Key Terms

terminal
switch
open circuit
electric current
coulomb (C)
ampere (A)
electrical resistance
resistor
load
potential difference (voltage)
volt

11.2 Electric Circuits: Analogies and Characteristics

Beginning with a set of ideas based on observations, scientists often make a model or develop an analogy to represent what they think is happening. Some models are physical representations, such as a model of a water molecule or of the solar system, like the one shown in **Figure 11.8**. Many models are mathematical, such as a model of climate change.

Study Toolkit

Multiple Meanings Consider the everyday meaning and the scientific meaning of the word *model*. How does knowing the everyday meaning help you understand the scientific meaning?

Models and Analogies

Models and analogies represent parts of reality. An analogy makes a comparison between two existing things that are similar in some ways but different in others. For example, the flow of water is an analogy for an electric current. A model is something that is constructed to give a simplified representation of an object or a process. You have seen models of an atom or a molecule. These models give a basic sense of what they are representing, but do not include many of the details.

Models and analogies allow scientists to make predictions that can be tested and thus can guide future experiments. In this section, you will examine different analogies and models for what happens when a battery or its components are connected in a circuit.

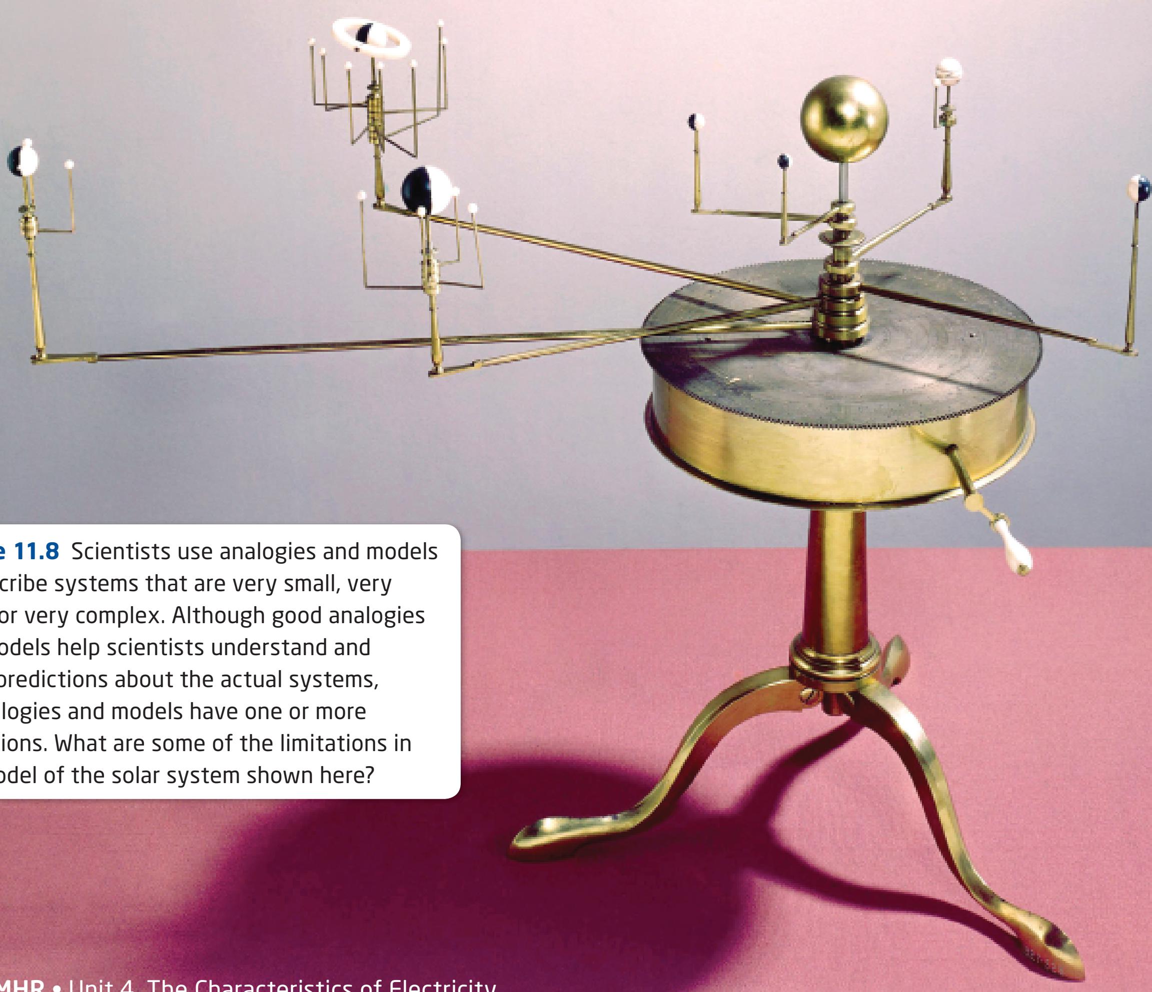


Figure 11.8 Scientists use analogies and models to describe systems that are very small, very large, or very complex. Although good analogies and models help scientists understand and make predictions about the actual systems, all analogies and models have one or more limitations. What are some of the limitations in the model of the solar system shown here?

Electric Circuits

