SERIES CIRCUITS

5

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Identify a series resistive circuit
- Determine the current throughout a series circuit
- Determine total series resistance
- 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
- Reference ground
- Open
- Short

A CIRCUIT APPLICATION PREVIEW

In the application, 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.prenhall.com/floyd

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; and, 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.

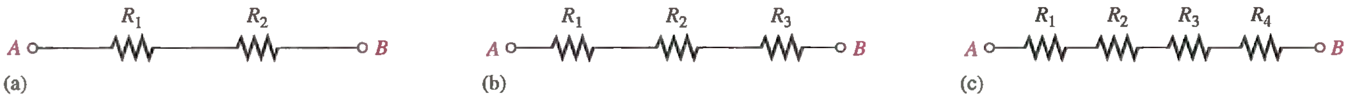
5–1 RESISTORS IN SERIES

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.



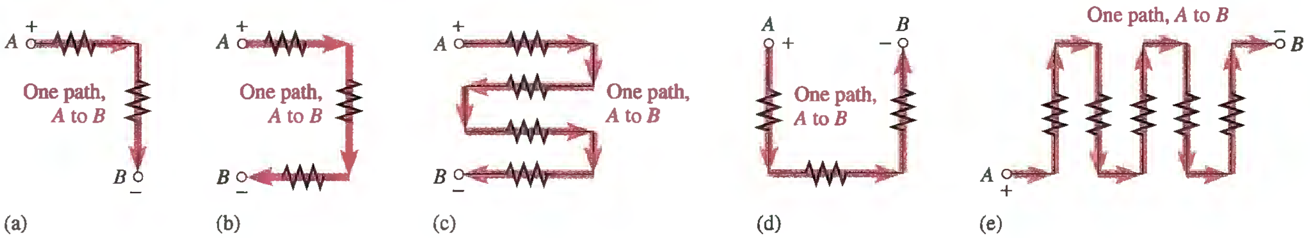
▲ FIGURE 5–1

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.



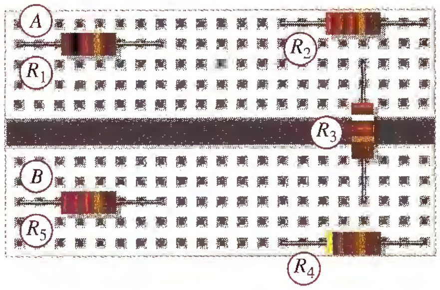
▲ FIGURE 5–2

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

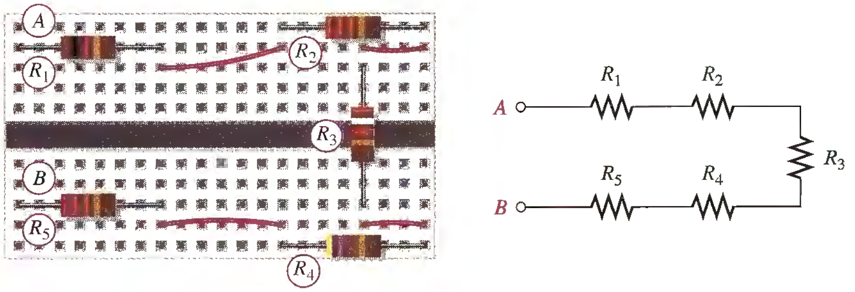
Suppose that there are five resistors positioned on a protoboard as shown in Figure 5–3. Wire them together in series so that, starting from the positive (+) terminal, R_1 is first, R_2 is second, R_3 is third, and so on. Draw a schematic showing this connection.

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.

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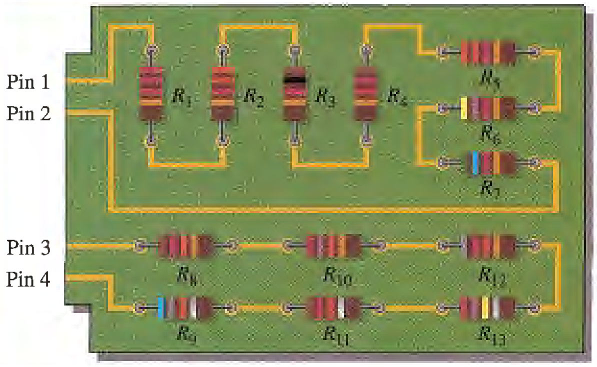
*Answers are at the end of the chapter.

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 $R_{13} = 270\,\text{k}\Omega$.

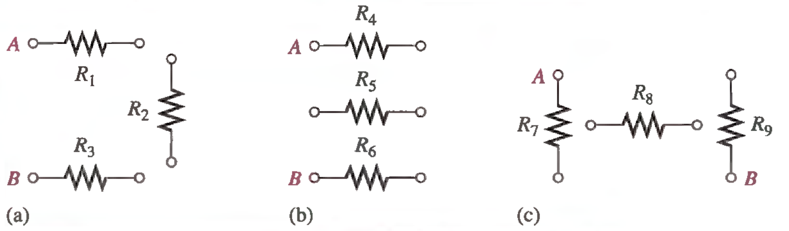
Related Problem How is the circuit changed when pin 2 and pin 3 in Figure 5–5 are connected?

SECTION 5–1 REVIEW

Answers are at the end of the chapter.

1. How are the resistors connected in a series circuit?
2. How can you identify a series circuit?
3. 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*.
4. Connect each group of series resistors in Figure 5–6 in series with each other.

▶ FIGURE 5–6



(a) (b) (c)

5–2 CURRENT IN A SERIES CIRCUIT

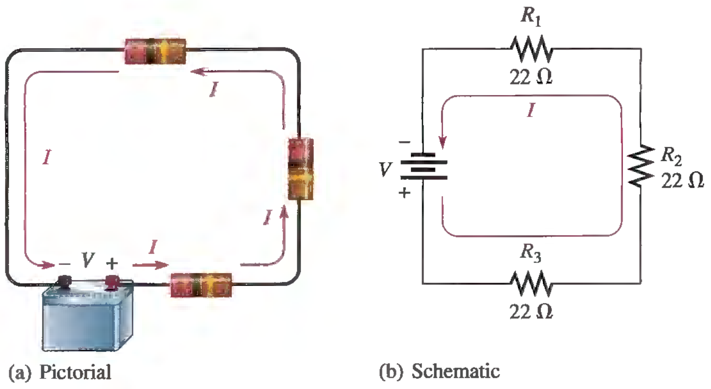
The current is the same through all points in a series circuit. The current through each resistor in a series circuit is the same as the current through all the other resistors that are in series with it.

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 5–7 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 can branch off and go somewhere else. 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.

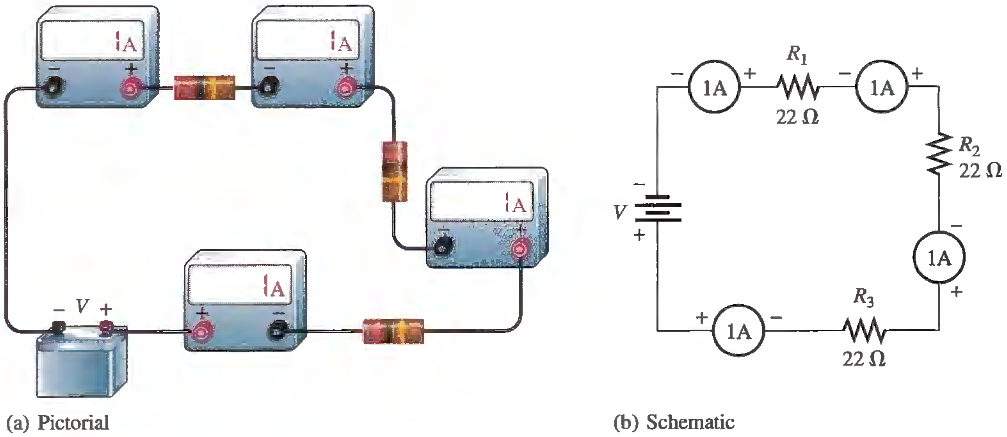
Let's assume that the battery in Figure 5–7 supplies one ampere of current to the series resistance. There is one ampere of current out of the battery's positive terminal. When ammeters are connected at several points in the circuit, as shown in Figure 5–8, each meter reads one ampere.



(a) Pictorial (b) Schematic

FIGURE 5–7

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



(a) Pictorial (b) Schematic

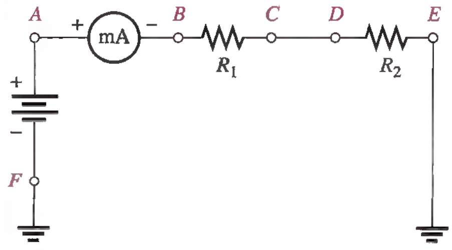
FIGURE 5–8

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

SECTION 5–2 REVIEW

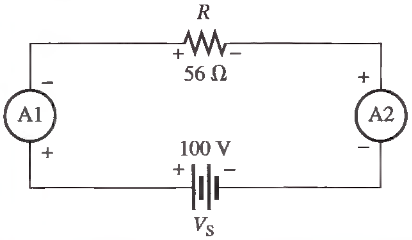
1. In a circuit with a 10 Ω and a 4.7 Ω resistor in series, there is 1 A of current through the 10 Ω resistor. How much current is through the 4.7 Ω resistor?
2. A milliammeter is connected between points *A* and *B* in Figure 5–9. It measures 50 mA. If you move the meter and connect it between points *C* and *D*, how much current will it indicate? Between *E* and *F*?

FIGURE 5–9



3. In Figure 5–10, how much current does ammeter 1 indicate? How much current does ammeter 2 indicate?
4. Describe current in a series circuit?

FIGURE 5–10



5–3 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 5–11 illustrates how series resistances add to increase the total resistance. Figure 5–11(a) has a single 10 Ω resistor. Figure 5–11(b) shows another 10 Ω resistor connected

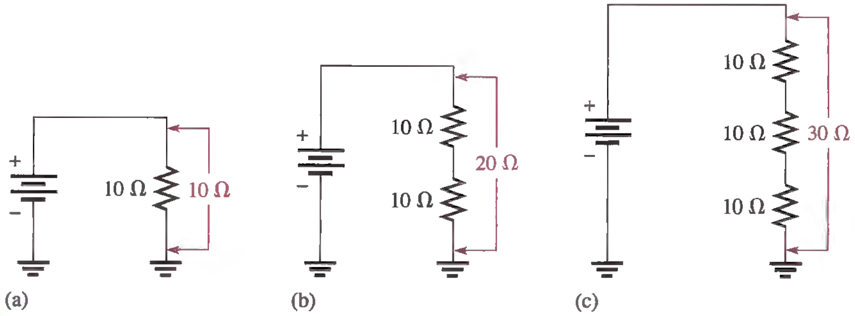


FIGURE 5–11

Total resistance increases with each additional series resistor.

in series with the first one, making a total resistance of 20 Ω. If a third 10 Ω resistor is connected in series with the first two, as shown in Figure 5–11(c), the total resistance becomes 30 Ω.

Series Resistance Formula

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

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

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

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

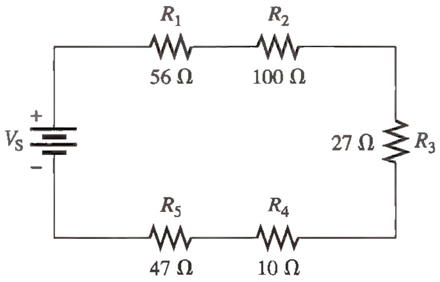
If there are six resistors in series ($n = 6$), the total resistance formula is

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

To illustrate the calculation of total series resistance, let's determine R_T in the circuit of Figure 5–12, 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 5–12 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.



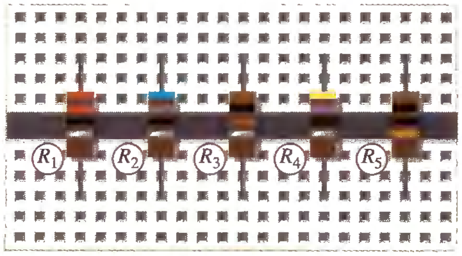
▲ FIGURE 5–12

Example of five resistors in series.

EXAMPLE 5–3

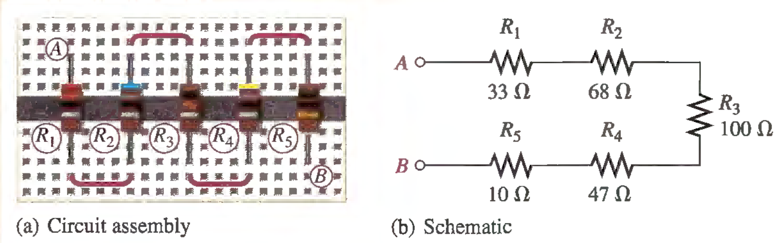
Connect the resistors in Figure 5–13 in series, and determine the total resistance, R_T.

▸ FIGURE 5–13



Solution The resistors are connected as shown in Figure 5–14. Find the total resistance by adding all the values.

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



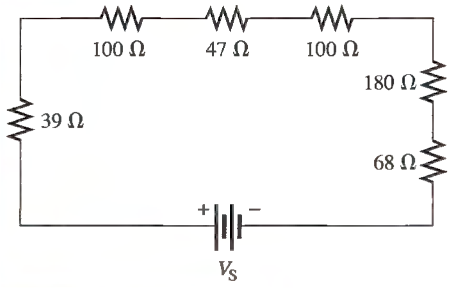
(a) Circuit assembly (b) Schematic

▲ **FIGURE 5–14**

Related Problem Determine the total resistance in Figure 5–14(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 5–15?



