UNIT 3

Electricity and Magnetism

Chapter 6

Electricity and Electric Circuits

Introduction to Chapter 6

Electricity is everywhere around us. We use electricity to turn on lights, cool our homes, and run our TVs, radios, and portable phones. There is electricity in lightning and in our bodies. Even though electricity is everywhere, we can't easily see what it is or how it works. In this chapter, you will learn the basic ideas of electricity. You will learn about electric circuits and electric charge, the property of matter responsible for electricity.

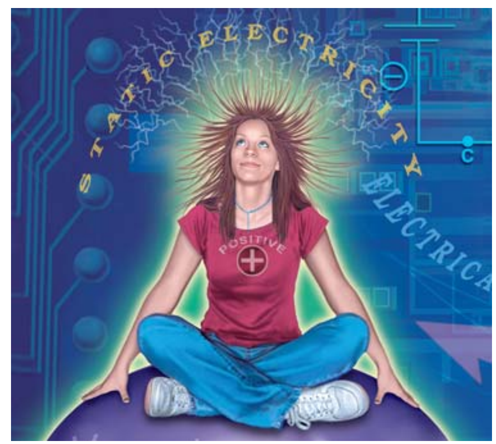
Investigations for Chapter 6

6.1	**What Is a Circuit?**	*What is an electric circuit?*

Can you make a bulb light? In this Investigation, you will build and analyze a circuit with a bulb, battery, wires, and switch. You will also learn to draw and understand diagrams of electric circuits using standard electrical symbols.

6.2	**Charge**	*What is moving through a circuit?*

In this Investigation, you will create two kinds of static electricity and see what happens when the two charges come together. During the Investigation, you will also demonstrate that there only two kinds of charge.



Learning Goals

In this chapter, you will:

- ✔ Build simple circuits.
- ✔ Trace circuit paths.
- ✔ Interpret the electric symbols for battery, bulb, wire, and switch.
- ✔ Draw a circuit diagram of a real circuit.
- ✔ Explain why electrical symbols and circuit diagrams are useful.
- ✔ Explain how a switch works.
- ✔ Identify open and closed circuits.
- ✔ Charge pieces of tape and observe their interactions with an electroscope.
- ✔ Identify electric charge as the property of matter responsible for electricity.
- ✔ List the two forms of electric charge.
- ✔ Describe the forces electric charges exert on each other.
- ✔ Describe how lightning forms.

Vocabulary

circuit diagram	electric circuits	electroscope	positive charge
closed circuit	electrical symbols	natural world	static electricity
coulomb	electrically charged	negative charge	versorium
electric charge	electrically neutral	open circuit	

6.1 What Is a Circuit?

There are lots of electrical devices and wires around us. What is inside those light bulbs, stereos, toasters, and other electrical devices? All these devices contain electric circuits. In this section, you will figure out how to build circuits with a bulb, batteries, wires, and a switch, and learn how to draw circuit diagrams using electrical symbols.

Electricity

Why learn about electricity? We use electricity every day. Our homes, stores, and workplaces all use many electrical appliances and devices such as electric ovens, TVs, stereos, toasters, motors that turn fans, air conditioners, heaters, light bulbs, etc. In fact, the use of electricity has become so routine that many of us don't stop to think about what happens when we switch on a light or turn on a motor. If we do stop to look, we find that most of what is "happening" is not visible. What exactly is electricity? How does it work?

What is electricity? *Electricity* usually means the flow of something called *electric current* in wires, motors, light bulbs, and other devices. Think about making a water wheel turn. Water flows over the wheel and as it falls, it gives up energy and the wheel turns. We build ponds, canals, and pipes to carry water from one place to another where we want to use it.

Electric current Electric current is like water, except it flows through solid metal so we can't usually see it. Just like water, electric current can carry energy over great distances. Look around you and you can probably see wires carrying electric current into houses and buildings.

Electricity can be powerful and dangerous Electric current can be very powerful. An electric saw can cut wood 30 times faster that a hand saw (Figure 6.2). An electric motor the size of a basketball can do as much work as five big horses or 15 strong men. Electric current can also be dangerous. Touching a live electric wire can give you a very serious injury. The safe use and understanding of electricity is what this unit is about.

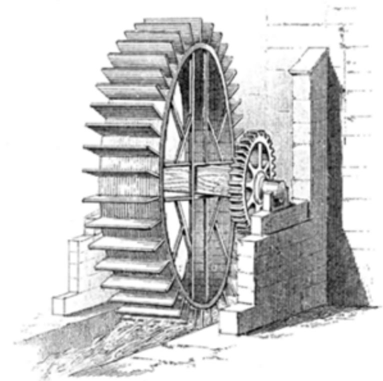


Figure 6.1: *A water wheel uses a current of water to turn a wheel and do useful work.*

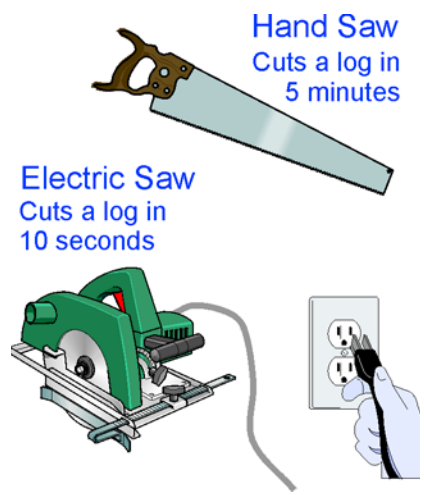
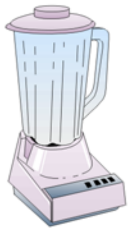


Figure 6.2: *Electricity uses an electric current to power light bulbs and electric motors.*

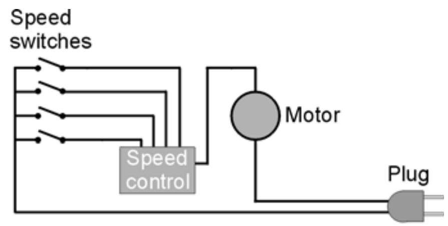
Electric circuits

What is an electric circuit?

To start to understand electricity, let's look inside a simple electrical appliance, like an electric blender. Inside are lots of wires and other electrical parts. The wires, switches, and motors are connected in **electric circuits**. An electric circuit is something that provides a path through which electricity travels.



Electric blender



Circuit inside

Circuits also exist in the natural world

Circuits are not confined to appliances, wires, and devices built by people. People's first experience with electricity was in the **natural world**. Some examples of circuits are:

- The wiring that lights your house is an electric circuit.
- The nerves in your body create electric circuits.
- Lightning, clouds, and the planet Earth form an electric circuit.
- The car battery, ignition switch, and starter form an electric circuit.

Electric circuits are like water pipes

Electric circuits are similar to pipes and hoses for water (Figure 6.3). You can think of wires as pipes for electricity. The big difference is that you can't get the electricity to leave the wire. If you cut a water pipe, the water comes out. If you cut a wire, the electricity immediately stops flowing. Electric current cannot flow except in complete circuits.

Switches turn circuits on and off

Because a complete path through wire is need for electricity to work, a switch works by breaking or completing the circuit path. When a switch is on, the circuit path is complete. When a switch is off, the circuit path is broken (Figure 6.4).

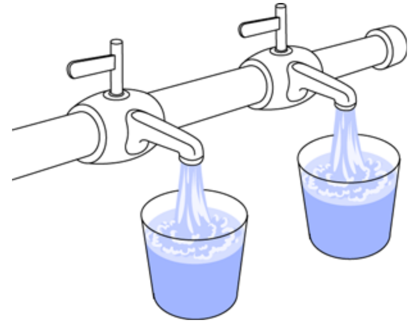
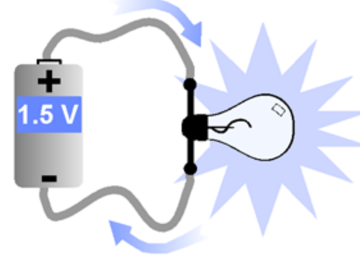


Figure 6.3: *We use pipes to carry the flow of water where we need it.*

Electric current only flows in closed circuits.



Electric current does not flow in open circuits.

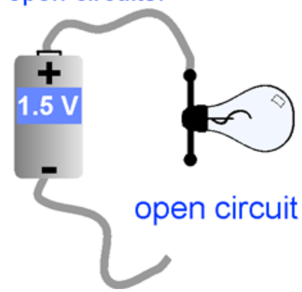


Figure 6.4: *We use electric circuits with wires to carry the flow of electricity where we need it.*

Circuit diagrams and electrical symbols

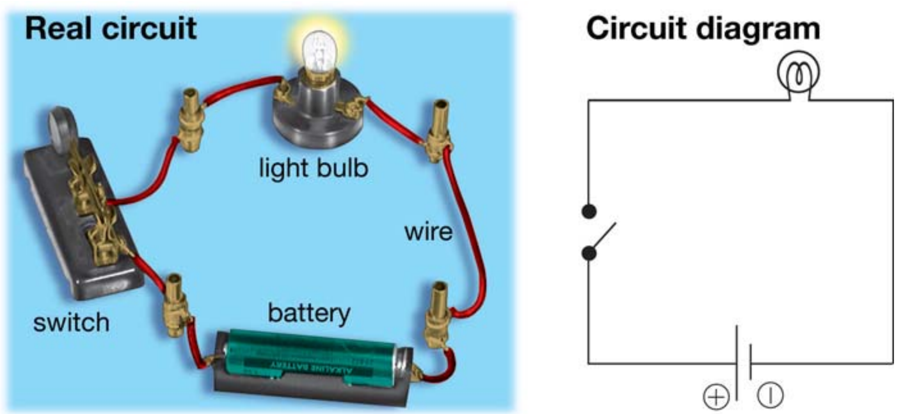
Circuit diagrams

Circuits are made up of wires and electrical parts, such as *batteries*, *light bulbs*, *motors*, or *switches*. When people build and design circuits to accomplish a task, they use a special kind of drawing called a circuit diagram. In a circuit diagram we use symbols to represent parts of the circuit. These electrical symbols are quicker to draw and can be read by anyone familiar with electricity.

A circuit diagram uses electrical symbols

A circuit diagram is a shorthand method of describing a real circuit. By using a diagram with standard symbols you don't have to draw a battery and bulb realistically every time you need to write down a circuit you have made. Figure 6.5 shows some common things you find in a circuit and their electrical symbols.

The graphic below shows a photograph of a simple circuit and a circuit diagram. The circuit diagram represents the simple circuit. See if you can match the symbols in the circuit diagram with each part of the simple circuit.



Resistors and what they represent

In many circuit diagrams any electrical device is shown as a *resistor*. A resistor is an electrical component that uses energy. In a few sections, you will see that when analyzing how a circuit works, we often treat things like light bulbs as if they were resistors.

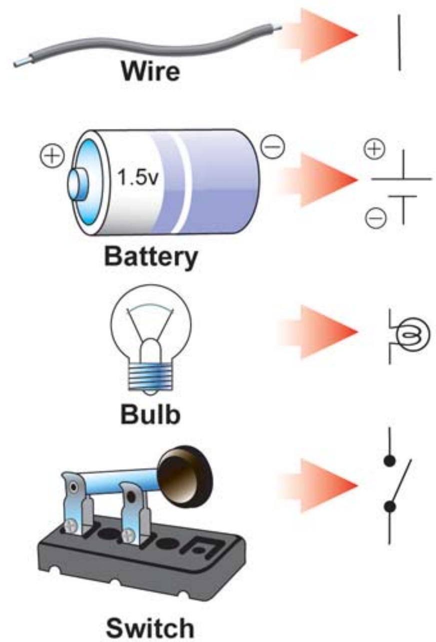


Figure 6.5: *Commonly used electric parts and their symbols*

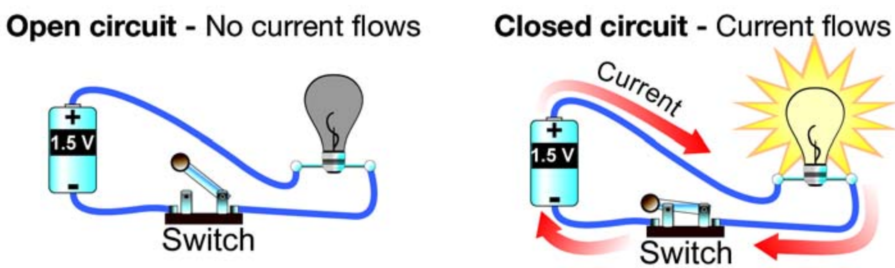
Open and closed circuits

Circuits are controlled by switches

You have just learned that we use switches to turn electricity on and off. Turning the switch off creates a break in the wire. The break stops the flow of current because electricity travels through the metal wire but can't normally travel through air.

Open and closed circuits

A circuit with a switch turned to the off position or a circuit with any break in it is called an open circuit. Electricity can't travel through an open circuit. When the switch is turned to the on position, there are no longer any breaks anywhere in the wire and the light goes on. This is called a closed circuit. Electricity can travel easily through a closed circuit.



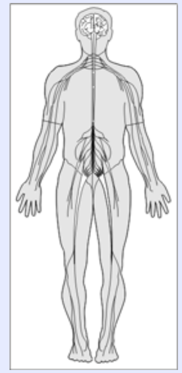
Trace circuits to test them

A common problem found in circuits is that an unintentional break occurs. When building circuits it is a good idea to trace your finger around the wires to tell if the circuit is open or closed. If there are any breaks, the circuit is open. If there is a complete loop then the circuit is closed.

Short circuits

A *short circuit* is not the same as either open or closed circuits. A short circuit is usually an accidental extra path for current to flow. Short circuits are covered in more detail in a later section when we talk about *parallel* and *series* circuits.

Spinal cord injuries



Our nervous system is a network of electric circuits including the brain, spinal cord, and many nerves. Motor nerves branch out from the spinal cord and send electrical messages to muscles, telling them to contract so that you can move. If a motor nerve is injured, an open circuit is created. The message from the brain can no longer reach the muscle, so the muscle no longer works.

Although a surgeon can sew the two ends of a broken nerve back together, scar tissue forms that blocks the circuit. If a person injures a small nerve (a motor nerve in the thumb, for example), they may regain movement after a period of time as other nerves create alternate paths for the signal. However, injury to a large bundle of nerves, like the spinal cord, is irreparable. That is why spinal cord injuries can cause paralysis.

6.2 Charge

You have built circuits and made light bulbs glow. Now we will find out exactly what is moving through those wires. In this section, you will learn about electric charge and build a simple electroscope to observe the electrical forces exerted by electric charges on each other.

Electricity

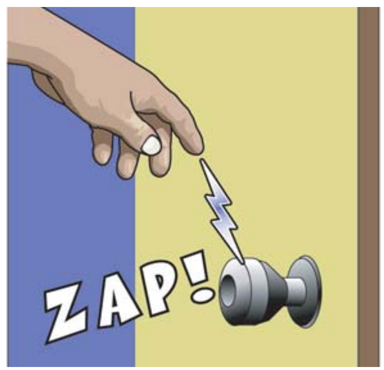
Use of electricity is relatively new

The understanding and use of electricity is relatively recent history. Michael Faraday discovered the principles of the electric motor in 1830. The electric light was invented by Thomas Edison in 1879. Two lifetimes later we now see light bulbs and motors everywhere.

Faraday and Edison were only two of the many people who observed, investigated, and thought about electricity. Today's technology results from an accumulation of knowledge about electricity over a long period of time.

First experiments in electricity

To understand electricity, people first studied events like lightning and the sparks that can occur when certain materials are rubbed together. We observe the same effect when we rub our feet on a carpet and then feel a shock or see a spark when we touch a metal doorknob. *Something* in ordinary materials "electrifies" our body. What is it?



Electric charge

The source of the shock and the sparks is *electric charge*. Electric charge, like mass, is a fundamental property of matter. An important difference between mass and charge is that charge comes in two kinds, called positive charge and negative charge.

History of the terms positive and negative charge

The terms *positive* and *negative* to describe the opposite kinds of charge 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. Franklin claimed that when there was too much fluid in an object, it would exhibit positive charge behavior, and if there were not enough, the object would exhibit negative charge behavior. 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.

Electric charge

Static electricity

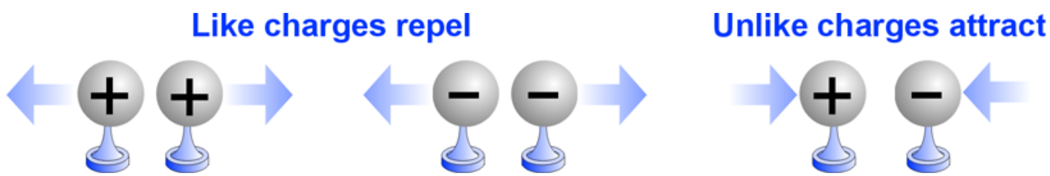
When we acquire a static charge from walking across a carpet, our bodies gain a tiny amount of excess negative charge. In general, if materials or objects carry excess positive or negative charge we say they are electrically charged. When charge builds up on an object or material it is sometimes referred to as static electricity.

