$  tells you that  $R_4$  is shorted because it must have 0 V across it. Figure 5–61 illustrates this troubleshooting technique.

► FIGURE 5–61

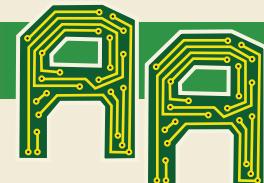
Troubleshooting a series circuit for a short using half-splitting.



**Related Problem** Assume that  $R_1$  is shorted in Figure 5–61. What would the Step 1 measurement be?

**SECTION 5-10  
CHECKUP**

1. Define *short*.
2. Define *open*.
3. What happens when a series circuit opens?
4. Name two general ways in which an open circuit can occur in practice. What may cause a short circuit to occur?
5. When a resistor fails, it will normally fail open. (T or F)
6. The total voltage across a string of series resistors is 24 V. If one of the resistors is open, how much voltage is there across it? How much is there across each of the good resistors?



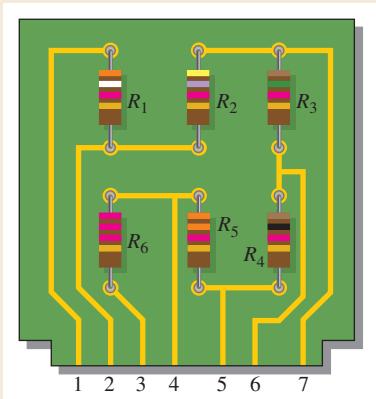
## Application Activity

For this application activity, you have a voltage-divider circuit board that has been given to you to check and evaluate. The purpose of the board is to provide five different reference voltage levels from a 12.0 V battery that has a 6.5 Ah rating. The reference voltages are for use in another circuit.

Your job is to check the existing circuit and predict the output voltages at each pin based on the resistor color codes. Then you will compare your predicted values with the measured voltages and determine if they are within the tolerance range of the expected values. If not, suggest why they are not as expected. You also need to confirm that power ratings of the resistors are adequate for the application and determine how long the battery will last with the voltage divider connected to it.

### The Schematic of the Circuit

1. Use Figure 5–62 to determine the resistor values and draw the schematic of the voltage-divider circuit. All the resistors on the board are  $\frac{1}{4}$  W.



▲ FIGURE 5–62

### The Voltages

2. A 12.0 V battery is connected between pins 1 and 3 of the voltage-divider board. Complete Table 5–1 (or a copy of the table), adding the expected voltages.

▼ TABLE 5–1

#### Voltage-divider Board Voltages

PIN	EXPECTED VOLTAGE	MEASURED VOLTAGE
1	0 V	0 V
2		2.75 V
3	12.0 V	12.0 V
4		10.5 V
5		8.22 V
6		7.31 V
7		6.59 V

3. Compare the expected voltage with the measured voltage and determine if the board is working as expected. If not, suggest a reason. Also, determine if the resistor power ratings are adequate for the application.

### The Battery

4. Find the total current drawn from the 12 V battery when the voltage-divider circuit is connected and determine how many days the 6.5 Ah battery will last.

### A Test Procedure

5. Determine how you would test the voltage-divider circuit board and what instruments you would use. Then detail your test procedure in a step-by-step format.

**Troubleshooting**

6. Determine the most likely fault for each of the following cases. Voltages are with respect to the negative battery terminal (pin 1 on the circuit board).
- ◆ No voltage at any of the pins on the circuit board
  - ◆ 12 V at pins 3 and 4. All other pins have 0 V.
  - ◆ 12 V at all pins except 0 V at pin 1
  - ◆ 12 V at pin 6 and 0 V at pin 7
  - ◆ 3.3 V at pin 2

**Review**

7. What is the total power dissipated by the voltage-divider circuit in Figure 5–62 with a 12 V battery?

8. What are the output voltages from the voltage divider if the positive terminal of a 6 V battery is connected to pin 3 and the negative terminal to pin 1?
9. When the voltage-divider board is connected to the electronic circuit to which it is providing positive reference voltages, which pin on the board should be connected to the ground of the electronic circuit?

**Multisim Analysis**

Using Multisim connect the circuit based on the schematic from Activity 1 and verify the output voltages specified in Activity 2. Insert faults determined in Activity 6 and verify the resulting voltage measurements.

**SUMMARY**

- The current is the same at all points in a series circuit.
- The total resistance in a series circuit is the sum of all resistors.
- The resistance between any two points in a series circuit is equal to the sum of all resistors connected between those two points.
- If all of the resistors in a series circuit are of equal value, the total resistance is the number of resistors multiplied by the resistance value of one resistor.
- Voltage sources in series add algebraically.
- Kirchhoff's voltage law: The sum of all the voltage drops around a single closed path in a circuit is equal to the total source voltage in that loop.
- Kirchhoff's voltage law: The algebraic sum of all the voltages (both source and drops) around a single closed path is zero.
- The voltage drops in a circuit are always opposite in polarity to the total source voltage.
- Conventional current is defined to be out of the positive side of a source and into the negative side.
- Conventional current is defined to be into the positive side of each resistor and out of the more negative (less positive) side.
- A voltage drop results from a decrease in energy level across a resistor.
- A voltage divider is a series arrangement of resistors connected to a voltage source.
- A voltage divider is so named because the voltage drop across any resistor in the series circuit is divided down from the total voltage by an amount proportional to that resistance value in relation to the total resistance.
- A potentiometer can be used as an adjustable voltage divider.
- The total power in a resistive circuit is the sum of all the individual powers of the resistors making up the series circuit.
- Reference ground (common) is zero volts with respect to all points that are compared to it in the circuit.
- *Negative ground* is the term used when the negative side of the source is grounded.
- *Positive ground* is the term used when the positive side of the source is grounded.
- The voltage across an open component in a series circuit always equals the source voltage.
- The voltage across a shorted component is always 0 V.

**KEY TERMS**

These key terms are also in the end-of-book glossary.

**Kirchhoff's voltage law** A law stating that (1) the sum of the voltage drops around a single closed path equals the source voltage in that loop or (2) the algebraic sum of all the voltages around any closed path in a circuit is zero.

**Open** A circuit condition in which the current path is broken.

**Series** In an electric circuit, a relationship of components in which the components are connected such that they provide a single current path between two points.

**Short** A circuit condition in which there is a zero or abnormally low resistance path between two points; usually an inadvertent condition.

**Voltage divider** A circuit consisting of series resistors across which one or more output voltages are taken.

**FORMULAS**

5-1	$R_T = R_1 + R_2 + R_3 + \dots + R_n$	Total resistance of $n$ resistors in series
5-2	$R_T = nR$	Total resistance of $n$ equal-value resistors in series
5-3	$V_S = V_1 + V_2 + V_3 + \dots + V_n$	Kirchhoff's voltage law
5-4	$V_1 + V_2 + V_3 + \dots + V_n = 0$	Kirchhoff's voltage law stated another way
5-5	$V_x = \left(\frac{R_x}{R_T}\right)V_S$	Voltage-divider formula
5-6	$P_T = P_1 + P_2 + P_3 + \dots + P_n$	Total power

**TRUE/FALSE QUIZ**

Answers are at the end of the chapter.

