Unit 7

Electricity and Magnetism

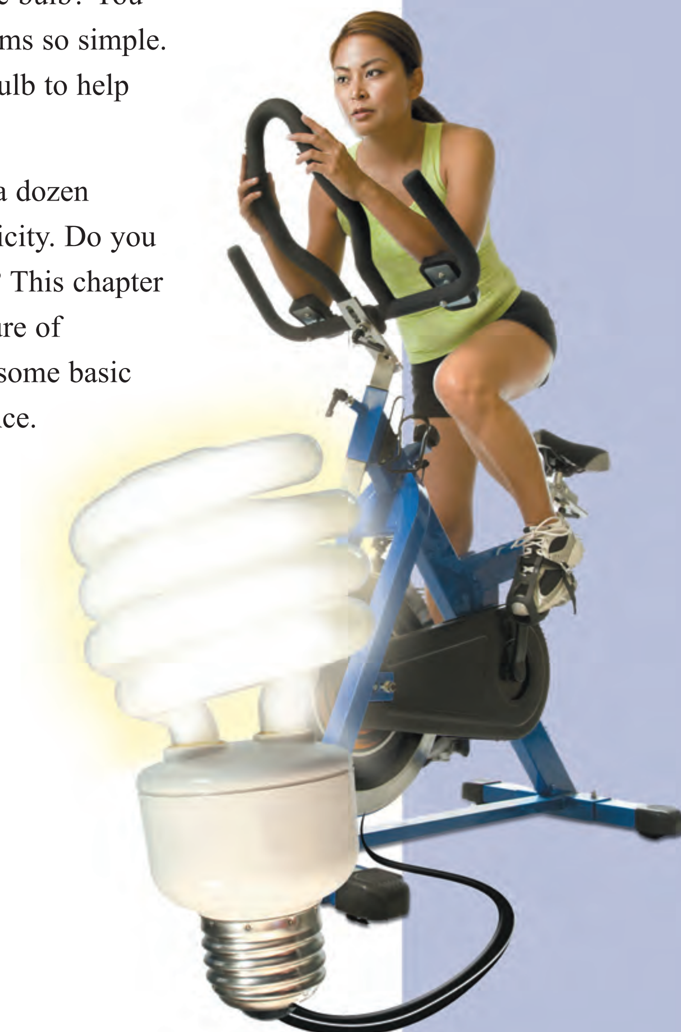
Try this at home

Find a strong magnet and some breakfast cereal that is advertised as "iron fortified." Place a small amount of cereal in a freezer-type zip top bag and gently crush the cereal into a fine powder. Spread some of the powder out into a thin layer inside the bag. Hold the magnet over the thin layer (outside the bag) and move it around. You will see pieces of the cereal moving with the magnet! Iron-fortified cereal actually has bits of iron metal in it, and the iron is attracted to the magnet.

Chapter 20
Electric Circuits

Suppose you had a stationary bicycle that was connected to a light bulb, so that when you pedaled the bicycle, the energy from the turning wheels lit the bulb. How fast would you have to pedal to generate enough electrical energy to light the bulb? You would be surprised at how hard you would have to pedal to do something that seems so simple. Some science museums have interactive exhibits like this bicycle-powered light bulb to help people see how much energy is needed to accomplish everyday tasks.

What would your life be like without electricity? You can probably name at least a dozen aspects of your morning routine alone that would change if you didn't have electricity. Do you know how electrical circuits work? Do you know what *voltage* and *current* mean? This chapter will give you the opportunity to explore electricity, electrical circuits, and the nature of electrical energy. Electricity can be powerful and dangerous, but when you know some basic facts about how electricity works, you can use electricity safely and with confidence.



Key Questions:

- ✔ *What is inside a AA battery, and how does it work?*
- ✔ *Why is the shock from a household outlet more dangerous if your skin is wet?*
- ✔ *Are there electrical circuits in the human body? In an electric eel?*

20.1 Charge

Mass is one of the more obvious properties of matter. However, matter has other properties that are often hidden. *Charge* is a fundamental property of all matter that can be overlooked. All matter has electrical (and magnetic) properties because the atoms that make up matter are held together by electromagnetic forces.

Positive and negative charge

Two kinds of electric charge

Virtually all the matter around you has electric charge because all atoms contain electrons (–) and protons (+). Electrons have negative charge and protons have positive charge. However, unlike mass, electric charge is usually hidden inside atoms. Charge is hidden because atoms are made with equal amounts of positive and negative charges. The forces from **positive** charges are canceled by **negative** charges, the same way that +1 and –1 add up to 0. Because ordinary matter has zero *net* (total) charge, most matter acts as if there is no electric charge at all.

Like charges repel and unlike charges attract

Whether two charges attract or repel depends on whether they have the same or opposite sign. A positive and a negative charge will attract each other. Two positive charges will repel each other. Two negative charges will also repel each other. The force between charges is shown in Figure 20.1.

Charge is measured in coulombs

The unit of charge is the **coulomb (C)**. The name was chosen in honor of Charles Augustin de Coulomb (1736–1806), the French physicist who performed the first accurate measurements of the force between charges. One coulomb is a *huge* amount of charge, as you will see on the next page.

Fundamental property of matter

Electric charge, like mass, is a fundamental property of matter. An important difference between mass and charge is that there are two types of charge, which we call positive and negative. We know there are two kinds because electric charges can attract or repel each other. As far as we know, there is only one type of mass. All masses *attract* each other through gravity.

VOCABULARY

positive, **negative** - the two kinds of electric charge.

coulomb (C) - the unit for electric charge.

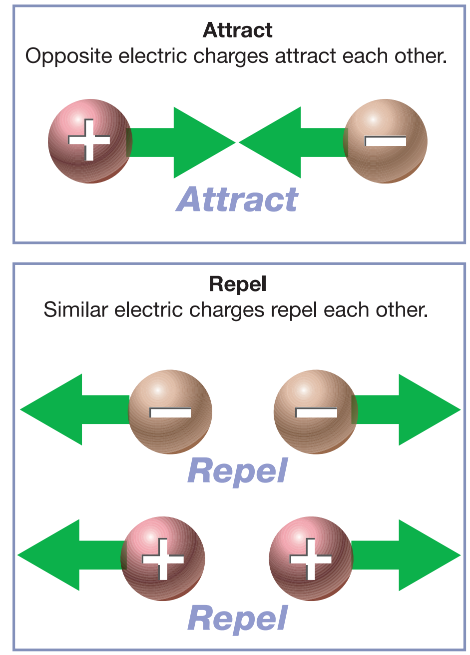


Figure 20.1: *The direction of forces on charges depends on whether they have the same or opposite charges.*

Static electricity

Neutral objects

Matter contains trillions and trillions of charged electrons and protons because matter is made of atoms. Neutral atoms have the same number of electrons and protons. Therefore, the charge of an atom is *exactly zero*. Similarly, there is perfect cancellation between positive and negative in matter leaving a *net charge* of precisely zero. An object with a net charge of zero is described as being **electrically neutral**. Your pencil, your textbook, even your body are electrically neutral, at least most of the time.

Charged objects

An object is **charged** when its net charge is *not* zero. If you have ever felt a shock when you have touched a doorknob or removed clothes from a dryer, you have experienced a charged object. An object with more negative than positive charge has a net negative charge overall. If it has more positive than negative charge, the object has a positive net charge. The net charge is also sometimes called *excess* charge because a charged object has an excess of either positive or negative charges.

Static electricity and charge

A tiny imbalance in either positive or negative charge on an object is the cause of **static electricity**. If two neutral objects are rubbed together, the friction often pulls some electrons off one object and puts them temporarily on the other. This is what happens to clothes in the dryer and to your socks when you walk on a carpet. The static electricity you feel when taking clothes from a dryer or scuffing your socks on a carpet typically results from an excess charge of less than one-millionth of a *coulomb*, the unit of charge.

What causes shocks

You get a shock because excess of charge of one sign strongly attracts charge of the other sign and repels charge of the same sign. When you walk across a carpet on a dry day, your body picks up excess negative charge. If you touch a neutral door knob some of your excess negative charge moves to the door knob. Because the door knob is a conductor, the charge flows *quickly*. The moving charge makes a brief, intense electric current between you and the door knob. The shock you feel is the electric current as some of your excess negative charge transfers to the door knob (Figure 20.2).

VOCABULARY

electrically neutral - describes an object that has equal amounts of positive and negative charges.

charged - describes an object whose net charge is not zero.

static electricity - a tiny imbalance between positive and negative charge on an object.

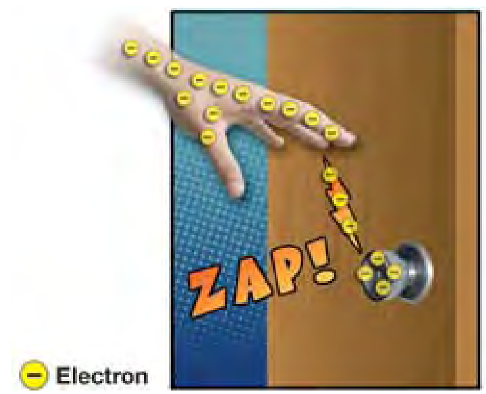


Figure 20.2: *The shock you get from touching a door knob on a dry day comes from moving charge.*

Electrical forces

The force between charges is very strong

Electric forces are incredibly strong. A millimeter cube of carbon the size of a pencil point contains about *77 coulombs* of positive and negative charge. If you could separate all the positive and negative charges by a distance of one meter, the attractive force between them would be about 50 thousand billion newtons!

This is about the weight of *three thousand million cars*. This is all from the charge in a single pencil point (Figure 20.3). The huge force between charges is the reason objects are usually electrically neutral.