The explanation of static cling

What happens when there is a buildup of excess charge? We observe that clothes fresh out of a dryer stick together. This is because all the tumbling and rubbing makes some clothes positive and others negative. Do you notice what happens when you brush your hair on a dry day? Each hair gets the same kind of charge and they repel each other, making your hair appear fuller.

Like charges repel, unlike charges attract

These scenarios show us how charges affect each other. A positive and a negative charge will pull each other closer. Two positive charges will push each other away. The same is true of two negative charges. The rule for the force between two charges is: Unlike charges attract each other and like charges repel each other.



Electrical forces

These forces between positive and negative charges are called electrical forces or electrostatic forces. If you increase the amount of one kind of charge on an object, it exerts a greater electrical force. This kind of force is very strong! Suppose you could separate the positive and negative charges in a bowling ball. The force between the separated charges would be 10 times the weight of the entire Earth!

Most matter is neutral

It is very difficult to separate the positive and negative charges in a bowling ball or in anything else. Most matter has the exact same amount of positive and negative charges. Total charge is zero, since the positives cancel the negatives. An object with zero charge is electrically neutral. The electrical events we observe are the result of the separation of relatively small amounts of charge.

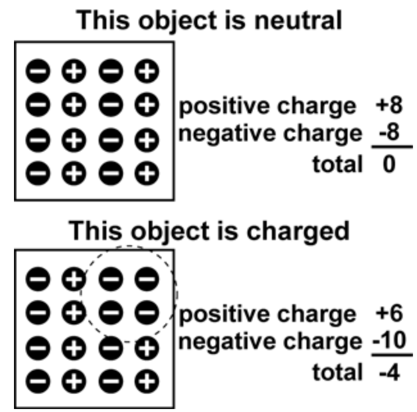


Figure 6.6: *Most matter is neutral, with equal amounts of positive and negative charge. If an object gains or loses one kind of charge, it is said to be charged.*

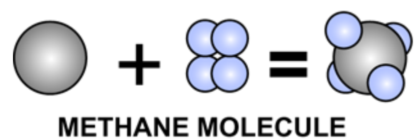


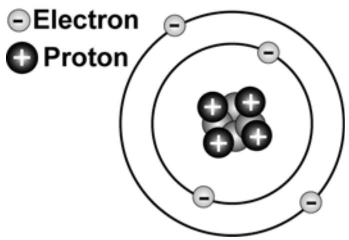
Figure 6.7: *You will study chemical reactions like the one shown above later in this book. Electrical forces are the cause of many properties of matter and all reactions.*

The coulomb and the atom

Electric charge is measured in coulombs

The unit of electric charge is the **coulomb** (C). The name is chosen in honor of Charles-Augustin de Coulomb (1736-1806), a French physicist who succeeded in making the first accurate measurements of the forces between charges in 1783.

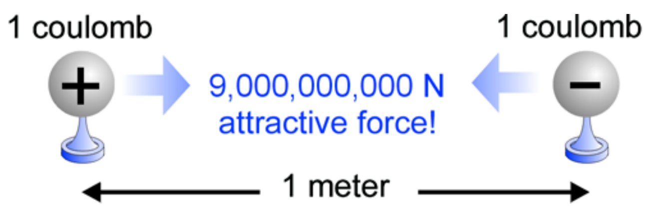
The charge of protons and electrons



Since Coulomb's time, people have discovered that different parts of the atom carry electric charge. The protons in the nucleus are positive and the electrons in the outer part of the atom are negative.

Electrical forces in atoms

Electrons in atoms stay close to the protons because they are attracted to each other. If you could put 1 coulomb of positive charge a meter away from the same amount of negative charge, the electrical force between them would be 9,000,000,000 (9 billion) newtons!



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.

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.

The negative charges in the cloud are attracted to the positively charged ground. When enough charges have been separated by the storm, the cloud, air, and ground 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.

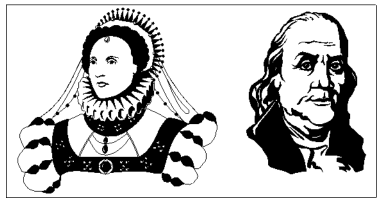
The electroscope

Detecting charge with an electroscope

We can detect charged objects by using an **electroscope**. The electroscope has two very light leaves that hang down. The leaves attract or repel each other depending on the charge nearby. By watching the leaves you can tell what kinds of electric charges are near, and roughly how strong they are. A more complex electroscope can measure the exact amount of charge present on an object. Figure 6.8 shows how the electroscope works.

The history of the electroscope

In sixteenth-century England, Queen Elizabeth I had a physician named William Gilbert who was very interested in magnetism because he thought that it might help his patients. Gilbert discovered that rubbing semiprecious stones would cause them to attract light objects. Like others of his time, Gilbert thought that static attraction was caused by magnetism. In his experiments, he found that some stones attracted better than others.



The versorium

To measure just how well these objects worked, he invented the first electrical instrument, the **versorium**. Like a compass needle, the thin, balanced pointer would swing to show a very small attraction. The versorium was the earliest version of today's electroscope.

Electrics and non-electrics

Objects like paper and straw that were attracted to the versorium Gilbert called electrics. Those that were not attracted, he called non-electrics. From these two words, Gilbert gets credit for making up the word ***electricity***.

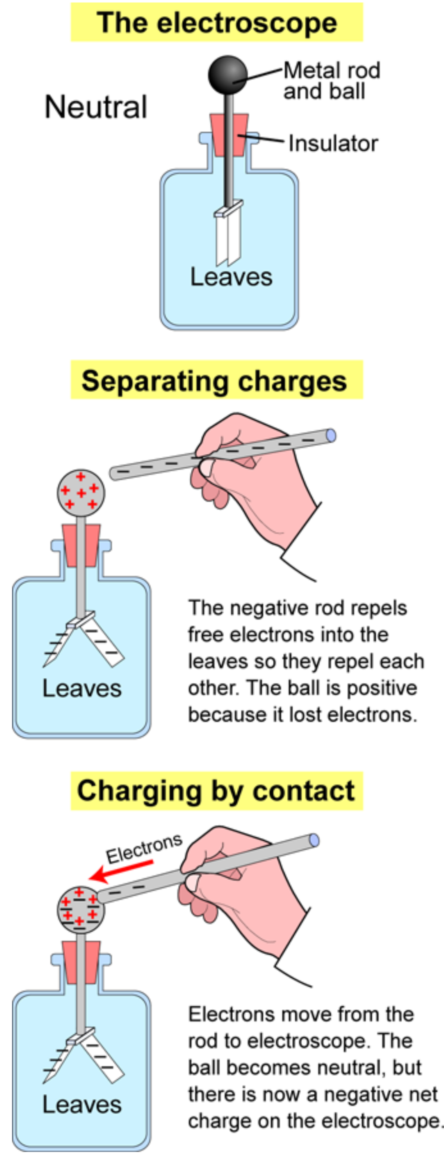


Figure 6.8: *How the electroscope works.*

Chapter 6 Review

Vocabulary Review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. electrical circuits	a. A shorthand method of drawing an electrical part
2. open circuit	b. A device that turns a circuit on and off by causing a break in a circuit
3. closed circuit	c. A circuit with no breaks in it
4. circuit diagram	d. Structures that provide paths through which electricity travels
5. electrical symbol	e. A shorthand method of drawing the physical arrangement of a circuit
	f. A circuit with one or more breaks in it

Set Two

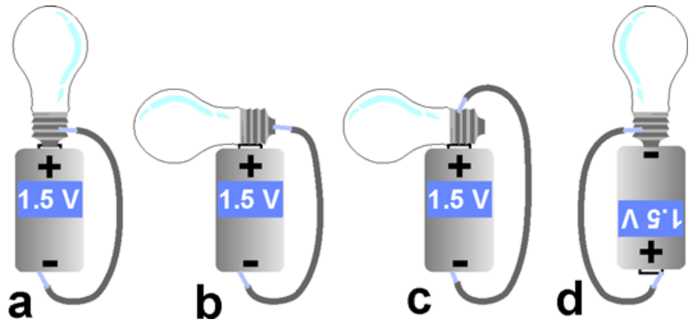
1. electric charge	a. A unit used in measuring the amount of charge
2. static electricity	b. The pushes and pulls that electric charges exert on each other
3. electrical force	c. Property of matter responsible for electrical events; it has two forms, positive and negative
4. electroscope	d. An instrument that can detect, and sometimes measure the amount of, electric charges
5. coulomb	e. An object that has equal amounts of positive and negative charges
	f. A buildup of charge on an object or material

Concept review

1. How are electrical circuits and systems of carrying water (such as the pipes that bring water to your house) alike? List at least two ways
2. List three examples of circuits from the reading.
3. Describe how a switch turns a circuit on and off.
4. Why do people use electrical symbols and circuit diagrams to describe a circuit?
5. What happens to the electrical connection of a nerve in the human body if the nerve is cut? Does the nerve ever fully heal?
6. List the kinds of electric charge and where they are found in an atom.
7. Objects can be charged or neutral. Explain what these two terms mean.
8. State the rules of attraction and repulsion between electric charges.
9. If you brush your hair for a long time, your hair may look fuller. Explain what is happening in terms of electric charges.
10. Use your own words to describe how lightning forms.
11. What is the name of the earliest electroscope?

Problems

1. Circle each diagram that shows a closed circuit that will light the bulb.



2. If any of the diagrams are not closed circuits, explain what you would do to close the circuit. You may, if you wish, draw your own picture to support your answer.
3. Build a circuit that has a battery, three wires, a bulb, and a switch. Draw a circuit diagram of this circuit.
4. In the electric charge Investigation, you used pieces of Scotch tape. If you simply took two pieces of tape off the roll and put them on the electroscope, you would see no interaction. If you put two pieces of tape together and then tear them apart quickly the two pieces of tape now attract each other. Explain what happened to the two pieces of tape that caused the attraction to occur.
5. A lightning rod is a safety device that is meant to be hit by lightning. Charges tend to concentrate on the pointed end of the lightning rod. Explain why the lightning rod would draw the lightning to itself.
6. In general, excess negative charge can move within a material, or be transferred from material to material. If you rub a balloon on your hair on a dry day, negative charge is transferred from your hair to the balloon. You bring the balloon close to a wall. The excess negative charge on the balloon repels the negative charges in the wall and the charges move to another part of the wall. The surface of the wall near the balloon is now positively charged. Will the balloon stick to the wall? Why or why not?

Applying your knowledge

1. Write a paragraph describing on what a typical day at home or school would be like if we had no electricity.
2. Examine the labels or instructions that come with home appliances and see if you can find examples of circuit diagrams. What parts of the diagrams do you recognize?
3. Research Benjamin Franklin’s experiments in electricity. Draw and label a picture showing one of his experiments.
4. Static cling causes clothes to stick together when they come out of the dryer. What kinds of material seem to stick together?

UNIT 3 Electricity and Magnetism

Chapter 7 Measuring Electricity

Introduction to Chapter 7

Have you ever thought about how electricity is measured? If you look at the back of many appliances you will see electrical units that are most likely unfamiliar to you, such as volts and amperes. Like all units, electrical units are measurements of useful quantities. In this chapter you will learn about voltage, the energy of charges, current, the rate of travel of charges, and resistance, the ability of objects to carry charges.

Investigations for Chapter 7

7.1	**Voltage**	*Why do charges move through a circuit?*

In this Investigation, you will learn how to use an electrical meter to measure voltage, and you will observe how a change in voltage affects a light bulb.

7.2	**Current**	*How do charges move through a circuit?*

In this Investigation, you will learn how to use an electrical meter to measure current, and you will observe how a change in current affects a light bulb.

7.3	**Resistance**	*How well does current travel through different materials and objects?*

In this Investigation, you will learn how to use an electrical meter to measure resistance, and you will observe how differences in materials and size affect current.

Learning Goals

In this chapter, you will:

- ✔ Measure volts with an electrical meter.
- ✔ Describe the role of a battery in a circuit.
- ✔ Describe the transfer of energy in a circuit.
- ✔ Explain the relationship between voltage and energy in a circuit.
- ✔ Describe current as a flow of electric charge.
- ✔ Measure amperes with an electrical meter.
- ✔ Classify materials as conductors, semiconductors, or insulators.
- ✔ Differentiate between electrical conductivity and resistance.
- ✔ Explain why metals are good electrical conductors.
- ✔ Measure ohms with an electrical meter.

Vocabulary

alternating current	direct current	electrical insulator	semiconductor
ampere	electrical conductivity	ohm	volt
battery	electrical conductor	resistance	voltage
current			

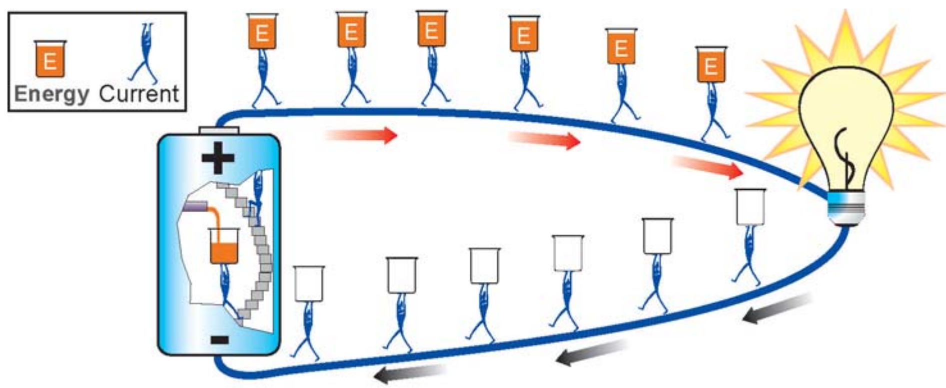
7.1 Voltage

Atoms are in everything and are made up of equal amounts of positive and negative charges. How is this useful in an electric circuit? In this section, you will learn that a battery adds energy to charge and makes it flow through circuits to do work for us.

Voltage

What does a battery do?

A **battery** uses chemical energy to move charges. If you connect a circuit with a battery the charges flow out of the battery carrying energy. They can give up their energy to electrical devices, like a light bulb. When a bulb is lit, the energy is taken from the charges which return to the battery to get more energy. A battery is an energy source for charges that flow in circuits.



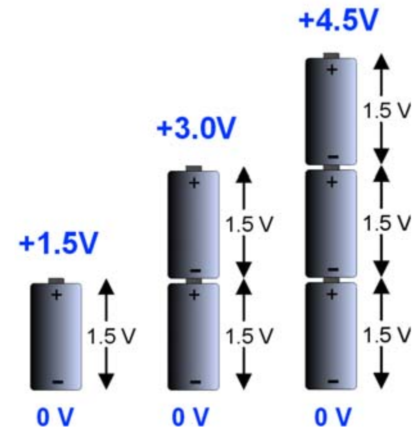


Figure 7.1: *The positive end of a 1.5 volt battery is 1.5 volts higher than the negative end. If you connect batteries positive-to-negative, each battery adds 1.5 volts to the total. Three batteries make 4.5 volts. Each charge coming out of the positive end of the 3-battery stack has 4.5 volts of energy.*

Volts measure the energy level in a circuit

We measure the energy level of any place in a circuit in **volts.** Charges gain and lose energy by changing their voltage. If a charge goes up from 1 volt to 3 volts, it *gains* 2 joules of energy. If the charge goes down from 3 volts to 1 volt, it *loses* 2 joules of energy.

Batteries add energy

A fully charged battery adds energy proportional to its voltage. The positive end of a 1.5 volt battery is 1.5 volts higher in energy than the negative end. That means every charge that leaves the positive end has 1.5 joules more energy than it had going in. This energy is what lights the light bulb. When the battery is dead, there is almost no energy to give to charges flowing through.

Voltage is related to potential energy

Voltage is related to *potential energy*, just like height is related to pressure in water flow. Imagine you have two tanks of water. One is higher than the other (Figure 7.2). The water in the higher tank has more energy than water in the lower tank. The water flows downhill, from high energy to low energy. A greater difference in height means that the water has more potential energy.

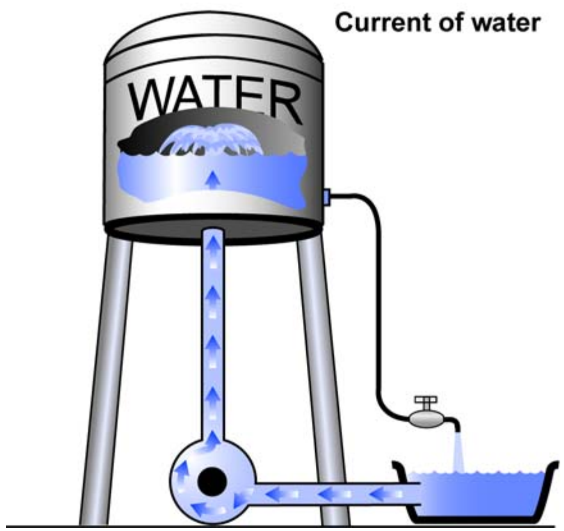
Differences in electrical energy are measured in volts. If there is a difference in volts, current will flow from the higher voltage to the lower voltage, just like water flows from higher energy to lower energy.