1. A series circuit can have more than one path for current.
2. The total resistance of a series circuit can be less than the largest resistor in that circuit.
3. If two series resistors are different sizes, the larger resistor will have the larger current.
4. If two series resistors are different sizes, the larger resistor will have the larger voltage.
5. If three equal resistors are used in a voltage divider, the voltage across each one will be one-third of the source voltage.
6. There is no valid electrical reason for installing flashlight batteries so that they are not all in the same direction.
7. Kirchhoff's voltage law is valid only if a loop contains a voltage source.
8. The voltage-divider equation can be written as  $V_x = (R_x/R_T)V_S$ .
9. The total power dissipated by all of the resistors in a series resistive circuit is the same as the power supplied by the source.
10. If point *A* in a circuit has a voltage of +10 V and point *B* has a voltage of -2 V, then  $V_{AB}$  is +8 V.

**SELF-TEST**

Answers are at the end of the chapter.

1. Two equal-value resistors are connected in series and there is a current of 2 mA into the first resistor. The amount of current out of the second resistor is
 

(a) equal to 2 mA      (b) less than 2 mA      (c) greater than 2 mA

2. To measure the current out of the third resistor in a circuit consisting of four series resistors, an ammeter can be placed
  - (a) between the third and fourth resistors
  - (b) between the second and third resistors
  - (c) at the positive terminal of the source
  - (d) at any point in the circuit
3. When a third resistor is connected in series with two series resistors, the total resistance
  - (a) remains the same
  - (b) increases
  - (c) decreases
  - (d) increases by one-third
4. When one of four series resistors is removed from a circuit and the circuit reconnected, the current
  - (a) decreases by the amount of current through the removed resistor
  - (b) decreases by one-fourth
  - (c) quadruples
  - (d) increases
5. A series circuit consists of three resistors with values of  $100\ \Omega$ ,  $220\ \Omega$ , and  $330\ \Omega$ . The total resistance is
  - (a) less than  $100\ \Omega$
  - (b) the average of the values
  - (c)  $550\ \Omega$
  - (d)  $650\ \Omega$
6. A 9 V battery is connected across a series combination of  $68\ \Omega$ ,  $33\ \Omega$ ,  $100\ \Omega$ , and  $47\ \Omega$  resistors. The amount of current is
  - (a) 36.3 mA
  - (b) 27.6 A
  - (c) 22.3 mA
  - (d) 363 mA
7. While putting four 1.5 V batteries in a four-cell flashlight, you accidentally put one of them in backward. The voltage across the bulb will be
  - (a) 6 V
  - (b) 3 V
  - (c) 4.5 V
  - (d) 0 V
8. If you measure all the voltage drops and the source voltage in a series circuit and add them together, taking into consideration the polarities, you will get a result equal to
  - (a) the source voltage
  - (b) the total of the voltage drops
  - (c) zero
  - (d) the total of the source voltage and the voltage drops
9. There are six resistors in a given series circuit and each resistor has 5 V dropped across it. The source voltage is
  - (a) 5 V
  - (b) 30 V
  - (c) dependent on the resistor values
  - (d) dependent on the current
10. A series circuit consists of a  $4.7\ k\Omega$ , a  $5.6\ k\Omega$ , and a  $10\ k\Omega$  resistor. The resistor that has the most voltage across it is
  - (a) the  $4.7\ k\Omega$
  - (b) the  $5.6\ k\Omega$
  - (c) the  $10\ k\Omega$
  - (d) impossible to determine from the given information
11. Which of the following series combinations dissipates the most power when connected across a 100 V source?
  - (a) One  $100\ \Omega$  resistor
  - (b) Two  $100\ \Omega$  resistors
  - (c) Three  $100\ \Omega$  resistors
  - (d) Four  $100\ \Omega$  resistors
12. The total power in a certain circuit is 1 W. Each of the five equal-value series resistors making up the circuit dissipates
  - (a) 1 W
  - (b) 5 W
  - (c) 0.5 W
  - (d) 0.2 W
13. When you connect an ammeter in a series-resistive circuit and turn on the source voltage, the meter reads zero. You should check for
  - (a) a broken wire
  - (b) a shorted resistor
  - (c) an open resistor
  - (d) answers (a) and (c)
14. While checking out a series-resistive circuit, you find that the current is higher than it should be. You should look for
  - (a) an open circuit
  - (b) a short
  - (c) a low resistor value
  - (d) answers (b) and (c)

## CIRCUIT DYNAMICS QUIZ

Answers are at the end of the chapter.

### Refer to Figure 5–68.

1. With a 10 V voltage source connected between points *A* and *B*, when the switches are thrown from position 1 to position 2, the total current from the source
  - (a) increases
  - (b) decreases
  - (c) stays the same
2. For the conditions described in Question 1, the current through  $R_3$ 
  - (a) increases
  - (b) decreases
  - (c) stays the same
3. When the switches are in position 1 and a short develops across  $R_3$ , the current through  $R_2$ 
  - (a) increases
  - (b) decreases
  - (c) stays the same
4. When the switches are in position 2 and a short develops across  $R_3$ , the current through  $R_5$ 
  - (a) increases
  - (b) decreases
  - (c) stays the same

### Refer to Figure 5–69.

5. If the current shown by one of the milliammeters increases, the current shown by the other two
  - (a) increases
  - (b) decreases
  - (c) stays the same
6. If the source voltage decreases, the current indicated by each milliammeter
  - (a) increases
  - (b) decreases
  - (c) stays the same
7. If the current through  $R_1$  increases as a result of  $R_1$  being replaced by a different resistor, the current indicated by each milliammeter
  - (a) increases
  - (b) decreases
  - (c) stays the same

### Refer to Figure 5–73.

8. If the switch is thrown from position *A* to position *B*, the ammeter reading
  - (a) increases
  - (b) decreases
  - (c) stays the same
9. If the switch is thrown from position *B* to position *C*, the voltage across  $R_4$ 
  - (a) increases
  - (b) decreases
  - (c) stays the same
10. If the switch is thrown from position *C* to position *D*, the current through  $R_3$ 
  - (a) increases
  - (b) decreases
  - (c) stays the same

### Refer to Figure 5–80(b).

11. If  $R_1$  is changed to  $1.2\text{ k}\Omega$ , the voltage from *A* to *B*
  - (a) increases
  - (b) decreases
  - (c) stays the same
12. If  $R_2$  and  $R_3$  are interchanged, the voltage from *A* to *B*
  - (a) increases
  - (b) decreases
  - (c) stays the same
13. If the source voltage increases from 8 V to 10 V, the voltage from *A* to *B*
  - (a) increases
  - (b) decreases
  - (c) stays the same