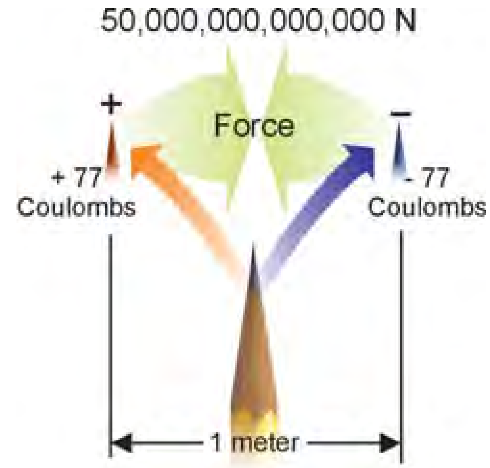


Figure 20.3: *If you could separate the charges in a pencil point by one meter, the force between the charges would be HUGE!*

Lightning and charged particles

Lightning is caused by a giant buildup of static charge. Before a lightning strike, particles in a cloud collide and charges are transferred from one particle to another. Positive charges tend to build up on smaller particles and negative charges on bigger ones.

Storm clouds

The forces of gravity and wind cause the particles to separate. Positively charged particles accumulate near the top of the cloud and negatively charged particles fall toward the bottom. Scientists from the National Aeronautics and Space Administration (NASA) have measured enormous buildups of negative charge in storm clouds. These negatively charged cloud particles repulse negative charges in the ground, causing the ground to become positively charged. This positive charge is why people who have been struck by lightning sometimes say they first felt their hair stand on end.

Lightning bolt

The negative charges in the cloud are attracted to the positively charged ground. The cloud, air, and ground can act like a giant circuit. All the accumulated negative charges flow from the cloud to the ground, heating the air along the path (to as much as 20,000°C) so that it glows like a bright streak of light. The air around a lightning bolt heats rapidly, and the expanding air creates sound waves that we hear as thunder. Thunder travels about 1 mile for every 5 seconds that you count between a flash of lightning and its thunder. If you see lightning, and count 15 seconds before you hear the thunder, divide 15 by 5 and you know that the lightning was about 3 miles away.

Photo courtesy NOAA/ERL/NSSL

Figure 20.4: *Lightning is created when negative charges in the cloud are attracted to the positively charged ground.*

Section 20.1 Review

1. Protons carry a _____ charge, and electrons carry a _____ charge.
2. Like charges _____, and opposite charges _____.
3. What does it mean to say an object is electrically neutral?
4. Explain the difference between an electrically charged and a neutral object. Does a neutral object contain no electric charge at all?
5. Why is mass usually a more obvious property of matter than charge?
6. What is a coulomb (C)?
7. If you rub an air-filled balloon on your hair, you can make it stick to a wall. When the balloon and your hair are rubbed together, electrons are transferred from your hair to the balloon.
   a. What is the net charge on the balloon after it is rubbed on your hair? Is it positive, negative, or zero?
   b. What do you think happens to the atoms near the wall's surface when the balloon is brought near the wall? (*Hint*: the balloon will stick to the wall.)
   c. What happens when you try to stick a charged balloon to a metal object, like a doorknob? Try it or do some research to find the answer and explain. Don't forget to include a Web site or book citation.
   d. The charged balloon experiments work better in dry weather than in damp weather. Why do you think this is so? Do some research to verify your answer. Don't forget to include a Web site or book citation.
8. What role do positive and negative charges play in the formation of lightning?

BIOGRAPHY

History of the terms positive and negative charge

Image courtesy of NOAA.

The terms *positive* and *negative* were first used by Benjamin Franklin (1706–1790). He and other scientists were seeking to describe their new observations about electricity. In 1733, French scientist Charles DuFay had published a book describing how like charges repel and unlike charges attract. He theorized that two fluids caused electricity: vitreous (positive) fluid and resinous (negative) fluid.

Later that century, Franklin invented his own theory that argued that electricity is a result of the presence of a single fluid in different amounts. Although scientists no longer believe that electricity is caused by different kinds of fluids, the words positive and negative are still used to describe the two types of charge.

20.2 Electric Circuits

Think of how often you use TV, radio, computers, refrigerators, and light bulbs. All of these things are possible because of electricity. The use of electricity has become so routine that most of us never stop to think about what happens when we switch on a light or turn on a motor. This section is about electricity and electric circuits. Circuits are usually made of wires that carry electricity and devices that use electricity.

VOCABULARY

electricity - the science of electric charge and current.

electric current - the flow of electric charge.

Electricity

What is electricity? **Electricity** usually means the flow of **electric current** in wires, motors, light bulbs, and other inventions. Electric current is what makes an electric motor turn or an electric stove heat up. Electric current is almost always invisible and comes from the motion of electrons or other charged particles.

Electric current Electric current is similar to a current of water, but electric current is not visible because it usually flows inside solid metal wires. Electric current can carry energy and do work just as a current of water can. For example, a waterwheel turns when a current of water exerts a force on it (Figure 20.5). A waterwheel can be connected to a machine such as a loom for making cloth, or to a millstone for grinding wheat into flour. Before electricity was available, waterwheels were used to supply energy to many machines. Today, the same tasks are done using energy from electric current. Look around you right now and you probably see wires carrying electric current into buildings.

Electricity can be powerful and dangerous Electric current can carry a great deal of energy. For example, an electric saw can cut wood much faster than a hand saw. An electric motor the size of a basketball can do as much work as five big horses or 15 strong people. Electric current also can be dangerous. Touching a live electric wire can result in serious injury. The more you know about electricity, the easier it is to use it safely.

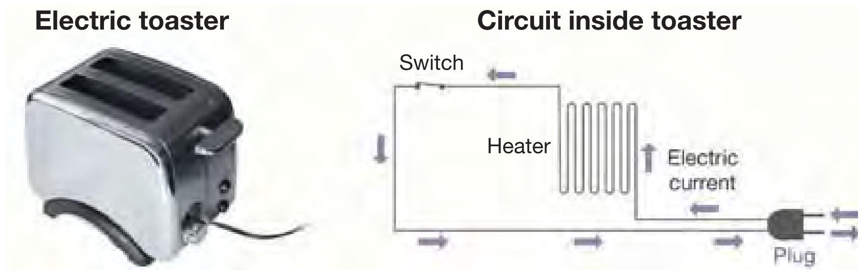
Figure 20.5: *A waterwheel uses the force of flowing water to run machines.*

SC.912.N.4.1-Explain how scientific knowledge and reasoning provide an empirically-based perspective to inform society's decision making.

Electric circuits

Electricity travels in circuits

An **electric circuit** is a complete path through which electricity travels. A good example of a circuit is the one in an electric toaster. Bread is toasted by heaters that convert electrical energy to heat. The circuit has a switch that turns on when the lever on the side of the toaster is pushed down. With the switch on, electric current enters through one side of the plug from the socket in the wall, and goes through the toaster and out the other side of the plug.



Wires are like pipes for electricity

Wires in electric circuits are similar in some ways to pipes and hoses that carry water (Figure 20.6). Wires act like pipes for electric current. Current enters the house on the supply wire and leaves on the return wire. The big difference between wires and water pipes is that you cannot get electricity to leave a wire the way water leaves a pipe. If you cut a water pipe, the water flows out. If you cut a wire, the electric current stops immediately.

Examples of circuits in nature

Circuits are not confined to appliances, wires, and devices built by people. The first experience humans had with electricity was in the natural world. These are some examples of natural circuits:

- The tail of an electric eel makes a circuit when it stuns a fish with a jolt of electricity.
- The Earth makes a gigantic circuit when lightning carries electric current between the clouds and the ground.
- The nerves in your body are an electrical circuit that carries messages from your brain to your muscles.

VOCABULARY

electric circuit - a complete path through which electric charge can flow.

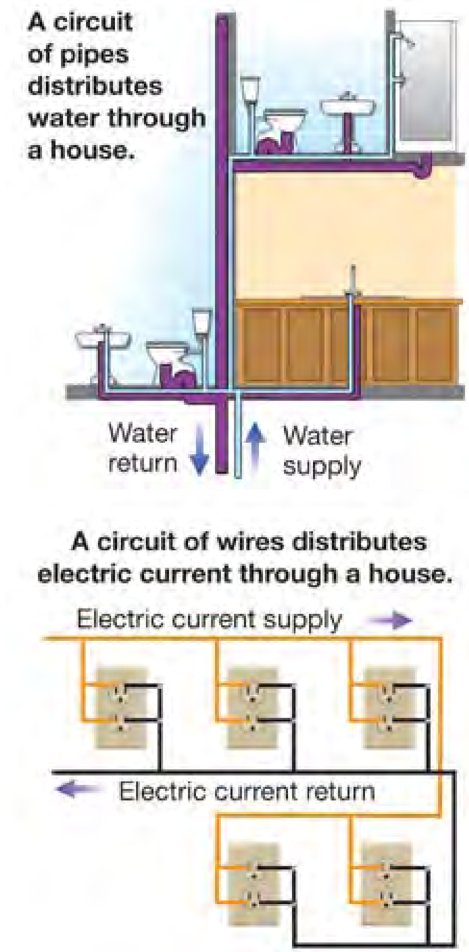


Figure 20.6: *Comparing "circuits" for water and electricity.*

Circuit diagrams and electrical symbols

VOCABULARY

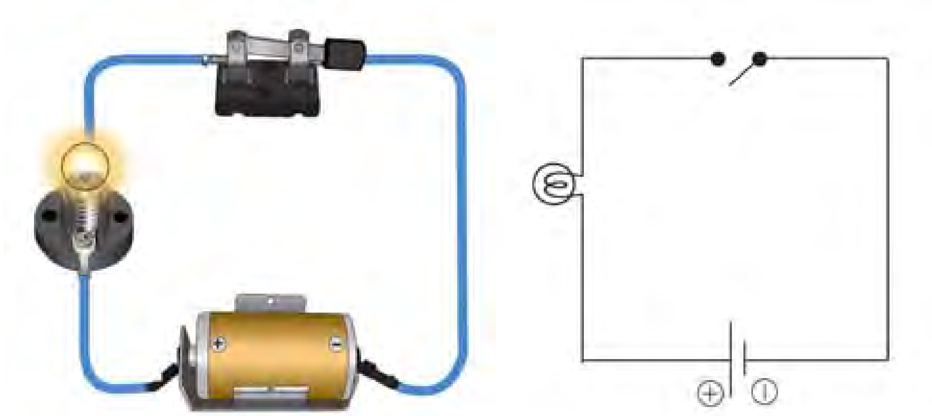
resistor - a component that is used to control current in many circuits.