▲ **FIGURE 5–15**

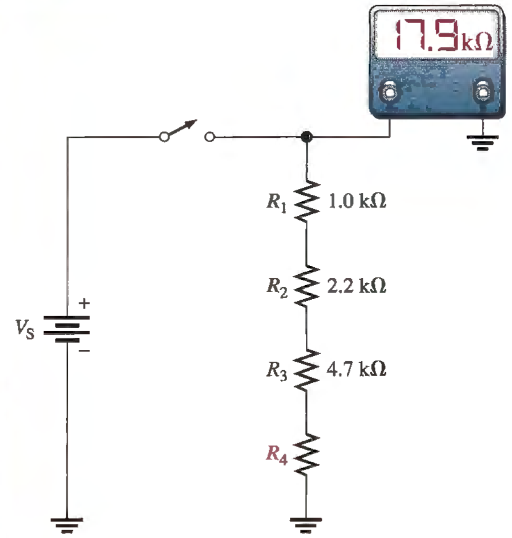
Solution Sum all the values.

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

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 5–16.

FIGURE 5–16



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

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

Related Problem Determine the value of R_4 in Figure 5–16 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 shortcut 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 Ω) = 500 Ω. In general, the formula is expressed as

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

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.

$$R_T = 22\,\Omega + 22\,\Omega + 22\,\Omega + 22\,\Omega + 22\,\Omega + 22\,\Omega + 22\,\Omega + 22\,\Omega = \mathbf{176\,\Omega}$$

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

$$R_T = 8(22\,\Omega) = \mathbf{176\,\Omega}$$

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

SECTION 5–3 REVIEW

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

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.

$$V_R = I_T R_x$$

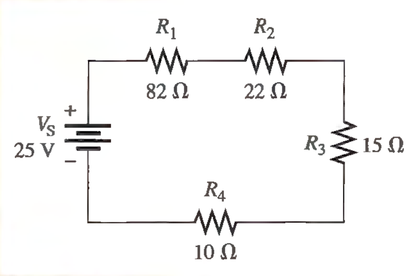
5. The polarity of a voltage drop across a resistor is positive at the end of the resistor that is closest to the positive terminal of the voltage source.
6. The current through a resistor is defined to be in a direction from the positive end of the resistor to the negative end.
7. An open in a series circuit prevents current; and, 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.

$$R_T = R_1 + R_2 + R_3 + R_4 = 82\,\Omega + 22\,\Omega + 15\,\Omega + 10\,\Omega = 129\,\Omega$$

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

$$I = \frac{V_S}{R_T} = \frac{25\text{ V}}{129\,\Omega} = 0.194\text{ A} = \mathbf{194\text{ mA}}$$

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 194 mA through it.

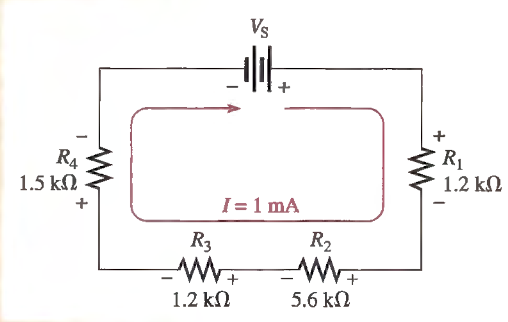
Related Problem What is the current in the circuit of Figure 5–17 if R_4 is changed to 100 Ω?

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.

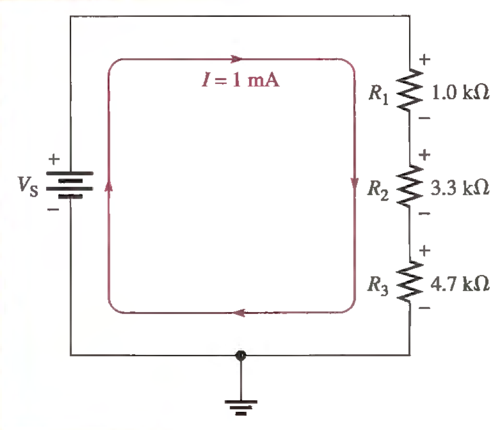
$$V_S = IR_T = (1\text{ mA})(9.5\,\text{k}\Omega) = \mathbf{9.5\text{ V}}$$

Related Problem Calculate V_S if the 5.6 kΩ resistor is changed to 3.9 kΩ with the current the same.

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?



▲ FIGURE 5–19

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 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

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

The voltage across R_2 is

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

The voltage across R_3 is

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

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.

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

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 $I = 5$ mA. Calculate the maximum value of V_S as follows:

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

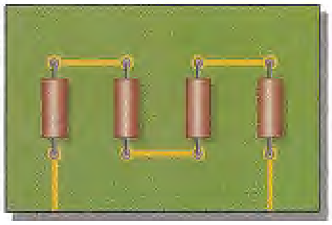
Related Problem Repeat the calculations for V_1, V_2, V_3, V_S, and $V_{S(max)}$ if $R_3 = 2.2\text{ k}\Omega$ and I is maintained at 1 mA.

Use Multisim file E05-09 to verify the calculated results in this example and to confirm your calculations for the related problem.

EXAMPLE 5–10

Some resistors are not color-coded with bands but have the values stamped on the resistor body. When the circuit board shown in Figure 5–20 was assembled, the resistors were erroneously mounted with the labels turned down, and there is no documentation showing the resistor values. Without removing the resistors from the board, use Ohm's law to determine the resistance of each one. Assume that a multimeter and a power supply are available but the ohmmeter function of the multimeter does not work.

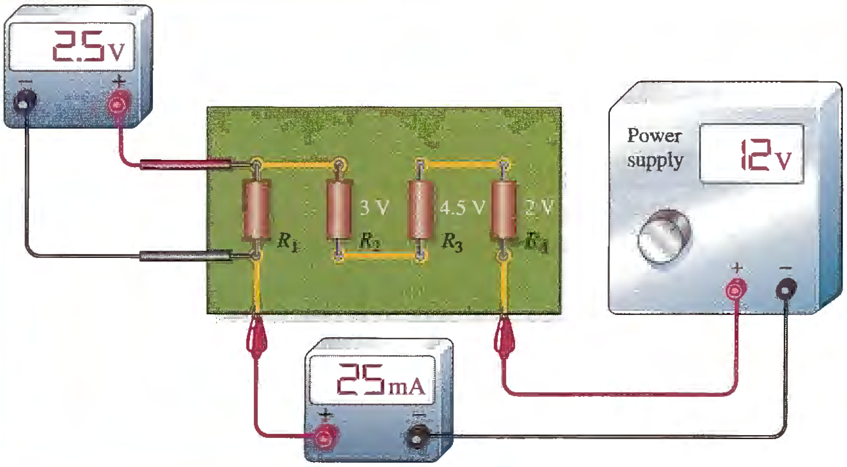
FIGURE 5–20



Solution The resistors are all in series, so the current is the same through each one. Measure the current by connecting a 12 V source (arbitrary value) and an ammeter as shown in Figure 5–21. Measure the voltage across each resistor. Start with the voltmeter across the first resistor, and then repeat this measurement for the other three resistors. For illustration, the voltage values indicated on the board are assumed to be the measured values.

FIGURE 5–21

The voltmeter readings across each resistor are indicated.



Determine the resistance of each resistor by substituting the measured values of current and voltage into the Ohm's law formula.

$$R_1 = \frac{V_1}{I} = \frac{2.5\text{ V}}{25\text{ mA}} = \mathbf{100\ \Omega}$$

$$R_2 = \frac{V_2}{I} = \frac{3\text{ V}}{25\text{ mA}} = \mathbf{120\ \Omega}$$

$$R_3 = \frac{V_3}{I} = \frac{4.5\text{ V}}{25\text{ mA}} = \mathbf{180\ \Omega}$$

$$R_4 = \frac{V_4}{I} = \frac{2\text{ V}}{25\text{ mA}} = \mathbf{80\ \Omega}$$

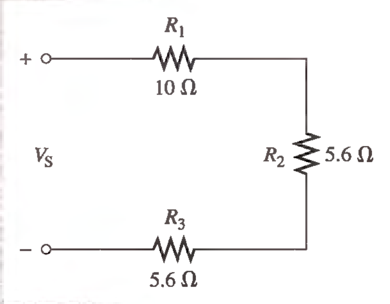
Notice that the largest-value resistor has the largest voltage drop across it.

Related Problem What is an easier way to determine the resistance values?

SECTION 5–4 REVIEW

1. A 10 V battery is connected across three 100 Ω 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 5–22?

FIGURE 5–22



3. How much voltage is dropped across each resistor in Figure 5–22 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?

5–5 VOLTAGE SOURCES IN SERIES

Recall that a voltage source is an energy source that provides a constant voltage to a load. Batteries and electronic power supplies 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

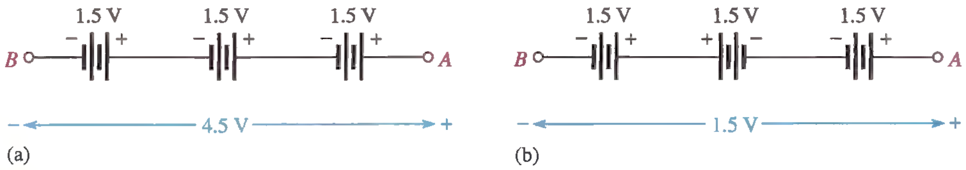


FIGURE 5–23

Voltage sources in series add algebraically.

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.

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

When the voltage sources are all in the same direction in terms of their polarities, as in Figure 5–23(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 5–23(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 5–24.

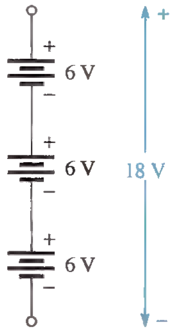


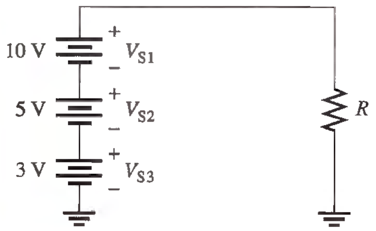
FIGURE 5–24

Connection of three 6 V batteries to obtain 18 V.

EXAMPLE 5–11

What is the total source voltage ($V_{S(tot)}$) in Figure 5–25?

FIGURE 5–25

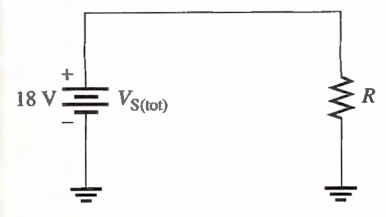


Solution The polarity of each source is the same (the sources are connected in the same direction in the circuit). Add the three voltages to get the total.

$$V_{S(tot)} = V_{S1} + V_{S2} + V_{S3} = 10\text{ V} + 5\text{ V} + 3\text{ V} = \mathbf{18\text{ V}}$$

The three individual sources can be replaced by a single equivalent source of 18 V with its polarity as shown in Figure 5–26.

FIGURE 5–26



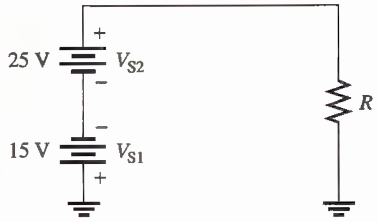
Related Problem If V_{S3} in Figure 5–25 is reversed, what is the total source voltage?

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

Determine $V_{S(tot)}$ in Figure 5–27.

FIGURE 5–27

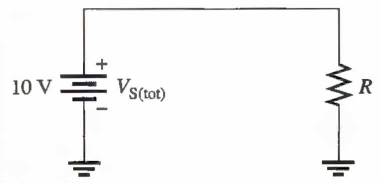


Solution These sources are connected in opposing directions. If you go clockwise around the circuit, you go from plus to minus through V_{S1}, and minus to plus through V_{S2}. The total voltage is the difference of the two source voltages (algebraic sum of oppositely signed values). The total voltage has the same polarity as the larger-value source. Here we will choose V_{S2} to be positive.

$$V_{S(tot)} = V_{S2} - V_{S1} = 25\text{ V} - 15\text{ V} = \mathbf{10\text{ V}}$$

The two sources in Figure 5–27 can be replaced by a single 10 V equivalent source with polarity as shown in Figure 5–28.

FIGURE 5–28



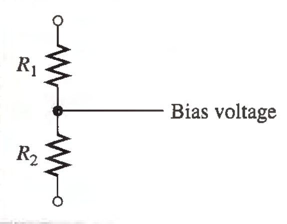
Related Problem If an 8 V source in the direction of V_{S1} is added in series in Figure 5–27, what is $V_{S(tot)}$?

Use Multisim file E05-12 to verify the calculated results in this example and to confirm your calculation for the related problem.

SECTION 5–5 REVIEW

1. Four 1.5 V flashlight batteries are connected in series plus to minus. What is the total voltage of all four cells?
2. How many 12 V batteries must be connected in series to produce 60 V? Draw a schematic that shows the battery connections.
3. The resistive circuit in Figure 5–29 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.
4. Determine the total source voltage in each circuit of Figure 5–30.
5. Draw the equivalent single-source circuit for each circuit of Figure 5–30.

FIGURE 5–29



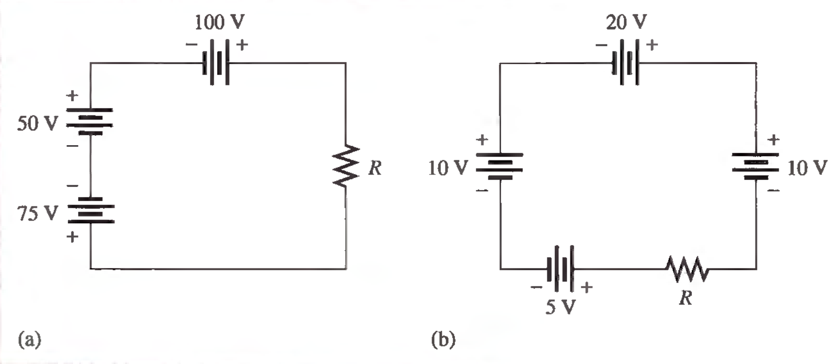


FIGURE 5–30

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.