As you learned in Section 11.1, an electric circuit is a closed path along which electrons can flow from and return to an energy source. The two locations in a cell that must be connected to other components are the positive **terminal** and the negative terminal, which are shown in **Figure 11.9**. Another way to state this is that the cell has two types of poles: a positive pole and a negative pole. In a flashlight, you may have discovered that the way the cell is connected in the circuit affects the operation of the flashlight bulb. As you investigate circuits, you will need to distinguish between the two terminals.

terminal location on a cell that must be connected to other components to form a circuit

switch a control device that can complete or break the circuit to which it is connected

open circuit a circuit that contains a gap or break

Switches and Wires

A **switch** is a control device. It is a conductor that can complete or break the circuit it is connected to. A switch is not essential for a circuit to operate, but it is usually included for convenience. A connecting wire is a conductor that joins different circuit components, such as a bulb and a switch. The connecting wires you will use in the investigations are metal wires, usually made from copper or aluminum, covered with an insulator made of plastic or rubber. On a circuit board, the connecting wires are strips of metal that are printed on the board.

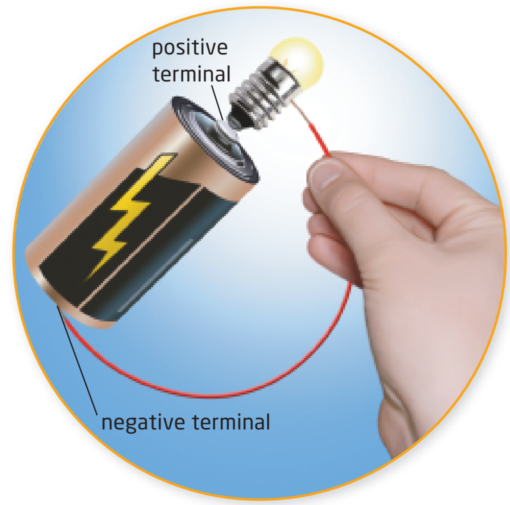


Figure 11.9 This is the simplest circuit that can make a flashlight bulb glow. The casing, filament, and base of the bulb are connected to form part of a circuit.

Open Circuits

Electrons do not flow through any part of a circuit where there is a gap or break. Opening a switch creates a gap, and any devices that are connected to the switch, such as a light bulb, will stop working. There are many ways that a gap or break can occur in a circuit, but all have the same effect as opening a switch. An **open circuit**, shown in **Figure 11.10**, is one in which there is a gap or break in the circuit.

For example, if a bulb is loose and does not make contact with the base of its socket, the circuit is open and the bulb will not glow. A break in the filament of an incandescent bulb, which emits light because of the high temperature of the filament, also creates an open circuit. This is the most common reason why a bulb does not glow. In an incandescent bulb, electrical energy heats the tungsten filament to roughly 2500°C.