Circuit diagrams

Circuits are made up of wires and electrical parts such as *batteries*, *light bulbs*, *motors*, and *switches*. When designing a circuit, people make drawings to show how the parts are connected. Electrical drawings are called *circuit diagrams*. In a circuit diagram, symbols are used to represent each part of the circuit. These *electrical symbols* make drawing circuits quicker and easier than drawing realistic pictures.

Electrical symbols

A circuit diagram is a shorthand method of describing a working circuit. The electric symbols used in circuit diagrams are standard so that anyone familiar with electricity can build the circuit by looking at the diagram. Figure 20.7 shows some common parts of a circuit and their electrical symbols. The picture below shows an actual circuit on the left and its circuit diagram on the right. Can you identify the real parts with their symbols? Note that the switch is open in the circuit diagram, but closed in the photograph. Closing the switch completes the circuit so the light bulb lights.



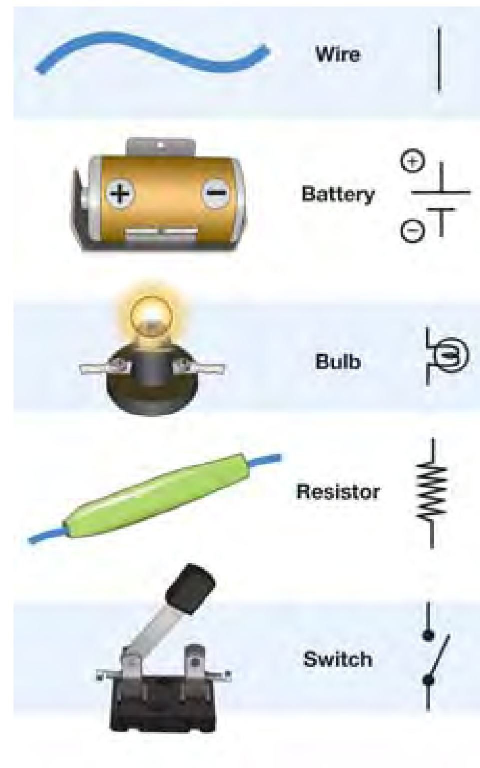


Figure 20.7: *These electrical symbols are used when drawing circuit diagrams.*

Resistors

A **resistor** is an electrical device that uses the energy carried by electric current in a specific way. In many circuit diagrams any electrical device that uses energy is shown with a resistor symbol. A light bulb, heating element, speaker, or motor can be drawn with a resistor symbol. When you analyze a circuit, many electrical devices may be treated as resistors when figuring out how much current is in the circuit.

SC.912.P.10.15-Investigate and explain the relationships among current, voltage, resistance, and power.

Open and closed circuits

Batteries All electric circuits must have a source of energy. Circuits in your home get their energy from power plants that generate electricity. Circuits in flashlights, cell phones, and portable radios get their energy from batteries. Some calculators have solar cells that convert energy from the sun or other lights into electrical energy. Of all the types of circuits, those with batteries are the easiest to understand. We will focus on battery circuits for now and will eventually learn how circuits in buildings work.

Open and closed circuits It is necessary to be able to turn off light bulbs, radios, and most other devices in circuits. One way to turn off a device is to stop the current by "breaking" the circuit. Electric current can only flow when there is a complete and unbroken path from one end of the circuit to the other. A circuit with no breaks is called a **closed circuit** (Figure 20.8). A light bulb will light only when it is part of a closed circuit. Opening a switch or disconnecting a wire creates a break in the circuit and stops the current. A circuit with any break in it is called an **open circuit**.

Switches **Switches** are used to turn electricity on and off. Flipping a switch to the *off* position creates an open circuit by making a break in the wire. The break stops the current because electricity cannot normally travel through air. Flipping a switch to the *on* position closes the break and allows the current to flow again, to supply energy to the bulb, radio, or other device.

Breaks in circuits A switch is not the only way to make a break in a circuit. An incandescent light bulb burns out when the thin wire that glows inside it breaks. This creates an open circuit and explains why a burned-out bulb cannot light. Today, incandescent bulbs are being replaced with compact fluorescent light bulbs (CFLs) which use less electrical energy to put out the same amount of light. CFLs work differently than incandescent bulbs. Instead of a heating a thin wire inside, a CFL is a coiled glass tube that contains a gas. When the circuit is closed, electricity passes through the gas-filled tube and causes the atoms in the gas to emit light. Just like incandescent bulbs however, when a CFL bulb does finally quit working, the circuit will be broken and the CFL will need to be replaced.

VOCABULARY

closed circuit - a circuit with the switch in the *on* position, so there are *no* breaks and charge can flow.

open circuit - a circuit with the switch in the *off* position, so there *is* a break and charge cannot flow.

switch - a device for alternately allowing and not allowing charge to flow in a circuit.

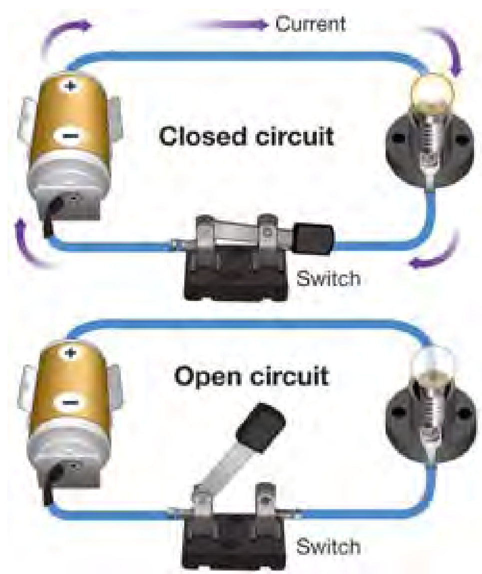
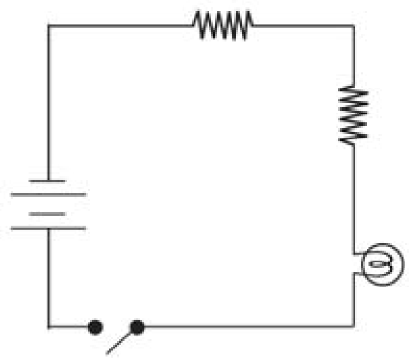


Figure 20.8: *There is current in a closed circuit but not in an open circuit.*

Section 20.2 Review

1. How are electric circuits and systems for carrying water in buildings similar?
2. Give one example of a circuit found in nature and one example of a circuit created by people.
3. Draw a circuit diagram for the circuit in Figure 20.9.
4. What is the difference between an open circuit and a closed circuit?
5. What does a resistor do in a circuit? Give an example.
6. Use the circuit diagram below to answer the following questions.



   a. How many bulbs are there in this circuit?
   b. How many batteries?
   c. How many resistors?
   d. How many switches?
   e. Is this circuit open or closed? Justify your answer.
7. When you turn "on" a light switch in a room, does this open or close the circuit? Explain.

Figure 20.9: *Question 3.*

20.3 Current and Voltage

Current is what carries energy in a circuit. Like water current, electric current only flows when there is a difference in energy between two locations that are connected. Water flows downhill from higher gravitational potential energy to lower energy. Electric current flows “downhill” from higher electrical potential energy to lower electrical potential energy.

Current

Measuring electric current

Electric current is measured in units called **amperes (A)**, or amps, for short. The unit is named in honor of Andre-Marie Ampere (1775–1836), a French physicist who studied electricity and magnetism. A small battery-powered flashlight bulb uses about 1/2 amp of electric current.

Current flows from positive to negative

Examine a battery and you will find a positive and a negative end. The positive end on a AA, C, or D battery has a raised bump, and the negative end is flat. A battery’s electrical symbol uses a long line to show the positive end and a short line to show the negative end.

Current in equals current out

Electric current from a battery flows out of the positive end and returns back into the negative end. An arrow can be used to show the direction of current on a circuit diagram (Figure 20.10). In most electric circuits, negative charge flows, and you would think the correct direction would be negative to positive. It is practical and conventional, however, to describe current as flowing from positive to negative, or from high voltage to low voltage. The amount of electric current coming out of the positive end of the battery must always be the same as the amount of current flowing into the negative end. You can picture this with steel balls flowing through a tube. When you push one in, one comes out. The rate at which the balls flow in equals the rate at which they flow out.

VOCABULARY

ampere (A) - the unit of electric current.

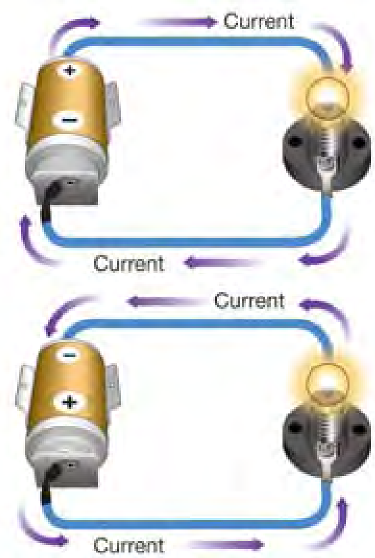


Figure 20.10: *Direction of electric current.*

SCIENCE FACT

Either positive or negative charges can make an electric current, depending on the circuit materials. In the human body, current is the movement of both positive and negative charges. In ordinary electric circuits, current is the movement of negative charge in metal conductors.