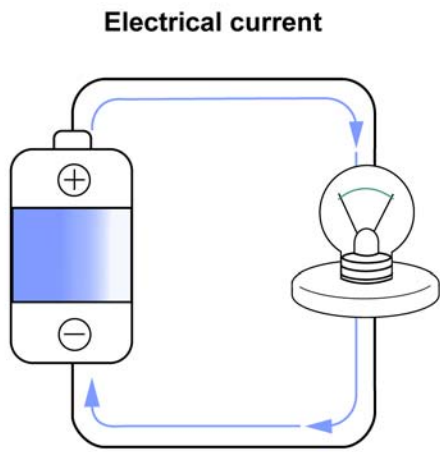
A battery is like a water tower

A water tower and pump make a good analogy for a battery. The pump lifts water up to the tower by giving it energy. The water can flow out and give the energy back. In a battery, chemical reactions provide energy to pump charges from low voltage to high voltage. The charges can then flow back to low voltage and give their energy back to turn motors and light bulbs.

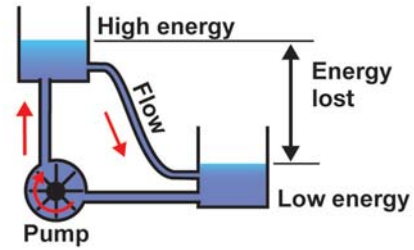
Wires are like water pipes

The water tower is connected by a pipe to a faucet in a house that is lower than the tower. If you open the faucet, the difference in energy makes the water flow. In a circuit, the wires act like pipes to carry the charges from high voltage to low voltage. If you connect the switch, the current will flow.





Water flows from high energy (height) to lower energy.



Electric charge flows from high energy (voltage) to lower energy.

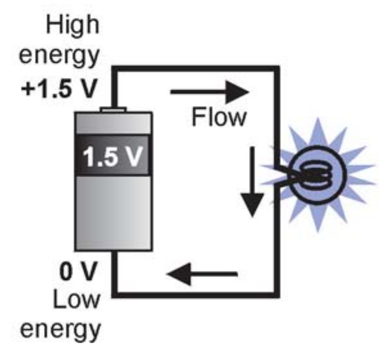


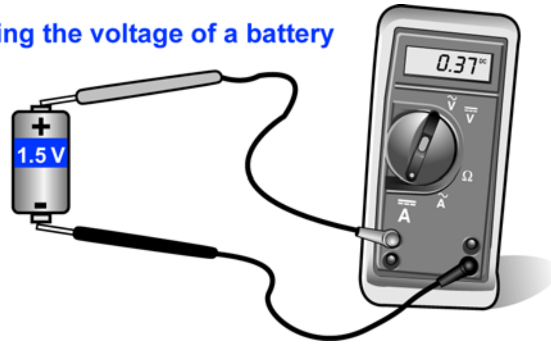
Figure 7.2: *Water flows from high energy to low energy. The energy difference is related to the difference in height. Electric charge also flows from high energy to low energy, but the energy difference is related to the difference in volts.*

Measuring voltage

Connecting a meter to measure volts

Volts measure the energy difference between two places in a circuit. To measure volts you have to connect a meter to two places. The meter measures the voltage difference between the two. If you connect a meter to the two ends of a battery you should read at least 1.5 volts from the negative end to the positive end. A fresh battery might even give you more than 1.5 volts.

Measuring the voltage of a battery

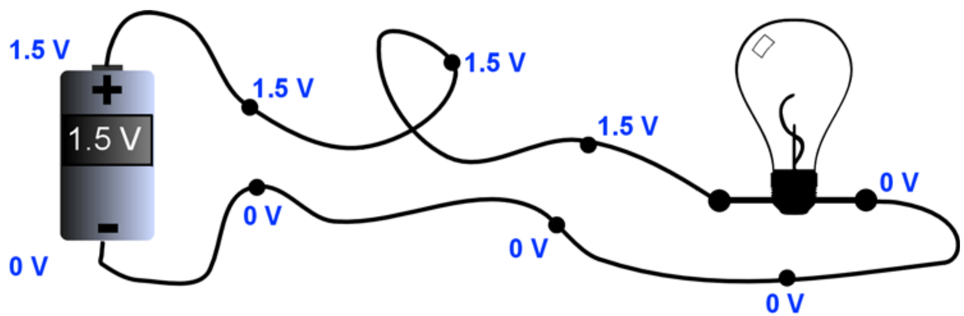


Choosing a voltage reference

Since voltage is measured from one point to another, we usually assign the negative terminal of a battery to be zero volts (0 V). This makes the voltage of every other place in the circuit relative to the negative end of the battery.

All points on a wire are the same voltage

Every point in a circuit connected to the same wire is at the same voltage. Charges move easily through copper so they do not lose much energy. That is why we make electrical wires out of copper. Since the charges all have the same energy, the voltage is the same everywhere along the wire.



The volt

Voltage is measured in volts (V). The volt is named for the Italian physicist Alessandro Volta (1745-1827), who invented the first battery in 1800. Volta's batteries used pans of different chemicals connected by metal strips. Today's batteries are very similar except the chemicals are contained in convenient, safe packages of useful sizes.

One volt is equal to 1 joule of energy for each coulomb of charge.

Voltage drops when energy is used

Voltage is reduced when energy is used

If we connect anything that uses energy, like a light bulb, we reduce the voltage. This should make sense since voltage is a measure of energy. Anything that uses energy (motors, bulbs, resistors) lowers the voltage since it takes energy away from any moving charges in the circuit.

Two examples of circuits

Suppose you connect two circuits as shown in Figure 7.3. Both circuits have 1.5 volts as the highest voltage and zero volts as the lowest voltage. One circuit has a single light bulb and the other circuit has two bulbs.

The single-bulb circuit is much brighter. This is because all the energy is used up in one bulb. The voltage goes from 1.5 V to 0 V across the bulb.

In the two-bulb circuit, the voltage drops from 1.5 volts to 0 across *two* bulbs. The voltage starts at 1.5 volts. After the first light bulb the voltage is reduced to 0.75 volts because the first bulb used half the energy. The second light bulb reduces the voltage another 0.75 volts, to get down to zero. Each bulb only "sees" a voltage difference of 0.75 volts so each of the two bulbs gets less energy, and is dimmer.

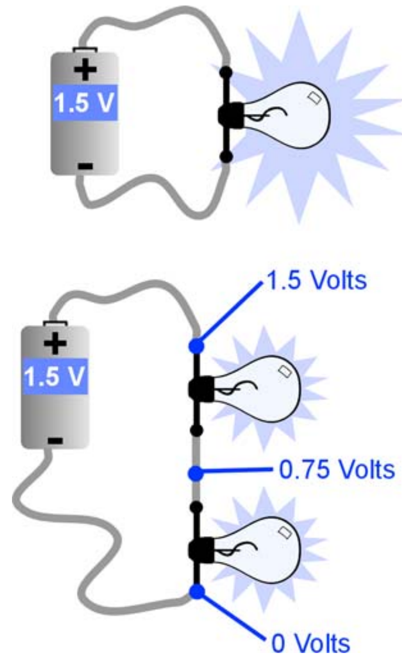
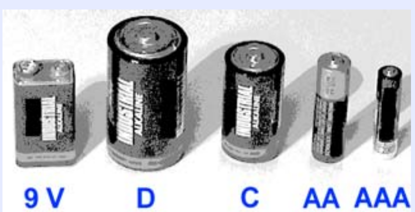


Figure 7.3: *Every time you connect something that uses energy, like a light bulb, some of the voltage is reduced. One bulb is bright because it gets all the energy. Two bulbs are dimmer because each one gets only half the energy. The voltage is lower between the two bulbs because the first bulb uses up half the energy.*

Batteries, energy, and voltage



What is the difference between AA, AAA, C, and D batteries? If you measure the voltage of each, you will see that it is the same. The main difference between them is that the AAA battery is small, and does not store as much energy. AAA batteries will not last as long as D batteries. Think of two identical cars, one with an extra-big gas tank and one with a regular gas tank. Both cars go the same speed, but the one with the big gas tank will keep going longer.

If you need charge that has more energy, you must increase the voltage. Radio batteries have 9 volts and car batteries have 12 volts. In a 12-volt battery each charge that flows carries 12 joules of energy.

Some kinds of batteries can be recharged. Batteries made with nickel and cadmium (NiCad) are used in cell phones and power tools because they can be recharged many times.

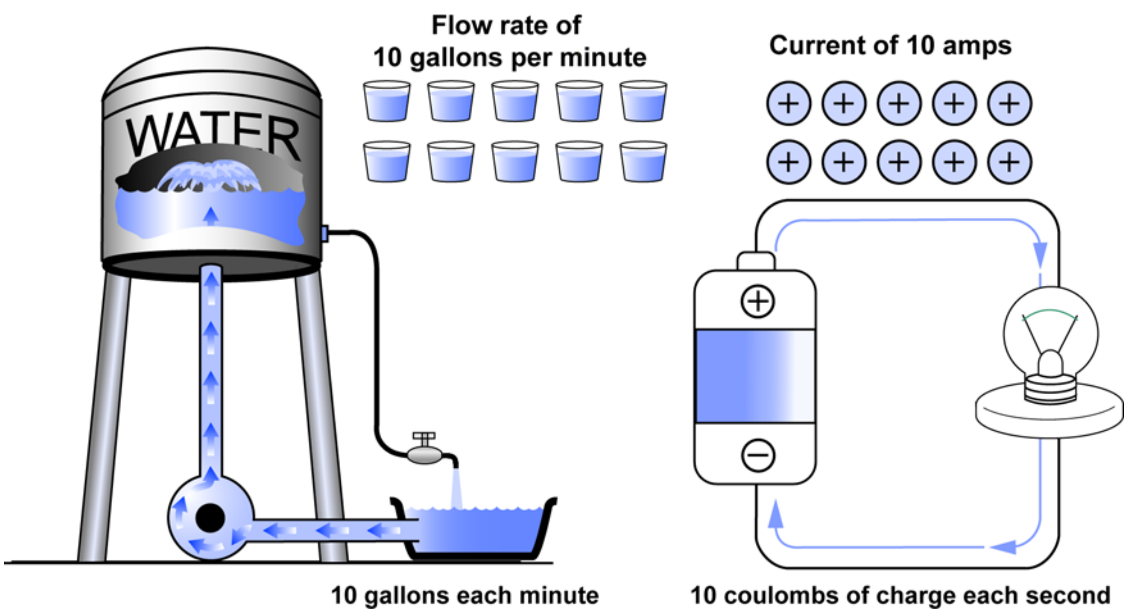
7.2 Current

In the last section, you learned that charges move from places of high voltage in a circuit to places of lower voltage. Electrical current is how we describe the flow of charges. Current is what flows through wires and does work, like making light or turning a motor.

Current

Current is flow of charge

Current is the flow of electric charges. You can think of electrical current much as you would think of a current of water. If a faucet is on, you can measure the rate of water flow by finding out how much water comes out in one minute. You might find that the current (or flow) is 10 gallons per minute. In a circuit, you can measure the current, but it is measured in amperes. One ampere is a flow of one coulomb per second. A current of 10 amperes means that 10 coulombs of charge flow through the wire every second.



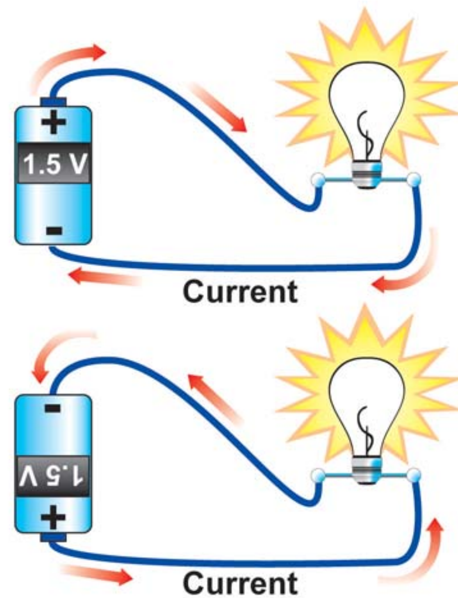


Figure 7.4: *Current flows from plus to minus, or from high voltage to low voltage.*

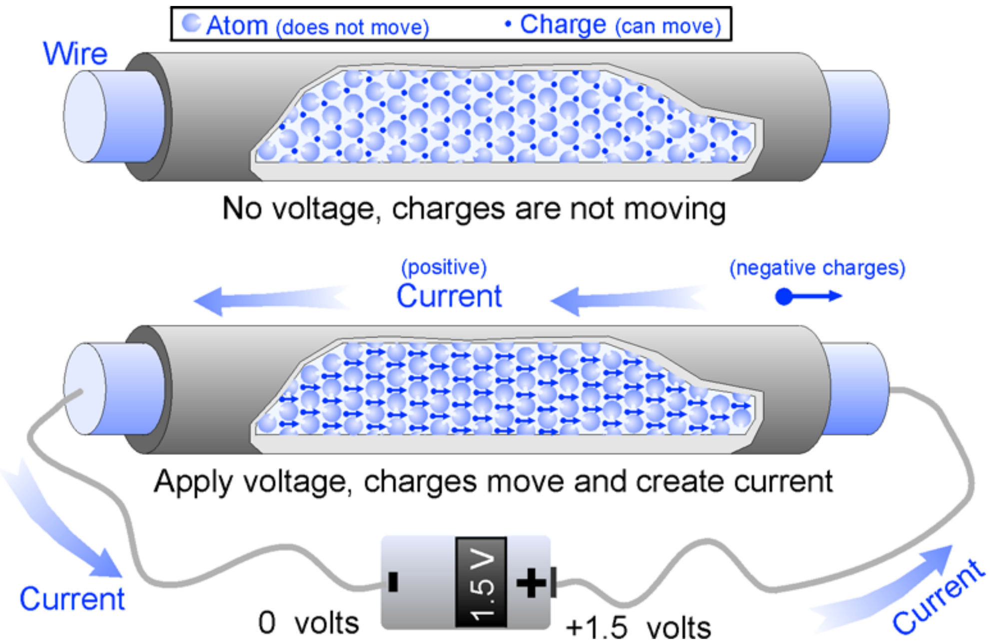
Where does electrical current come from?

Charges are very small

When you look at a wire, you can't see current. The particles that carry charge are electrons. Electrons are parts of atoms, and they are so small that they can flow in the spaces between atoms. That is why we can't see any movement in a wire.

The charges are already in the wire

Batteries do not provide most of the charges that flow in a circuit. Current occurs because electrons in the battery repel electrons in the wire, which repel other electrons in the wire, and so on. This is why a light goes on as soon as you connect your circuit together. Since the wire is made of copper atoms, there are plenty of electrons. When there is no voltage, electrons in the wire do not flow in a current.

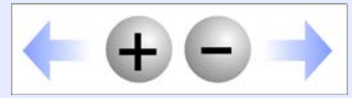


Things to remember:

A voltage difference supplies energy to make charges flow.

Current carries energy and does work.

What really flows?



Either positive charges or negative charges can move to make an electric current. The type of charge depends upon the materials that make up the circuit. For example, in the human body, current is the movement of both positive and negative charges in nerves.

Electric current was first thought to be positive charge moving from plus to minus.

In reality, most charge flow in circuits is the movement of *negative* charge from minus to plus.

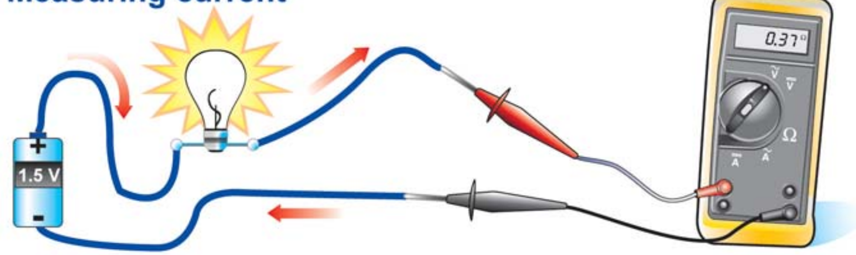
In practical electricity, we still say current flows from plus to minus or from high voltage to low voltage. The fact that it is actually negative charge moving does not matter when working with most electric circuits.

Measuring current

The ampere or amp 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 electromagnetism.

Definition of 1 amp One amp is a flow of 1 coulomb of charge per second. A 100-watt light bulb uses a little more than 1 amp of current. A single D battery can supply a few amps of current for about a half hour before being completely drained.