### Refer to Figure 5–87.

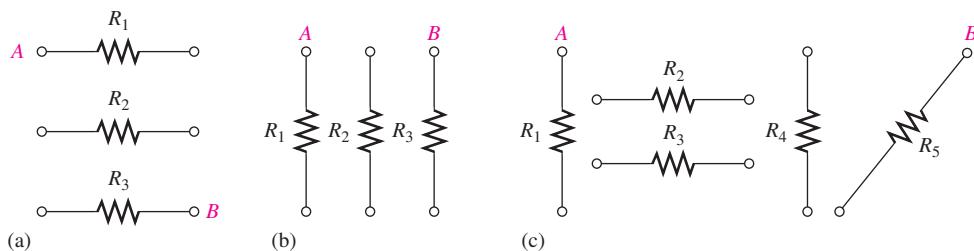
14. If the 9 V source is reduced to 5 V, the current in the circuit
  - (a) increases
  - (b) decreases
  - (c) stays the same
15. If the 9 V source is reversed, the voltage at point *B* with respect to ground
  - (a) increases
  - (b) decreases
  - (c) stays the same

**PROBLEMS**

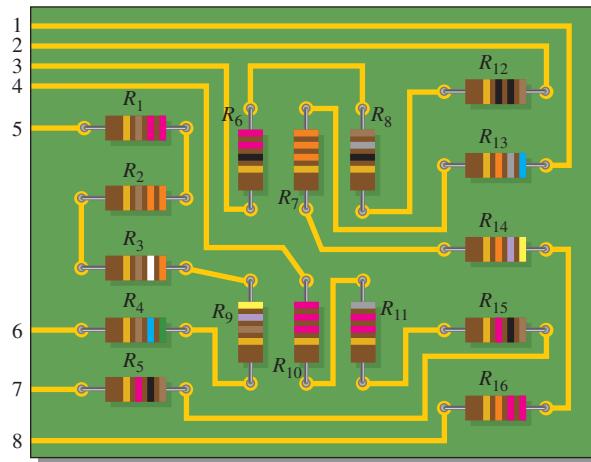
More difficult problems are indicated by an asterisk (\*).  
Answers to odd-numbered problems are at the end of the book.

**SECTION 5-1****Resistors in Series**

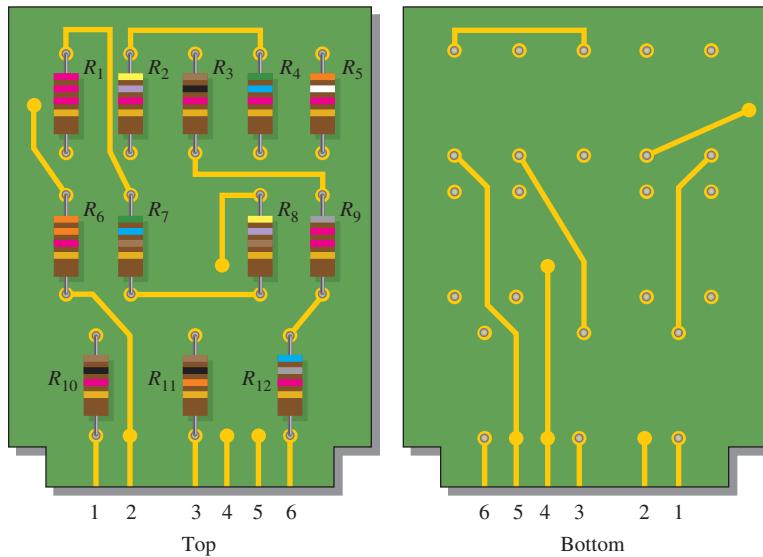
1. Connect each set of resistors in Figure 5-63 in series between points *A* and *B*.

**► FIGURE 5-63**

2. Determine the groupings of resistors in Figure 5-64 that are series connections. Show how to interconnect the pins to put all the resistors in series.

**► FIGURE 5-64**

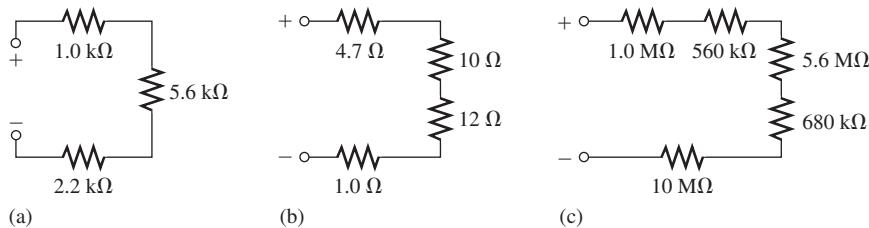
3. Determine the nominal resistance between pins 1 and 8 in the circuit board in Figure 5-64.  
4. Determine the nominal resistance between pins 2 and 3 in the circuit board in Figure 5-64.  
5. On the double-sided PC board in Figure 5-65, identify each group of series resistors. Note that many of the interconnections feed through the board from the top side to the bottom side.

**► FIGURE 5-65**

## SECTION 5–2 Total Series Resistance

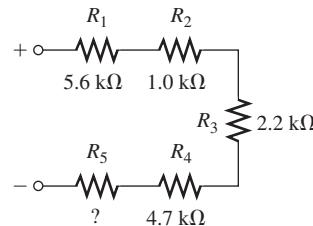
6. The following resistors (one each) are connected in a series circuit:  $1.0\ \Omega$ ,  $2.2\ \Omega$ ,  $5.6\ \Omega$ ,  $12\ \Omega$ , and  $22\ \Omega$ . Determine the total resistance.
7. Find the total resistance of each of the following groups of series resistors:
  - (a)  $560\ \Omega$  and  $1,000\ \Omega$
  - (b)  $47\ \Omega$  and  $56\ \Omega$
  - (c)  $1.5\text{ k}\Omega$ ,  $2.2\text{ k}\Omega$ , and  $10\text{ k}\Omega$
  - (d)  $1.0\text{ M}\Omega$ ,  $470\text{ k}\Omega$ ,  $1.0\text{ k}\Omega$ ,  $2.2\text{ M}\Omega$
8. Calculate  $R_T$  for each circuit of Figure 5–66.

► FIGURE 5–66



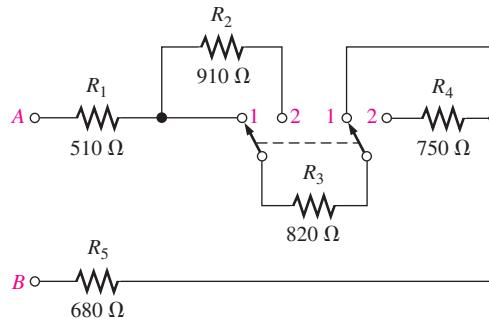
9. What is the total resistance of twelve  $5.6\text{ k}\Omega$  resistors in series?
10. Six  $56\ \Omega$  resistors, eight  $100\ \Omega$  resistors, and two  $22\ \Omega$  resistors are all connected in series. What is the total resistance?
11. If the total resistance in Figure 5–67 is  $17.4\text{ k}\Omega$ , what is the value of  $R_5$ ?

► FIGURE 5–67



- \*12. You have the following resistor values available to you in the lab in unlimited quantities:  $10\ \Omega$ ,  $100\ \Omega$ ,  $470\ \Omega$ ,  $560\ \Omega$ ,  $680\ \Omega$ ,  $1.0\text{ k}\Omega$ ,  $2.2\text{ k}\Omega$ , and  $5.6\text{ k}\Omega$ . All of the other standard values are out of stock. A project that you are working on requires an  $18\text{ k}\Omega$  resistance. What combinations of the available values would you use in series to achieve this total resistance?
13. Find the total resistance in Figure 5–66 if all three circuits are connected in series.
  14. What is the total resistance from A to B for each switch position in Figure 5–68?