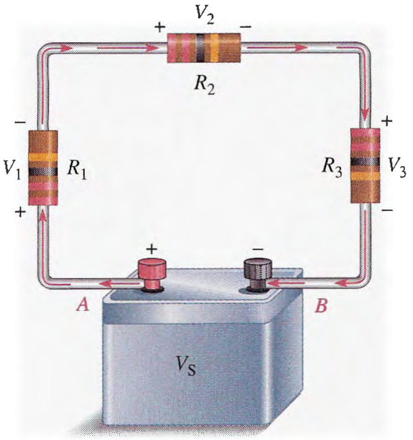
After completing this section, you should be able to

- **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 5–31, follow a clockwise loop around the circuit. Note that the source polarity is minus-to-plus and each

▶ **FIGURE 5–31**

Illustration of voltage polarities in a closed-loop circuit.



voltage drop is plus-to-minus. The voltage drops across resistors are designated as V_1, V_2, and so on.

In Figure 5–31, 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 level 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 5–31 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.

The general concept of Kirchhoff's voltage law is illustrated in Figure 5–32 and expressed by Equation 5–3.

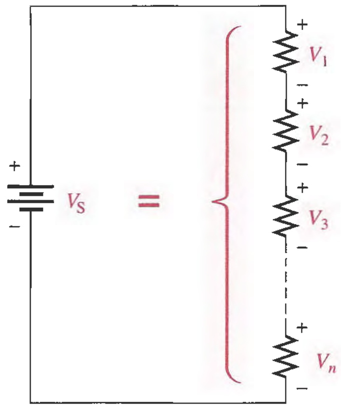
Equation 5–3

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

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

▶ **FIGURE 5–32**

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



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.

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

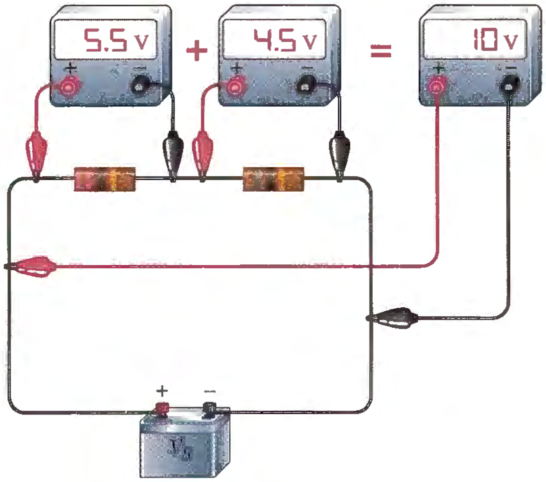
Therefore, another way of expressing Kirchhoff's voltage law in equation form is

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

Equation 5–4

You can verify Kirchhoff's voltage law by connecting a circuit and measuring each resistor voltage and the source voltage as illustrated in Figure 5–33. When the resistor voltages are added together, their sum will equal the source voltage. Any number of resistors can be added.

The three examples that follow use Kirchhoff's voltage law to solve circuit problems.



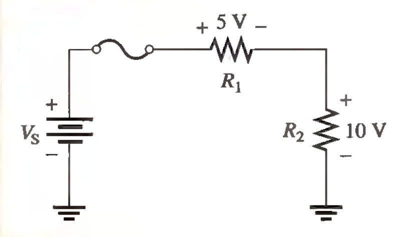
▲ FIGURE 5–33

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

EXAMPLE 5–13

Determine the source voltage V_S in Figure 5–34 where the two voltage drops are given. There is no voltage drop across the fuse.

▶ FIGURE 5–34



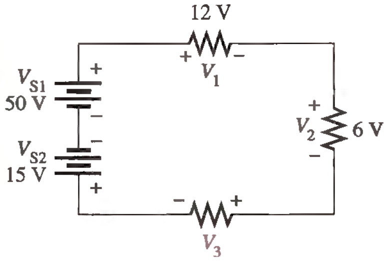
Solution By Kirchhoff's voltage law, (Eq. 5–3), the source voltage (applied voltage) must equal the sum of the voltage drops. Adding the voltage drops gives the value of the source voltage.

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

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?

EXAMPLE 5–14 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.

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

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

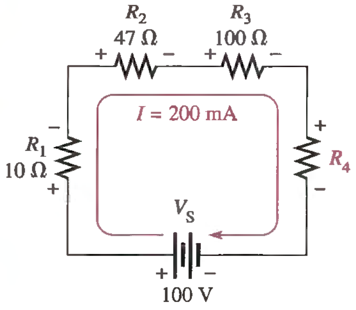
$$17\text{ V} - V_3 = 0\text{ V}$$
$$-V_3 = -17\text{ V}$$
$$V_3 = \mathbf{17\text{ V}}$$

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.

EXAMPLE 5–15 Find the value of R_4 in Figure 5–36.

FIGURE 5–36



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.

$$V_1 = IR_1 = (200\text{ mA})(10\ \Omega) = 2.0\text{ V}$$
$$V_2 = IR_2 = (200\text{ mA})(47\ \Omega) = 9.4\text{ V}$$
$$V_3 = IR_3 = (200\text{ mA})(100\ \Omega) = 20\text{ V}$$

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

$$\begin{aligned} V_S - V_1 - V_2 - V_3 - V_4 &= 0\text{ V} \\ 100\text{ V} - 2.0\text{ V} - 9.4\text{ V} - 20\text{ V} - V_4 &= 0\text{ V} \\ 68.6\text{ V} - V_4 &= 0\text{ V} \\ V_4 &= 68.6\text{ V} \end{aligned}$$

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

$$R_4 = \frac{V_4}{I} = \frac{68.6\text{ V}}{200\text{ mA}} = \mathbf{343\ \Omega}$$

This is most likely a 330 Ω resistor because 343 Ω is within a standard tolerance range (+5%) of 330 Ω.

Related Problem Determine R_4 in Figure 5–36 for $V_S = 150$ V and $I = 200$ mA.

Use Multisim file E05-15 to verify the calculated results in the example and to confirm your calculation for the related problem.

SECTION 5-6 REVIEW

1. State Kirchhoff's voltage law in two ways.
2. A 50 V source is connected to a series resistive circuit. What is the sum of the voltage drops in this circuit?
3. Two equal-value resistors are connected in series across a 10 V battery. What is the voltage drop across each resistor?
4. 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?
5. 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.

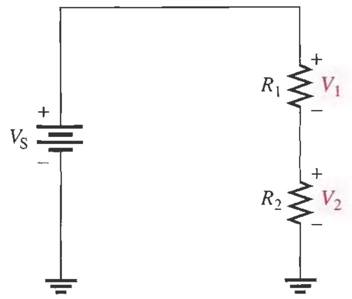
After completing this section, you should be able to

- **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 5–37 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

▶ FIGURE 5–37

Two-resistor voltage divider.



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.

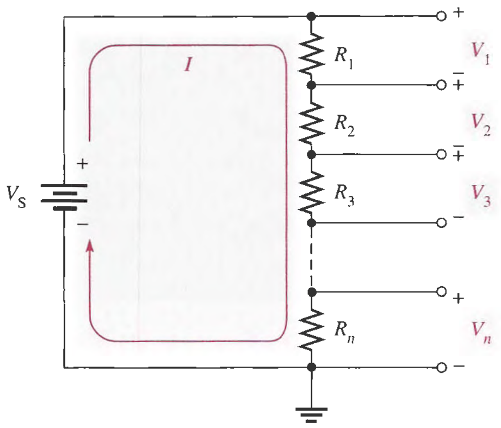
The total voltage drop around a single closed path divides among the series resistors in amounts directly proportional to the resistance values. For example, in Figure 5–37, if V_S is 10 V, R_1 is 50 Ω, and R_2 is 100 Ω, then V_1 is one-third the total voltage, or 3.33 V, because R_1 is one-third the 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 5–38, where n can be any number.

▶ FIGURE 5–38

Generalized voltage divider with n resistors.



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 5–38, the total resistance is $R_1 + R_2 + R_3 + \cdots + R_n$. 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

Equation 5–5

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

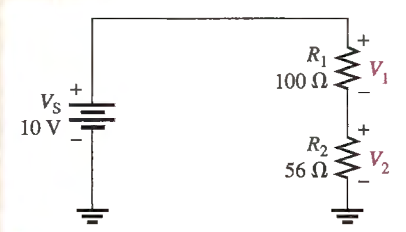
Equation 5–5 is the general voltage-divider formula, which can be stated as follows:

> **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 5–39.

FIGURE 5–39



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 Ω and V_S is 10 V. Substitute these values into the voltage-divider formula.

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

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:

$$V_2 = V_S - V_1 = 10\text{ V} - 6.41\text{ V} = \mathbf{3.59\ V}$$

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

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

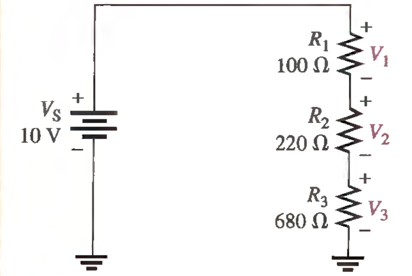
Related Problem Find the voltages across R_1 and R_2 in Figure 5–39 if R_2 is changed to 180 Ω.

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 5–40.

FIGURE 5–40



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

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 not always 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.

$$V_1 = \left(\frac{R_1}{R_T}\right)V_S = \left(\frac{100\ \Omega}{1000\ \Omega}\right)10\text{ V} = \mathbf{1\ V}$$

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

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

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 5–40 are changed to 680 Ω, what are the voltage drops?

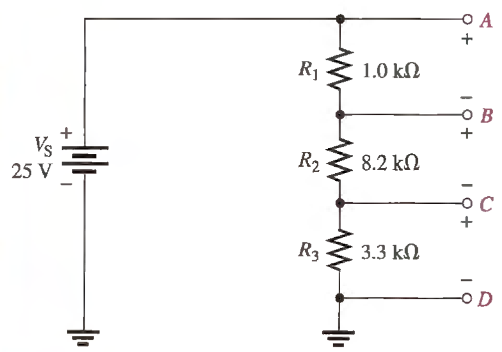
Use Multisim file E05-17 to verify the calculated results in this example and to confirm your calculations for the related problem.

EXAMPLE 5–18

Determine the voltages between the following points in the voltage divider of Figure 5–41:

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

FIGURE 5–41



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.

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

$$V_{AB} = \left(\frac{R_1}{R_T}\right)V_S = \left(\frac{1.0\text{ k}\Omega}{12.5\text{ k}\Omega}\right)25\text{ V} = \mathbf{2\text{ V}}$$

(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 $R_1 + R_2$.

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

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

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

(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 $R_2 + R_3$.

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

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

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

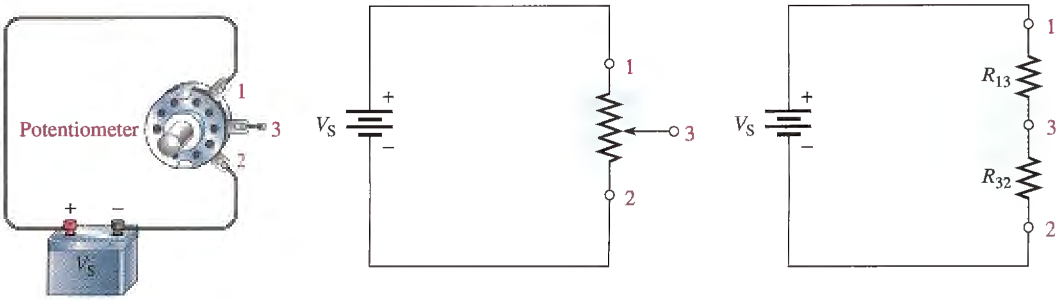
If you connect this voltage divider, you can verify each of the calculated voltages by connecting a voltmeter between the appropriate points in each case.

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 potentiometer connected to a voltage source is shown in Figure 5–42(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



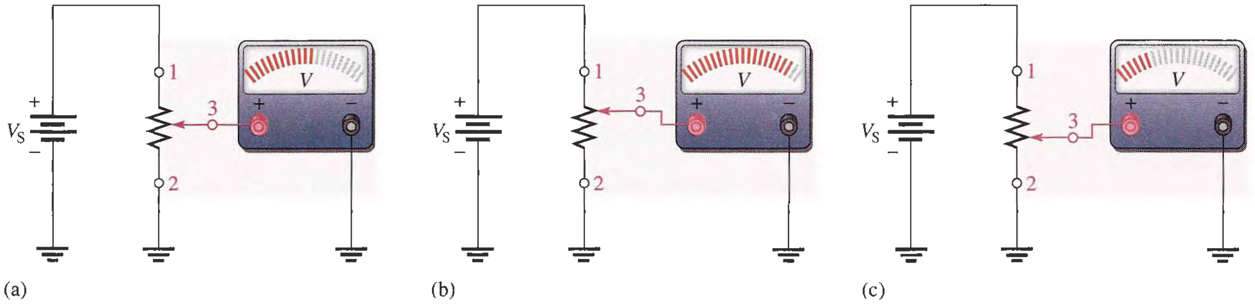
(a) Pictorial (b) Schematic (c) Equivalent schematic

▲ **FIGURE 5–42**

The potentiometer used as a voltage divider.

illustrated by separating the total resistance into two parts, as shown in Figure 5–42(c). The resistance between terminal 1 and terminal 3 (R_{13}) is 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.

Figure 5–43 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.

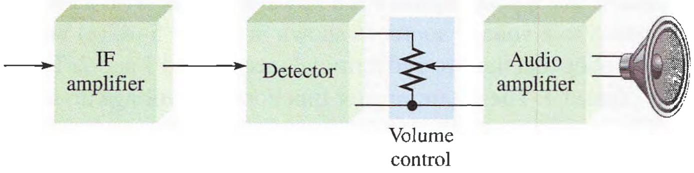


▲ FIGURE 5–43

Adjusting the voltage divider.