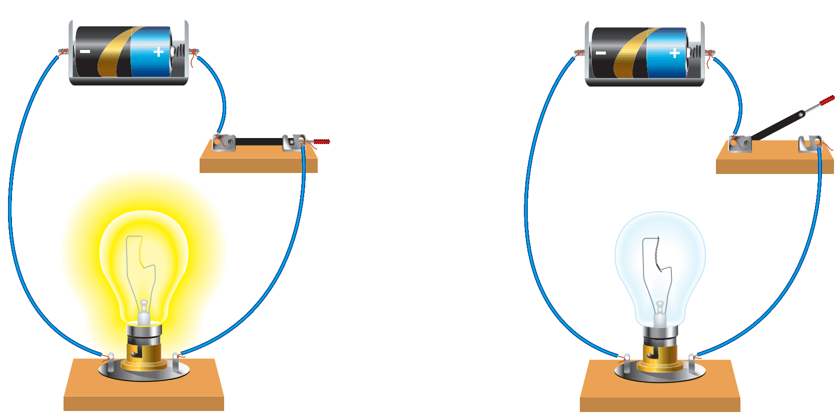


Figure 11.10 A circuit, which is the same as a closed circuit, allows electrons to flow from and return to an energy source. When there is a break in the circuit, the result is an open circuit through which current does not flow.

The Movement of Electrons

If a conductor, such as a metal wire, is not part of an electric circuit, its electrons move in random directions, frequently colliding with other electrons or with ions. Thus, as shown in **Figure 11.11**, although the conductor's electrons move very fast, the electrons do not flow in one direction along the wire.

The chemical reactions that occur inside a cell cause charges to separate. An excess of electrons builds up at one electrode, thus making it negatively charged. The other electrode has a deficit of electrons and hence is positively charged. This charge separation produces an electric field along the wires and components in the circuit to which the cell is connected. The electric field moves through the circuit at almost the speed of light, exerting a force on the electrons and protons in the circuit.

Electrons Flow in One Direction in a Circuit

In a solid, only the free electrons are able to move. The electric field produced by the cell forces the free electrons to move, overall, in one direction, although there are still collisions among the electrons, as shown in **Figure 11.12**. The instant a circuit is completed, the electrons begin to flow, just as when you turn on a fan, it forces molecules in air to move in one direction.

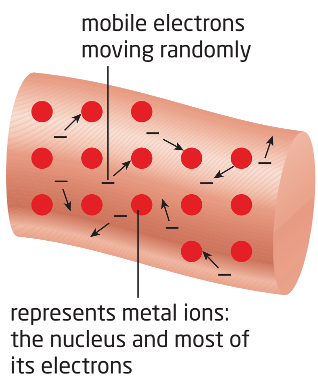


Figure 11.11 If a conductor is not connected to a source of electrical energy, the electrons move in random directions.

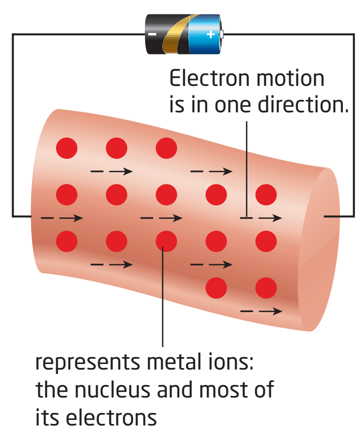


Figure 11.12 The cell produces an excess of electrons at the negative terminal, producing an electric field in the conductor. The electric field causes the electrons to move in one direction through the wire.

Electric Current

electric current the rate of movement of electric charge

Electric current refers to the rate of movement of electric charge. In an electric circuit, the current is due to the flow of electrons. The flow of water in a river is an analogy for the flow of electrons through a conductor. If you were standing on a river bank, you might think about how much water is passing by. It is unlikely that you would think about the flow of water in terms of the number of individual molecules passing by per second. Instead, you might think about a very large amount of water, such as cubic metres of water, passing by per second.

Unit of Charge

The electric charge passing by a point in a circuit is measured in terms of a very large number of electrons. The unit of electric charge is the coulomb. One **coulomb (C)** is the quantity of charge that is equal to the charge of 6.25×10^{18} electrons.

coulomb (C) the quantity of charge that is equal to the charge of 6.25×10^{18} electrons