► FIGURE 5–68

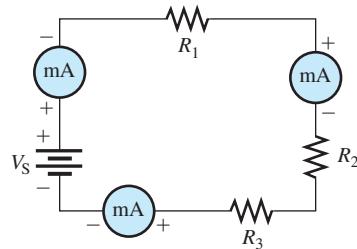


## SECTION 5–3 Current in a Series Circuit

15. What is the current through each resistor in a series circuit if the total voltage is  $12\text{ V}$  and the total resistance is  $120\ \Omega$ ?
16. The current from the source in Figure 5–69 is  $5\text{ mA}$ . How much current does each milliammeter in the circuit indicate?

17. Show how to connect a voltage source and an ammeter to the PC board in Figure 5–64 to measure the current in  $R_1$ . Which other resistor currents are measured by this setup?

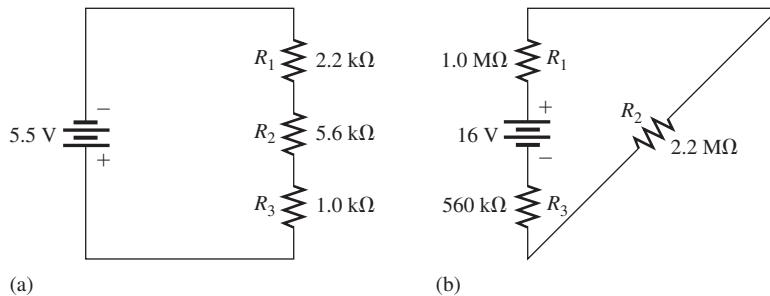
► FIGURE 5–69



- \*18. Using 1.5 V batteries, a switch, and three lamps, devise a circuit to apply 4.5 V across either one lamp, two lamps in series, or three lamps in series with a single-control switch. Draw the schematic.

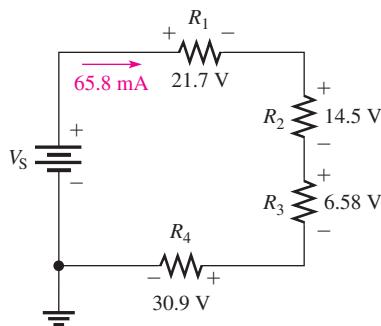
#### SECTION 5–4 Application of Ohm's Law

19. What is the current in each circuit of Figure 5–70?

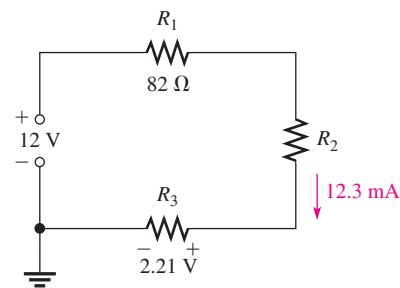


▲ FIGURE 5–70

20. Determine the voltage drop across each resistor in Figure 5–70.  
 21. Three  $470\ \Omega$  resistors are connected in series with a 48 V source.  
   (a) What is the current in the circuit?  
   (b) What is the voltage across each resistor?  
   (c) What is the minimum power rating of the resistors?  
 22. Four equal-value resistors are in series with a 5 V battery, and 2.23 mA are measured. What is the value of each resistor?  
 23. What is the value of each resistor in Figure 5–71?  
 24. Determine  $V_{R1}$ ,  $R_2$ , and  $R_3$  in Figure 5–72.



▲ FIGURE 5–71

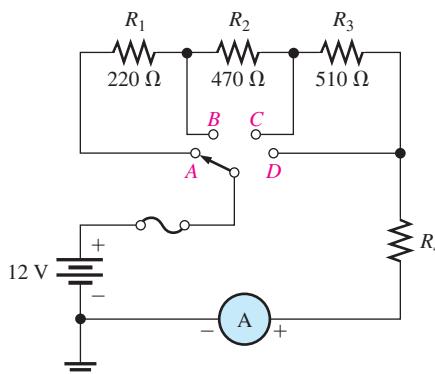


▲ FIGURE 5–72

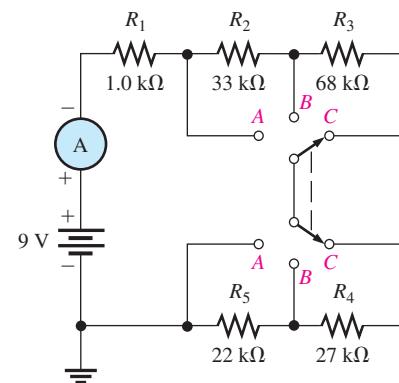
25. For the circuit in Figure 5–73 the meter reads 7.84 mA when the switch is in position *A*.

- (a) What is the resistance of  $R_4$ ?
- (b) What should be the meter reading for switch positions *B*, *C*, and *D*?
- (c) Will a  $\frac{1}{4}$  A fuse blow in any position of the switch?

26. Determine the current measured by the meter in Figure 5–74 for each position of the ganged switch.



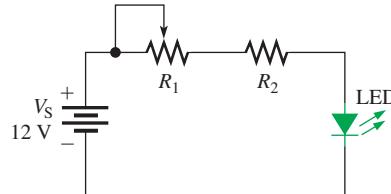
▲ FIGURE 5–73



▲ FIGURE 5–74

27. Refer to Figure 5–75. Assume the green LED drops 2.0 V across it when it is on. The maximum current in the LED is to be set at 10 mA and the minimum current is 2.0 mA. Choose values for  $R_1$  and  $R_2$  to meet these requirements.

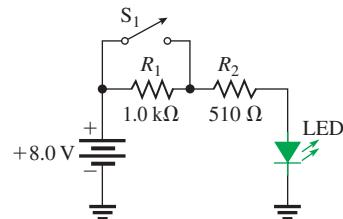
► FIGURE 5–75



28. Refer to Figure 5–76. Assume there is a 2.0 V drop across the green LED.

- (a) What is the current in the LED when the switch is open?
- (b) What is the current when the switch is closed?

► FIGURE 5–76



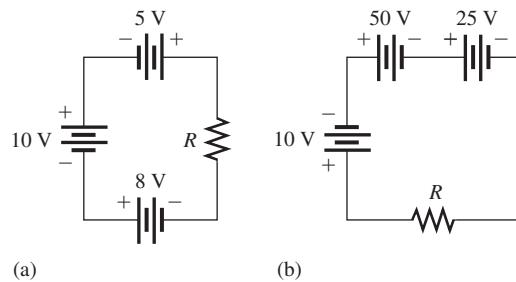
## SECTION 5–5 Voltage Sources in Series

29. *Series aiding* is a term sometimes used to describe voltage sources of the same polarity in series. If a 5 V and a 9 V source are connected in this manner, what is the total voltage?

30. The term *series opposing* means that sources are in series with opposite polarities. If a 12 V and a 3 V battery are series opposing, what is the total voltage?