Applications

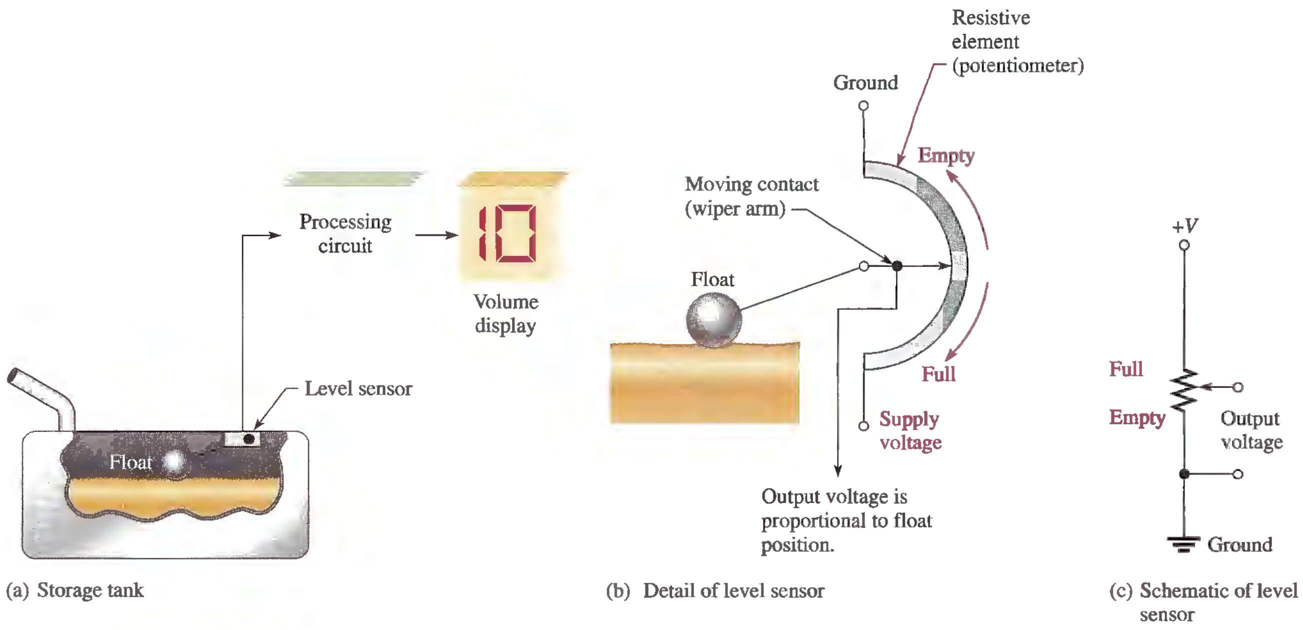
The volume control of radio or TV receivers is a common application of a potentiometer used as a voltage divider. Since the loudness of the sound is dependent on the amount of voltage associated with the audio signal, you can increase or decrease the volume by adjusting the potentiometer, that is, by turning the knob of the volume control on the set. The block diagram in Figure 5–44 shows how a potentiometer can be used for volume control in a typical receiver.



▲ FIGURE 5–44

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

Another application of a voltage divider is illustrated in Figure 5–45, which depicts a potentiometer voltage divider 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 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).



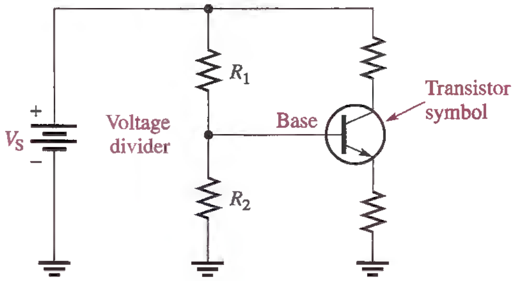
(a) Storage tank (b) Detail of level sensor (c) Schematic of level sensor

▲ FIGURE 5–45

A potentiometer voltage divider used in a level sensor.

Still another application for voltage dividers is 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.

These examples are only three out of many possible applications of voltage dividers.



◀ FIGURE 5–46

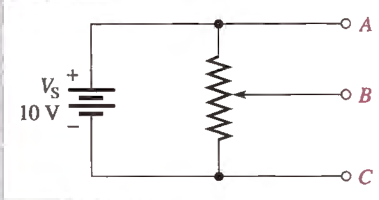
The voltage divider used as a bias circuit for a transistor amplifier, where the voltage at the base of the transistor is determined by the voltage divider as $V_{base} = (R_2/(R_1 + R_2))V_S$.

SECTION 5–7 REVIEW

1. What is a voltage divider?
2. How many resistors can there be in a series voltage-divider circuit?
3. Write the general formula for voltage dividers.
4. If two series resistors of equal value are connected across a 10 V source, how much voltage is there across each resistor?
5. A 47 kΩ resistor and an 82 kΩ resistor are connected as a voltage divider. The source voltage is 100 V. Draw the circuit, and determine the voltage across each of the resistors.

6. The circuit of Figure 5–47 is an adjustable voltage divider. If the potentiometer is linear, where would you set the wiper in order to get 5 V from *A* to *B* and 5 V from *B* to *C*?

▸ FIGURE 5–47



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

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

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:

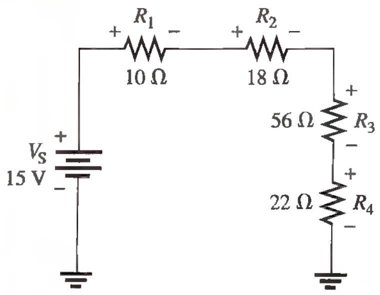
$$P_T = V_S I$$
$$P_T = I^2 R_T$$
$$P_T = \frac{V_S^2}{R_T}$$

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 5–19

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.

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

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

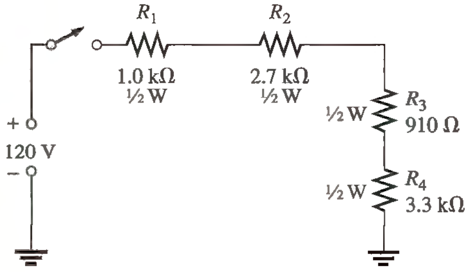
Related Problem What is the power in the circuit of Figure 5–48 if V_S is increased to 30 V?

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 5–20

Determine if the indicated power rating (½ W) of each resistor in Figure 5–49 is sufficient to handle the actual power. If a rating is not adequate, specify the required minimum rating.

▶ FIGURE 5–49



Solution First, determine the total resistance.

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

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.

$$P_1 = I^2R_1 = (15\text{ mA})^2(1.0\text{ k}\Omega) = \mathbf{225\text{ mW}}$$
$$P_2 = I^2R_2 = (15\text{ mA})^2(2.7\text{ k}\Omega) = \mathbf{608\text{ mW}}$$
$$P_3 = I^2R_3 = (15\text{ mA})^2(910\ \Omega) = \mathbf{205\text{ mW}}$$
$$P_4 = I^2R_4 = (15\text{ mA})^2(3.3\text{ k}\Omega) = \mathbf{743\text{ mW}}$$

R_2 and R_4 do not have a rating sufficient to handle the actual power, which exceeds ½ 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 REVIEW

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 Ω, a 330 Ω, and a 680 Ω resistor in series. There is a current of 1 A through the circuit. What is the total power?

5–9 VOLTAGE MEASUREMENTS

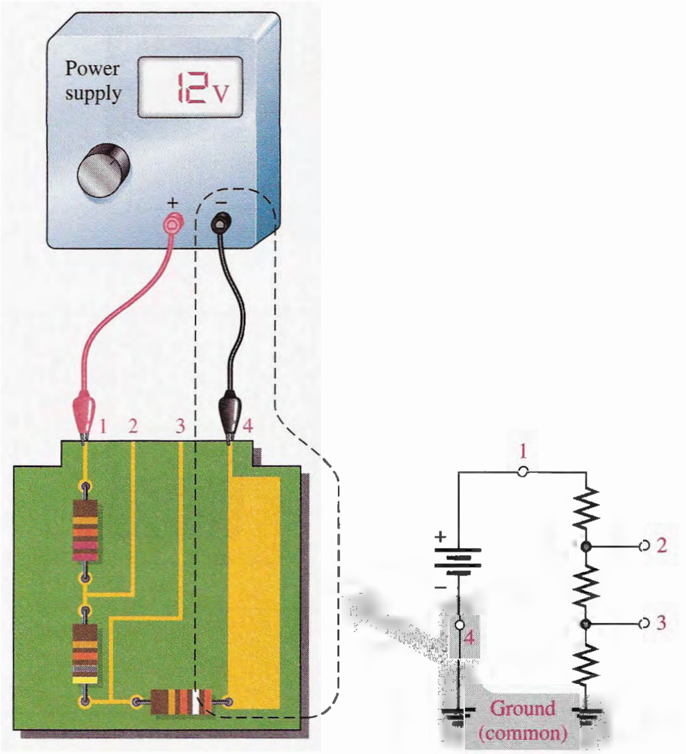
Voltage is relative. That is, the voltage at one point in a circuit is always measured relative to another point. For example, if we say that there are +100 V at a certain point in a circuit, we mean that the point is 100 V more positive than some designated reference point in the circuit. This reference point is called the ground or common point.

After completing this section, you should be able to

- **Measure voltage with respect to ground**
  - Determine and identify ground in a circuit
  - Define the term *reference ground*

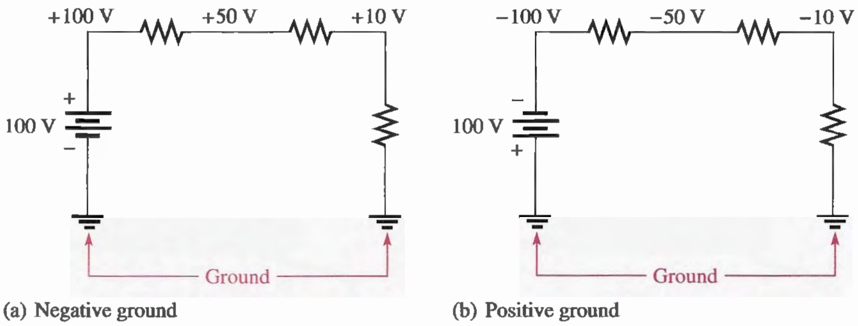
The concept of *ground* was introduced in Chapter 2. In most electronic equipment, a large conductive area on a printed circuit board or the metal housing is used as the **reference ground** or **common**, as illustrated in Figure 5–50.

Reference ground has a potential of zero volts (0 V) with respect to all other points in the circuit that are referenced to it, as illustrated in Figure 5–51. In part (a), the negative side of the source is grounded, and all voltages indicated are positive with respect to ground. In part (b), the positive side of the source is ground. The voltages at all other points are therefore negative with respect to ground. Recall that all points shown grounded in a circuit are connected together through ground and are effectively the same point electrically.



▲ FIGURE 5–50

Simple illustration of ground in a circuit.



(a) Negative ground

(b) Positive ground

▲ FIGURE 5–51

Example of negative and positive grounds.

Measuring Voltages with Respect to Ground

When you measure voltages with respect to the reference ground in a circuit, connect one meter lead to the reference ground, and the other to the point at which the voltage is to be measured. In a negative ground circuit, as illustrated in Figure 5–52, the negative meter terminal is connected to the reference ground. The positive terminal of the voltmeter is then connected to the positive voltage point. The meter reads the positive voltage at point *A* with respect to ground.

For a circuit with a positive ground, the positive voltmeter lead is connected to reference ground, and the negative lead is connected to the negative voltage point, as indicated in Figure 5–53. Here the meter reads the negative voltage at point *A* with respect to ground.

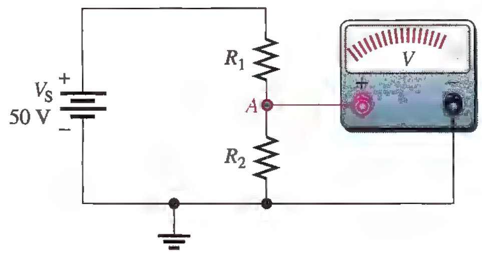


FIGURE 5–52

Measuring a voltage with respect to negative ground.

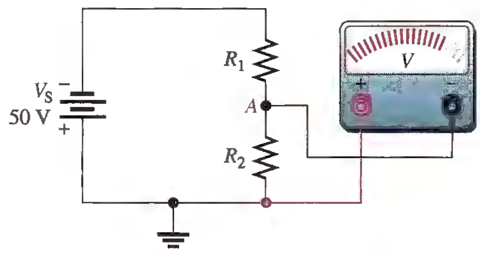


FIGURE 5–53

Measuring a voltage with respect to positive ground.

When you must measure voltages at several points in a circuit, you can clip the ground lead to ground at one point in the circuit and leave it there. Then move the other lead from point to point as you measure the voltages. This method is illustrated pictorially in Figure 5–54 and in equivalent schematic form in Figure 5–55.