Voltage

Energy and voltage

Voltage is a measure of electric potential energy, just like height is a measure of gravitational potential energy. Voltage is measured in **volts (V)**. Like other forms of potential energy, a voltage difference means there is energy that can be used to do work. With electricity, the energy becomes useful when we let the voltage difference cause current to flow through a circuit. Current is what actually flows and does work. A difference in voltage provides the energy that causes current to flow (Figure 20.11).

What voltage means

A voltage difference of 1 volt means 1 amp of current does 1 joule of work in 1 second. Since 1 joule per second is a watt (power), *voltage is the power per amp of current that flows*. Every amp of current flowing out of a 1.5 V battery carries 1.5 watts of power. The voltage in your home electrical system is 120 volts, which means each amp of current carries 120 watts of power.

Using a meter to measure voltage

A *voltmeter* measures voltage. A more useful meter is a **multimeter**, which can measure voltage or current, and sometimes also resistance. To measure voltage, the meter's probes are touched to two places in a circuit or across a battery. The meter shows the difference in voltage between the two places.

Meters measure voltage difference

The meter reads *positive* voltage if the red (positive) probe is at a higher voltage than the black probe. The meter reads negative when the black probe is at the higher voltage. The meter reads voltage *differences* between its probes. If both probes are connected to the same place, the meter reads zero.

VOCABULARY

voltage - a measure of electric potential energy.

volt (V) - the measurement unit for voltage.

multimeter - a measuring instrument for current, voltage, and resistance.

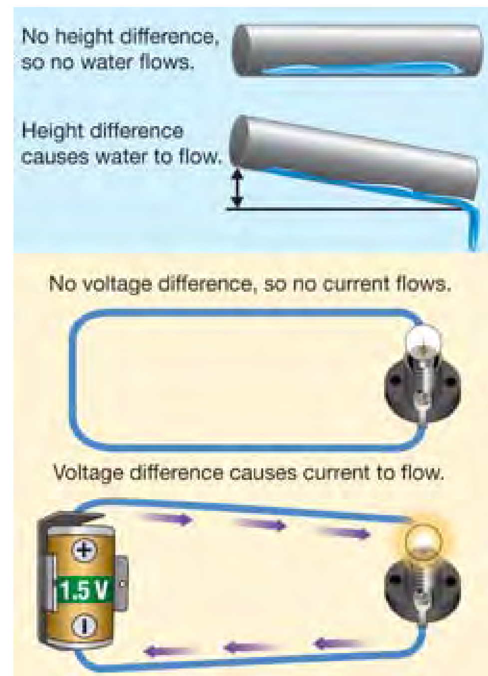


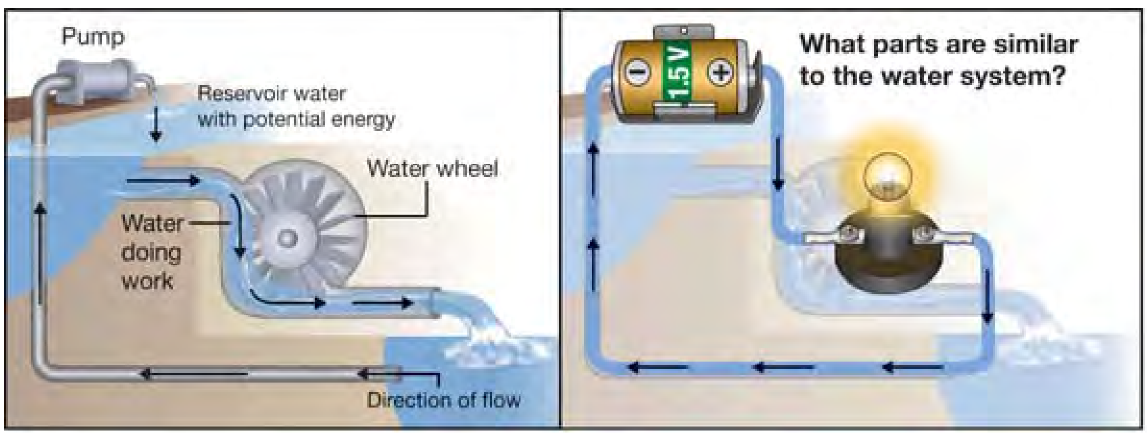
Figure 20.11: *A change in height causes water to flow in a pipe. Current flows in this circuit because a battery creates a voltage difference.*

MA.912.S.1.2-Determine appropriate and consistent standards of measurement for the data to be collected in a survey or experiment.
SC.912.P.10.15-Investigate and explain the relationships among current, voltage, resistance, and power.

Batteries

Batteries A **battery** uses chemical energy to create a voltage difference between its two terminals. When current leaves a battery, it carries energy. The current gives up its energy as it passes through an electrical device such as a light bulb. When a bulb is lit, the electrical energy is taken from the current and is transformed into light and heat energy. The current returns to the battery, where it gets more energy.

Batteries are like pumps Consider the water system shown below. The water pump raises the water level, increasing the potential energy of the water. As the water flows down, its potential energy is converted into kinetic energy at the water wheel. How is a simple circuit similar? The pump keeps the water level different in the water system, and in the electrical circuit, the battery keeps the positive and negative charges separate. As long as the water level is different in the water system, the water can flow. As long as there is an area of charge separation in an electrical circuit, current can flow. This is why the battery is a sort of "pump." Chemical reactions in a battery give the energy to the current. The current then flows through the circuit, carrying the energy to any motors or bulbs (which are like the water wheel in the water system). The current gets a "refill" of energy each time it passes through the battery, for as long as the battery's stored energy lasts.



VOCABULARY

battery - a device that transforms chemical energy to electrical energy, and provides electrical force in a circuit.

TECHNOLOGY

Batteries and Cells

Battery voltage depends on how the battery is constructed and what chemicals it uses. A simple household zinc-carbon (alkaline) battery is 1.5 volts, and it is technically called a *cell*, not a battery. A, AA, AAA, C, and D cells all have 1.5 volts each. The D cell is the largest, and carries the most energy, so a D cell can last longer than a smaller 1.5-volt cell.

If you have a device made up of more than one cell, you have a battery. A 9 volt battery is made up of three 1.5-volt alkaline cells. A car battery is usually 12 volts, and is made up of 6 lead acid cells that are 2 volts each.

It is acceptable, although not entirely scientifically correct, to use the term *battery* when referring to A, AA, AAA, C, or D cells.

Measuring current in a circuit

Measuring current with a meter

Electric current can be measured with a multimeter. However, if you want to measure current you must force the current to pass *through* the meter. That usually means you must break your circuit somewhere and rearrange wires so that the current must flow through the meter. For example, Figure 20.12 shows a circuit with a battery and bulb. The meter has been inserted into the circuit to measure current. If you trace the wires, the current comes out of the positive end of the battery, through the light bulb, *through the meter*, and back to the battery. The meter in the diagram measures 0.37 amps of current. Some electrical meters, called *ammeters*, are designed specifically to measure only current.

Figure 20.12: *Current must pass through the meter when it is being measured.*

Setting up the meter

If you use a multimeter, you also must remember to set its dial to measure the type of current in your circuit. Multimeters can measure two types of electric current, called alternating current (AC) and direct current (DC). You will learn about the difference between alternating and direct current in the next chapter. For circuits with light bulbs and batteries, you must set your meter to read direct current, or DC. The symbols for AC and DC are shown in Figure 20.13.

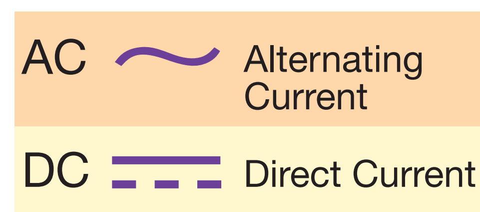


Figure 20.13: *A multimeter often uses these symbols for AC and DC settings.*

Protect the meter

A meter can be damaged if too much current passes through it. Always be sure there is a light bulb or some other resistor in the circuit with the meter. This way, you are unlikely to overload the meter with too much current.

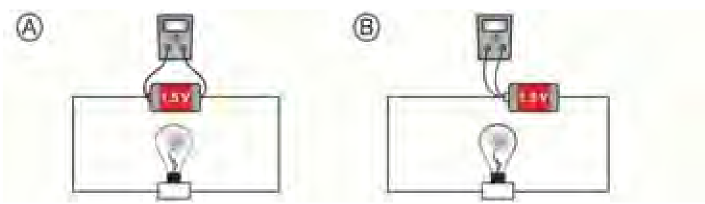
To protect its delicate electronics, most meters contain a *circuit breaker* or *fuse*. Circuit breakers and fuses are fast-acting, automatic switches that open a circuit if they sense too much current.

A circuit breaker can be reset the way a switch can be flipped. A broken fuse, however, is similar to a burned out light bulb and must be replaced for the meter to work again. The meter you use in your electric circuit investigations has a fuse inside. To replace the fuse, you will need a replacement fuse and a small screwdriver to open up the back of the meter. Your teacher can show you how this is done. To make your investigations easier, be careful when connecting current measurements and you won't have to replace the fuse!

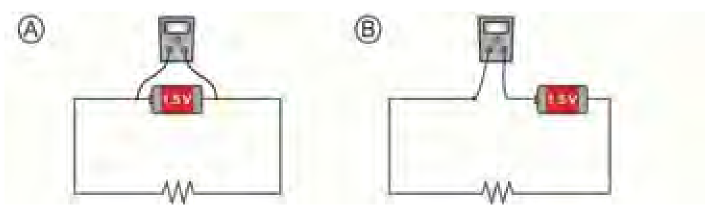
SC.912.P.10.15-Investigate and explain the relationships among current, voltage, resistance, and power.