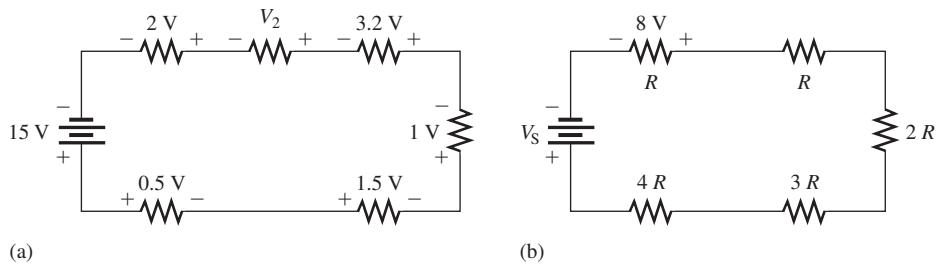
31. Determine the total source voltage in each circuit of Figure 5–77.

► FIGURE 5-77

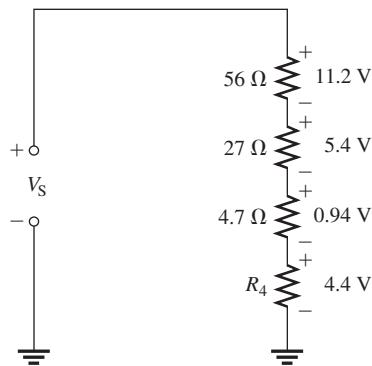
**SECTION 5-6 Kirchhoff's Voltage Law**

32. The following voltage drops are measured across three resistors in series: 5.5 V, 8.2 V, and 12.3 V. What is the value of the source voltage to which these resistors are connected?
33. Five resistors are in series with a 20 V source. The voltage drops across four of the resistors are 1.5 V, 5.5 V, 3 V, and 6 V. How much voltage is dropped across the fifth resistor?
34. Determine the unspecified voltage drop(s) in each circuit of Figure 5-78. Show how to connect a voltmeter to measure each unknown voltage drop.

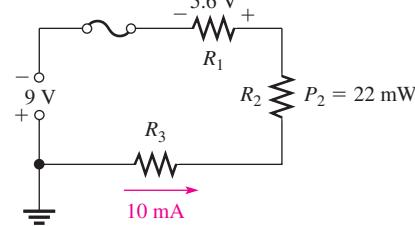
► FIGURE 5-78



35. In the circuit of Figure 5-79, determine the resistance of  $R_4$ .
36. Find  $R_1$ ,  $R_2$ , and  $R_3$  in Figure 5-80.



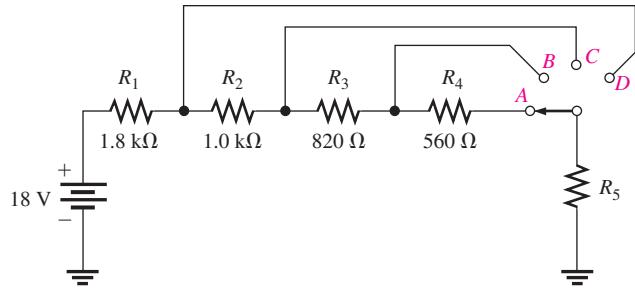
▲ FIGURE 5-79



▲ FIGURE 5-80

37. Determine the voltage across  $R_5$  for each position of the switch in Figure 5-81. The current in each position is as follows: A, 3.35 mA; B, 3.73 mA; C, 4.50 mA; D, 6.00 mA.
38. Using the result of Problem 35, determine the voltage across each resistor in Figure 5-79 for each switch position.

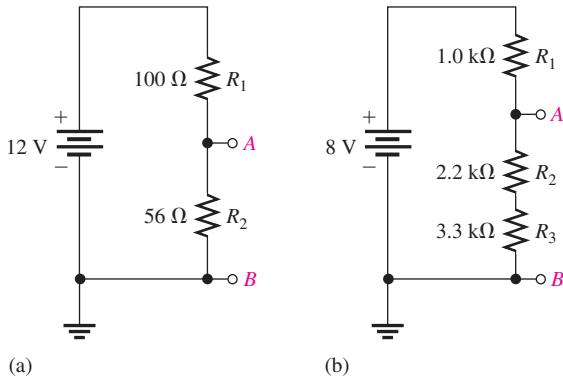
► FIGURE 5-81



## SECTION 5-7 Voltage Dividers

\*39. The total resistance of a circuit is  $560\ \Omega$ . What percentage of the total voltage appears across a  $27\ \Omega$  resistor that makes up part of the total series resistance?

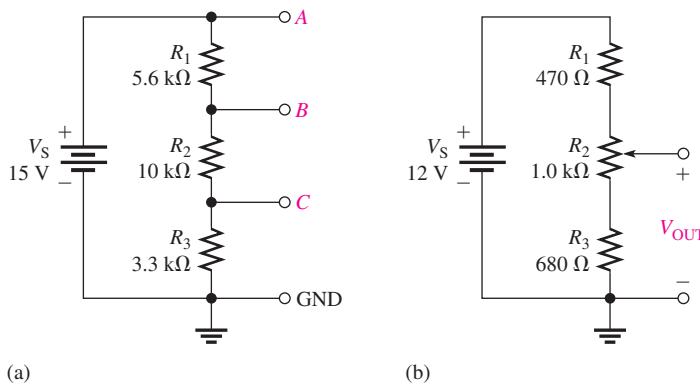
40. Determine the voltage between points A and B in each voltage divider of Figure 5-82.



▲ FIGURE 5-82

41. Determine the voltage with respect to ground for output A, B, and C in Figure 5-83(a).

42. Determine the minimum and maximum voltage from the voltage divider in Figure 5-83(b).

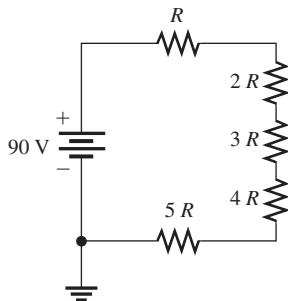


▲ FIGURE 5-83

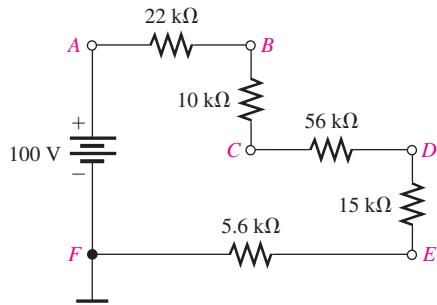
\*43. What is the voltage across each resistor in Figure 5-84?  $R$  is the lowest-value resistor, and all others are multiples of that value as indicated.

44. Determine the voltage at each point in Figure 5-85 with respect to the negative side of the battery.

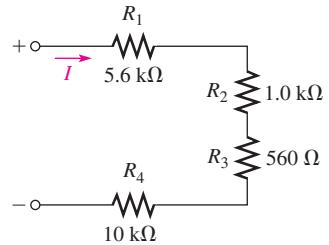
45. If there are 10 V across  $R_1$  in Figure 5-86, what is the voltage across each of the other resistors?