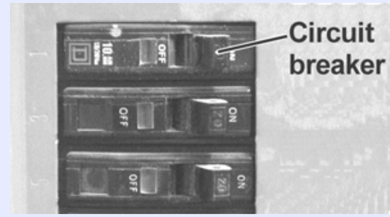
Measuring current To measure current you have to make it flow through the meter. The moving charges can't be counted unless they pass through the meter. That means you must connect the meter into your circuit so the current is forced to flow through it.



Setting up the meter Most meters have settings for both voltage and current. You will need to set your meter to measure current. Meters can also measure alternating current (AC) and direct current (DC). We will discuss AC and DC in a later section. For circuits with light bulbs and batteries you want to use the DC settings.

Be careful measuring current The last important thing about measuring current is that the meter itself can be damaged by too much current. Your meter may contain a *circuit breaker* or *fuse*. Circuit breakers and fuses are two kinds of devices that protect circuits from too much current. If your meter does not work the circuit breaker or fuse may have acted. A circuit breaker can be reset but a fuse must be replaced.

Circuit breakers



Electrical circuits in your house have a *circuit breaker* that stops too much current from flowing. Many wires in your house can carry 15 or 20 amps of current. Wires can get dangerously hot if they carry more current than they are designed for.

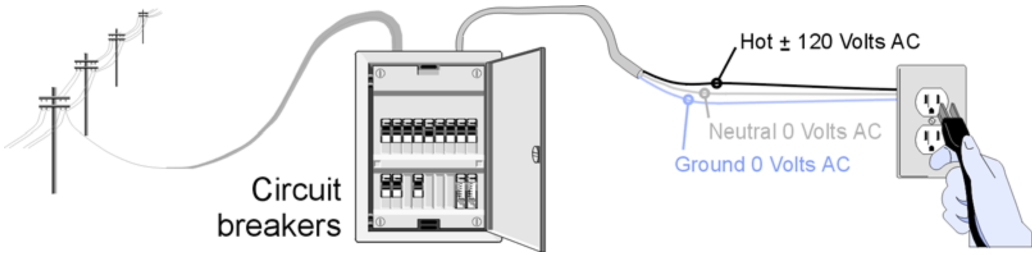
One of the things that can overload a circuit is using too many electrical appliances at once, such as an air conditioner and an iron on the same circuit. If many appliances try to draw too much current, the circuit breaker trips and breaks the circuit before the wires get hot enough to cause a fire.

A circuit breaker uses temperature-sensitive metal that expands with heat. When the current gets too high, the expanded metal bends and breaks the circuit. You have to unplug some appliances and reset the circuit breaker.

Electricity in your house

Circuits in your house

You use electric current in your house every day. When you plug in an electrical appliance, you connect it to a circuit created by wires in the walls. The wires eventually connect to power lines outside your house that bring the current from a power station.



AC current

The electricity in your house uses alternating current, also called AC current. This means the direction of the current goes back and forth. In the electrical system used in the United States, the current reverses direction 60 times per second. Each wall socket has three wires feeding it. The hot wire carries 120 volts AC. The neutral wire stays at zero volts. When you plug something in, current flows in and out of the hot wire, through your appliance (doing work) and back through the neutral wire. The ground wire is for safety and is connected to the ground near your house. If there is a short circuit in your appliance, the current flows through the ground wire rather than through you!

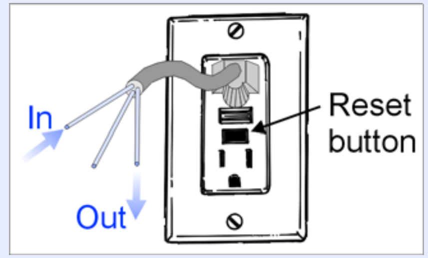
DC current

The current from a battery does not alternate. A battery only makes current that flows in one direction. This is called direct current, or DC. Most of the experiments you will do in the lab use DC current.

Household electricity is AC

For large amounts of electricity, we use AC current because it is easier to transmit and generate. All the power lines you see overhead carry AC current. Other countries also use AC current. However, in Europe, the current reverses itself 50 times per second rather than 60, and wall sockets are at a different voltage. When traveling in Europe, you need special adapters to use electrical appliances you bring from home.

What is a ground fault circuit interrupter?



Circuits in wet or damp locations are wired with a ground fault circuit interrupter (GFCI). You may have seen this device, with its red button, in a bathroom, or near the kitchen sink.

Plugs usually have two or three wires. Electricity goes in one wire of a plug and out another wire. The same current should go in and out. If there is a difference, then some of the electricity could be going through YOU instead of back through the plug. Current flowing through the human body is dangerous.

The GFCI senses differences and breaks the circuit if the current coming out of the plug is different from the current going back in. The GFCI disconnects the circuit in 0.03 seconds if it detects a leak as small as a few thousandths of an amp. A GFCI protects you from being electrocuted.

7.3 Resistance

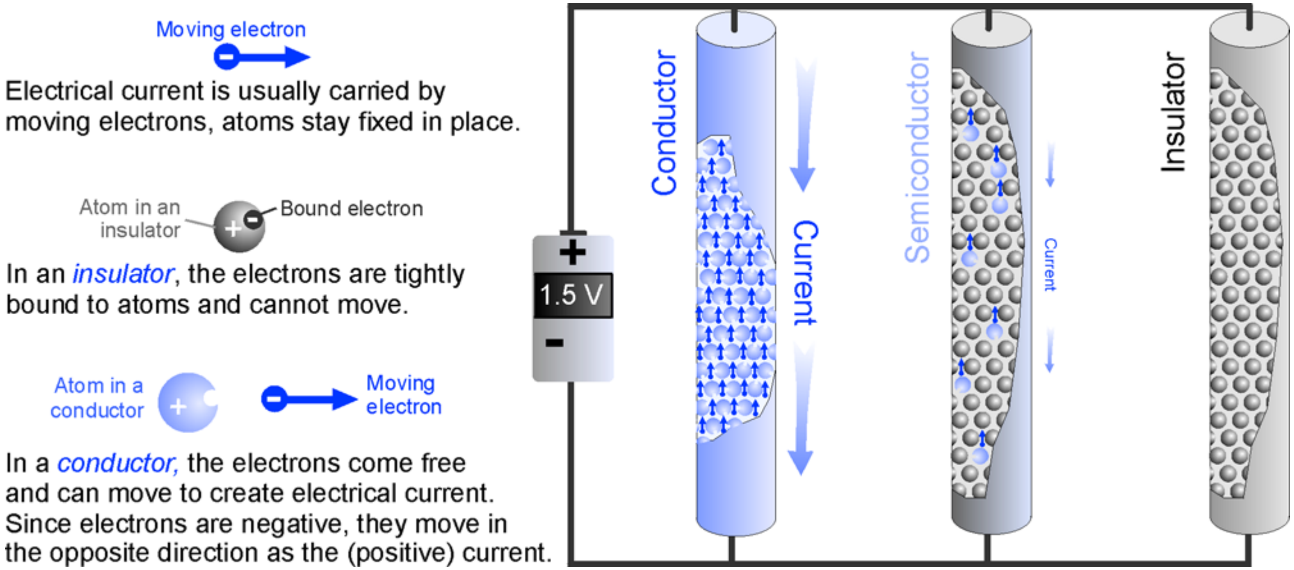
Parts of electrical devices are made up of metals but often have plastic coverings. Why are these materials chosen? How well does current move through these materials? In this section, you will learn about the ability of materials and objects to carry electrical current.

Conductors and insulators

What is a conductor? Charge flows very easily through some kinds of materials, like copper. We call a material like copper an **electrical conductor** because it can *conduct*, or carry, electrical current. Most metals are good conductors.

What is an insulator? Other materials, like glass or plastic, do not allow charge to flow. We call these materials **electrical insulators** because they insulate (or block) the flow of current.

What is a semiconductor? The third category of materials are not as easy-flowing as conductors, but not quite insulators either. These materials are named **semiconductors** because they are between conductors and insulators in their ability to carry current. Computer chips, LED's and some kinds of lasers are made from semiconductors.

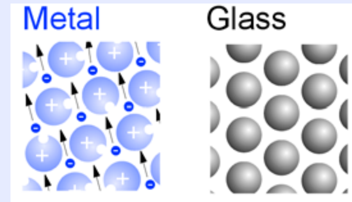


Electrical current is usually carried by moving electrons, atoms stay fixed in place.

In an *insulator*, the electrons are tightly bound to atoms and cannot move.

In a *conductor*, the electrons come free and can move to create electrical current. Since electrons are negative, they move in the opposite direction as the (positive) current.

Why are some materials conductors and some insulators?



Metals are good conductors. To understand why, we have to understand how metal atoms behave. When many metal atoms are together, like in a wire, they each lose one or more electrons. These "free" electrons can move around in a sea of atoms. Metals are good conductors because there are lots of "free" electrons to carry charge.

Glass is a good insulator. Glass does not have free electrons. When atoms of glass are together they keep their electrons tightly bound. Since no electrons can move free of their atoms, glass is a good insulator.

Conductivity

What makes a material a conductor or insulator?

Materials are not pure conductors or insulators. A little charge flows through all materials if you connect them to a battery. The difference is in how much current flows. If you do the experiments you find that the amount of current varies from very small to very large. The property of a material to allow charge to flow is called its **electrical conductivity**. Materials with high conductivity (like metals) allow charge to flow easily and are conductors. Materials with low conductivity block charge from flowing and are insulators.

Electrical conductivity	Category	Material
High	**conductors**	silver
		copper
		gold
		aluminum
		tungsten
		iron
	semiconductors	carbon
		silicon
		germanium
	insulators	air
		rubber
		paper
		Teflon
		plastics (varies by type)
		glass
Low		mica

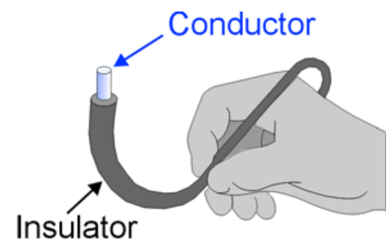


Figure 7.5: *A wire uses both conductors and insulators. The conductor carries the current through the center. The insulator keeps the current from reaching you when you touch the wire.*

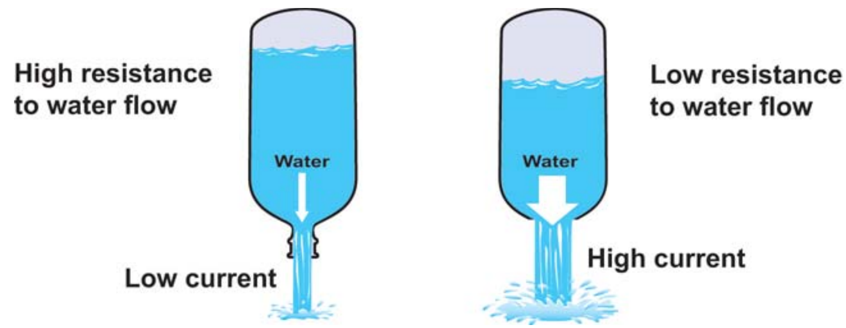
Resistance

Current and resistance

The **resistance** of an object measures how easily charges flow through. High resistance means it is difficult for current to flow. Low resistance means it is easy for current to flow.

Resistance of water flow

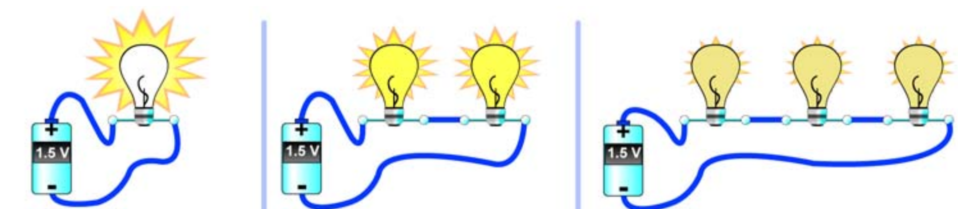
Emptying a jar of water through a narrow opening is a good example of resistance. If the opening of the jar is large, there is low resistance. Lots of water flows out quickly. If the opening of the jar is small, there is a lot of resistance. Water does not flow out as fast.



Electrical resistance

Electrical resistance restricts the flow of current. If the resistance is high, not much current flows. If the resistance is low, a lot of current flows.

Devices that use electrical energy have resistance. For example, light bulbs have resistance. If you string more light bulbs together the resistance adds up and the current goes down.



Breakdown voltage

You previously learned that lightning is caused by electric charge. In a thunderstorm, positive and negative charges become separated. The voltage difference becomes huge, reaching 10,000 volts per centimeter.

Air, usually a good insulator, breaks down under these conditions. The high voltage created by the storm rips the electrons away from atoms of air. The air conducts, and we see lightning.

The lowest voltage at which an insulator turns into a conductor is called its breakdown voltage. The breakdown of air occurs when 8,000 volts or more is applied across a centimeter of air.

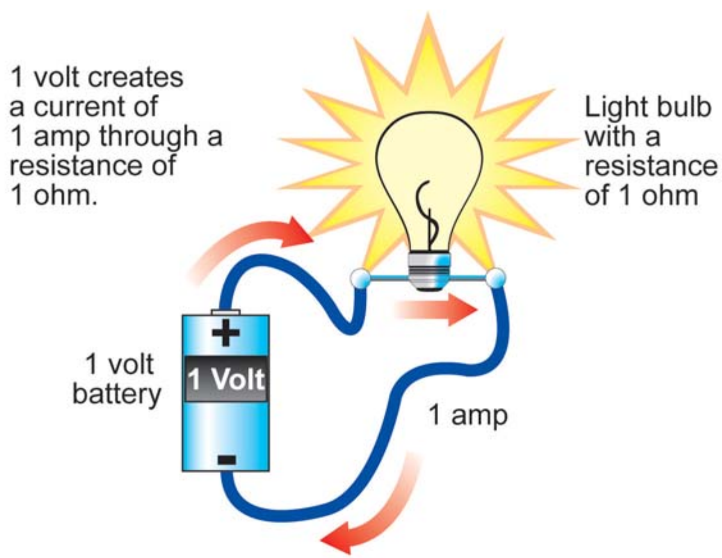
The ohm

Units of resistance

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." The ohm is named for the German physicist Georg S. Ohm (1787-1854). Ohm spent many years studying how circuits work.

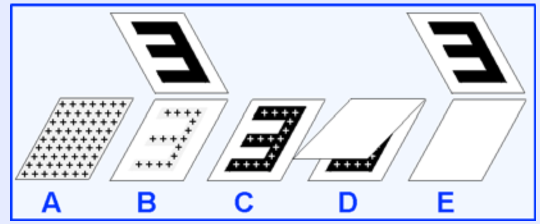
How much current flows in a circuit?

We can now answer the question of how much current flows in a circuit. If the voltage goes up, the current goes up too. If the resistance goes up, the current goes *down*. Voltage and resistance determine how much current flows in a circuit. If a circuit has a resistance of 1 ohm (1 Ω), then a current of 1 amp flows when a voltage of 1 volt is applied.



How a photocopier works

A photocopier has a plate coated with a thin layer of a special material (like selenium, arsenic, or tellurium) that acts as an insulator in the dark but as a conductor when exposed to light.



(A) The plate starts with a positive charge. Light creates an image on the plate **(B)**. The white areas of the image become conductive and let the charge flow away. The dark areas stay insulating and keep their positive charge.

Next, a negatively charged powdered ink (called toner) is brushed over the plate. Because opposite charges attract, the toner sticks to the positively charged areas of the plate **(C)**.

A piece of paper is given a positive charge, and held on the plate **(D)**. The paper attracts the ink and now has a perfect image made of powder **(E)**. To prevent the image from rubbing off, the paper is heated, which melts the toner onto the paper.

Why does a bulb light?

What's in a light bulb?

Electricity would not be so useful if it flowed equally through every material. Let's look at some of the materials in a light bulb. A light bulb contains a copper wire and a thin tungsten filament in a glass bulb filled with argon gas (Figure 7.6). Why are these materials chosen?

Copper wire

We use copper wire to conduct current to a light bulb filament because copper is a good conductor.

Tungsten filament

We use a thin tungsten filament for several reasons. Just as a narrow pipe resists water flow more than a wide pipe, the very thin filament resists the flow of current. Because of the high resistance of the tungsten filament, the current going through it generates a lot of heat. The filament continues to heat up until it reaches 2,500°C (4,500°F). The filament glows white as it heats up, creating the light that we see.

Most substances would melt under these circumstances. Tungsten is chosen because it does not melt until it reaches an even higher temperature. Tungsten also doesn't corrode easily.

Argon gas

We use argon inside the bulb because it is an inert gas. An inert gas will not interact with the hot tungsten. If the hot tungsten filament were in air, it would interact with the oxygen in air and burn up quickly like a match. The argon protects the tungsten so that it can heat up many, many times before breaking down.

Other kinds of light bulbs

Much of the electrical power going into a light bulb becomes heat, and not light. Fluorescent bulbs are more efficient because they convert more of the electrical energy to light than does a regular (incandescent) bulb. Researchers are trying to make lights from many new materials that are even more efficient. In the laboratory, tiny light emitting diodes (LED's) have been made that produce more light from less electricity than any other type of light source.