Section 20.3 Review

1. List the units for measuring current and voltage.
2. What is the difference between current and voltage, besides their units of measurement?
3. Why does a multimeter display a reading of zero when both of its probes are touched to the same end of a battery?
4. Study Figure 20.15 and answer the following questions. All batteries and bulbs are identical.
   a. Compare the voltage drop across the bulb in the one-bulb circuit with the voltage drops across each bulb in the four-bulb circuit.
   b. Which circuit will have more current, and why?
   c. Will there be a difference between the two circuits in bulb brightness? Why or why not?
5. The direction of electric current is away from the _____ end of the battery and toward the _____end.
6. What voltage would the electrical meter show in each of the diagrams below?



7. Which of the following diagrams shows the correct way to measure current in a circuit?



8. A flashlight needs three C batteries. How many volts of electricity does it need (Figure 20.14)?

Figure 20.14: *Question 8.*

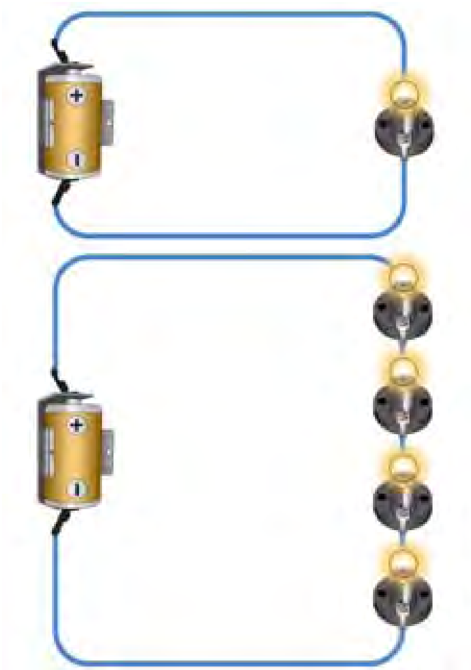


Figure 20.15: *Question 4.*

20.4 Resistance and Ohm's Law

You can apply the same voltage to different circuits and different amounts of current will flow. For example, when you plug in a desk lamp, the current through it is 1 amp. If a hair dryer is plugged into the same outlet (with the same voltage) the current is 10 amps. For a given voltage, the amount of current that flows depends on the *resistance* of the circuit.

VOCABULARY

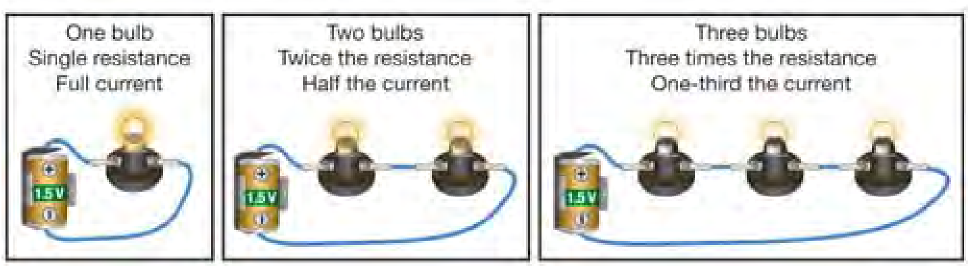
resistance - determines how much current flows for a given voltage. Higher resistance means less current.

Electrical resistance

Current and resistance **Resistance** is the measure of how strongly a wire or other object resists current flowing through it. A device with low resistance, such as a copper wire, can easily carry a large current. An object with a high resistance, such as a rubber band, can only carry a current so tiny it can hardly be measured.

A water analogy The relationship between electric current and resistance can be compared with water flowing from the open end of a bottle (Figure 20.16). If the opening is large, the resistance is low and lots of water flows out quickly. If the opening is small, the resistance is greater and the water flow is slow.

Circuits The total amount of resistance in a circuit determines the amount of current in the circuit for a given voltage. Every device that uses electrical energy adds resistance to a circuit. The more resistance the circuit has, the less the current. For example, if you string several light bulbs together, the resistance in the circuit increases and the current decreases, making each bulb dimmer than a single bulb would be.



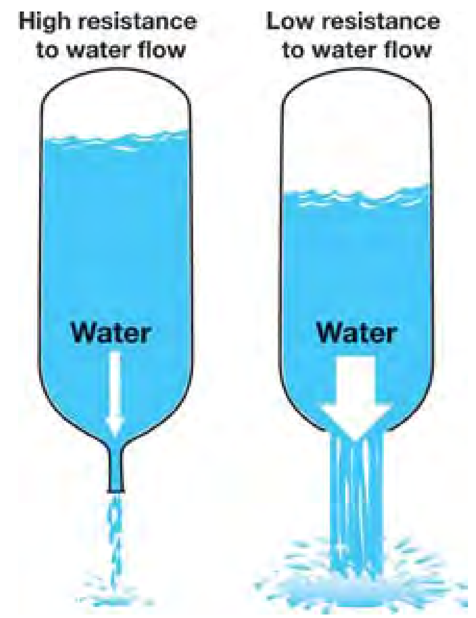
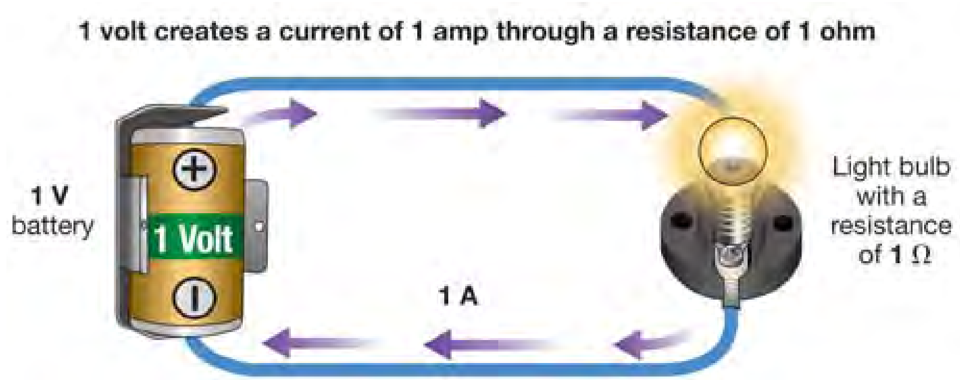


Figure 20.16: *The current is less when the resistance is great.*

SC.912.P.10.15-Investigate and explain the relationships among current, voltage, resistance, and power.

Measuring resistance

The ohm Electrical resistance is measured in units called **ohms**. This unit is abbreviated with the Greek letter *omega* (Ω). When you see Ω in a sentence, think or read "ohms." For a given voltage, the greater the resistance, the lesser the current. If a circuit has a resistance of one ohm, then a voltage of one volt causes a current of one ampere to flow.



Resistance of wires The wires used to connect circuits are made of metals such as copper or aluminum that have low resistance. The resistance of wires is usually so low compared with other devices in a circuit that you can ignore wire resistances when measuring or calculating the total resistance. The exception is when there are large currents. If the current is large, the resistance of wires may be important.

Measuring resistance You can use a multimeter to measure the resistance of wires, light bulbs, and other devices (Figure 20.17). You must first remove the device from the circuit. Then set the dial on the multimeter to the resistance setting and touch the probes to each end of the device. The meter will display the resistance in ohms (Ω), kilo-ohms (× 1,000 Ω), or mega-ohms (× 1,000,000 Ω).

VOCABULARY

ohm (Ω) - the unit of measurement for resistance.

Figure 20.17: *A multimeter can be used to measure resistance of a device.*

TECHNOLOGY

How Resistance is Measured

A multimeter measures resistance by forcing a precise amount of current to flow through an electrical device. The meter then measures the voltage across the device and calculates the resistance. The currents used to measure resistance are quite small, so any other current might interfere. That is why a device must be removed from the circuit to measure its resistance.

Ohm's law

Ohm's law The current in a circuit depends on the battery's voltage and the circuit's resistance. Voltage and current are *directly* related. Doubling the voltage doubles the current. Resistance and current are *inversely* related. Doubling the resistance cuts the current in half. These two relationships form **Ohm's law** (Figure 20.18). The law relates current, voltage, and resistance with one formula. If you know two of the three quantities, you can use Ohm's law to find the third.

VOCABULARY

Ohm's law - states that the current is *directly* related to the voltage and *inversely* related to the resistance.

OHM'S LAW

$$I = \frac{V}{R}$$

Current (A) — I; ***Voltage*** (V) — V; ***Resistance*** (Ω) — R

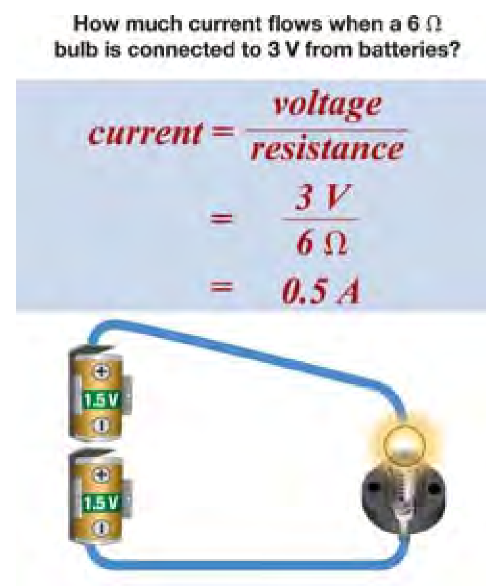


Figure 20.18: *An example of Ohm's law in action.*

Applying Ohm's law Ohm's law shows how resistance is used to control the current. If the resistance is low, then a given voltage will result in a large amount of current. Devices that need a large amount of current typically have lower resistance. For example, a small electric motor might have a resistance of only 1 ohm. When connected in a circuit with a 1.5-volt battery, the motor draws 1.5 amps of current. By comparison, a small light bulb with a resistance of 2.5 ohms in the same type of circuit would draw only 0.6 amps.