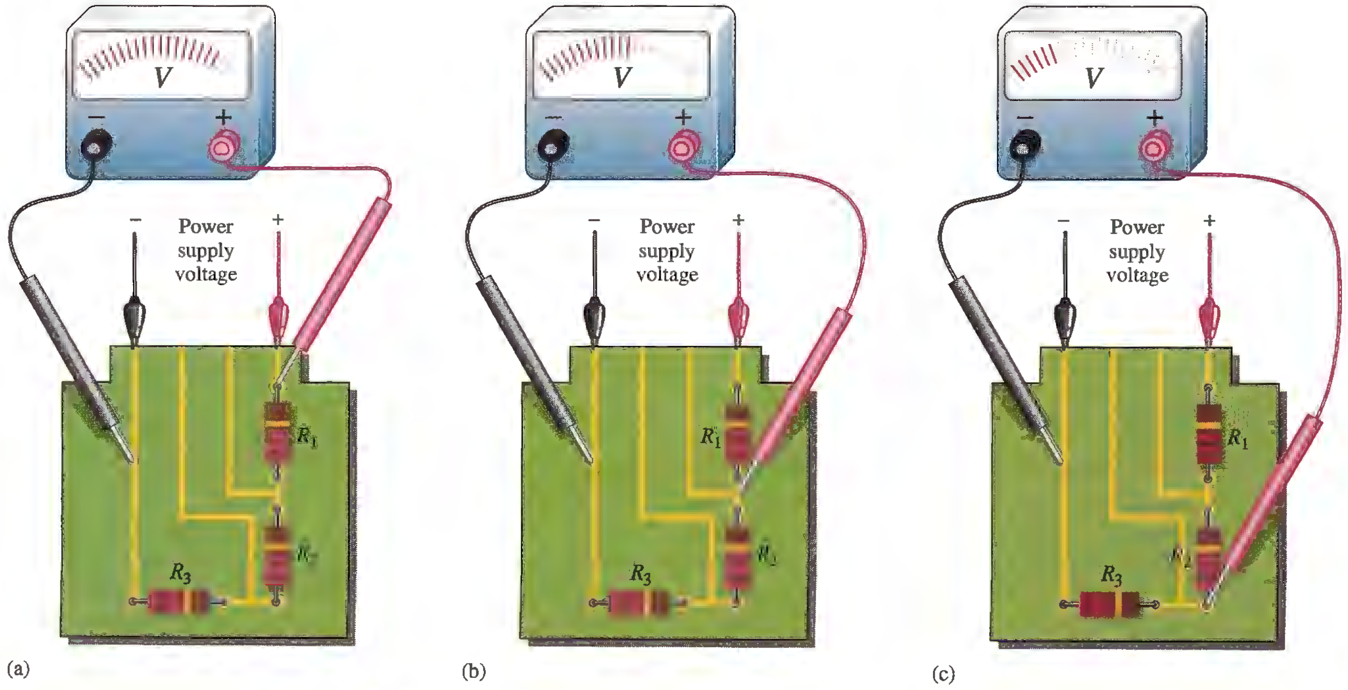
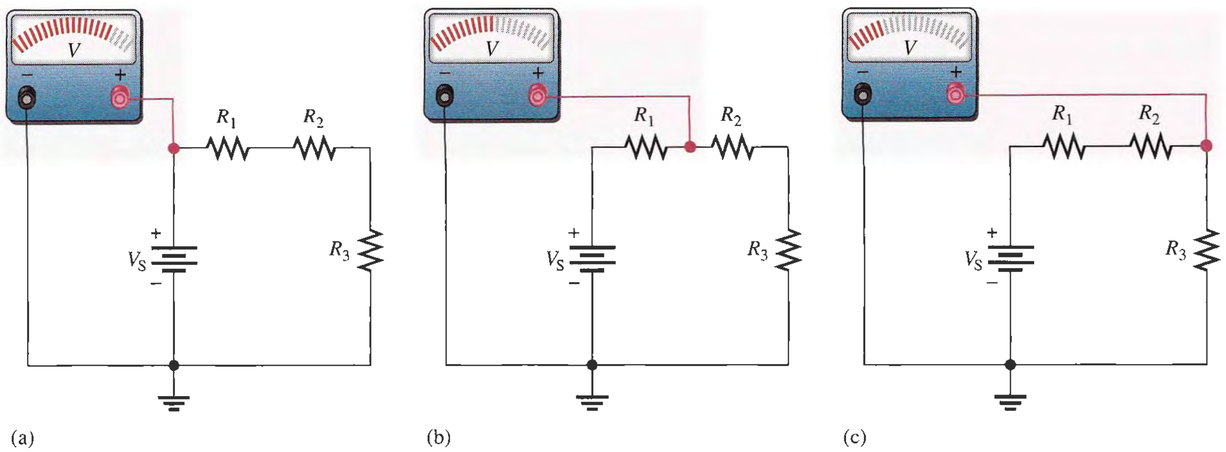


FIGURE 5–54

Measuring voltages at several points in a circuit with respect to ground.

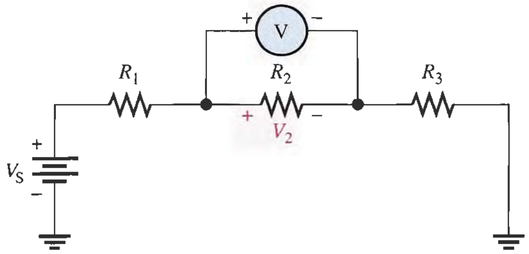


▲ FIGURE 5–55

Equivalent schematics for Figure 5–54.

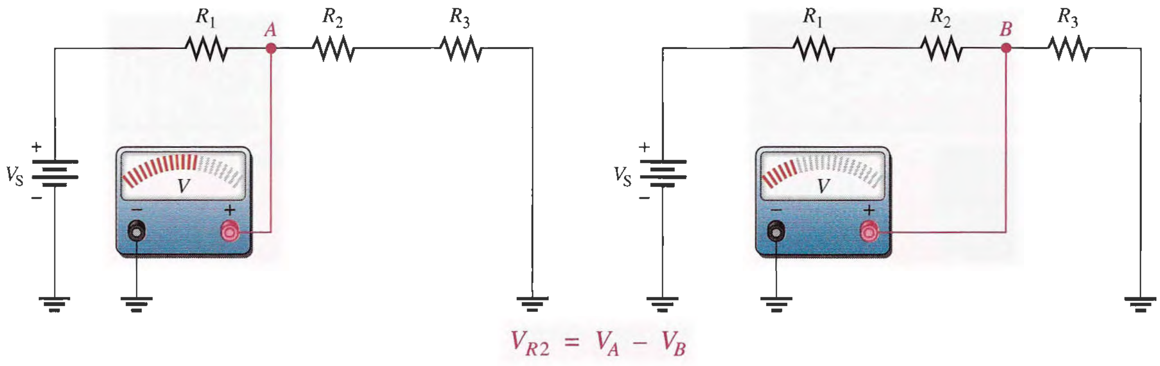
Measuring Voltage Across an Ungrounded Resistor

Voltage can normally be measured across a resistor, as shown in Figure 5–56, even though neither side of the resistor is connected to ground. If the measuring instrument is not isolated from power line ground, the negative lead of the meter will ground one side of the resistor and alter the operation of the circuit. In this situation, another method must be used, as illustrated in Figure 5–57. The voltages on each side of the resistor are measured with respect to ground. The difference of these two measurements is the voltage drop across the resistor.



▲ FIGURE 5–56

Measuring voltage across a resistor.



▲ FIGURE 5–57

Measuring voltage across R_2 with two separate measurements to ground. Note $V_A - V_B$ can be expressed as V_{AB}, where the second subscript letter, B, is the reference.

EXAMPLE 5–21

Determine the voltages with respect to ground of each of the indicated points in each circuit of Figure 5–58. Assume that 25 V are dropped across each resistor.

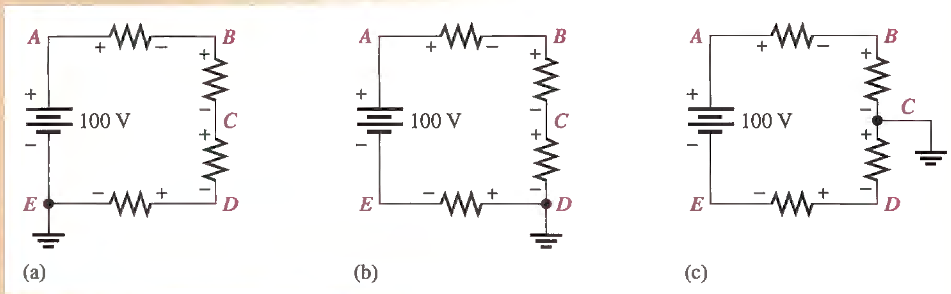


FIGURE 5–58

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:

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

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

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

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

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

Related Problem If the ground is at point *A* in the circuit in Figure 5–58, what are the voltages at each of the points with respect to ground?

Use Multisim file E05-21 to verify the calculated results in this example and to confirm your calculation for the related problem.

SECTION 5–9 REVIEW

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)

5–10 TROUBLESHOOTING

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

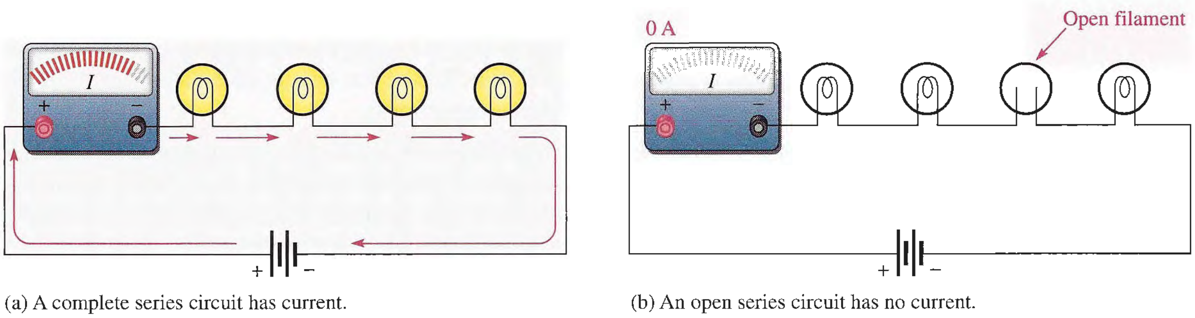
After completing this section, you should be able to

- **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 5–59.

An open in a series circuit prevents current.



(a) A complete series circuit has current.

(b) An open series circuit has no current.

▲ FIGURE 5–59

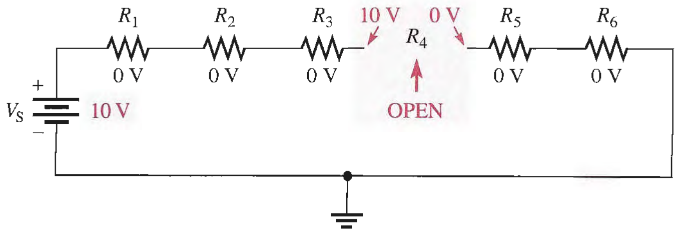
Current ceases when an open occurs.

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 circuit, as illustrated in Figure 5–60. The source voltage will appear across the open resistor in accordance with Kirchhoff's voltage law as follows:

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



▲ FIGURE 5–60

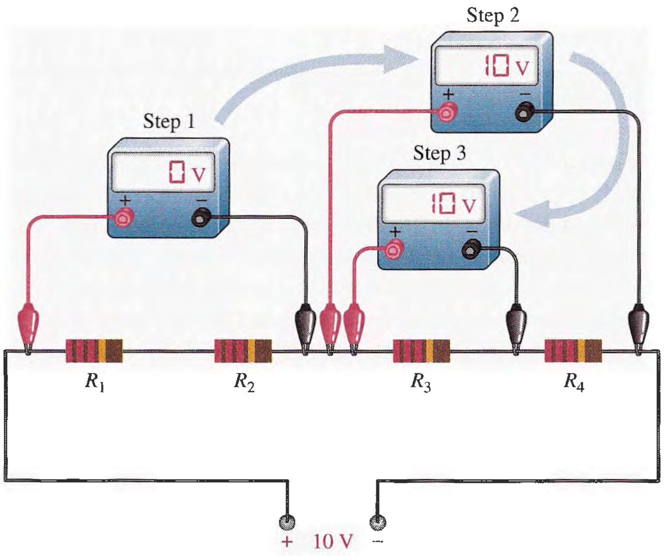
The source voltage appears across the open series resistor.

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 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 5–61.

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 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 5–61

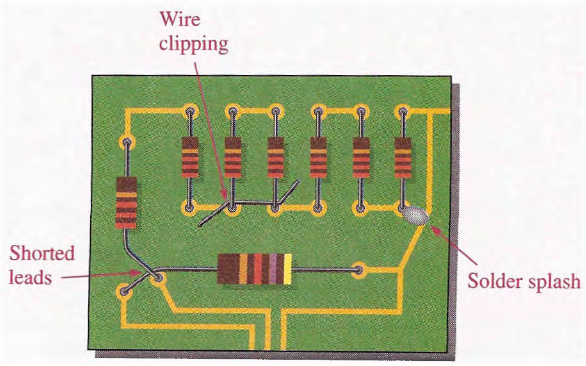
Troubleshooting a series circuit for an open using half-splitting.

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 is particularly common in circuits with a high component density. Several potential causes of short circuits are illustrated on the PC board in Figure 5–62.

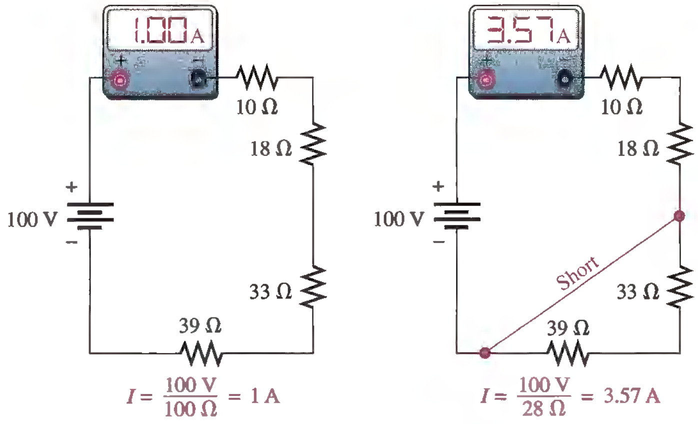
▶ FIGURE 5–62

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 5–63. Notice that the current increases as a result of the short.

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



(a) Before short

(b) After short

FIGURE 5–63

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.