▲ FIGURE 5-84



▲ FIGURE 5-85



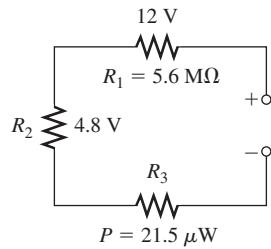
▲ FIGURE 5-86

- \*46. With the table of standard resistor values given in Appendix A, design a voltage divider to provide the following approximate voltages with respect to ground using a 30 V source: 8.18 V, 14.7 V, and 24.6 V. The current drain on the source must be limited to no more than 1 mA. The number of resistors, their values, and their wattage ratings must be specified. A schematic showing the circuit arrangement and resistor placement must be provided.
- \*47. Design a variable voltage divider to provide an output voltage adjustable from a minimum of 10 V to a maximum of 100 V within  $\pm 1\%$  using a 1 to 120 V source. The maximum voltage must occur at the maximum resistance setting of the potentiometer, and the minimum voltage must occur at the minimum resistance (zero) setting. The current is to be 10 mA.

## SECTION 5-8 Power in Series Circuits

48. Five series resistors each handle 50 mW. What is the total power?
49. If you double the voltage across a resistor, by how much does the power increase?
50. If the total resistance of a circuit is halved, what happens to the power?
51. What is the total power in the circuit in Figure 5-86? Use the results of Problem 45.
52. The following  $\frac{1}{4}$  W resistors are in series: 1.2 kΩ, 2.2 kΩ, 3.9 kΩ, and 5.6 kΩ. What is the maximum voltage that can be applied across the series resistors without exceeding a power rating? Which resistor will burn out first if excessive voltage is applied?
53. Find  $R_T$  in Figure 5-87.

► FIGURE 5-87

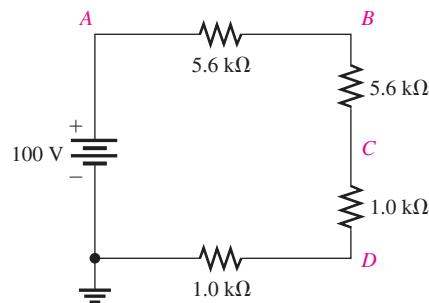


54. A certain series circuit consists of a  $\frac{1}{8}$  W resistor, a  $\frac{1}{4}$  W resistor, and a  $\frac{1}{2}$  W resistor. The total resistance is 2,400 Ω. If each of the resistors is operating in the circuit at its maximum power dissipation, determine the following:
- (a)  $I$       (b)  $V_T$       (c) The value of each resistor

## SECTION 5-9 Voltage Measurements

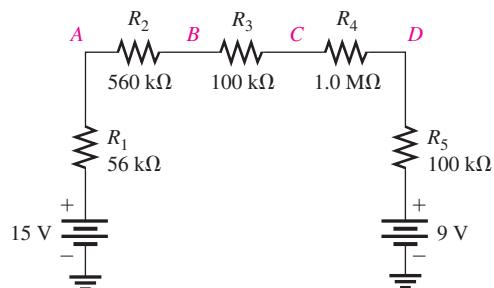
55. Determine the voltage at each point with respect to ground in Figure 5-88.

► FIGURE 5-88



56. In Figure 5-89, how would you determine the voltage across  $R_2$  by measuring, without connecting a meter directly across the resistor?

► FIGURE 5-89

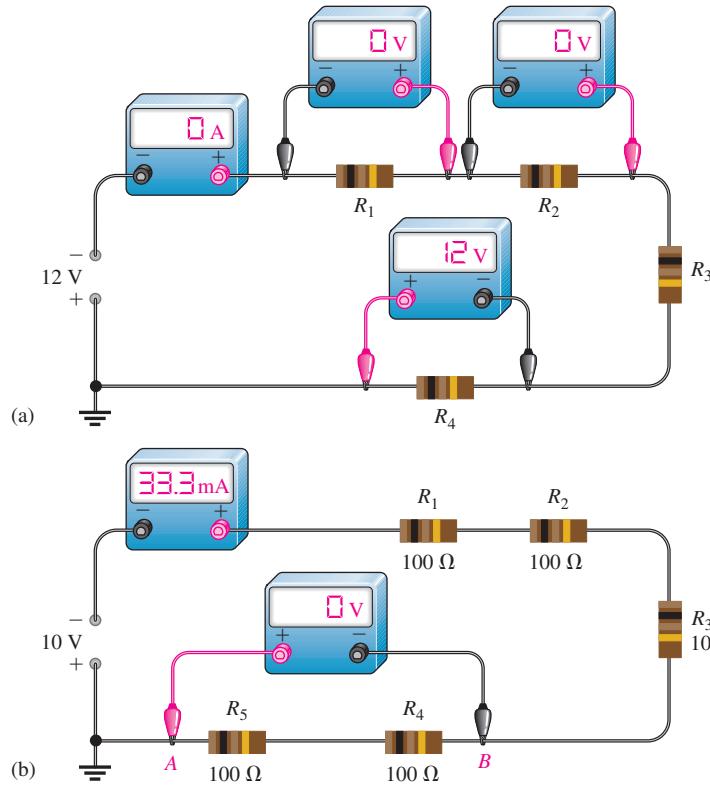


57. Determine the voltage at each point with respect to ground in Figure 5-89.  
 58. In Figure 5-89, what is  $V_{AC}$ ?  
 59. In Figure 5-89, what is  $V_{CA}$ ?

## SECTION 5-10 Troubleshooting

60. A string of five series resistors is connected across a 12 V battery. Zero volts is measured across all of the resistors except  $R_2$ . What is wrong with the circuit? What voltage will be measured across  $R_2$ ?

► FIGURE 5-90

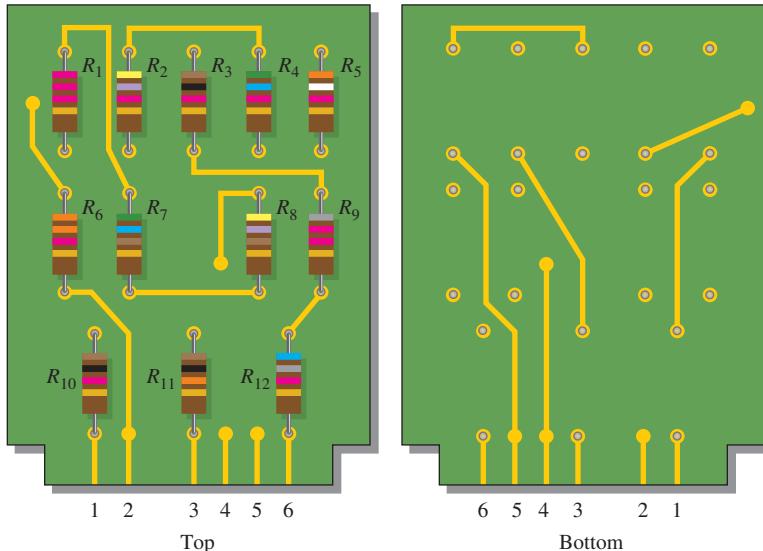


61. By observing the meters in Figure 5–90, determine the types of failures in the circuits and which components have failed.
62. What current would you measure in Figure 5–90(b) if only  $R_2$  were shorted?
- \*63. Table 5–2 shows the results of resistance measurements on the PC board in Figure 5–91. Are these results correct? If not, identify the possible problems.