Equation	Gives you...	If you know...
I = V/R	current (I)	voltage and resistance
V = IR	voltage (V)	current and resistance
R = V/I	resistance (R)	voltage and current

SC.912.N.3.3-Explain that scientific laws are descriptions of specific relationships under given conditions in nature, but do not offer explanations for those relationships.
SC.912.P.10.15-Investigate and explain the relationships among current, voltage, resistance, and power.

Solving Problems: Using Ohm's law

A toaster oven has a resistance of 12 ohms and is plugged into a 120-volt outlet. How much current does it draw?

1. Looking for: You are asked for the current in amperes.

2. Given: You are given the resistance in ohms and voltage in volts.

3. Relationships: Ohm's law: $I = \frac{V}{R}$

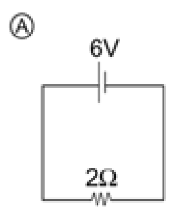
4. Solution: Plug in the values for *V* and *R*: $I = \frac{120\text{ V}}{12\ \Omega} = 10\text{ A}$

Your turn...

a. A laptop computer runs on a 24-volt battery. If the resistance of the circuit inside is 16 ohms, how much current does it use?

b. A motor in a toy car needs 2 amps of current to work properly. If the car runs on four 1.5-volt batteries, what is the motor's resistance?

c. What is the current in the circuit below?



KEYWORDS

Superconductivity

A *superconductor* allows current to flow without losing any energy as heat or light. What kinds of technology have been developed on the principles of superconductivity? What future technologies are being explored?

The LDX experiment at MIT uses a superconducting coil to explore fusion technology.

Solve first Look later

a. 1.5 A
b. 3 Ω
c. 3 A

SC.912.N.3.3-Explain that scientific laws are descriptions of specific relationships under given conditions in nature, but do not offer explanations for those relationships.
SC.912.N.3.4-Recognize that theories do not become laws, nor do laws become theories; theories are well supported explanations and laws are well supported descriptions.

The resistance of common objects

Resistances match operating voltage

The resistance of electrical devices ranges from small (0.001 ohms) to large (10×10^6 ohms). Every electrical device is designed with a resistance that causes the right amount of current to flow when the device is connected to the proper voltage. For example, a 100-watt light bulb has a resistance of 144 ohms. When connected to 120 volts from a wall socket, the current is 0.83 amps and the bulb lights (Figure 20.19). If you connect the same light bulb to a 1.5-volt battery it will not light. According to Ohm's law, the current is only 0.01 amps when 1.5 volts is applied to a resistance of 144 ohms. This amount of current will not light the bulb. All electrical devices draw the right amount of power only when connected to voltage they were designed for.

The resistance of skin

Electrical outlets are dangerous because you can get a fatal shock by touching the wires inside. So why can you safely handle a 9-volt battery? The reason is Ohm's law. The typical resistance of dry skin is 100,000 ohms or more. According to Ohm's law, 9 V ÷ 100,000 Ω is only 0.00009 A. This is not enough current to be harmful. On average, nerves in the skin can feel a current of around 0.0005 amps. You can get a dangerous shock from 120 volts from a wall socket because that is enough voltage to force 0.0012 amps (120 V ÷ 100,000 Ω) through your skin, and you certainly can feel that!

Water lowers skin resistance

Wet skin has much lower resistance than dry skin. Because of the lower resistance, the same voltage will cause more current to pass through your body when your skin is wet. The combination of water and 120-volt electricity is especially dangerous because the high voltage and lower resistance make it possible for large (possibly fatal) currents to flow.

Changing resistance

The resistance of many electrical devices varies with temperature. For example, the amount of resistance a light bulb contributes to a circuit increases as its temperature increases (due to the current running through it). Devices that have a variable resistance like this are referred to as *non-ohmic*, because you can't use Ohm's law to predict the current when there is an ever-changing resistance (Figure 20.20). The small light bulbs in your circuit kit are non-ohmic, so you will use fixed resistors to apply Ohm's law to your simple circuits.

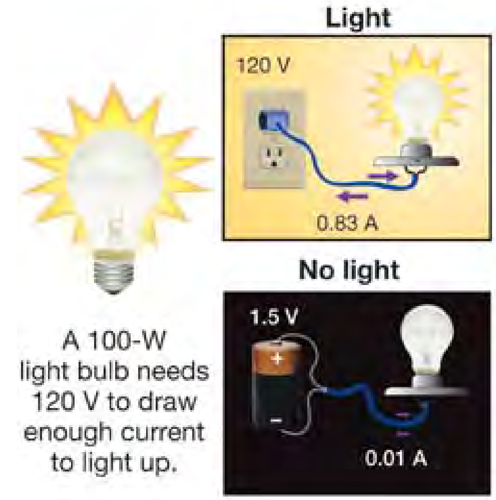


Figure 20.19: *A light bulb designed for use in a 120-volt household circuit does not light when connected to a 1.5-volt battery.*

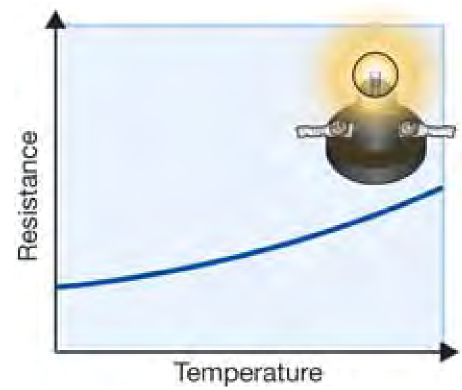


Figure 20.20: *The resistance of many materials, including those in light bulbs, increases as temperature increases. A light bulb is said to be "non-Ohmic" for this reason.*

SC.912.P.10.15-Investigate and explain the relationships among current, voltage, resistance, and power.

Conductors and insulators

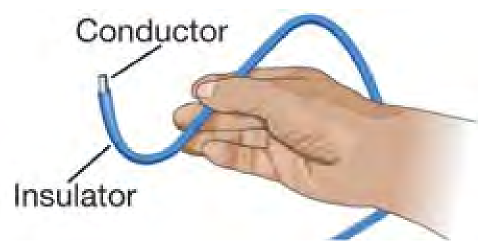
Conductors Current passes easily through some materials, such as copper, which are called conductors. A **conductor** can *conduct*, or carry, electric current. The electrical resistance of wires made from conductors is low. Most metals are good conductors.

Insulators Other materials, such as rubber, glass, and wood, do not allow current to easily pass through them. These materials are called **insulators,** because they insulate against, or block, the flow of current.

Semiconductors Some materials are in between conductors and insulators. These materials are called **semiconductors** because their ability to carry current is higher than an insulator but lower than a conductor. Computer chips, televisions, and portable radios are among the many devices that use semiconductors. You may have heard of a region in California called *Silicon Valley.* Silicon is a semiconductor commonly used in computer chips. An area south of San Francisco is called Silicon Valley because there are many semiconductor and computer companies located there.

Comparing materials No material is a perfect conductor or insulator. Some amount of current will always flow in any material if a voltage is applied. Even copper (a good conductor) has some resistance. Figure 20.21 shows how the resistances of various conductors, semiconductors, and insulators compare.

Applications of conductors and insulators Both conductors and insulators are necessary materials in human technology. For example, a wire has one or more conductors on the inside and an insulator on the outside. An electrical cable may have 20 or more conductors, each separated from the others by a thin layer of insulator. The insulating layer prevents the other wires or other objects from being exposed to the current and voltage carried by the conducting core of the wire.



VOCABULARY

conductor - a material with low electrical resistance. Metals such as copper and aluminum are conductors.

insulator - a material with high electrical resistance. Plastic and rubber are good insulators.

semiconductor - a material between conductor and insulator in its ability to carry current.

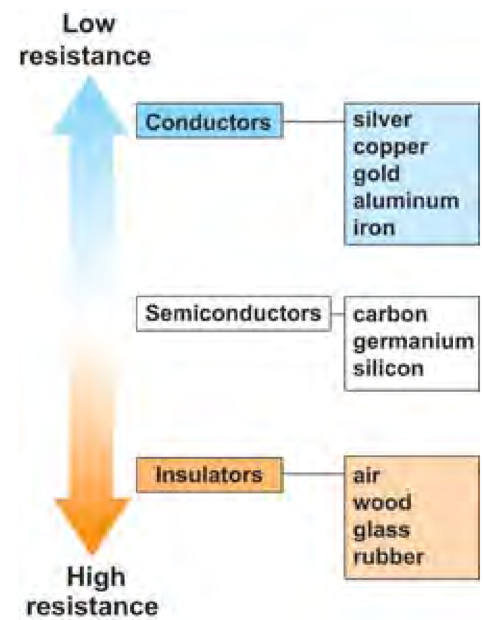


Figure 20.21: *Comparing the resistance of materials.*

SC.912.P.10.14-Differentiate among conductors, semiconductors, and insulators.

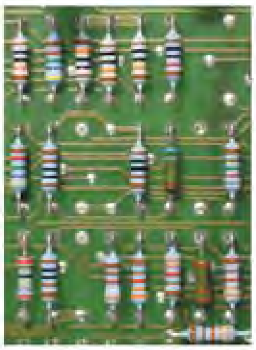
Resistors

Resistors are used to control current

Resistors are electrical components that are designed to have a specific resistance that remains the same over a wide range of currents. Resistors are used to control the current in circuits. They are found in many common electronic devices such as computers, televisions, telephones, and stereos.