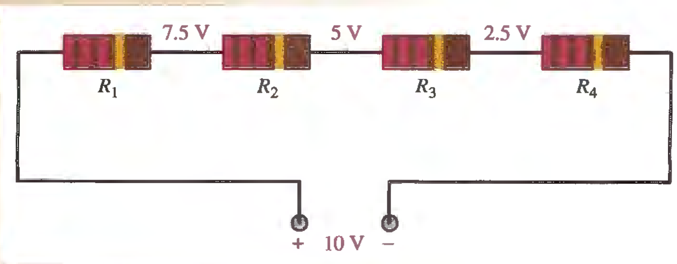
In order to troubleshoot a short, measure the voltage across each resistor until you get a reading of 0 V. This is the straightforward approach and does not use half-splitting. In order to apply the half-splitting method, you must know the correct voltage at each point in the circuit and compare it to measured voltages. Example 5–22 illustrates using half-splitting to find a short.

EXAMPLE 5–22

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 5–64 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 5–64

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 5–65 illustrates this troubleshooting technique.

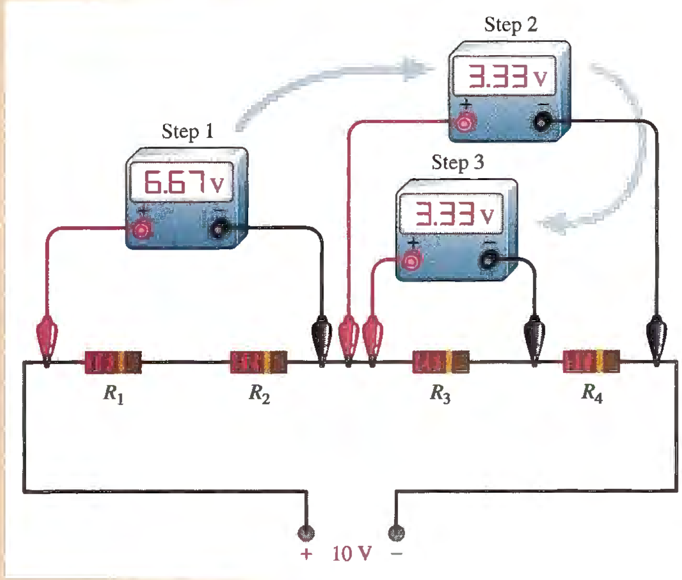


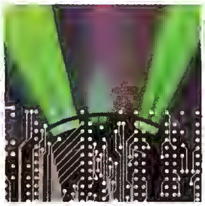
FIGURE 5–65

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

Related Problem Assume that R_1 is shorted in Figure 5–65. What would the Step 1 measurement be?

SECTION 5–10 REVIEW

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?

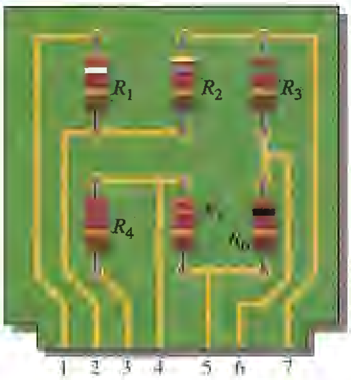


A Circuit Application

For this application, you have a voltage-divider circuit board to evaluate and modify if necessary. You will use it to obtain five different voltage levels from a 12 V battery that has a 6.5 Ah rating. The voltage divider provides positive reference voltages to an electronic circuit in an analog-to-digital converter. Your job is to check the circuit to see if it provides the following voltages within a tolerance of ±5% with respect to the negative side of the battery: 10.4 V, 8.0 V, 7.3 V, 6.0 V, and 2.7 V. If the existing circuit does not provide the specified voltages, you will modify it so that it does. Also, you must make sure that the 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

◆ Use Figure 5–66 to determine the resistor values and draw the schematic of the voltage-divider circuit. All the resistors on the board are ¼ W.



▲ FIGURE 5–66

The Voltages

◆ Determine the voltage at each pin on the circuit board with respect to the negative side of the battery when the positive side of the 12 V battery is connected to pin 3 and the negative side is connected to pin 1. Compare the existing voltages to the following specifications:

Pin 1: negative terminal of 12 V battery
Pin 2: 2.7 V ± 5%
Pin 3: positive terminal of 12 V battery
Pin 4: 10.4 V ± 5%
Pin 5: 8.0 V ± 5%
Pin 6: 7.3 V ± 5%
Pin 7: 6.0 V ± 5%

◆ If the output voltages of the existing circuit are not the same as those stated in the specifications, make the necessary changes in the circuit to meet the specifications. Draw a schematic of the modified circuit showing resistor values and adequate power ratings.

The Battery

◆ 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

◆ 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

◆ 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).

1. No voltage at any of the pins on the circuit board
2. 12 V at pins 3 and 4. All other pins have 0 V.
3. 12 V at all pins except 0 V at pin 1
4. 12 V at pin 6 and 0 V at pin 7
5. 3.3 V at pin 2

Review

1. What is the total power dissipated by the voltage-divider circuit in Figure 5–66 with a 12 V battery?
2. 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?
3. 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?

SUMMARY

- The current is the same at all points in a series circuit.
- The total series resistance is the sum of all resistors in the series circuit.
- The total resistance between any two points in a series circuit is equal to the sum of all resistors connected in series 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.
- Ground (common) is zero volts with respect to all points referenced 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 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 (drops and source) around a single closed path is zero.

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

Reference ground A method of grounding whereby the metal chassis that houses the assembly or a large conductive area on a printed circuit board is used as the common or reference point.

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	$R_T = R_1 + R_2 + R_3 + \cdots + R_n$	Total resistance of *n* resistors in series
5–2	$R_T = nR$	Total resistance of *n* equal-value resistors in series
5–3	$V_S = V_1 + V_2 + V_3 + \cdots + V_n$	Kirchhoff's voltage law

5–4	$V_S - V_1 - V_2 - V_3 - \cdots - V_n = 0$	Kirchhoff's voltage law stated another way
5–5	$V_x = \left(\dfrac{R_x}{R_T}\right)V_S$	Voltage-divider formula
5–6	$P_T = P_1 + P_2 + P_3 + \cdots + P_n$	Total power

SELF-TEST

Answers are at the end of the chapter.

1. Five 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 Ω, 220 Ω, and 330 Ω. The total resistance is

(a) less than 100 Ω **(b)** the average of the values **(c)** 550 Ω **(d)** 650 Ω

6. A 9 V battery is connected across a series combination of 68 Ω, 33 Ω, 100 Ω, and 47 Ω 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 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 kΩ, a 5.6 kΩ, and a 10 kΩ resistor. The resistor that has the most voltage across it is

(a) the 4.7 kΩ **(b)** the 5.6 kΩ
(c) the 10 kΩ **(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 Ω resistor **(b)** Two 100 Ω resistors
(c) Three 100 Ω resistors **(d)** Four 100 Ω 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 5–70.

1. 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

2. If the source voltage decreases, the current indicated by each milliammeter

   (a) increases (b) decreases (c) stays the same

3. 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.

4. 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

5. For the conditions described in Question 4, the current through R_3

   (a) increases (b) decreases (c) stays the same

6. 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

7. 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 5–77.

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 5–84(b).

11. If R_1 is changed to 1.2 kΩ, 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 5–91.

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

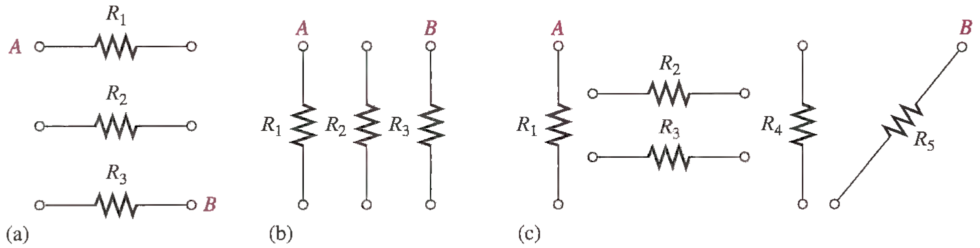
PROBLEMS

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

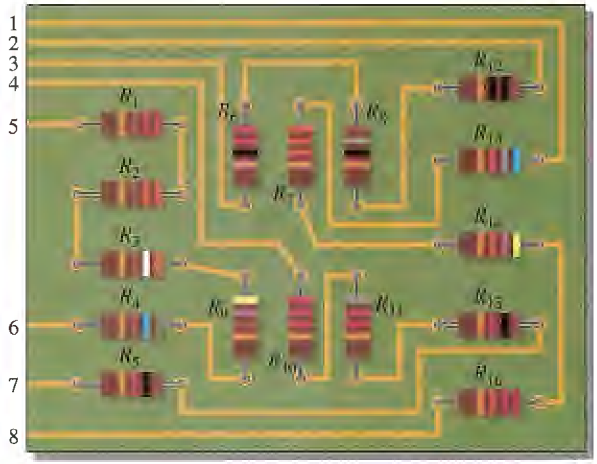
1. Connect each set of resistors in Figure 5–67 in series between points A and B.

▶ **FIGURE 5–67**



2. Determine which resistors in Figure 5–68 are in series. Show how to interconnect the pins to put all the resistors in series.

▶ **FIGURE 5–68**

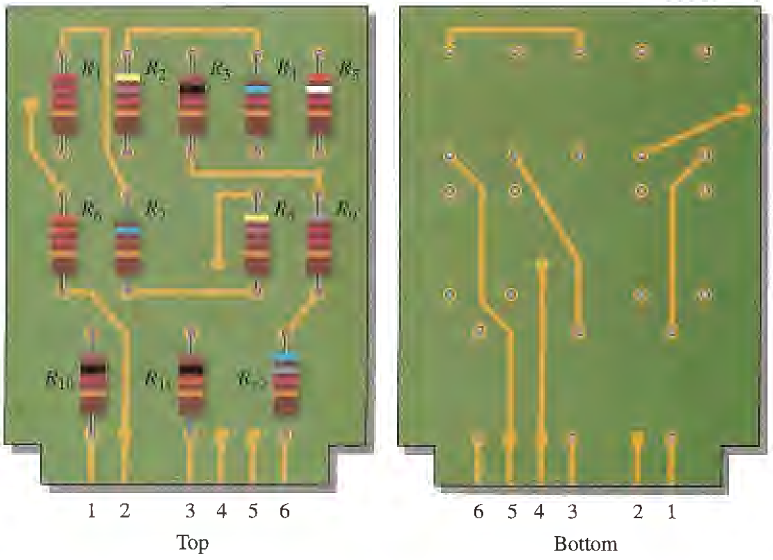


3. Determine the nominal resistance between pins 1and 8 in the circuit board in Figure 5–68.

4. Determine the nominal resistance between pins 2 and 3 in the circuit board in Figure 5–68.

5. On the double-sided PC board in Figure 5–69, 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 5–69**

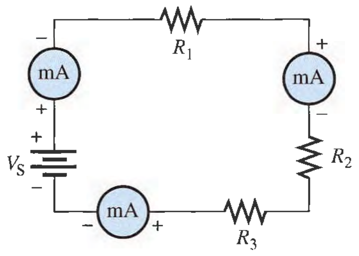


SECTION 5–2 Current in a Series Circuit

6. What is the current through each resistor in a series circuit if the total voltage is 12 V and the total resistance is 120 Ω?

7. The current from the source in Figure 5–70 is 5 mA. How much current does each milliammeter in the circuit indicate?

▶ FIGURE 5–70



8. Show how to connect a voltage source and an ammeter to the PC board in Figure 5–68 to measure the current in R_1. Which other resistor currents are measured by this setup?

***9.** 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 5–3 Total Series Resistance

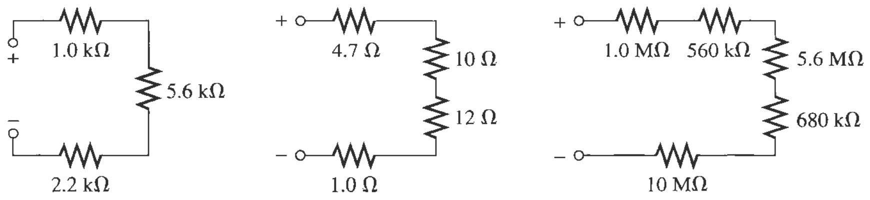
10. The following resistors (one each) are connected in a series circuit: 1.0 Ω, 2.2 Ω, 5.6 Ω, 12 Ω, and 22 Ω. Determine the total resistance.

11. Find the total resistance of each of the following groups of series resistors:

(a) 560 Ω and 1000 Ω **(b)** 47 Ω and 56 Ω

(c) 1.5 kΩ, 2.2 kΩ, and 10 kΩ **(d)** 1.0 MΩ, 470 kΩ, 1.0 kΩ, 2.2 MΩ

12. Calculate R_T for each circuit of Figure 5–71.



(a) (b) (c)

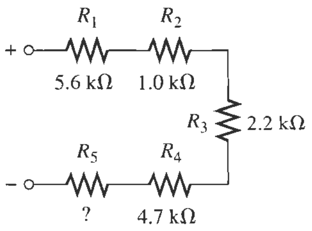
▲ FIGURE 5–71

13. What is the total resistance of twelve 5.6 kΩ resistors in series?

14. Six 56 Ω resistors, eight 100 Ω resistors, and two 22 Ω resistors are all connected in series. What is the total resistance?