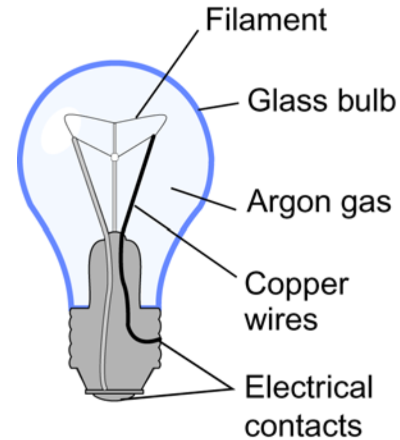


Figure 7.6: *Some parts of a light bulb. There are two electrical contacts in the base of the light bulb. Both of these must come in contact with an electrical circuit for the light bulb to work.*

Chapter 7 Review

Vocabulary Review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. battery	a. Flow rate of electric charges
2. voltage	b. The representation of circuit current as the flow of positive charges
3. volt	c. The commonly used unit of measurement for current, equal to coulombs/second
4. current	d. A device that uses energy of chemical reactions to separate positive and negative charges
5. ampere	e. The amount of potential energy per unit of charge
	f. The commonly used unit of measurement for voltage, equal to joules/coulomb

Set Two

1. amp	a. Current that moves in only one direction through a wire
2. alternating current	b. A material that conducts current easily
3. direct current	c. A material that conducts current poorly
4. conductor	d. The abbreviation often used for ampere
5. insulator	e. Current that reverses direction through a wire
	f. The representation of circuit current as the flow of negative charges

Set Three

1. semiconductor	a. A material that conducts current when exposed to light
2. electrical conductivity	b. The ability of an object to resist current
3. resistance	c. The ability of a material to conduct current
4. ohm	d. The commonly used unit of measurement for resistance
	e. A material that conducts current at a medium rate

Concept review

1. Explain in two or three sentences how a battery creates potential energy.
2. Explain how a water pump and battery are similar in terms of creating potential energy.
3. Explain the difference between a AA alkaline battery and a D alkaline battery. Discuss both voltage and life span.
4. The measurement of current in a circuit is similar to the measurement of the flow of water out of a faucet. Explain why this is so.
5. A circuit breaker is a safety device that shuts down a circuit when the current is too high. Describe how a circuit breaker works.
6. The electrical system in the United States runs on __________ current.
7. A battery circuit runs on ___________ current.
8. A ground fault circuit interrupter is usually wired into circuits that are in wet or damp locations. What is the main purpose of this device?
9. Explain why a circuit contains a copper wire with a plastic cover over the wire.
10. List one example of each of the following.
    a. electrical conductor
    b. electrical insulator
    c. semiconductor
11. A light bulb uses a very thin tungsten filament to provide light.
    a. Why is the filament thinner than the copper wire used in circuit wiring?
    b. Why is tungsten a good material for the filament?

Problems

1. When two batteries are connected together correctly, their voltage adds together. If a circuit has two AA alkaline batteries (connected correctly!), how many joules of energy does each coulomb of charge have at the battery terminals?
2. When you use a meter to measure battery voltage, you place one probe on one battery terminal and one probe on the other battery terminal. Why do you measure voltage in this way?
3. When measuring the voltage of a D alkaline battery, which is usually at 1.5 volts, you accidentally reverse the probes. The probe that is set at zero volts is placed at the positive terminal and the other probe is placed at the negative terminal. What will the meter read now?
4. A toaster oven uses a current of 650 coulombs each minute. What is the current in amps?

5. You build a circuit with one battery and a bulb. You remove the wire from the positive terminal of the battery, insert the meter in the circuit, and measure the current. The meter reads 0.5 amps. You remove the meter and rebuild your circuit. Now you remove the wire from the negative terminal of the battery, insert the meter, and measure the current at this new point in the circuit. What will the meter read now?
6. When you measure current of a circuit with an electrical meter you keep the circuit on and insert the meter at one point in the circuit. Explain why.
7. List these materials in order from least to greatest resistance: light bulbs, clip leads, air, and pencil lead.
8. You have two pieces of wire of the same size, one made of copper and the other made of iron. Which wire is the better conductor?
9. An electrical meter measures resistance of an object by applying a voltage through the material and then measuring how much current the object will carry. Do you measure resistance of an object when it is in a working circuit, or do you turn the circuit off first? Explain your answer.

Applying your knowledge

1. With an adult, inspect all cords and plugs in your home. Make sure that the insulation cover on them is in good condition, without breaks or cracks. With help, replace any damaged cords or plugs.

2. Brain and nerve cells communicate by the movement of charged chemicals, which is a type of current. Some diseases, like epilepsy, occur because of currents that occur when they shouldn't. Research electrical currents in the brain and problems that occur when the system doesn't work correctly.

3. Create a table that lists how the nerves in your body are alike and different from electrical wires used in your home. Come up with two statements that show how they are alike and two statements that show they are different.

4. The "electricity" generated by the beating heart is monitored by an electrocardiograph (an ECG or EKG). The results called an electrocardiogram are used to diagnose heart problems. Write a brief paragraph describing how an electrocardiograph works.

5. With an adult, find out the location of the circuit breakers for your home. If the circuit breakers aren't labeled, determine which outlets are connected to which fuse or circuit breaker, and then label them.

UNIT 3

Electricity and Magnetism

Chapter 8

Electrical Relationships

Introduction to Chapter 8

You have learned that mathematical models are used to describe the exact relationships between physical quantities. What relationships exist among voltage, current and resistance? How can we use these relationships to analyze circuits? What are practical applications of these relationships?

Investigations for Chapter 8

8.1	**Ohm's Law**	*How are voltage, current, and resistance related?*

In this Investigation, you will use a step-by-step method to determine the mathematical relationship between voltage, current, and resistance in a circuit.

8.2	**Work, Energy, and Power**	*How much does it cost to use the electrical appliances in your home?*

You previously studied power in a mechanical system. What does power mean in an electric circuit? How much power do everyday appliances need? In this Investigation, you will learn how to read power ratings on electrical appliances and use this information to estimate electrical costs in your home.

Learning Goals

In this chapter, you will:

- Measure how current changes when voltage is increased.
- Measure how current changes when resistance is increased.
- Describe how voltage, current, and resistance are related.
- Use Ohm's law to solve circuit problems.
- Explain why resistors are used in a circuit.
- Define power as the rate at which energy flows.
- Describe relationships between work, energy, and power.
- Calculate power use in a circuit.
- Rank the amount of power used by various household appliances.
- Estimate the cost per month of using a common household appliance.
- Use dimensional analysis to find out what we buy from electric utility companies.
- Explain how to choose a safe extension cord.

Vocabulary

horsepower	kilowatt-hour	potentiometer	resistor
kilowatt	Ohm's law	power	watt

8.1 Ohm's Law

You know about three important electrical quantities: voltage, current, and resistance. Of the three, current is the one that carries energy through a circuit. How does the current depend on the voltage and resistance? In this section you will learn the fundamental relationship for circuits known as Ohm's law.

One volt causes a current of 1 amp to flow through a resistance of 1 ohm.

What is Ohm's law?

The relationship between amps, volts, and ohms

If you have been working with circuits, you probably have an idea of how voltage, current, and resistance are related. You know that if you increase the voltage, the current goes up. You know that if you increase the resistance by adding a second light bulb, the current goes down.

Ohm's law

German physicist Georg S. Ohm (1787-1854) experimented with circuits to find the exact mathematical relationship present in most circuits. The relationship that he discovered is called Ohm's law.

Ohm's law

Current (amps) → $$I = \frac{V}{R}$$

Voltage (volts)

Resistance (ohms, Ω)

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

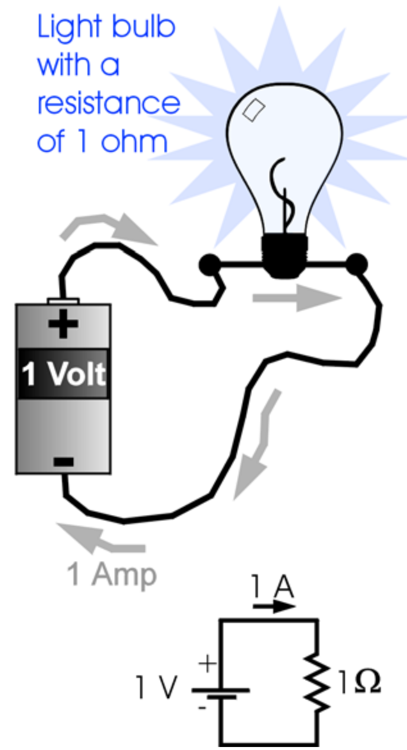
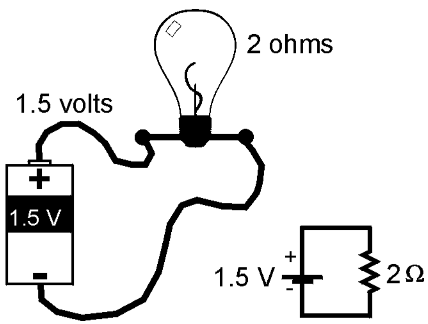


Figure 8.1: *Ohm's law in a circuit.*

Using Ohm's law to analyze circuits

Ohm's law can be used to predict any of the three variables given the other two. Sometimes you want to know the current in the circuit. Sometimes you want to know voltage or resistance. Use the problem-solving steps to help set up and work through problems.

Example: A light bulb with a resistance of 2 ohms is connected to a 1.5 volt battery as shown. Calculate the current that will flow.



Solution:

(1) We are asked for the current, I.

(2) We know V and R.

(3) Use the formula $I = V \div R$.

(4) Plug in numbers.
$I = 1.5\ V \div 2\ \Omega = 0.75\ A$

Answer: 0.75 amps will flow in the circuit.

Example: A light bulb requires 3 amps to produce light. The resistance of the bulb is 1.5 ohms. How many batteries do you need if each battery is 1.5 volts?

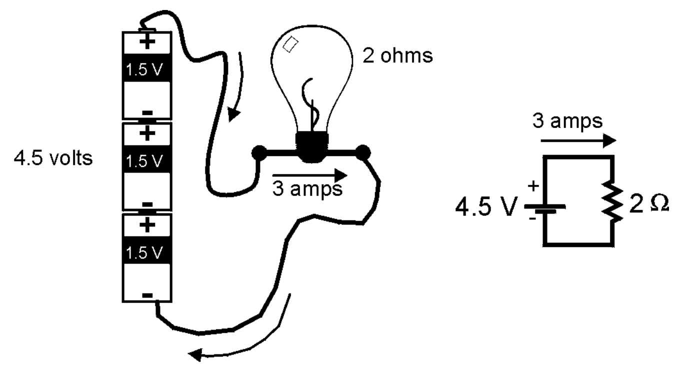
(1) We are asked for the number of batteries, which means we need to know the voltage since each battery is 1.5 volts.

(2) We know current and resistance.

(3) Use the formula $V = IR$.

(4) Plug in numbers.
$V = 3\ A \times 1.5\ \Omega = 4.5\ V$

Answer: Each battery can produce 1.5 volts so we need three batteries to get the required 4.5 volts.



Graphing and Ohm's law

Devices and Ohm's law

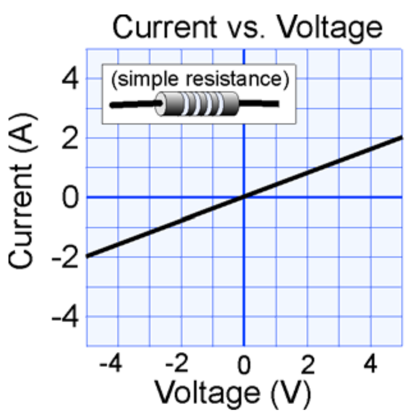
Ohm's law tells us how much current flows for different amounts of voltage. If a device has the same resistance under different conditions we say that it obeys Ohm's law. We can predict current flow at different voltages. Not all electrical devices obey Ohm's law! If resistance changes, a device does *not* obey Ohm's law. For example, a light bulb's resistance increases when voltage and current increase.

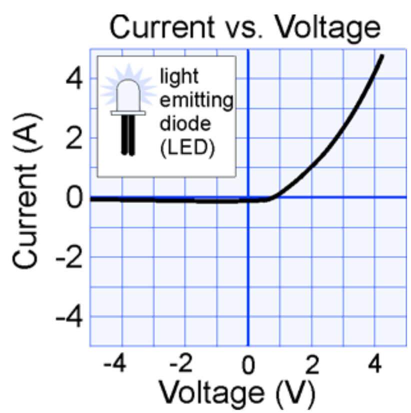
The current vs. voltage graph

A current vs. voltage graph shows us if resistance changes. Often, these graphs have both positive and negative values of current and voltage. These positive and negative values are just a way to refer to the direction of current in a wire. You can apply voltage two ways across a wire (Figure 8.2). How you apply voltage determines current direction. One direction is positive and the other negative.

I vs. V for a diode

A simple resistor obeys Ohm's law—its current vs. voltage graph is a straight line. Resistance is the same at all values of voltage and current. For a *diode*, the graph is not a straight line. A diode only allows charge to flow in one direction! This is why current is zero when voltage is negative. Diodes do not obey Ohm's law. Diodes, like computer chips, are made from semiconductors.





Finding resistance from a graph

You can find resistance from a current vs. voltage graph. If the graph is a straight line (obeying Ohm's law), pick a point on the line. Read voltage and current (Figure 8.3) from the graph. Calculate resistance using the R = V/I form of Ohm's law.

Positive and negative

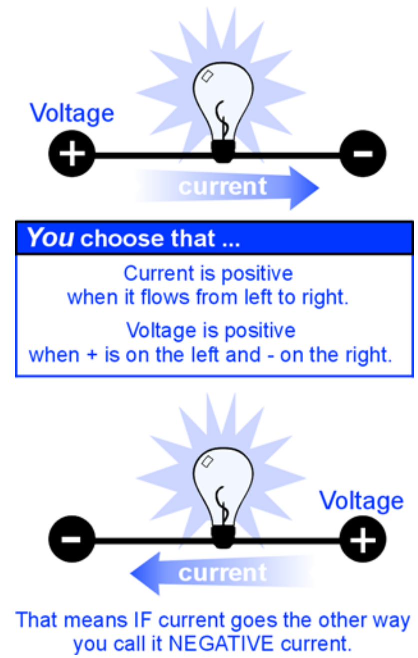


Figure 8.2: *How to interpret positive and negative voltage. You have to choose which direction to call positive. After you choose, the other direction is negative!*

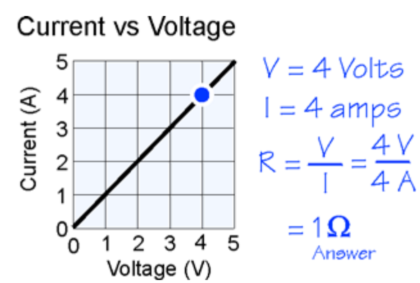
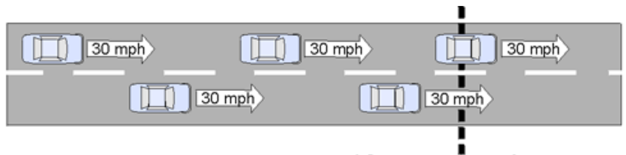


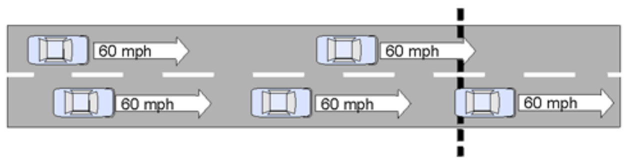
Figure 8.3: *Using a graph of current vs. voltage to determine resistance.*

Temperature and Ohm's law

The cause of resistance

Resistance happens because the charges bounce into and around atoms as they weave their way through a material. If the voltage goes up, the charges move a little faster between atoms and we get more current. Think about a highway. On a stretch of road there may be the same number of cars whether they are going 30 or 60 miles per hour. But, at 60 mph, twice as many cars flow past you per minute compared with 30 mph. Materials obey Ohm's law because the speed of moving charges increases proportionally with voltage.





Resistance of metals increases with temperature

Even if a material obeys Ohm's law, its resistance can change when it is cooler or warmer. Atoms gain energy when they are heated up. With extra energy, the atoms move around more. They collide more often with moving charges that make up the current. The extra collisions mean that hot metal has more resistance than cold metal.