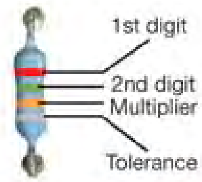
Fixed resistors

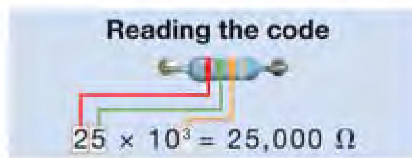
There are two main types of resistors: fixed and variable. Fixed resistors have a resistance that cannot be changed. If you have ever looked at a circuit board inside a computer or other electrical device, you have seen fixed resistors. They are small skinny cylinders or rectangles with colored stripes on them. Because resistors are so tiny, it is impossible to label each one with the value of its resistance in numbers. Instead, the colored stripes are a code that tells you the resistance (see below).



Color	Number
black	0
brown	1
red	2
orange	3
yellow	4
green	5
blue	6
violet	7
grey	8
white	9

Color	Tolerance
silver	+/- 10%
gold	+/- 5%
brown	+/- 1%





Variable resistors

Variable resistors, also called **potentiometers**, can be adjusted to have a resistance within a certain range. If you have ever turned a dimmer switch or volume control, you have used a potentiometer. When the resistance of a dimmer switch increases, the current decreases, and the bulb gets dimmer. Inside a potentiometer is a circular resistor and a little sliding contact called a wiper (Figure 20.22). If the circuit is connected at A and C, the resistance is always 100 Ω. But if the circuit is connected at A and B, the resistance can vary from 0 Ω to 100 Ω. Turning the dial changes the resistance between A and B and also changes the current (or voltage) in the circuit.

VOCABULARY

potentiometer - a type of variable resistor that can be adjusted to give resistance within a certain range.

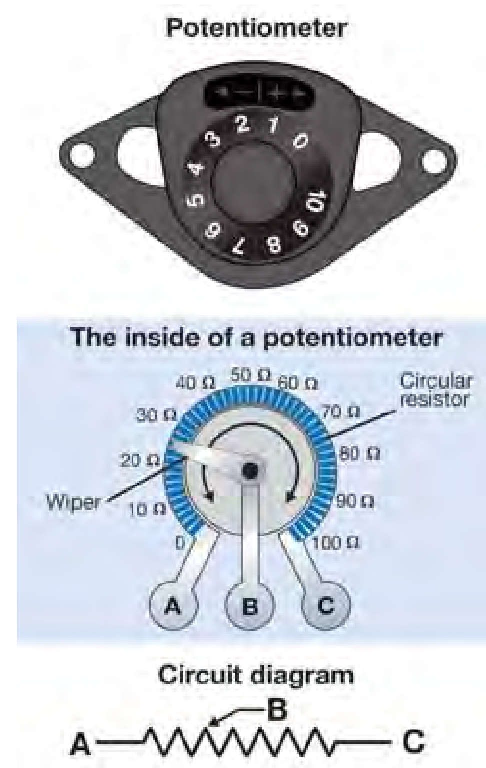


Figure 20.22: *The resistance of this potentiometer can vary from 0 Ω to 100 Ω.*

SC.912.P.10.14-Differentiate among conductors, semiconductors, and insulators.

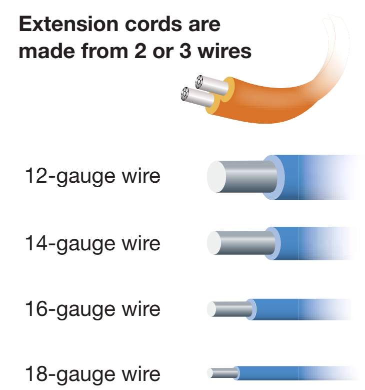
Section 20.4 Review

1. List the units and their abbreviations for resistance, voltage, and current.
2. What happens to the current if a circuit's resistance increases?
3. What happens to the current if a circuit's voltage increases?
4. A circuit contains one light bulb and a battery. What happens to the total resistance in the circuit if you replace the one light bulb with a string of four identical bulbs? Why?
5. Why can you safely handle a 1.5-V battery without being electrocuted?
6. A flashlight bulb has a resistance of about 6 Ω. It works in a flashlight with two AA alkaline batteries. About how much current does the bulb draw?
7. What voltage produces a 6 A current in a circuit that has a total resistance of 3 Ω?
8. What is a circuit's resistance if 12 V produces 2 A of current?
9. If you plug a device that has a resistance of 15 Ω into a 120-V outlet, how much current does it draw?
10. What is the difference between a conductor and an insulator? Give an example of each.
11. Do some research to find out why semiconductors are so important to computer technology. Don't forget to include Web site or book citations.
12. What is a fixed resistor, and where could you find fixed resistors in your home?
13. What is a variable resistor, and where could you find variable resistors in your home?
14. Look on the back or underside of different appliances and devices in your home. Find two that list the current and voltage each uses. Calculate the resistance of each.

TECHNOLOGY

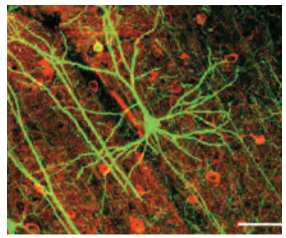
Extension Cord Safety

The label on an extension cord will tell you how many amps of current it can safely carry. The length and wire thickness are both important. Always check to see if the extension cord can carry at least as much current as the device you plug in will require. Many fires have been caused by using the wrong extension cord!



Wire Gauge	Current (amps)
12	20
14	15
16	10
18	7

The Shocking Truth You Are Wired!

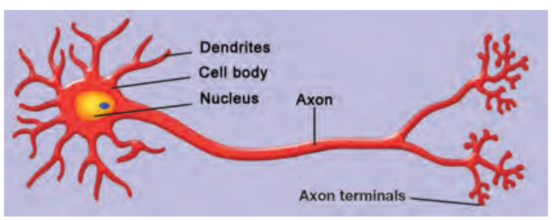


Did you know that there are electric circuits in your body? Obviously, they aren't the kind made from batteries, bulbs, and wires—and there certainly isn't anything like lightning flashing around in there. However, there are electric circuits of a different type inside your body, and you couldn't survive without them.

Withdrawal Reflexes

Have you ever accidentally touched a hot stove? The first thing you do is pull your hand back quickly—without even thinking about it.

A withdrawal reflex like this happens because electrical signals are sent through the nerve network in your body. When you touch a hot stove, nerve endings in your fingers send a signal to nerves in your spinal cord. From the spinal cord, the signal is transferred to nerve fibers that control muscles in your hand and arm, causing them to contract, jerking your hand away from the stove. All of this happens in a split second!



Neurons

Your nervous system uses specialized cells called neurons to transfer electrical signals from one part of your body to another. A neuron has three basic parts: the cell body; a long, thin portion called the axon; and finger-like projections called dendrites.

Battery Circuits vs. Body Circuits

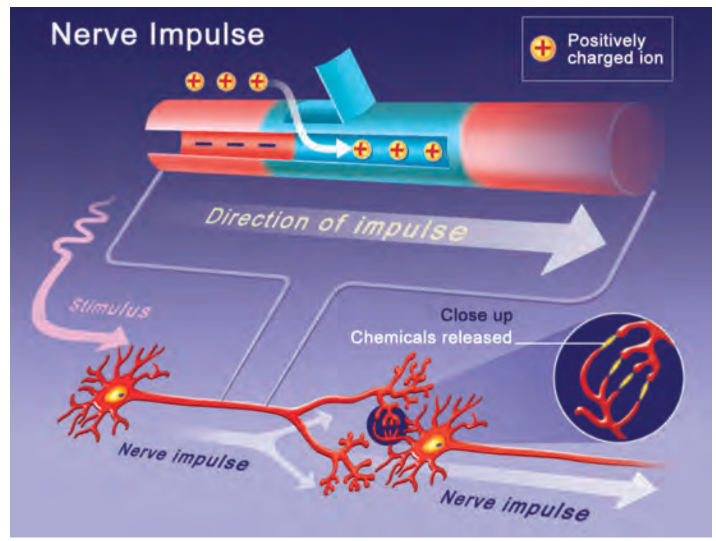
Unlike the components of the electric circuits you built in class, most neurons don't touch one another. Instead, as the electrical signal reaches the end of the axon, a chemical called a neurotransmitter is released. The chemical is picked up by receptors on the next neuron's dendrites. The dendrites then activate their own cell body to continue sending the signal along the axon.

Electricity in your home works because negatively charged electrons in the wires are free to carry the electrical current. This doesn't happen in the electric circuits of your body. Instead, the electrical current is carried by positively charged ions.

How Does a Nerve Impulse Work?

When a neuron is at rest, the inside of the cell membrane is electrically negative compared with the outside.

1. An outside stimulus, like touching a hot stove, causes the neuron's cell membrane to open tiny channels that let positively charged ions into the cell. One area of the neuron now has a positively charged inside relative to the outside.



2. In a type of chain reaction, depolarization occurs along the entire neuron. As downstream channels open to let positive ions in, the previously depolarized areas let positive ions back out. As the ions leave, the membrane once again becomes negatively charged compared with the outside, as it was before the outside stimulus occurred.

SC.912.P.10.14–Differentiate among conductors, semiconductors, and insulators.

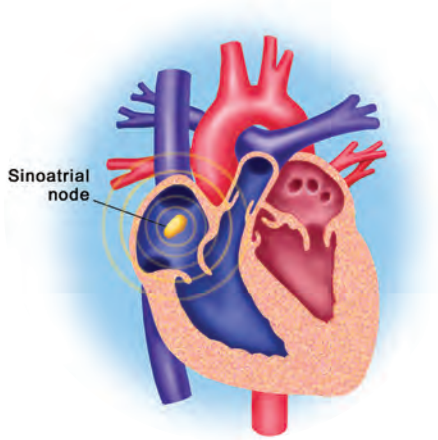
3. The nerve impulse continues from neuron to neuron, across the gaps (synapses) between neurons, like a row of falling dominoes. The positive ions move in and out of one neuron, and at the gap between neurons, a chemical neurotransmitter is released to allow the depolarization to continue along the next neuron. In this way, nerve impulses or messages are conducted from one area of the body to another.