15. If the total resistance in Figure 5–72 is 17.4 kΩ, what is the value of R_5?

▶ FIGURE 5–72

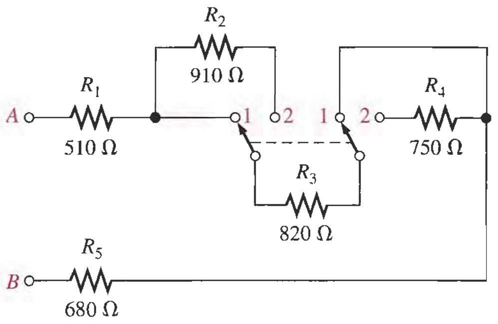


*16. You have the following resistor values available to you in the lab in unlimited quantities: 10 Ω, 100 Ω, 470 Ω, 560 Ω, 680 Ω, 1.0 kΩ, 2.2 kΩ, and 5.6 kΩ. All of the other standard values are out of stock. A project that you are working on requires an 18 kΩ resistance. What combinations of the available values would you use in series to achieve this total resistance?

17. Find the total resistance in Figure 5–71 if all three circuits are connected in series.

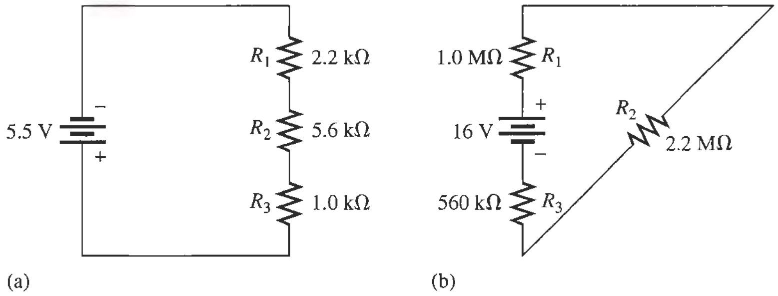
18. What is the total resistance from A to B for each switch position in Figure 5–73?

▶ FIGURE 5–73



SECTION 5–4 Application of Ohm's Law

19. What is the current in each circuit of Figure 5–74?



(a)

(b)

▲ FIGURE 5–74

20. Determine the voltage drop across each resistor in Figure 5–74.

21. Three 470 Ω resistors are connected in series with a 48 V source.

(a) What is the current is in the circuit?

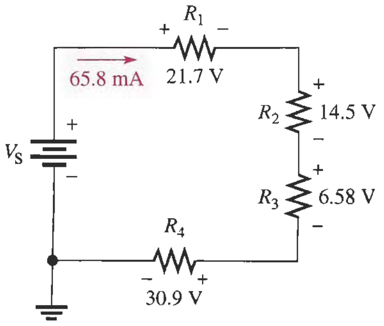
(b) What is the voltage across each resistor?

(c) What is the minimum power rating of the resistors?

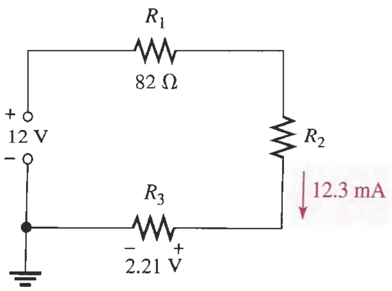
22. Four equal-value resistors are in series with a 5 V battery, and 2.23 mA are measured. What is the value of each resistor?

23. What is the value of each resistor in Figure 5–75?

24. Determine V_{R1}, R_2, and R_3 in Figure 5–76.



▲ FIGURE 5–75



▲ FIGURE 5–76

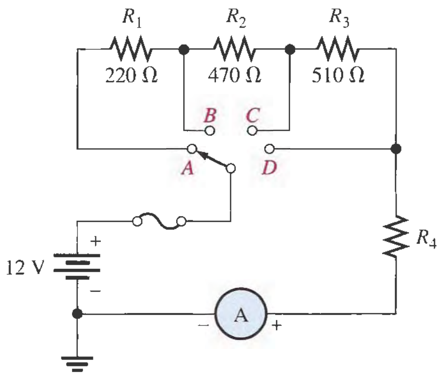
25. For the circuit in Figure 5–77 the meter reads 7.84 mA when the switch is in position *A*.

(a) What is the resistance of R_4?

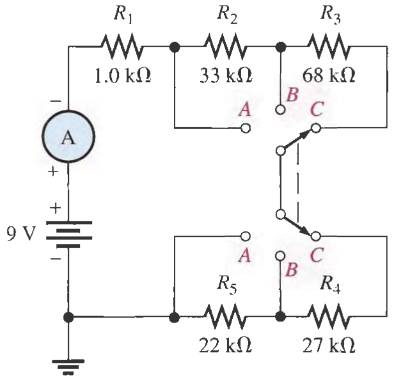
(b) What should be the meter reading for switch positions *B*, *C*, and *D*?

(c) Will a ¼ A fuse blow in any position of the switch?

26. Determine the current measured by the meter in Figure 5–78 for each position of the ganged switch.



▲ FIGURE 5–77



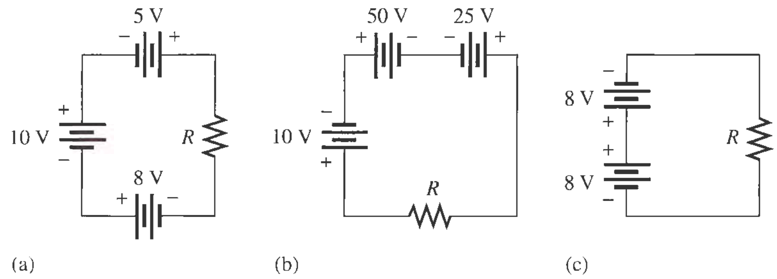
▲ FIGURE 5–78

SECTION 5–5 Voltage Sources in Series

27. *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?

28. 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?

29. Determine the total source voltage in each circuit of Figure 5–79.



(a) (b) (c)

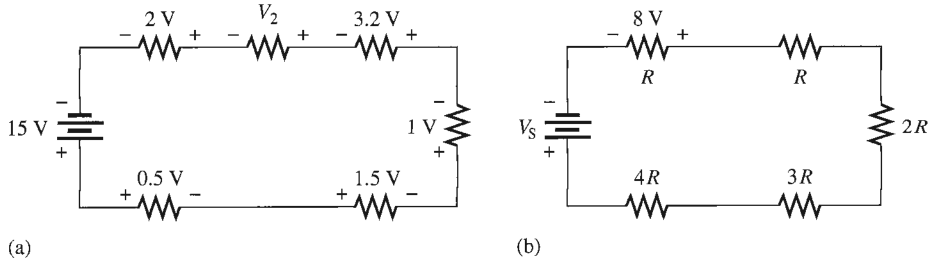
▲ FIGURE 5–79

SECTION 5–6 Kirchhoff's Voltage Law

30. 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?

31. 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?

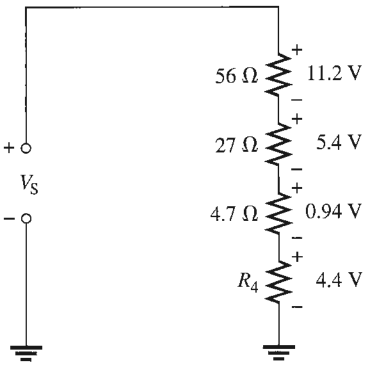
32. Determine the unspecified voltage drop(s) in each circuit of Figure 5–80. Show how to connect a voltmeter to measure each unknown voltage drop.



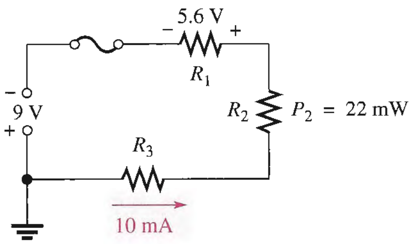
▲ FIGURE 5–80

33. In the circuit of Figure 5–81, determine the resistance of R_4.

34. Find R_1, R_2, and R_3 in Figure 5–82.



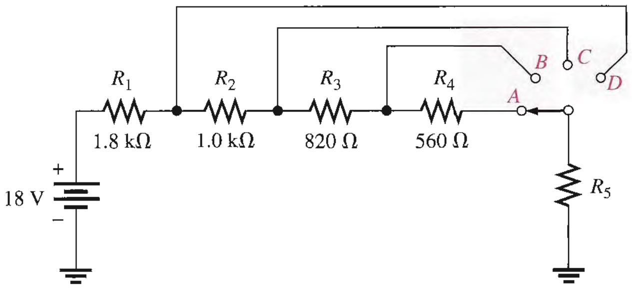
▲ FIGURE 5–81



▲ FIGURE 5–82

35. Determine the voltage across R_5 for each position of the switch in Figure 5–83. The current in each position is as follows: *A*, 3.35 mA; *B*, 3.73 mA; *C*, 4.50 mA; *D*, 6.00 mA.

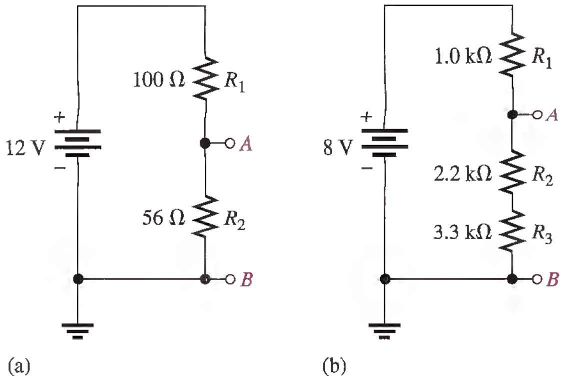
36. Using the result of Problem 35, determine the voltage across each resistor in Figure 5–83 for each switch position.



▲ FIGURE 5–83

SECTION 5–7 Voltage Dividers

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



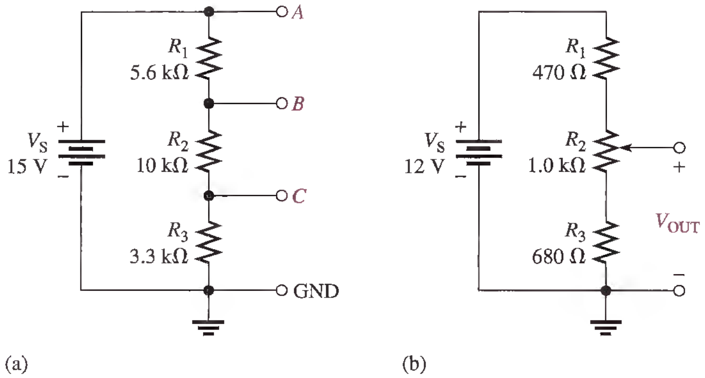
▲ FIGURE 5–84

38. Determine the voltage between points A and B in each voltage divider of Figure 5–84.

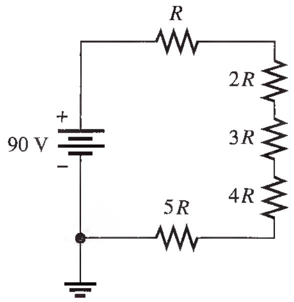
39. Determine the voltage with respect to ground for output A, B, and C in Figure 5–85(a).

40. Determine the minimum and maximum voltage from the voltage divider in Figure 5–85(b).

***41.** What is the voltage across each resistor in Figure 5–86? R is the lowest-value resistor, and all others are multiples of that value as indicated.



▲ FIGURE 5–85

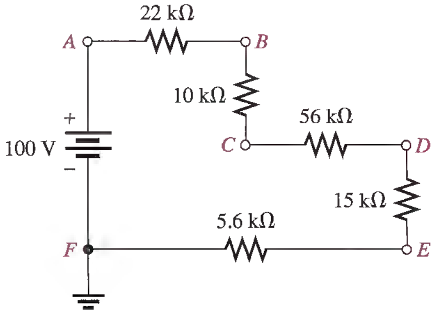


▲ FIGURE 5–86

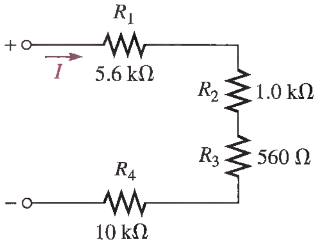
42. Determine the voltage at each point in Figure 5–87 with respect to the negative side of the battery.

43. If there are 10 V across R_1 in Figure 5–88, what is the voltage across each of the other resistors?

***44.** 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,



▲ FIGURE 5–87



▲ FIGURE 5–88

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.

***45.** Design a variable voltage divider to provide an output voltage adjustable from a minimum of 10 V to a maximum of 100 V within ±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

46. Five series resistors each handle 50 mW. What is the total power?

47. What is the total power in the circuit in Figure 5–88? Use the results of Problem 43.

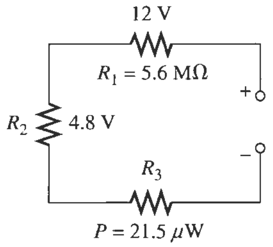
48. The following ¼ W resistors are in series: 1.2 kΩ, 2.2 kΩ, 3.9 kΩ, and 5.6 kΩ. What is the maximum voltage that can be applied across the series resistors without exceeding a power rating? Which resistor will burn out first if excessive voltage is applied?

49. Find R_T in Figure 5–89.

50. A certain series circuit consists of a ⅛ W resistor, a ¼ W resistor and a ½ W resistor. The total resistance is 2400 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

▶ FIGURE 5–89

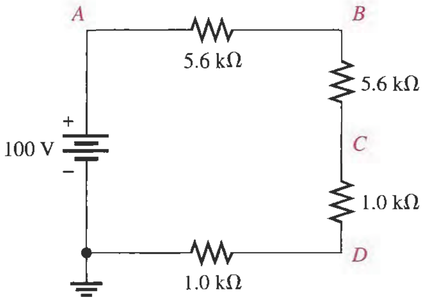


SECTION 5–9 Voltage Measurements

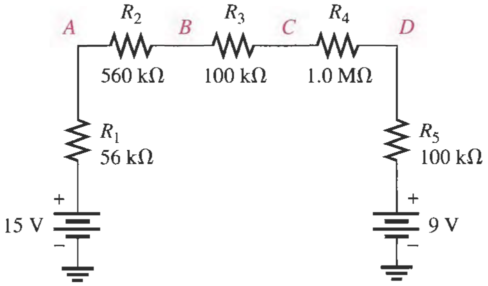
51. Determine the voltage at each point with respect to ground in Figure 5–90.