Activity 11-3

Charged Cereal and Moving Marbles

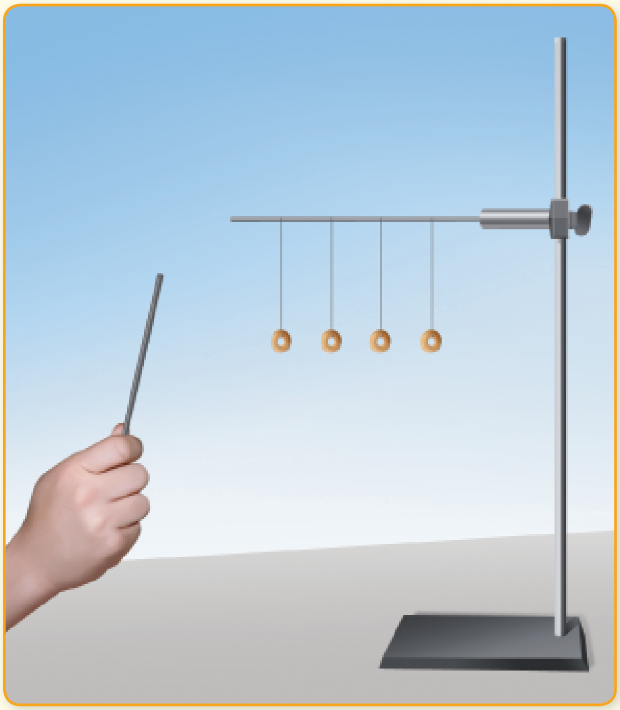
As soon as you switch on a lamp, the light bulb begins to glow. Thus, the energy that is carried by the electrons in the circuit must be transmitted almost immediately. Does this mean that the electrons in the circuit are moving very quickly?

Safety Precautions

- If you are allergic to animal fur, do not handle this material.

Materials

- ebonite rod
- fur
- cereal
- insulating thread
- scissors
- retort stand with a clamp and rod
- marbles or ball bearings
- tubing (open at both ends)



This simple cereal electroscope can be used to represent the very rapid transmission of electric force.

Procedure

1. Put together a retort stand, clamp, and rod so that the rod extends over the base of the stand.
2. Cut four identical lengths of thread. Tie one piece of cereal to each piece of thread, and then tie the other end of the thread to the rod. You should have four pieces of cereal suspended at the same height, as shown.
3. Rub the ebonite rod with fur. Then charge each piece of cereal by contact with the ebonite rod.
4. Rub the ebonite rod with fur again to make sure that it has a good charge. Bring the rod close to the end of the suspended pieces of cereal and observe what happens to the other pieces.
5. Fill a horizontal piece of tubing with marbles (or ball bearings).
6. Add one more marble (or ball bearing) to one end of the tube. Record what happens at the other end of the tube.

Questions

1. Summarize how each analogy represents the flow of electrons through a conductor in a circuit. Explain where the electrons that move through the circuit come from, and where the energy that powers the movement of the electrons comes from.
2. How did each analogy represent the flow of energy through the conductor?
3. What does each analogy predict about the movement of electrons in a circuit, compared with how fast the interactions between electrons carry energy through the circuit?
4. What represented the cell in each analogy?
5. Describe some of the limitations of each analogy.
6. In what ways is each analogy similar to your own ideas about electricity?

Amperes and Ammeters

The unit of electric current is the **ampere (A)** [pronounced AM-pir]. A current of 1.0 A in a circuit means that 1.0 C of charge passes a given point in the circuit every second. The current through a small flashlight bulb that is connected to one AA cell is about 0.3 A. Thus, 1.88×18^{18} electrons pass a given point each second. The units for charge and electric current honour the work of two French scientists, Charles Augustin de Coulomb (1736–1806) and André Marie Ampère (1775–1806). Electric current is measured using an ammeter, such as the one shown in **Figure 11.13**.

ampere (A) the unit of electric current, equivalent to one coulomb per second

Sense of *time*

In one way, water flowing in a river is a poor analogy for electric current. Imagine water flowing in a river at a slow walking pace, about 1 m/s. This is about 10 000 times faster than the drift of electrons in a circuit that is connected to a cell. Snails move faster than electrons! If electron drift is only about 0.01 cm/s, why does a light bulb glow as soon as you close the switch that is controlling it?

Electric Fields and Circuits

The separation of charges between the two electrodes in a cell gives rise to an electric field. This field transmits an electric force through a circuit at almost the speed of light, causing electrons at every point in the circuit to flow almost immediately. Thus, a light bulb in the circuit goes on at once.

Conventional Current

Electrical engineers often describe the direction of electric current as the direction in which a positive charge would move. The positive charge description is called conventional current. Both *conventional current* and *electron flow* can be used to describe electric circuits, as long as each is used consistently. In this text, electrical current is described as electron flow.

Figure 11.13 An ammeter measures the current at one location in a circuit.