4. In a split second, your muscle receives the message to contract and pull your hand away from the source of heat. It all happens because of the flow of charged material. Your nervous system and your muscles are controlled by electrical impulses; some of them can move at upwards of 250 miles per hour!

Withdrawal reflexes are just one of many actions in your body that happen as a result of electrical signals. Your emotions, decisions, and physical actions all happen when nerve impulses transmit electrical signals through neurons in your brain, spinal cord, and body.

What Makes Your Heart Beat?

Did you know that electrical signals cause your heart to beat? There is specialized electrical tissue in your heart called the sinoatrial node. This specialized group of cells releases positive ions that carry an electrical message to the muscle cells all over the heart. This stimulates the heart to contract and pump blood throughout the body. People often refer to heart contractions as the "heartbeat."



For your heart to pump blood effectively, it must beat regularly, in a rhythmic pattern. The sinoatrial node is usually very good at sending rhythmic electrical impulses to the muscle cells, so the contractions happen steadily and regularly. However, if the sinoatrial node needs extra help, a surgeon can implant an artificial pacemaker to send the regular electrical impulses.

If you have ever seen doctors working in an emergency room on television or in a movie, you have probably seen a device called a defibrillator. A defibrillator uses an electric current to make a patient's heart start beating again after a heart attack or other trauma. Small, portable defibrillators are now being placed in schools, airports, and other public buildings. These devices have saved many lives by allowing trained people to help heart attack victims before paramedics arrive.

Electricity and Living Things

Many processes inside you (and other living things) depend on internal electric circuits. Most organisms keep this "shocking truth" to themselves, but not the electric eel! These South American river fish can stun unsuspecting prey with a 500-volt, 1 amp electric current generated through a flow of positive ions in specialized abdominal organs.

Questions:

1. Compare and contrast battery and bulb circuits with the circuits of your nervous system. How are they alike? How are they different?

2. Why would someone need to have a pacemaker? What do defibrillators do, and why are they made available in somepublic places?

3. There are hundreds of organisms that, like the electric eel, use electricity for more than just internal body processes. Do an Internet search. Choose two of the animals (other than the electric eel), name them, and write a brief description of how much electricity they produce and how they use it.

Neuron image courtesy of Wei-Chung Allen Lee, Hayden Huang, Guoping Feng, Joshua R. Sanes, Emery N. Brown, Peter T. So, and Elly Nedivvi.

Chapter 20 Assessment

Vocabulary

Select the correct term to complete the sentences.

ampere	electrically neutral	positive
battery	electricity	potentiometer
charged	insulator	resistance
closed circuit	multimeter	resistor
conductor	negative	semiconductor
coulomb	ohm	static electricity
electric circuit	Ohm's law	switch
electric current	open circuit	volt
		voltage

Section 20.1

1. The unit in which charge is measured is the ____.
2. An object is ____ when it has equal numbers of positive and negative charges.
3. All atoms have protons, which carry a(n) ____ charge.
4. All atoms have electrons, which carry a(n) ____ charge.
5. ____ is caused by a tiny imbalance of positive or negative charge.
6. A(n) ____ object is not electrically neutral.

Section 20.2

7. ____ is what flows and carries energy in a circuit.
8. A(n) ____ is used to create a break in a circuit.
9. A(n) ____ has a complete path for the current and contains no breaks.
10. A light bulb, motor, or speaker acts as a(n) ____ in a circuit.
11. A circuit diagram uses electrical symbols to represent a(n) ____.
12. ____ is the science of electric current and charge.
13. When a light switch is in the "off" position, you have a(n) ____.

Section 20.3

14. The unit for current is the ____.
15. A(n) ____ provides voltage for a circuit.
16. ____ is a measure of electric potential energy.
17. Use a(n) ____ to measure current or voltage in a circuit.
18. The ____ is the unit for measuring voltage.

Section 20.4

19. The ____ is the unit for measuring resistance.
20. ____ explains the relationship between current, voltage, and resistance in a circuit.
21. Wires in a circuit are made of a material that is a(n) ____, such as copper.
22. ____ is the measure of how strongly a material resists current.
23. A(n) ____ like rubber or plastic has high electrical resistance.
24. Silicon is an example of a(n) ____.
25. A(n) ____ is a type of variable resistor.

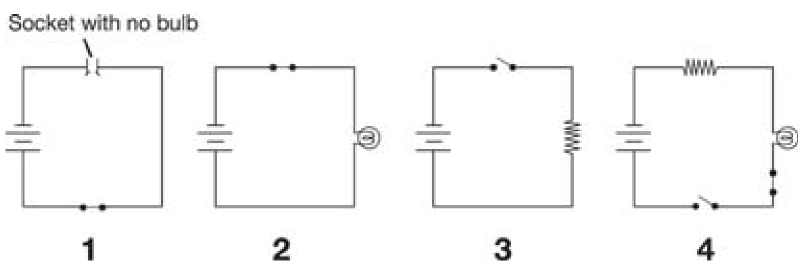
Concepts

Section 20.1

1. Like charges ____ and opposite charges ____.
2. What does it mean to say an object is electrically neutral?
3. Is an object's net charge positive or negative if it loses electrons?
4. Why don't you usually notice electric forces between objects?
5. What unit is used for measuring charge, and where did the name come from?
6. Why do clothes sometimes stick together when you pull them out of the dryer?

Section 20.2

7. Use the illustrations below to answer the following questions.



   a. Which of the circuit(s) is/are closed?
   b. Which circuit(s) will *not* light a bulb?
   c. For any open circuits in the illustration, explain why the circuit is open.

8. Why are symbols used in circuit diagrams?
9. Draw the electrical symbol for each of the following devices.
   a. battery
   b. resistor
   c. switch
   d. wire

Section 20.3

10. How does voltage cause current to do work?
11. Explain how a battery in a circuit is similar to a water pump.
12. What are the differences between a multimeter, an ammeter, and a voltmeter?
13. Suppose you have a closed circuit containing a battery that is lighting a bulb.
    a. Explain how you would use a multimeter to measure the voltage across the bulb.
    b. Explain how you would use a multimeter to measure the current in the circuit.
14. What should you do to protect the multimeter when you measure current?

Section 20.4

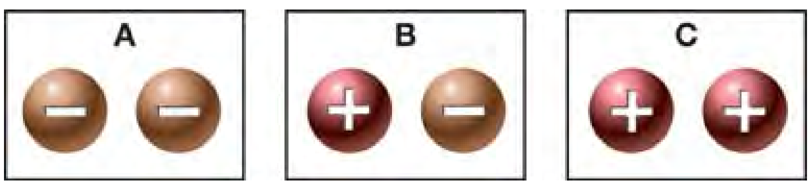
15. What does it mean to say that current and resistance in a circuit are inversely related?
16. What does it mean to say that current and voltage in a circuit are directly related?
17. According to Ohm's law, the current in a circuit increases if the ____ increases. The current decreases if the ____ increases.

18. A battery is connected to a light bulb, creating a simple circuit. Explain what will happen to the *current* in the circuit if
    a. the bulb is replaced with a bulb having a higher resistance.
    b. the battery is replaced with a battery having a greater voltage.
19. Explain why electrical wires are made of copper covered in a layer of plastic. Use the terms *insulator* and *conductor* in your answer.

Problems

Section 20.1

1. Describe the forces between the positive and negative electric charges in each pair below.

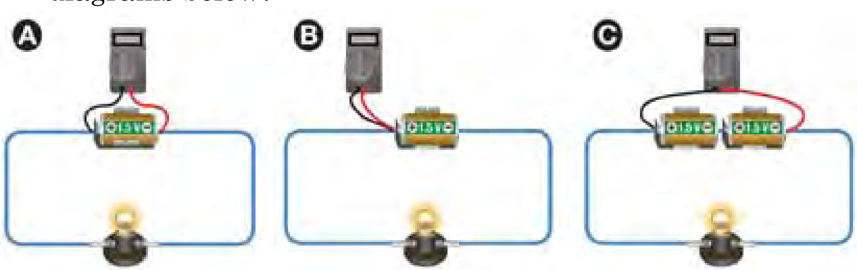


Section 20.2

2. Draw a circuit diagram of a circuit containing a battery, three wires, a light bulb, and a switch.

Section 20.3

3. What voltage would the multimeter show in each of the diagrams below?



Section 20.4

4. What happens to the current in a circuit if the resistance triples? If the voltage triples?
5. A hair dryer draws a current of 10 A when plugged into a 120 V outlet. What is the resistance of the hair dryer?
6. A digital camera uses one 6 V battery. The circuit that runs the flash and takes the pictures has a resistance of 3 Ω. What is the current in the circuit?

Applying Your Knowledge

Section 20.1

1. On very dry days, when you use a comb or a brush, your hair sometimes stands on end and maybe even sticks to the comb or brush. Explain why this happens in terms of electric charge.

Section 20.2

2. A wire carrying an electric current is often likened to a pipe carrying water. What part of this analogy is incorrect?

Section 20.3

3. Design an experiment to determine whether more expensive household batteries last longer than cheaper ones. Don't forget to carefully select your controls! With your teacher's approval, try your experiment and report your findings.
4. Standard voltage for electrical circuits in the United States is 120 volts. Is this the standard voltage in other countries? Do some research and report your findings.

Section 20.4

5. Why can't you use an electric blender purchased in the United States in another country, like Spain or China?

LA.910.2.2.3-The student will organize information to show understanding or relationships among facts, ideas, and events.