52. In Figure 5–91, how would you determine the voltage across R_2 by measuring, without connecting a meter directly across the resistor?

53. Determine the voltage at each point with respect to ground in Figure 5–91.



▲ FIGURE 5–90

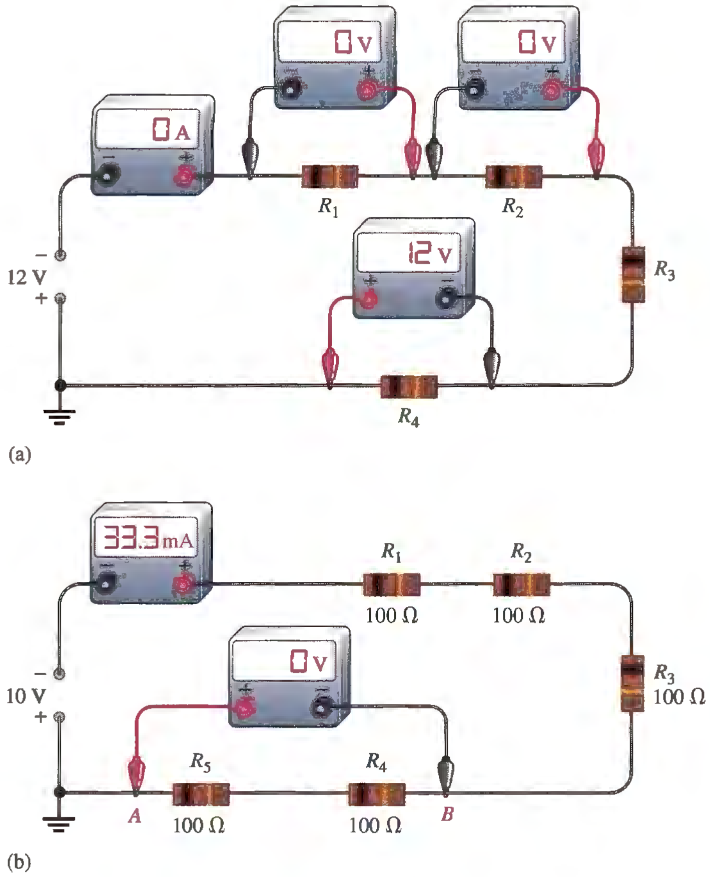


▲ FIGURE 5–91

SECTION 5–10 Troubleshooting

54. 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 5–92



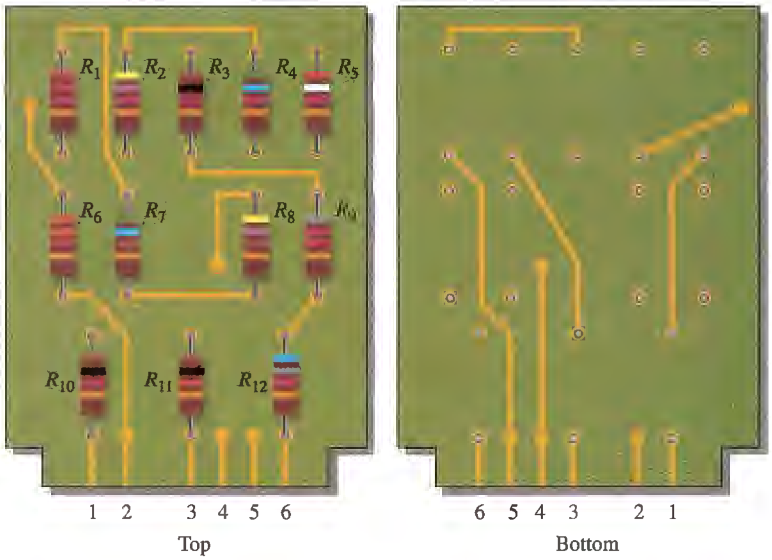
55. By observing the meters in Figure 5–92, determine the types of failures in the circuits and which components have failed.

56. What current would you measure in Figure 5–91(b) if only R_2 were shorted?

***57.** Table 5–1 shows the results of resistance measurements on the PC board in Figure 5–93. Are these results correct? If not, identify the possible problems.

TABLE 5–1

BETWEEN PINS	RESISTANCE
1 and 2	∞
1 and 3	∞
1 and 4	4.23 kΩ
1 and 5	∞
1 and 6	∞
2 and 3	23.6 kΩ
2 and 4	∞
2 and 5	∞
2 and 6	∞
3 and 4	∞
3 and 5	∞
3 and 6	∞
4 and 5	∞
4 and 6	∞
5 and 6	19.9 kΩ



▲ FIGURE 5–93

***58.** You measure 15 kΩ between pins 5 and 6 on the PC board in Figure 5–93. Does this indicate a problem? If so, identify it.

***59.** In checking out the PC board in Figure 5–93, you measure 17.83 kΩ between pins 1 and 2. Also, you measure 13.6 kΩ between pins 2 and 4. Does this indicate a problem on the PC board? If so, identify the fault.

***60.** The three groups of series resistors on the PC board in Figure 5–93 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. 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 ½ W.

- **(a)** What has happened?
- **(b)** Specifically, what must you do to fix the problem?
- **(c)** At what voltage did the failure occur?

Multisim Troubleshooting and Analysis

These problems require your Multisim CD-ROM.

61. Open file P05-61 and measure the total series resistance.

62. Open file P05-62 and determine by measurement if there is an open resistor and, if so, which one.

63. Open file P05-63 and determine the unspecified resistance value.

64. Open file P05-64 and determine the unspecified source voltage.

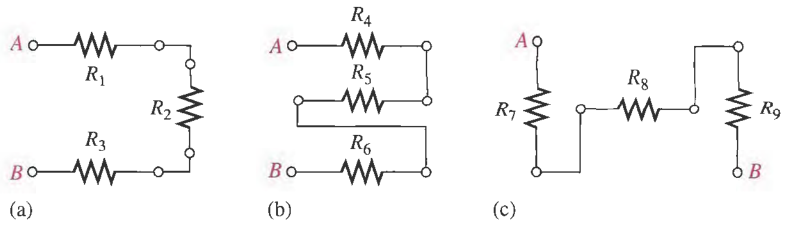
65. Open file P05-65 and find the shorted resistor if there is one.

ANSWERS

SECTION REVIEWS

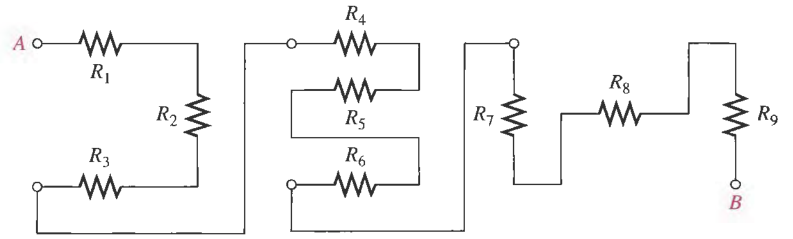
SECTION 5–1 Resistors in Series

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



(a) (b) (c)

▲ FIGURE 5–94



▲ FIGURE 5–95

3. See Figure 5–94.
4. See Figure 5–95.

SECTION 5–2 Current in a Series Circuit

1. $I = 1\ \text{A}$
2. The milliammeter measures 50 mA between C and D and 50 mA between E and F.
3. $I = 100\ \text{V}/56\ \Omega = 1.79\ \text{A}$; 1.79 A
4. In a series circuit, current is the same at all points.

SECTION 5–3 Total Series Resistance

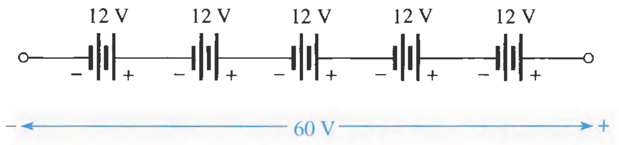
1. $R_T = 1.0\ \Omega + 2.2\ \Omega + 3.3\ \Omega + 4.7\ \Omega = 11.2\ \Omega$
2. $R_T = 100\ \Omega + 2(56\ \Omega) + 4(12\ \Omega) + 330\ \Omega = 590\ \Omega$
3. $R_5 = 13.8\ \text{k}\Omega - (1.0\ \text{k}\Omega + 2.7\ \text{k}\Omega + 5.6\ \text{k}\Omega + 560\ \Omega) = 3.94\ \text{k}\Omega$
4.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

SECTION 5–4 Application of Ohm's Law

1. $I = 10\ \text{V}/300\ \Omega = 33.3\ \text{mA}$
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. $R = \frac{1}{4}(5\ \text{V}/4.63\ \text{mA}) = 270\ \Omega$

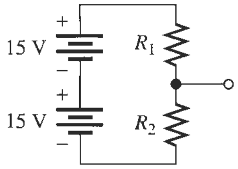
SECTION 5–5 Voltage Sources in Series

1. $V_T = 4(1.5\ \text{V}) = 6.0\ \text{V}$
2. $60\ \text{V}/12\ \text{V} = 5$; see Figure 5–96.

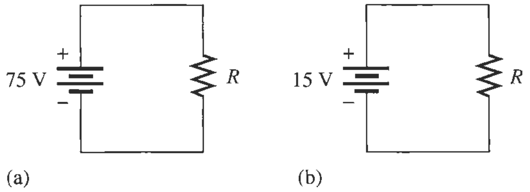


▲ FIGURE 5–96

3. See Figure 5–97.
4. **(a)** $V_{S(tot)} = 100\text{ V} + 50\text{ V} - 75\text{ V} = 75\text{ V}$
   (b) $V_{S(tot)} = 20\text{ V} + 10\text{ V} - 10\text{ V} - 5\text{ V} = 15\text{ V}$
5. See Figure 5–98.



▲ FIGURE 5–97



(a) (b)

▲ FIGURE 5–98

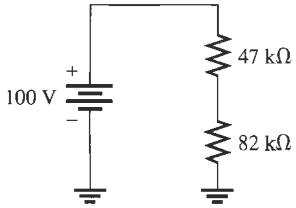
SECTION 5–6 Kirchhoff's Voltage Law

1. **(a)** Kirchhoff's law states the algebraic sum of the voltages around a closed path is zero;
   (b) Kirchhoff's law states the sum of the voltage drops equals the total source voltage.
2. $V_T = V_S = 50\text{ V}$
3. $V_1 = V_2 = 5\text{ V}$
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. Two or more resistors form a voltage divider.
3. $V_x = (R_x/R_T)V_S$
4. $V_R = 10\text{ V}/2 = 5\text{ V}$
5. $V_{47} = (47\text{ k}\Omega/129\text{ k}\Omega)100\text{ V} = 36.4\text{ V}$; $V_{82} = (82\text{ k}\Omega/129\text{ k}\Omega)100\text{ V} = 63.6\text{ V}$; see Figure 5–99.
6. Set the wiper at the midpoint.

► FIGURE 5–99



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. $P_T = (1\text{ A})^2(1110\ \Omega) = 1110\text{ W}$

SECTION 5–9 Voltage Measurements

1. The reference point in a circuit is called ground or common.
2. True
3. True

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 Rs

A Circuit Application

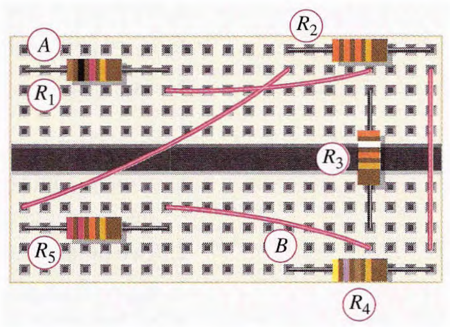
1. $P_T = (12\text{ V})^2/16.6\text{ k}\Omega = 8.67\text{ mW}$
2. Pin 2: 1.41 V; Pin 6: 3.65 V; Pin 5: 4.01 V; Pin 4: 5.20 V; Pin 7: 3.11 V
3. Pin 3 connects to ground.

RELATED PROBLEMS FOR EXAMPLES

5–1 **(a)** See Figure 5–100.

(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 5–100



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

5–3 258 Ω

5–4 12.1 kΩ

5–5 6.8 kΩ

5–6 4440 Ω

5–7 114 mA

5–8 7.8 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 Use an ohmmeter.

5–11 12 V

5–12 2 V

5–13 10 V and 20 V; $V_{fuse} = V_S = 30\text{ V}$; $V_{R1} = V_{R2} = 0\text{ V}$

5–14 47 V

5–15 593 Ω. This is most likely a 560 Ω resistor because 593 Ω is within a standard tolerance (+10%) of 560 Ω.

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 $V_{AB} = 4\text{ V}$; $V_{AC} = 36.8\text{ V}$; $V_{BC} = 32.8\text{ V}$; $V_{BD} = 46\text{ V}$; $V_{CD} = 13.2\text{ V}$

5–19 8.49 W

5–20 $P_1 = 0.92$ W (1 W); $P_2 = 2.49$ W (5 W); $P_3 = 0.838$ W (1 W); $P_4 = 3.04$ W (5 W)

5–21 $V_A = 0$ V; $V_B = -25$ V; $V_C = -50$ V; $V_D = -75$ V; $V_E = -100$ V

5–22 3.33 V

SELF-TEST

1. (a) **2.** (d) **3.** (b) **4.** (d) **5.** (d) **6.** (a) **7.** b) **8.** (c)

9. (b) **10.** (c) **11.** (a) **12.** (d) **13.** (d) **14.** (d)

CIRCUIT DYNAMICS QUIZ

1. (a) **2.** (b) **3.** (a) **4.** (b) **5.** (b) **6.** (c)

7. (a) **8.** (a) **9.** (a) **10.** (b) **11.** (b) **12.** (c)

13. (a) **14.** (a) **15.** (b)