Superconductivity

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

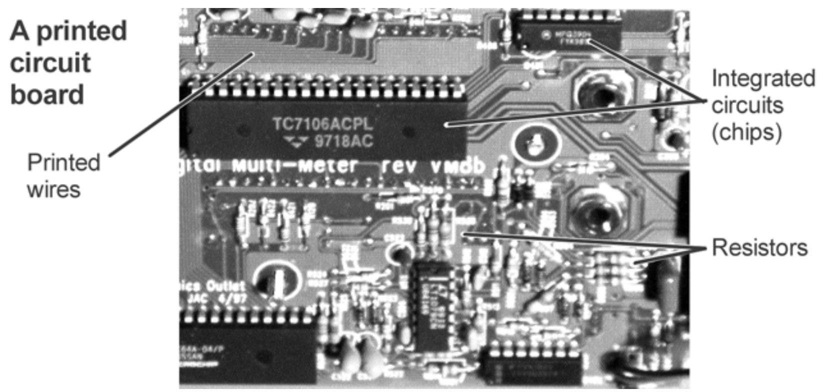
What happens to the resistance of a material as its temperature is lowered? This question intrigued Dutch physicist Heike Kamerlingh Onnes (1853-1926). In 1911, he discovered that when mercury is cooled to 269 degrees below zero (-269°C), its resistance suddenly drops to zero. He called this property "superconductivity." A *superconductor* allows current to flow without losing *any* energy as heat or light.

Until the 1960s, superconductivity remained of little practical value because it was very hard and expensive to cool wires down to such extremely low temperatures. A few practical uses were invented, such as the magnetic resonance imaging machines found in many hospitals. In the 1980s, scientists made another big discovery. They discovered special ceramic materials that become superconductors at higher temperatures. Although they still must be cooled to -70°C, the new superconductors work at temperatures 200 degrees warmer than mercury. Engineers are working with these "high temperature" superconductors to see if they can be used to make more efficient motors, generators, power cables, and magnetically levitated trains.

Resistors

What is a resistor? Using Ohm's law, if the voltage is prescribed, then the only way we can change the current is by changing the resistance. Components called **resistors** are used to control current in many circuits. Resistors are made from materials that keep the same resistance over a wide range of temperatures and currents.

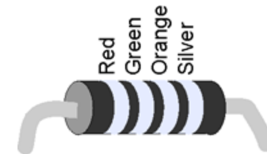
Fixed and variable resistors There are many kinds of resistors. The two basic kinds are fixed and variable. A fixed resistor always has the same value. An application of fixed resistors is a three-way light switch. Each setting connects the circuit to a different resistor. The three values of resistance determine three levels of current. The three levels of current control the brightness of the bulb.



If you look inside a stereo or telephone you will find a circuit board. The circuit board has wires printed on it and is covered with little parts. The little parts are called **electronic components** and are soldered to the circuit board. Many of the components are resistors, which look like small skinny cylinders with colored stripes on them. Because they are so tiny, it is impossible to write how much resistance each one has. The colored stripes are a code that tells you the resistance.

Example:

Figure out the value of this resistor.



(1) The first two stripes are a number. Red (2) and green (5) make 25.

(2) The third stripe is the multiplier. Orange is 1,000.

(3) The fourth stripe is the accuracy tolerance. Silver is +/- 10%.

The example resistor is 25,000 ohms.

Resistor Color Codes

Color	Digit	Multiplier
Black	0	1
Brown	1	10
Red	2	100
Orange	3	1,000
Yellow	4	10,000
Green	5	100,000
Blue	6	1,000,000
Violet	7	10,000,000
Gray	8	not a multiplier
White	9	not a multiplier

Electrical controls

What are controls?

Every time you turn a knob or push a switch you are using an electrical control. We use controls for lights, motors, air conditioners, and almost every electrical device you can think of. Many controls use variable resistors.

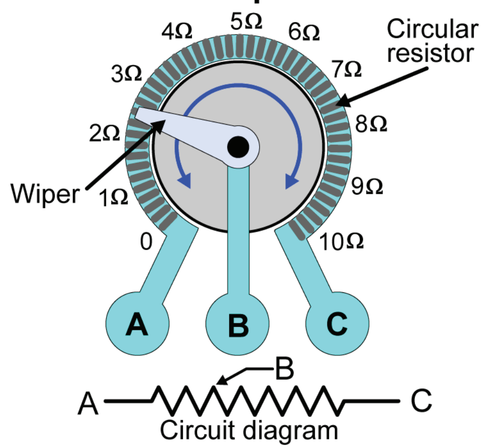
Making a dimmer switch

An application of variable resistors is a dimmer switch. As you turn the dimmer switch from low to high, it changes the resistance, which also changes the current. Current is increased as the resistance goes down, and the bulb glows brighter in response.

The potentiometer

A **potentiometer** is a variable resistor. Inside the potentiometer is a circular resistor and a little sliding contact called a wiper. As shown in the diagram below, the wiper moves when you turn the knob and is connected to a wire (B). You choose the resistance by turning the knob.

The inside of a potentiometer



How the potentiometer works

Potentiometers (or *pots* for short) have three wires. The resistance between A and C always stays the same. As you turn the knob the resistance between A and B changes. The resistance between B and C also changes. With the wiper rotated like the diagram above, the resistance between A and B is 2 ohms. The resistance between B and C is 8 ohms (10 minus 2).

You can choose how to connect a potentiometer into your circuit to change the resistance from zero to the maximum value of the potentiometer. For the potentiometer in the diagram the resistance can vary between zero and 10 ohms.

Lewis Latimer


Photo courtesy of Queens Library

Lewis Latimer was born in Chelsea, Massachusetts in 1848, six years after his parents escaped from slavery in Virginia.

As a child, Lewis loved to read and draw. When he was sixteen, Lewis joined the U.S. Navy, fighting for the Union in the Civil War. Afterward, He worked in a law office in Boston that specialized in helping people patent their inventions. There he taught himself how to use draftsmen's tools to make scale drawings of machines.

Latimer met Alexander Graham Bell at that office. Working late, Latimer made blueprints and helped Bell file the papers for his telephone patent—just hours before a rival.

A new job as a mechanical draftsman for the U.S. Electric Lighting company helped Latimer learn about incandescent lighting. Four years later, Thomas Edison hired Latimer as an electrical engineer and patent advisor. Latimer was later invited to join the prestigious research team known as Edison's pioneers. Latimer improved incandescent bulb design by replacing a paper filament with a carbon one. He also wrote the first engineer's handbook on electric lighting.

8.2 Work, Energy, and Power

If you look carefully at a stereo, hair dryer, or other household appliance, you find that most devices list a “power rating” that tells how many watts the appliance uses. In this section you will learn what these power ratings mean, and how to figure out the electricity costs of using various appliances.

Electric power

The three electrical quantities

We have now learned three important electrical quantities:

Amps	Current is what flows in a circuit. Current is measured in amps.
Volts	Voltage measures the potential energy difference between two places in a circuit. Voltage differences make current flow.
Ohms	Resistance measures the ability to resist the flow of current.

Paying for electricity

Electric bills sent out by utility companies don’t charge by the volt, the amp, or the ohm. You may have noticed that electrical appliances in your home usually include another unit – the *watt*. Most appliances have a label that lists the number of watts or kilowatts. You may have purchased 60-watt light bulbs, or a 900-watt hair dryer, or a 1500-watt toaster oven. Electric companies charge for the energy you use, which depends on how many watts each appliance consumes in a given month.

A watt is a unit of power

The **watt** (W) is a unit of **power**. Power, in the scientific sense, has a precise meaning. Power is the rate at which energy is flowing. Energy is measured in joules. Power is measured in joules per second. One joule per second is equal to one watt. A 100-watt light bulb uses 100 joules of energy *every second*.

Where does the electrical power go?

Electrical power can be easily transformed into many different forms. An electric motor takes electrical power and makes mechanical power. A light bulb turns electrical power into light and a toaster oven turns the power into heat. The same unit (watts) applies to all forms of energy flow, including light, motion, electrical, thermal, or many others.

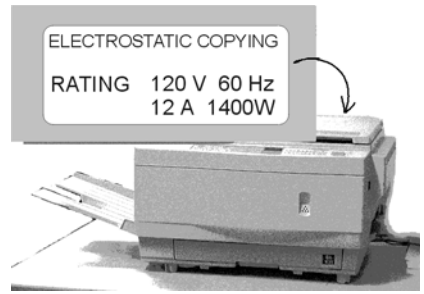


Figure 8.4: *The back of an electrical device often tells you how many watts it uses.*

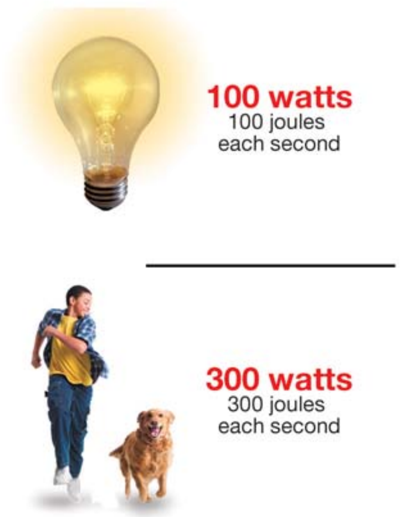


Figure 8.5: *One watt is an energy flow of one joule per second. A 100-watt light bulb uses 100 joules every second. A person running uses about 300 watts, or 300 joules every second.*

How can we measure power in a circuit?

Power in a circuit

Power in a circuit can be measured using the tools we already have. Remember that one watt equals an energy flow of one joule per second.

Amps	One amp is a flow of one coulomb of charge per second
Volts	One volt is an energy of one joule per coulomb of charge

If these two quantities are multiplied together, you will find that the units of coulombs cancel out, leaving the equation we want for power.

Voltage x Current = Power

$$\frac{\text{Joules}}{\cancel{\text{Coulomb}}} \times \frac{\cancel{\text{Coulomb}}}{\text{Second}} = \frac{\text{Joules}}{\text{Second}}$$

Power = voltage × current

Watts equal joules/second, so we can calculate electrical power in a circuit by multiplying voltage times current.

Electrical Power

Power (watts) → $P = V\,I$ ← Voltage (volts), Current (amps)

Watts and kilowatts

A larger unit of power is sometimes needed. The 1500-watt toaster oven may instead be labeled "1.5 kW." A **kilowatt** (kW) is equal to 1000 watts or 1000 joules per second.

Horsepower

The other common unit of power often seen on electric motors is the **horsepower**. One horsepower is 746 watts. Electric motors you find around the house range in size from 1/25th of a horsepower (30 watts) for a small electric fan to 2 horsepower (1492 watts) for an electric saw.

Electric cars

Many people believe that all cars will eventually be electric because electric cars give off little or no pollution. Electric cars are challenging to build because of the power you need. A gas engine for a car makes 100 horsepower, or about 75,000 watts.

Suppose you want to use 12-volt batteries, like the ones used to *start* cars today. To make 75 kilowatts of power at 12 volts, you need a current of 6,250 amps! By comparison, most people's homes use less than 100 amps.

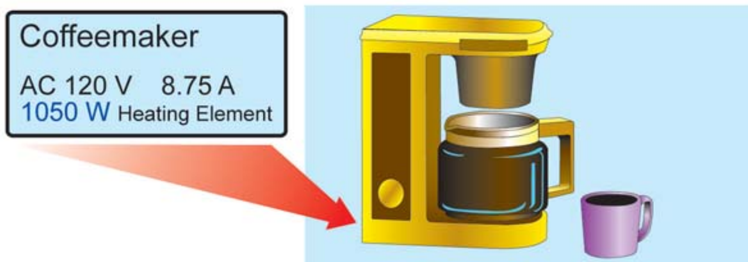
The solution is to use more efficient motors and higher voltages. Research into electric cars is being done all over the world.

You buy electricity by the kilowatt-hour

Kilowatt-hours What do we buy from the electric utility company? Let's look at a utility bill. Utility companies charge customers for a unit called the kilowatt-hour (abbreviated kWh). One kilowatt-hour means that a kilowatt of power has been used for one hour.

You pay for kilowatt-hours Electric companies charge for kilowatt-hours over a set period of time, often a month. Your home is connected to a meter that counts up total number of kilowatt-hours used and a person comes to read the meter once a month.

Estimating your electric bill If you know the cost per kilowatt-hour that your utility company charges, you can estimate the cost of running an appliance for a period of time.



Example: Your electric company charges 14 cents per kilowatt-hour. Your coffeemaker has a power rating of 1,050 watts. The coffeemaker is on for about 1 hour each day. What does this cost you each month in electricity?

Solution: Find the number of kilowatts of power that the coffeemaker uses.
1,050 W × 1 kW/1,000 W = 1.05 kW

Find the kilowatt-hours used by the coffeemaker each day.
1.05 kW × 1 hr/day = 1.05 kWh per day

Find the kilowatt-hours of electricity used by the coffeemaker each month. Assume there are 30 days in a month.
1.05 kWh/day × 30 days/month = 31.5 kWh per month

Find the cost of using the coffeemaker for one month.
31.5 kWh/month × $0.14/kWh = $4.41 per month

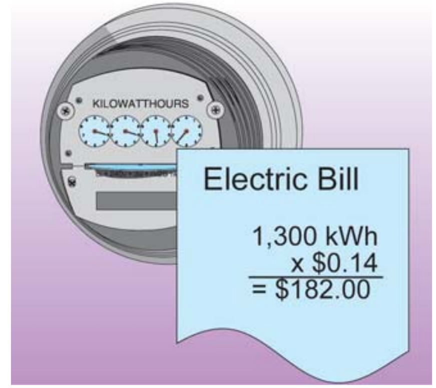


Figure 8.6: *Every month most people pay an electric bill that charges for the kilowatt-hours of energy used.*

Typical power ratings

Appliance	Power (watts)
Electric stove	5,000
Electric heater	1,500
Hair dryer	1,200
Iron	800
Washing machine	750
Light	100
Small fan	50
Clock radio	10

Electricity, power, and heat

How do you get more power?

How do you get more power when you need it? From the power formula we can see that increasing voltage or current will increase power. The disadvantage of raising voltage is that the electricity in your standard outlets is at 120 volts, and it is hard to change. Some appliances use 240 volts, but they have special plugs because 240 volts is more dangerous than 120 volts.

Higher power usually means more current

The more usual way to get higher power is to use more current. However, when current flows through a wire, part of the energy is transformed into heat. More current means more heat. If too much power goes into heat, the wire could melt or start a fire.

Reducing heat in electrical wires

Fortunately, there is a way to let more current flow through a wire without making more heat. Remember (from Ohm's law) that voltage is current times resistance. If we make the resistance smaller, more current can flow with less voltage change along the wire. Since power is voltage times current, less voltage means less power is lost as heat.

Different size wires have different resistance

Lower resistance is the reason wires come in different sizes. Thick wire has lower resistance and can safely carry more current than thin wire (Figure 8.7). Often we use extension cords to plug in electric tools or appliances. Extension cords come with many thicknesses, or *gauges*, of wire. Typical kinds of extension cords you can buy have 18 gauge wire, 16 gauge wire, 14 gauge wire, and 12 gauge wire (Figure 8.8). The bigger the gauge, the higher the resistance. To carry a lot of current, you want low resistance, so you need lower gauge (fatter) wires.

Length and resistance

The length of a wire also affects its resistance. The longer a wire is, the more resistance it has. Think about moving around your school and how you can get through a short, crowded hallway quickly. But, it takes a long time to get down a long, crowded hallway.

Check your extension cords for safety

If you look at an extension cord, it 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!

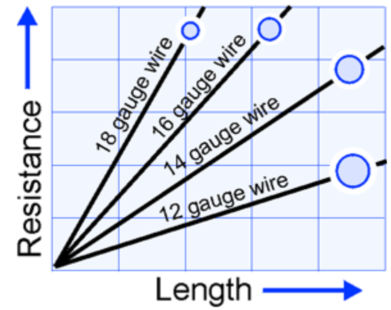
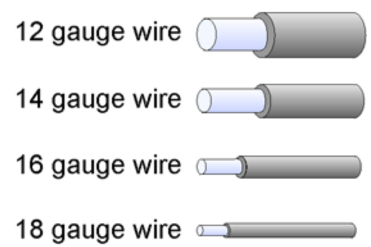


Figure 8.7: *The resistance of a wire depends on the length and size. Longer length means greater resistance. Bigger diameter means lower resistance.*



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

Figure 8.8: *The safe amount of current for different gauges of wire.*

Chapter 8 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One		Set Two	
1. Ohm's law	a. A semiconductor component that allows current to flow in one direction only	1. potentiometer	a. A unit equal to 100 watts
2. diode	b. A shorthand method of describing the resistance of a resistor	2. watt	b. The use of a kilowatt of power for one hour
3. superconductor	c. A component used to control current in circuits because it has a relatively constant resistance	3. power	c. The unit commonly used to measure power, equal to joules/second
4. resistor	d. A part soldered onto a circuit board	4. kilowatt	d. A unit equal to 1000 watts
5. electronic component	e. An equation relating voltage, current and resistance in a circuit	5. kilowatt-hour	e. The rate at which work is being performed
	f. A material that has zero resistance at low temperatures		f. A variable resistor

Concept review

1. Explain what will happen to the value of current in a circuit if the voltage is increased.
2. Explain what will happen to the value of current in a circuit if the resistance is increased.
3. High resistance leads to an increase in heat. A person repaired a broken light in a house and replaced the copper wire with a thin piece of aluminum. Explain why this replacement is a fire hazard.
4. Explain why the amps rating on an extension cord should be the same as, or larger than, the current drawn by the device plugged into the extension cord.
5. What is the scientific definition of power?
6. What type of work is done by an electric fan? (In other words, electrical energy is changed into what other form(s) when the fan is running?)
7. What is the metric unit used to measure power?
8. List three appliances and their power ratings.