► TABLE 5–2

BETWEEN PINS	RESISTANCE
1 and 2	$\infty$
1 and 3	$\infty$
1 and 4	4.23 k $\Omega$
1 and 5	$\infty$
1 and 6	$\infty$
2 and 3	23.6 k $\Omega$
2 and 4	$\infty$
2 and 5	$\infty$
2 and 6	$\infty$
3 and 4	$\infty$
3 and 5	$\infty$
3 and 6	$\infty$
4 and 5	$\infty$
4 and 6	$\infty$
5 and 6	19.9 k $\Omega$

- \*64. You measure 15 k $\Omega$  between pins 5 and 6 on the PC board in Figure 5–91. Does this indicate a problem? If so, identify it.
- \*65. In checking out the PC board in Figure 5–91, you measure 17.83 k $\Omega$  between pins 1 and 2. Also, you measure 13.6 k $\Omega$  between pins 2 and 4. Does this indicate a problem on the PC board? If so, identify the fault.
- \*66. The three groups of series resistors on the PC board in Figure 5–91 are connected in series with each other to form a single series circuit by connecting pin 2 to pin 4 and pin 3 to pin 5.



▲ FIGURE 5–91

A voltage source is connected across pins 1 and 6 and an ammeter is placed in series. As you increase the source voltage, you observe the corresponding increase in current. Suddenly, the current drops to zero and you smell smoke. All resistors are  $\frac{1}{2}$  W.

- What has happened?
- Specifically, what must you do to fix the problem?
- At what voltage did the failure occur?



### Multisim Troubleshooting and Analysis

These problems require Multisim.

- Open file P05-67 and measure the total series resistance.
- Open file P05-68 and determine by measurement if there is an open resistor and, if so, which one.
- Open file P05-69 and determine the unspecified resistance value.
- Open file P05-70 and determine the unspecified source voltage.
- Open file P05-71 and find the shorted resistor if there is one.

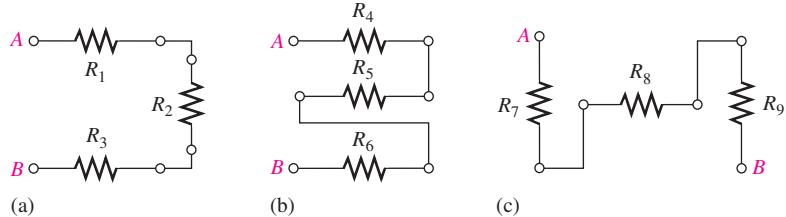
## ANSWERS

### SECTION CHECKUPS

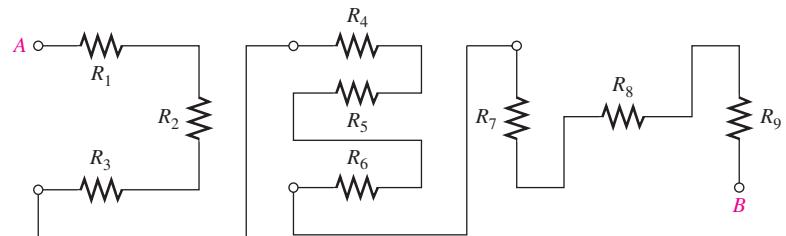
#### SECTION 5–1

##### Resistors in Series

- Series resistors are connected end-to-end in a “string” with each lead of a given resistor connected to a different resistor.
- There is a single current path in a series circuit.



▲ FIGURE 5–92



▲ FIGURE 5–93

- See Figure 5–92.
- See Figure 5–93.

#### SECTION 5–2

##### Total Series Resistance

- $R_T = 1.0 \Omega + 2.2 \Omega + 3.3 \Omega + 4.7 \Omega = 11.2 \Omega$
- $R_T = 100 \Omega + 2(56 \Omega) + 4(12 \Omega) + 330 \Omega = 590 \Omega$
- $R_5 = 13.8 \text{ k}\Omega - (1.0 \text{ k}\Omega + 2.7 \text{ k}\Omega + 5.6 \text{ k}\Omega + 560 \Omega) = 3.94 \text{ k}\Omega$
- $R_T = 12(56 \Omega) = 672 \Omega$
- $R_T = 20(5.6 \text{ k}\Omega) + 30(8.2 \text{ k}\Omega) = 358 \text{ k}\Omega$

### SECTION 5–3 Current in a Series Circuit

1.  $I = 20 \text{ mA}$
2. The milliammeter measures 50 mA between  $C$  and  $D$  and 50 mA between  $E$  and  $F$ .
3.  $I = 10 \text{ V}/560 \Omega = 17.9 \text{ mA}; 17.9 \text{ mA}$
4. In a series circuit, current is the same at all points.

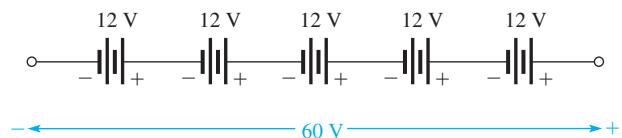
### SECTION 5–4 Application of Ohm's Law

1.  $I = 6 \text{ V}/300 \Omega = 20 \text{ mA}$
2.  $V_S = (50 \text{ mA})(21.2 \Omega) = 1.06 \text{ V}$
3.  $V_1 = (50 \text{ mA})(10 \Omega) = 0.5 \text{ V}; V_2 = (50 \text{ mA})(5.6 \Omega) = 0.28 \text{ V}; V_3 = (50 \text{ mA})(5.6 \Omega) = 0.28 \text{ V}$
4.  $R = \frac{1}{4}(5 \text{ V}/4.63 \text{ mA}) = 270 \Omega$
5.  $R = 130 \Omega$

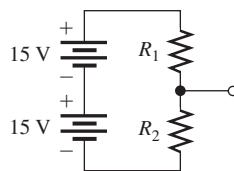
### SECTION 5–5 Voltage Sources in Series

1.  $V_T = 4(1.5 \text{ V}) = 6.0 \text{ V}$
2.  $60 \text{ V}/12 \text{ V} = 5$ ; see Figure 5–94.

► FIGURE 5–94



► FIGURE 5–95



3. See Figure 5–95.
4.  $V_{S(\text{tot})} = 9 \text{ V} + 6 \text{ V} + 15 \text{ V} = 30 \text{ V}$
5.  $3.0 \text{ V}$

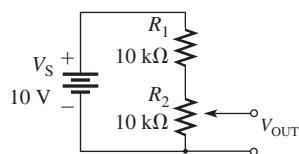
### SECTION 5–6 Kirchhoff's Voltage Law

1. (a) Kirchhoff's law states that the algebraic sum of the voltages around a closed path is zero;  
(b) Kirchhoff's law states that the sum of the voltage drops equals the total source voltage.
2.  $V_T = V_S = 50 \text{ V}$
3.  $120 \text{ V}$
4.  $V_3 = 25 \text{ V} - 10 \text{ V} - 5 \text{ V} = 10 \text{ V}$
5.  $V_S = 1 \text{ V} + 3 \text{ V} + 5 \text{ V} + 8 \text{ V} + 7 \text{ V} = 24 \text{ V}$