Learning Check

1. Compare and contrast a closed circuit and an open circuit.
2. What is the practical unit of electric charge? Why is this unit used?
3. When the switch for an appliance is closed, the appliance comes on instantaneously. What travels at the speed of light in an electric circuit? See **Figures 11.11** and **11.12**.
4. When a tree is struck by lightning, a charge flows between the cloud, the air, the tree, and the ground. Is this an electric circuit? Explain your answer.

Electrical Resistance

The free electrons in a solid move when an electric field is produced by a cell. The electrons do not get very far, however, before colliding with ions or other electrons in the solid. These collisions interfere with the flow of electrons. **Electrical resistance** is a property of a substance that hinders electric current and converts electrical energy to other forms of energy. In many circuits, a **resistor** is used to decrease the electric current through a component by a specific amount. **Figure 11.14** shows a model for electrical resistance. How could this analogy be modified to represent a material with a lower resistance?

The molecular make-up of a material determines the number of collisions that occur between electrons and atoms or ions. Thus, the resistance to electric current varies for different materials. In general, metals have lower resistance than non-metals, and this is why metal wires are used to make circuit connections. Among metals, only silver has a lower electrical resistance than copper. Copper is used for connections in many circuits, however, because it is less expensive than silver.

electrical resistance the property of a substance that hinders electric current and converts electrical energy to other forms of energy

resistor a device used in an electric circuit to decrease the current through a component by a specific amount

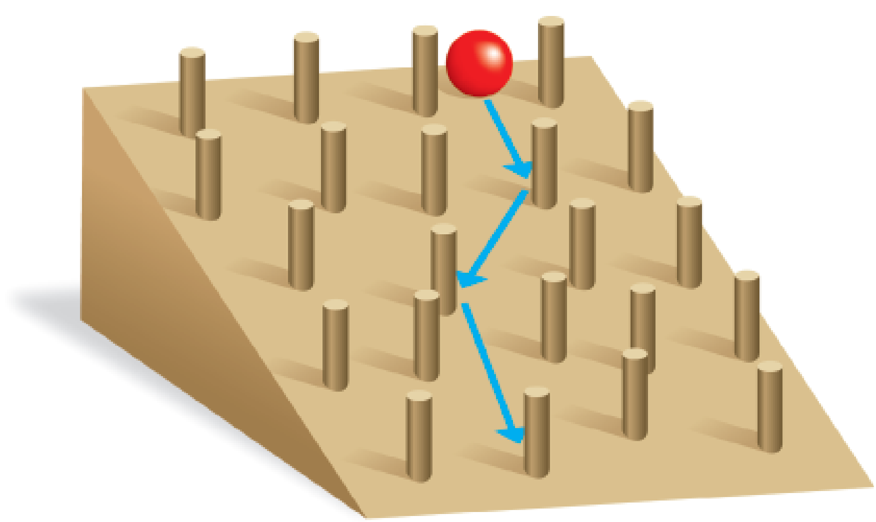


Figure 11.14 This diagram shows a model for electrical resistance. A marble (which represents an electron) collides with pegs (which represent the metal ions in a conductor). Earth's gravity makes the marble move in one general direction, just as the electric field of a cell makes the electrons in a conductor move in one general direction through a circuit.

Loads

load a resistor or any other device that transforms electrical energy into heat, motion, sound, or light

When electrons collide with metal ions, some energy is converted into heat. We make use of the electrical energy that is transformed into light in the filaments of incandescent light bulbs. We make use of the electrical energy that is transformed into heat in the heating elements of toasters, hair dryers, and room heaters. A **load** is a resistor or any other device that transforms electrical energy into heat, motion, sound, or light.

Potential Difference (Voltage)

Go to **scienceontario** to find out more

Cells that provide electrical energy for portable devices come in a wide variety of sizes. You may have noticed that AAA, AA, C, and D cells are all marked "1.5 V." This value is related to the amount of work that is done on each coulomb of charge that moves between the terminals of the cell. Thus, each cell shown in **Figure 11.15** does the same amount of work on a coulomb of charge in a circuit.