9. Express the metric unit of power in fundamental units.

10. Power companies charge us for kilowatt-hours. What type of quantity is being measured by a kilowatt-hour?

Problems

1. A hair dryer draws a current of 10 amps. If it is plugged into a 120-volt circuit, what is the resistance of the hair dryer?
2. A child's toy robot draws a current of 2.0 amps. The robot's circuit has a total resistance of 4.5 ohms. What is the total voltage of the battery or batteries required by the toy?
3. A flashlight bulb has a resistance of approximately 6 ohms. It works in a flashlight with two AA alkaline batteries. About how much current does the bulb draw?
4. Household circuits in the United States commonly run on 120 volts of electricity. Frequently, circuit breakers are installed that open a circuit if it is drawing more than 15 amps of current. What is the minimum amount of resistance that must be present in the circuit to prevent the circuit breaker from activating?
5. A 2,500-watt room air conditioner could also be called a ________ kilowatt appliance.
6. If you bake potatoes in a 900-watt microwave oven for 15 minutes, how many kilowatt-hours of electrical energy have you consumed?
7. If a toaster oven draws 6 amps of current when plugged into a 120-volt outlet, what is the power rating of the appliance?
8. A student uses three appliances in her dormitory room: a 1,200-watt iron, which she uses 3.5 hours per month; a lamp with a 100-watt bulb which she uses 125 hours per month; and a 700-watt coffee maker, which she uses 15 hours per month
   a. How many kilowatt-hours of electrical energy are consumed in one month by each of these appliances?
   b. If the local utility company charges 15 cents per kilowatt-hour of electrical energy consumed, how much does it cost per month to operate each appliance?
9. Calculate the current through each of the following bulbs if they are connected to a 120-volt circuit in your house.

   a. 40 W   b. 60 W   c. 100 W   d. 150 W

Applying your knowledge

1. Using power ratings, analyze how much your family spends to run every appliance in your home. Enact a plan to reduce electricity use and see if your family saves money.
2. With an adult, check the safety of appliances that are plugged into extension cords, in your home or school. Make sure that the current ratings of the extension cord meet or exceed the current ratings of the appliance.
3. Find out what programs are available through your local utility company to reduce electricity use (discounted low-wattage bulbs, home energy checks, etc.). Prepare a pamphlet on the programs.
4. Research superconductivity. Find out what it is and what applications it may have.

UNIT 3

Electricity and Magnetism

Chapter 9

Circuits

Introduction to Chapter 9

In our homes, you can have many electrical devices on at any one time. How is this possible? What do circuits in our homes look like? In this chapter, you will learn about the two kinds of circuits, called *series circuits* and *parallel circuits*. In series circuits, all the current flows through one path. In parallel circuits, current can flow through two or more paths.

Investigations for Chapter 9

9.1	**More Electric Circuits**	*What kinds of electric circuits can you build?*

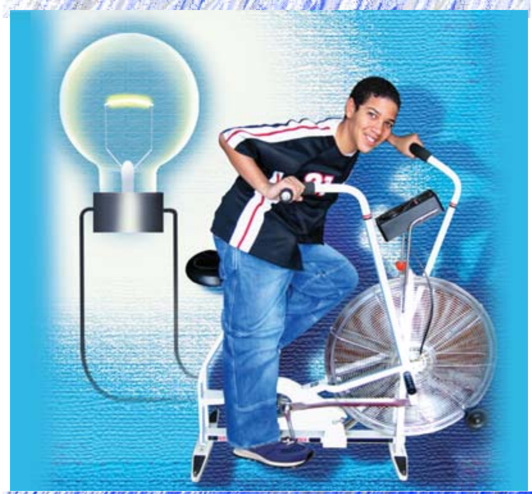
In this Investigation, you will compare how two kinds of circuits work by building and observing series and parallel circuits. You will explore an application of these circuits by wiring two switches in series and in parallel.

9.2	**Series Circuits**	*How do you use Ohm's law in series circuits?*

In this Investigation, you will find out how to add resistance in a series circuit. You will also build a light bulb circuit with a dimmer switch and use this circuit to graph the resistance of a light bulb at different levels of current.

9.3	**Parallel Circuits**	*How do parallel circuits work?*

In this Investigation, you will analyze how a parallel circuit works by measuring voltage and current in different parts of the circuit. You will use your understanding of parallel circuits to design a battery voltage tester circuit.



Learning Goals

In this chapter, you will:

- ✔ Identify a series circuit.
- ✔ Identify a parallel circuit.
- ✔ Describe how our houses are wired.
- ✔ Build series and parallel circuits.
- ✔ Calculate total resistance in series circuits.
- ✔ Build circuits with fixed and variable resistors.
- ✔ Analyze series circuits using Ohm's law.
- ✔ Use Kirchhoff's voltage law to find the voltage drop across a circuit component.
- ✔ Compare current in series and parallel circuits.
- ✔ Compare voltage in series and parallel circuits.
- ✔ Use Kirchhoff's current law to find an unknown current in a parallel circuit.
- ✔ Identify a short circuit.
- ✔ Explain why a short circuit is dangerous.

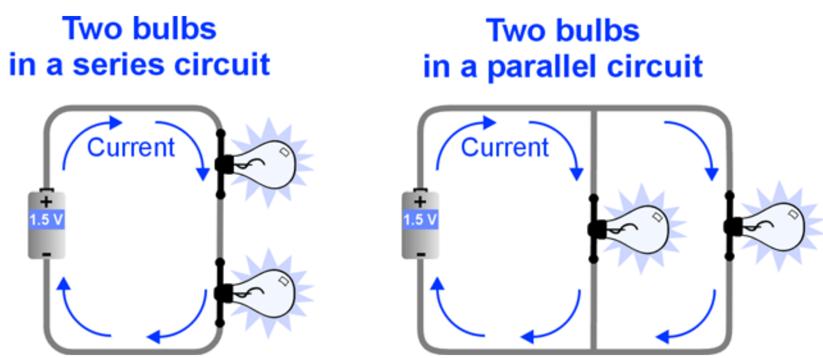
Vocabulary

Kirchhoff's current law	parallel circuit	short circuit
Kirchhoff's voltage law	series circuit	

9.1 More Electric Circuits

We use electric circuits for thousands of different things from cars to computers. In this section you will learn about two basic ways to put circuits together. These two types of circuits are called *series* and *parallel*. Series circuits have only one path; the flow of charge has only one place to go. Parallel circuits have branching points and multiple paths for current to flow.

Series circuits

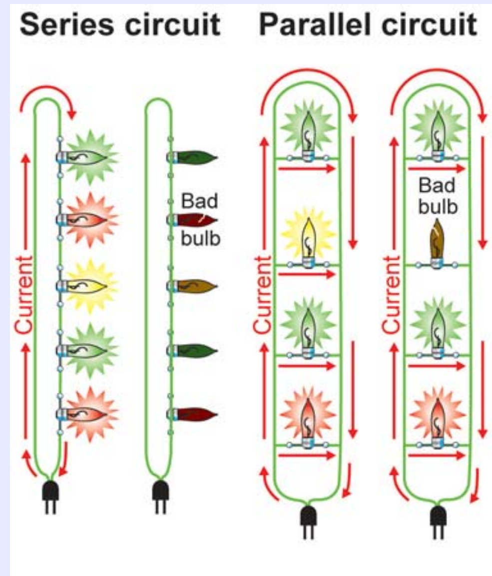


What is a series circuit? In a **series circuit** the current can only take one path. All the current flows through every part of the circuit. All the circuits you have studied so far have been series circuits. For example, if you have a battery, a light bulb, and one switch, everything is connected in series because there is only one path through the circuit.

What is a parallel circuit? In a **parallel circuit** the current can take more than one path. Parallel circuits have at least one branch where the current can split up.

Combinations It is possible to create circuits with both series and parallel wiring. You need at least three light bulbs. Can you think of a way to wire three bulbs using both series and parallel connections?

Holiday lights



Many people use strings of lights to decorate their houses, especially at holiday time. Inexpensive versions of lights are wired in series, while better ones are wired in parallel.

In the series circuit, if one bulb goes bad the whole circuit is broken and no bulbs light. It is very difficult to find the bad bulb to replace it because all the lights are out.

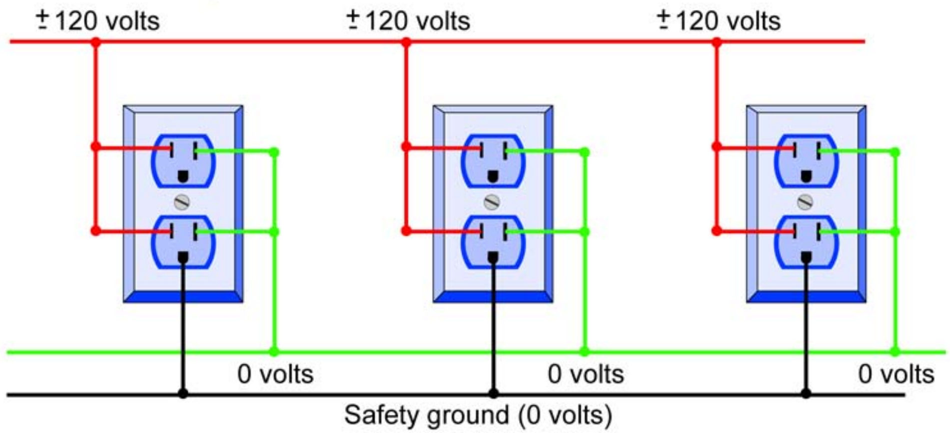
In the parallel circuit, each bulb has its own path for current, independent of the others. If one bulb fails, the others will still light. The bad bulb is easy to spot and replace.

Household wiring

Parallel circuits for homes and buildings

The electrical circuits in homes and buildings are parallel circuits. There are two great advantages of parallel circuits that make them a better choice than series circuits.

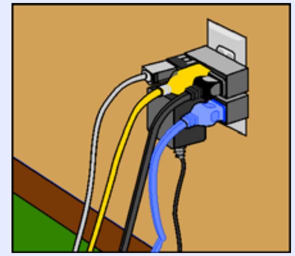
1. Each outlet has its own current path. This means one outlet can have something connected and turned on (with current flowing), while another outlet has nothing connected or something turned off (no current flowing).
2. Every outlet sees the same voltage because one side of each outlet is connected to the same wire.



Why series circuits would not work

Parallel circuits mean that a light in your home can be on at the same time that the TV is off. If our homes were wired in series, turning off *anything* electrical in the house would break the whole circuit. This is not practical; we would have to keep everything on all the time just to keep the refrigerator running! Also, in a series circuit, everything you plugged in would use some energy and would lower the voltage available to the next outlet.

What happens if you plug in too many things?



In a parallel circuit, each connection uses as much current as it needs. If you plug in a coffeemaker that uses 10 amps and a toaster oven that uses 10 amps, a total of 20 amps needs to come through the wire.

If you plug too many appliances into the same outlet, you will eventually use more current than the wires can carry without overheating. Your circuit breaker will click open and stop the current. You should unplug things to reduce the current in the circuit before resetting the circuit breaker.

9.2 Series Circuits

Ohm's law is a powerful tool for analyzing circuits. You have studied Ohm's law in a series circuit with one resistor. In this section you will learn how to analyze more complex series circuits with more than one resistance.

Current and voltage in a series circuit

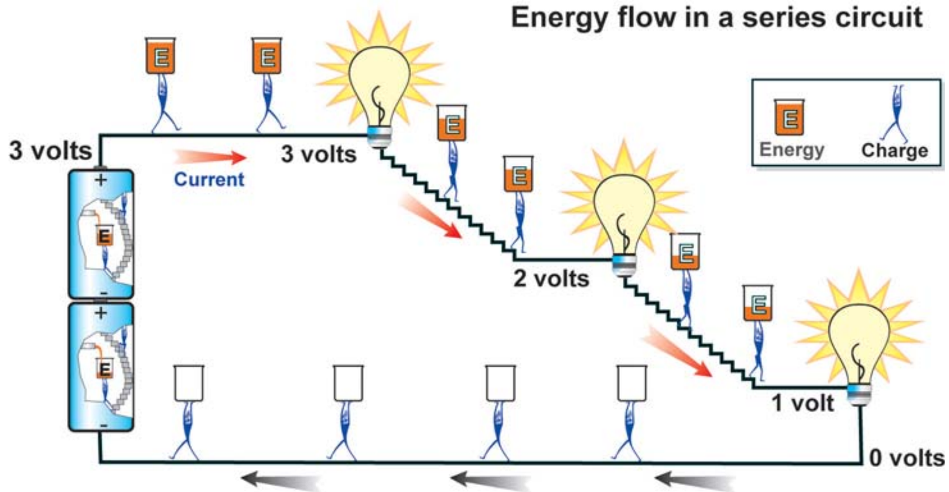
In a series circuit, current is the same at all points

In a series circuit, all current flows through a single path. What goes into one end of the wire must come out the other end of the wire. The value of current is the same at all points in the circuit. The amount of current is determined by the voltage and resistance in the circuit, using Ohm's law.

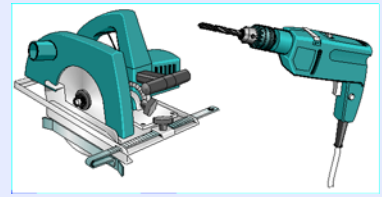
Voltage is reduced by each resistance

The law of conservation of energy helps us to understand what happens to energy in a series circuit. Consider a circuit with three bulbs. Using two batteries, every charge starts at 3 volts. As each charge moves through the circuit, some energy is transformed into light by each bulb. That means that after every bulb, the energy must be lower. We see the lower energy as a drop in voltage from 3 volts, to 2 volts, to 1 volt and finally down to zero volts after the last bulb.

Energy flow in a series circuit



Using power tools



If you know people who work with power tools, you may have noticed that they use a heavy extension cord when the regular cord can't reach. One reason to use a heavy cord is that it can safely carry the amps used by power tools.

There is a second reason as well. If a thin extension cord is used, the motor in a power tool can overheat and burn out. This happens because the voltage available for the motor is lower than it should be.

The motor gets lower voltage when energy is lost along the cord. This energy loss is called a voltage drop, and is related to resistance. Heavy extension cords have lower resistance and use less energy than thin cords of the same length.

How to find the current in a series circuit

Start with resistance and voltage

You need to know how much resistance the circuit has to find the current. In many cases you know the voltage, such as from a battery. If you know the resistance, Ohm's law can be used to find the current.

Each resistance in a series circuit adds to the total. You can think of it like adding pinches to a hose (Figure 9.1). Each pinch adds some resistance. The total resistance is the sum of the resistances from each pinch.

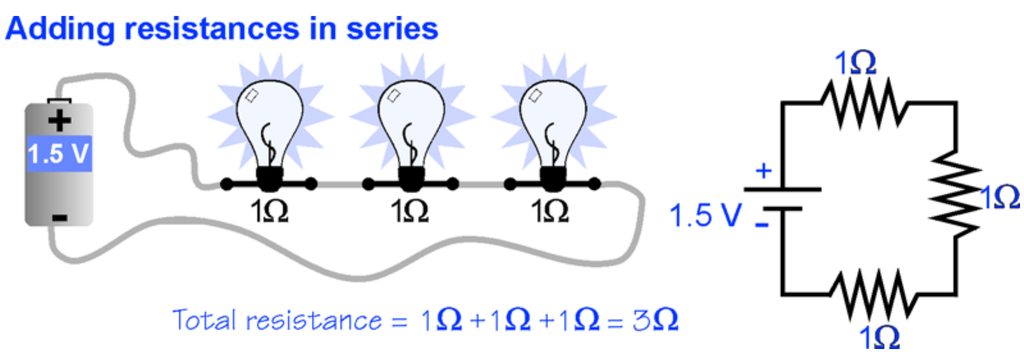
Two ways to find the current

How would you find the exact amount of total resistance in a series circuit? You could use several methods:

- You could measure total voltage and current through the circuit, and use Ohm's law to calculate the total resistance of the circuit (R = V/I).
- You could add together the resistance of each component in the circuit.

Add up resistances to get the total

If you know the resistance of each component, you can simply add them up to get the total for the circuit. Once you know the total resistance, use Ohm's law to calculate the current.



Ignore resistance of wires and batteries

Every part in a circuit has some resistance, even the wires and batteries. However, light bulbs, resistors, motors and heaters usually have much greater resistance than wires and batteries. Therefore, when adding resistances up, we can almost always leave out the resistance of wires and batteries.