### SECTION 5–7 Voltage Dividers

1. A voltage divider is a circuit with two or more series resistors in which the voltage taken across any resistor or combination of resistors is proportional to the value of that resistance.
2.  $V_x = (R_x/R_T)V_S$
3.  $V_R = 10 \text{ V}/2 = 5 \text{ V}$
4. 0.0637
5. See Figure 5–96

► FIGURE 5–96



**SECTION 5–8 Power in Series Circuits**

1. Add the power in each resistor to get total power.
2.  $P_T = 2 \text{ W} + 5 \text{ W} + 1 \text{ W} + 8 \text{ W} = 16 \text{ W}$
3.  $P_T = (1 \text{ A})^2(1,110 \Omega) = 1,110 \text{ W}$

**SECTION 5–9 Voltage Measurements**

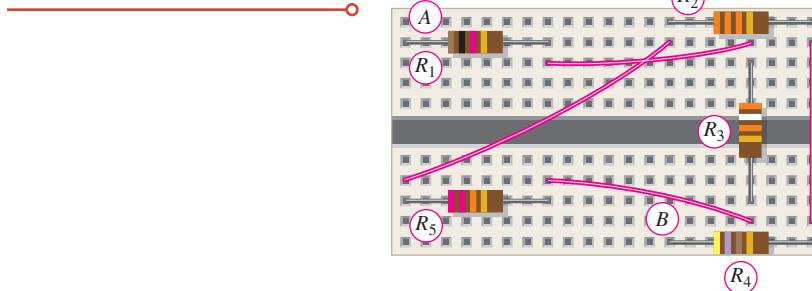
1. The reference point in a circuit is called ground or common.
2. True
3. True
4.  $V_{BA} = -5.0 \text{ V}$

**SECTION 5–10 Troubleshooting**

1. A short is a zero resistance path that bypasses a portion of a circuit.
2. An open is a break in the current path.
3. When a circuit opens, current ceases.
4. An open can be created by a switch or by a component failure. A short can be created by a switch or, unintentionally, by a wire clipping or solder splash.
5. True, a resistor normally fails open.
6. 24 V across the open  $R$ ; 0 V across the other  $R_s$

**RELATED PROBLEMS FOR EXAMPLES**

- 5–1** (a) See Figure 5–97.  
(b)  $R_1 = 1.0 \text{ k}\Omega$ ,  $R_2 = 33 \text{ k}\Omega$ ,  $R_3 = 39 \text{ k}\Omega$ ,  $R_4 = 470 \Omega$ ,  $R_5 = 22 \text{ k}\Omega$

**► FIGURE 5–97**

- 5–2** All resistors on the board are in series.

**5–3**  $258 \Omega$

**5–4**  $12.1 \text{ k}\Omega$

**5–5**  $6.8 \text{ k}\Omega$

**5–6**  $4,440 \Omega$

**5–7**  $18.0 \text{ mA}$

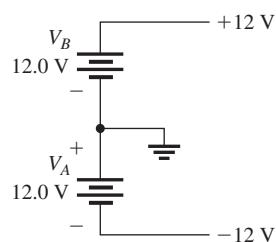
**5–8**  $7.8 \text{ V}$

**5–9**  $V_1 = 1 \text{ V}$ ,  $V_2 = 3.3 \text{ V}$ ,  $V_3 = 2.2 \text{ V}$ ;  $V_S = 6.5 \text{ V}$ ;  $V_{S(\max)} = 32.5 \text{ V}$

**5–10**  $R_2 = 275 \Omega$

**5–11**  $24 \text{ V}$

**5–12** See Figure 5–98.

**► FIGURE 5–98**

**5-13** 10 V and 20 V;  $V_{\text{fuse}} = V_S = 30 \text{ V}$ ;  $V_{R1} = V_{R2} = 0 \text{ V}$ **5-14** 930  $\Omega$ **5-15** 47 V**5-16**  $V_1 = 3.57 \text{ V}$ ;  $V_2 = 6.43 \text{ V}$ **5-17**  $V_1 = V_2 = V_3 = 3.33 \text{ V}$ **5-18**  $V_{AB} = 4 \text{ V}$ ;  $V_{AC} = 36.8 \text{ V}$ ;  $V_{BC} = 32.8 \text{ V}$ ;  $V_{BD} = 46 \text{ V}$ ;  $V_{CD} = 13.2 \text{ V}$ 

$$\text{5-19} \quad V_x = \left( \frac{R_x}{R_T} \right) V_S$$

$$\frac{V_x}{V_S} = \frac{R_x}{R_T} = \frac{R_x}{R + R_x}$$

$$\frac{1.5 \text{ V}}{4.5 \text{ V}} = \frac{90 \text{ k}\Omega}{R + 90 \text{ k}\Omega}$$

$$1.5 \text{ V}(R + 90 \text{ k}\Omega) = (4.5 \text{ V})(90 \text{ k}\Omega)$$

$$1.5R = 270 \text{ }\Omega$$

$$R = 180 \text{ }\Omega$$

**5-20** 8.49 W**5-21**  $P_1 = 0.92 \text{ W}$  (1 W);  $P_2 = 2.49 \text{ W}$  (5 W);  $P_3 = 0.838 \text{ W}$  (1 W);  $P_4 = 3.04 \text{ W}$  (5 W)**5-22**  $V_A = 0 \text{ V}$ ;  $V_B = -25 \text{ V}$ ;  $V_C = -50 \text{ V}$ ;  $V_D = -75 \text{ V}$ ;  $V_E = -100 \text{ V}$ **5-23** 3.33 V**TRUE/FALSE QUIZ**

- |             |             |             |             |              |
|-------------|-------------|-------------|-------------|--------------|
| <b>1.</b> F | <b>2.</b> F | <b>3.</b> F | <b>4.</b> T | <b>5.</b> T  |
| <b>6.</b> T | <b>7.</b> F | <b>8.</b> T | <b>9.</b> T | <b>10.</b> F |

**SELF-TEST**

- |               |               |                |                |                |                |                |
|---------------|---------------|----------------|----------------|----------------|----------------|----------------|
| <b>1.</b> (a) | <b>2.</b> (d) | <b>3.</b> (b)  | <b>4.</b> (d)  | <b>5.</b> (d)  | <b>6.</b> (a)  | <b>7.</b> (b)  |
| <b>8.</b> (c) | <b>9.</b> (b) | <b>10.</b> (c) | <b>11.</b> (a) | <b>12.</b> (d) | <b>13.</b> (d) | <b>14.</b> (d) |

**CIRCUIT DYNAMICS QUIZ**

- |               |                |                |                |                |                |                |               |
|---------------|----------------|----------------|----------------|----------------|----------------|----------------|---------------|
| <b>1.</b> (b) | <b>2.</b> (b)  | <b>3.</b> (c)  | <b>4.</b> (a)  | <b>5.</b> (a)  | <b>6.</b> (b)  | <b>7.</b> (a)  | <b>8.</b> (a) |
| <b>9.</b> (a) | <b>10.</b> (b) | <b>11.</b> (b) | <b>12.</b> (c) | <b>13.</b> (a) | <b>14.</b> (a) | <b>15.</b> (b) |               |