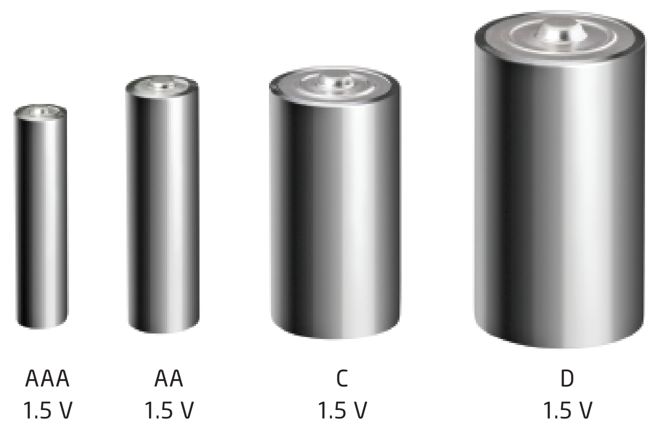


Figure 11.15 These cells give electrons in a circuit the same amount of energy. They have different sizes because they contain different quantities of materials. The D cell on the right will last longer than the other cells because it contains the most electrolyte material.

Electric Potential Energy

Potential energy is the energy due to the position of an object in a field that the object interacts with. It is called *potential* energy because it has the potential, to do work. Electric potential energy is the potential energy of charge that interacts with an electric field. The amount of electric charge is analogous to the weight of the box in **Figure 11.16**.

Cells cause chemical reactions that do work on the electric charge, analogous to lifting the box. When a charge flows through a flashlight bulb, it enters the filament with a certain amount of energy and exits with less energy. This is analogous to what happens when a box on a higher shelf tumbles to a lower shelf. The energy of the heat and light that are produced at the filament of a light bulb is equal to the change in the energy of the charge that flows through the filament.

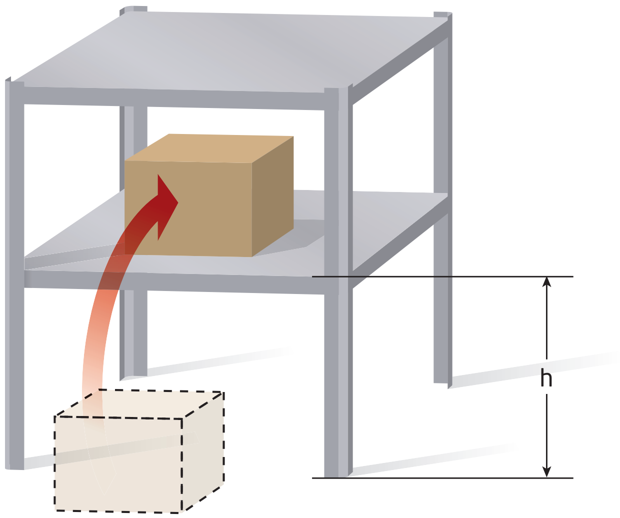


Figure 11.16 The box has gravitational potential energy. If you want to lift the box to put it on a shelf, you have to do some work. The changes in energy when the box moves up or down are analogous to the changes in the energy of a charge moving through a power source and then through a load in a circuit.

Potential Difference and the Volt

The difference between the electric potential energy per unit of charge at two points in a circuit is called **potential difference**.

Potential difference is often referred to as *voltage*. However, what is being described is the *difference* in electric potential energy per unit of charge between two points. There is no such thing as voltage at a single point in a circuit. In the SI system of measurement, all forms of energy are measured in joules (J). As you know, the coulomb (C) is the unit of electric charge. Potential difference is the difference in potential energy per coulomb of charge between two points in a circuit.

$$\text{potential difference} = \frac{\text{difference in potential energy (J)}}{\text{charge (C)}}$$

Thus, the units for potential difference are J/C. This combination of units is called the **volt** (V), named to honour the work of Alessandro Volta (1745–1827). For example, a cell marked "1.5 V" will do 1.5 J of work moving a coulomb of electrons from the negative terminal, through the circuit, to the positive terminal. A voltmeter is used to measure potential difference. **Figure 11.17** shows a *multimeter*, which can be set to act as a voltmeter

An electric charge does not lose energy when it moves along a perfect conductor with no resistance. Connecting wires used in circuits have such low resistance that, for most purposes, they can be considered perfect conductors. The potential difference along the length of the connecting wires you will use in your investigations is so small that it can be neglected. You can check this when you measure the properties of a circuit.

potential difference (voltage) the difference between the electric potential energy per unit of charge at two points in a circuit

volt the unit for potential difference, equivalent to one joule (J) per coulomb (C)

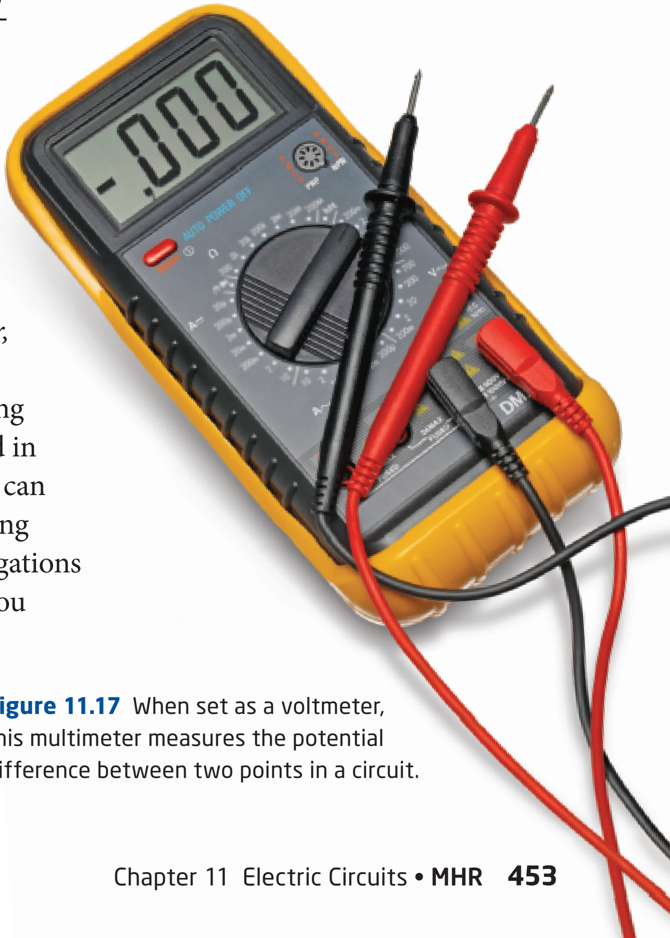


Figure 11.17 When set as a voltmeter, this multimeter measures the potential difference between two points in a circuit.

Section 11.2 Review

Section Summary

- An electric circuit is a closed path along which electrons powered by an energy source can flow.
- In a circuit that is connected to a cell, electrons move very slowly from the negative terminal to the positive terminal in the external circuit.
- The electric field in an operating circuit transmits energy at almost the speed of light.
- Electric current is the rate of flow of electric charge in a circuit, and it is measured in amperes (A) using an ammeter.
- Electrical resistance is a property of a substance that hinders electric current and converts electrical energy to other forms of energy.
- Potential difference (voltage) is the difference between the electric potential energy per unit of charge at two points in a circuit, and it is measured in volts (V) using a voltmeter.

Review Questions

A **1.** Compare and contrast a water tap in your home and an electrical switch.

K/U **2.** Refer back to **Figure 11.15**. Why does a D cell last longer than an AA cell?

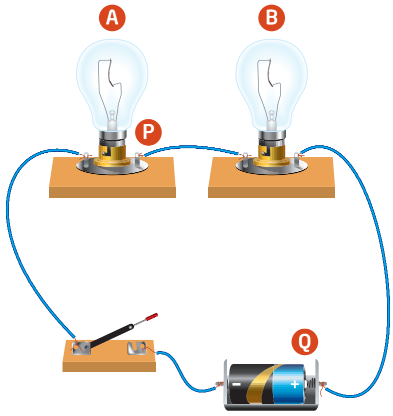
K/U **3.** Is the potential difference between the terminals of a cell in a circuit fixed, or does it depend on the components that are connected in the circuit?

K/U **4. a.** What combination of units is equivalent to the ampere?

b. What combination of units is equivalent to the volt?

C **5.** Using a diagram, explain how the current through two different conductors can be different, even though the electrons in each conductor are moving at the same speed.

T/I **6.** In the circuit shown on the right, the bulbs are identical.



a. When the switch is closed, how will the energy converted into light and heat by bulb **A** compare with the energy converted into light and heat by bulb **B**?

b. What will happen to the intensity of each bulb if a wire is connected between points **P** and **Q**?

K/U **7.** What is an electrical load? Give several examples of electrical loads.

K/U **8.** Why is the potential difference between two points in a good conductor so small that it can be neglected?