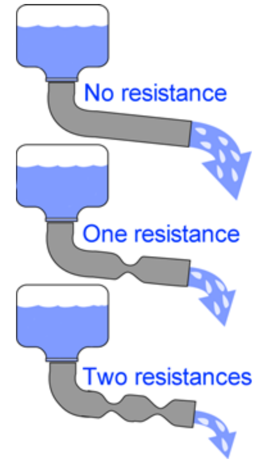


Figure 9.1: *Each time a hose is pinched, the flow of water slows more.*

Example:

How much current is in a circuit with a 1.5 volt battery and three 1 ohm resistances (bulbs) in series?

Solution

Add the resistance of each component:

1 ohm + 1 ohm + 1 ohm = 3 ohms

Use Ohm's law to calculate the current from the voltage and the total resistance.

I = V/R = 1.5 volts ÷ 3 ohms
= 0.5 amps

Answer: 0.5 amps

Voltage in a series circuit

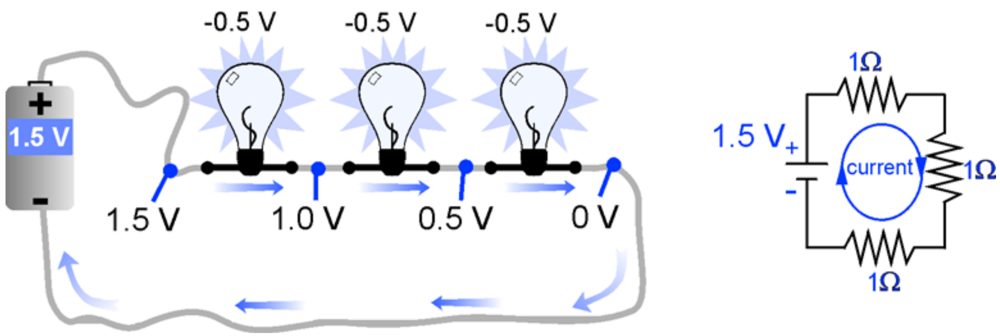
Each resistance drops the voltage

You have learned that energy is not created or destroyed. This rule is known as the law of conservation of energy. However, energy is constantly being transformed from one form to another. As current flows along a series circuit, each resistance uses up some of the energy. As a result, the voltage gets lower after each resistance.

The voltage drop

We often say each separate resistor creates a *voltage drop*. If you know the current and resistance, Ohm's law can be used to calculate the voltage drop across each resistor. For example, in the three-bulb series circuit, the voltage drop across each bulb is 0.5 volts (Figure 9.2).

Each resistance drops the voltage



Kirchhoff's law

Over the entire circuit, the energy taken out must equal the energy supplied by the battery. This means the total of all the voltage drops must add up to the total voltage supplied by the battery (energy in). This rule is known as Kirchhoff's voltage law, after German physicist Gustav Robert Kirchhoff (1824-87):

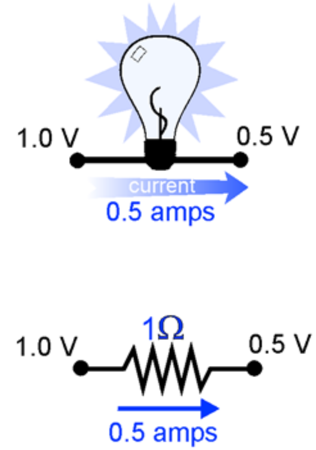
Kirchhoff's voltage law

Around any closed circuit, all the voltage changes must add up to zero.

Batteries raise voltage, resistances lower voltage.
For the example circuit above, the total of all voltage changes is:

$$\text{Voltage changes} = \underbrace{+1.5\text{ V}}_{\text{Battery}} - \underbrace{0.5\text{ V}}_{\text{Bulb}} - \underbrace{0.5\text{ V}}_{\text{Bulb}} - \underbrace{0.5\text{ V}}_{\text{Bulb}} = 0$$

Voltage drop across a resistor (bulb)



Calculating the voltage drop
Ohm's law

$V = IR$
$= (0.5\text{ amps}) \times (1\text{ ohm})$
$= 0.5\text{ volts}$

Figure 9.2: *When current flows through any resistance the voltage drops because some of the energy is used up. The amount of the voltage drop is given by Ohm's law.*

9.3 Parallel Circuits

In the last section, you learned how to analyze series circuits. In this section, you will take a closer look at parallel circuits. You previously learned that parallel circuits are used for almost all electrical wiring in houses and buildings.

Current in a parallel circuit

Separate paths are parallel branches

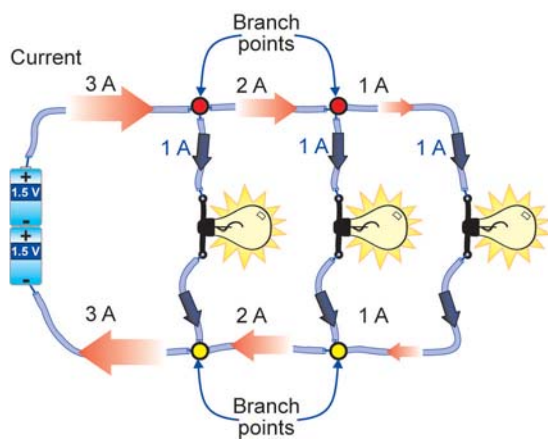
A parallel circuit has at least one point where the circuit divides, creating more than one path for current to flow. Each path in the circuit is sometimes called a *branch*. The current through a branch is also called the *branch current*.

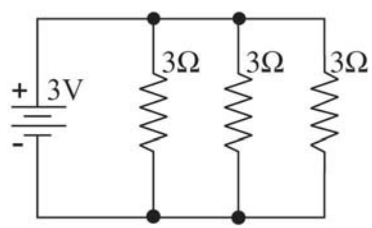
Kirchhoff's current law

When analyzing a parallel circuit, remember that the current always has to go somewhere. If current flows into a branching point in a circuit, the same total current must flow out again. This rule is known as Kirchhoff's current law.

Example, three bulbs in parallel

For example, suppose you have three light bulbs connected in parallel, and each has a current of 1 amp. The battery must supply 3 amps since each bulb draws 1 amp and there are 3 bulbs. At the first branch, 3 amps flow in, 1 amp flows down to the first bulb, and 2 amps flow on to the remaining 2 bulbs.





Why aren't birds electrocuted?

If high-voltage wires are so dangerous, how do birds sit on them without being instantly electrocuted? First, the bird's body has a higher resistance than the electrical wire. The current tends to stay in the wire because the wire is an easier path.

The most important reason, however, is that the bird has both feet on the same wire. That means the voltage is the same on both feet and no current flows through the bird.

If a bird had one foot on the wire and the other foot touching the electric pole, then there would be a voltage difference. A lot of electricity would pass through the bird.

Voltage and resistance in a parallel circuit

Each branch sees the same voltage

In a parallel circuit the voltage is the same across each branch because all the branch points are on the same wire. One way to think of a parallel circuit is to imagine several series circuits connected to the same battery. Each branch has a path back to the battery without any other resistance in the way.

Branches don't always have the same current

The amount of current in each branch in a parallel circuit depends on how much resistance is in the branch. When you plug a desk lamp and a power saw into an outlet, they each use very different amounts of current (Figure 9.3).

Lower resistance means more current flows

You can calculate current through the lamp and saw with Ohm's law (Figure 9.4). The 100-watt bulb has a resistance of 145 ohms. Since the outlet has 120 volts across it, the bulb draws about 0.8 amps. A power saw has a much lower resistance, 12 ohms. Consequently, the power saw draws a much higher current of 10 amps when connected to the 120-volt outlet.

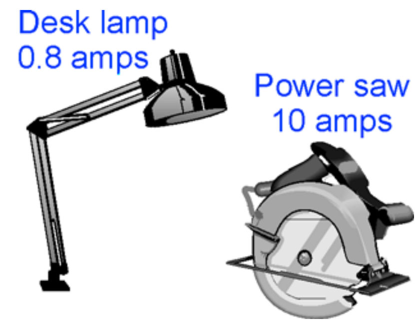
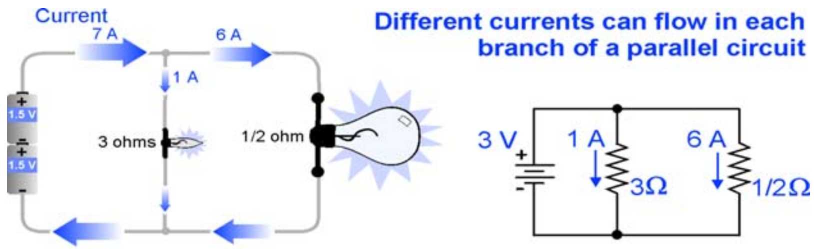


Figure 9.3: *Different appliances use different amounts of currrent.*

Example: Calculating currents in a parallel circuit

For the circuit and its diagram shown below, a student was able to calculate the currents from the information given about the circuit. Can you duplicate her work?



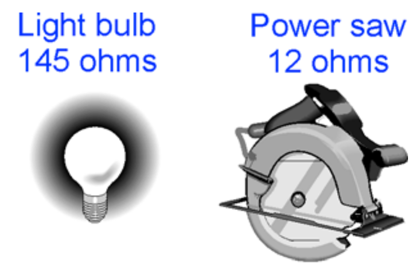
Step 1: Calculate current through each part of the circuit.

Step 2: You are given total voltage and the resistance of each bulb.

Step 3: Useful equations are: Ohm's law, $V = IR$, and Kirchhoff's current law, $I_t = I_1 + I_2$

Step 4: Branch 1 current: $I_1 = V/R_1$ Branch 2 current: $I_2 = V/R_2$ Total current: $I_t = I_1 + I_2$

Step 5: $I_1 = 3\text{ V} / 3\ \Omega = 1$ $I_2 = 3\text{ V} / 0.5\ \Omega = 6\text{ A}$ $I_t = 1\text{ A} + 6\text{ A} = 7\text{ A}$



$$I = \frac{V}{R} = \frac{120\text{ V}}{145\,\Omega} = 0.83\text{ amps}$$

$$I = \frac{V}{R} = \frac{120\text{ V}}{12\,\Omega} = 10\text{ amps}$$

Figure 9.4: *Calculating the current from the resistance and voltage. Household electric circuits are wired in parallel at 120 volts.*

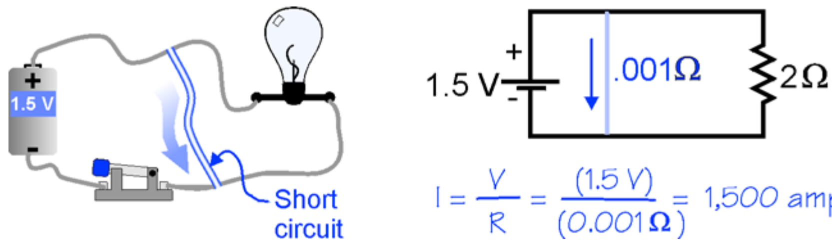
Open circuits and short circuits

What is a short circuit?

A **short circuit** is a circuit path with zero or very low resistance. You can create a short circuit by connecting a wire directly between two ends of a battery. Often, short circuits are accidentally caused by connecting a wire between two other wires at different voltages. This creates a parallel path with very low resistance. In a parallel circuit, the branch with the lowest resistance draws the most current (Figure 9.5).

Why short circuits are dangerous

Short circuits are dangerous because they can cause huge amounts of current. For example, suppose you connect a length of wire across a circuit creating a second current path as shown below. The resistance of the wire could be as low as 0.001 ohms. That means the current through your wire could be as high as 1,500 amps! This much current would melt the wire in an instant and probably burn you as well. Short circuits should always be a concern when working around electricity. Fuses or circuit breakers are protection from the high current of a short circuit.



$$I = \frac{V}{R} = \frac{(1.5\ V)}{(0.001\ \Omega)} = 1{,}500 \text{ amps}$$

Open and closed circuits

Open and closed circuits are not the same as short circuits. An open circuit means the current path has been broken, possibly by a switch (Figure 9.5). Current cannot flow in an open circuit. A closed circuit is a circuit that is complete and allows current to flow.

Protecting against short circuits

Every electrical outlet in your house or apartment is connected to a circuit breaker that allows a maximum of 15 or 20 amps to flow. If something electrical breaks and causes a short circuit, the breaker will open before the current has time to cause a fire. If a circuit breaker always trips when you plug in an appliance, that appliance probably has a short circuit.

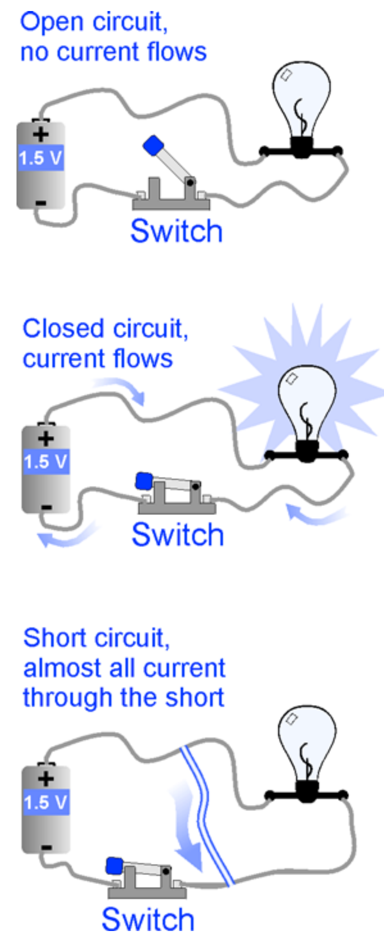


Figure 9.5: *A short circuit is a very low resistance path that can draw huge amounts of current. An open circuit is a break in the circuit that shuts off the flow of current. Switches are used to open and close circuits.*

Chapter 9 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One	
1. series circuit	a. In a circuit, all the voltage drops must add up to the total voltage supplied by the battery
2. parallel circuit	b. A circuit that has only one path for the flow of charge
3. Kirchhoff's voltage law	c. A circuit that has more than one path for the flow of charge
4. Kirchhoff's current law	d. Two switches wired in parallel
5. short circuit	e. A circuit path with very low resistance
	f. If current flows into a branch in the circuit, the same amount of current must flow out again

Concept review

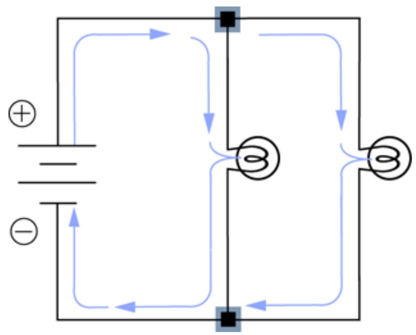
1. Explain the advantage of using a parallel circuit if you have more than one device in the circuit.
2. Imagine that an electrician wired the kitchen in your house so that all the outlets were connected in a single series circuit. Describe what you would have to do to keep the refrigerator running constantly.
3. If you have a light, and one switch that controls it, the light and the switch are wired in ________.
4. Is the current at every point in a series circuit the same?
5. What happens to the total resistance of a series circuit as you add more resistance? Does total resistance of the circuit decrease, increase, or stay the same?
6. Explain why Kirchhoff's voltage law is an application of the law of conservation of energy.
7. Describe what happens to the potential energy of charges in a circuit as they move through a bulb.
8. What happens to the total current of a parallel circuit as you add more branches with current through them? Does total current of the circuit decrease, increase, or stay the same?

9. The voltage across each branch of a parallel circuit is equal to the ________.

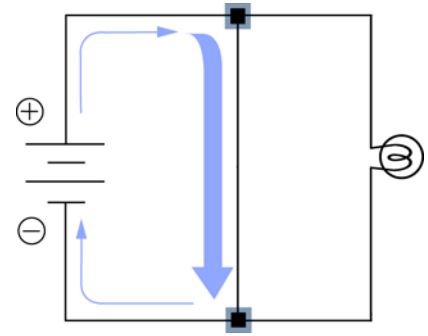
10. If a parallel circuit has two branches with equal resistance, what is the total resistance of the circuit?

11. For each diagram below, label the circuit *series*, *parallel*, or *short circuit*. The arrows indicate the flow of current.

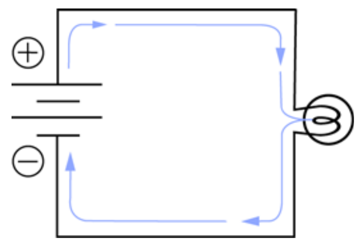
    a.



    b.

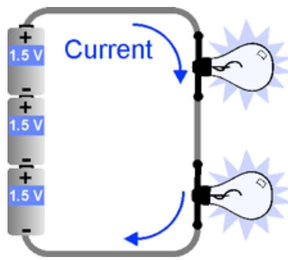


    c.



Problems

1. Answer the following:
    a. A circuit with three 1.5-volt batteries has two matching light bulbs. What is the voltage drop across each light bulb?
    b. Explain how you figured out your answer.

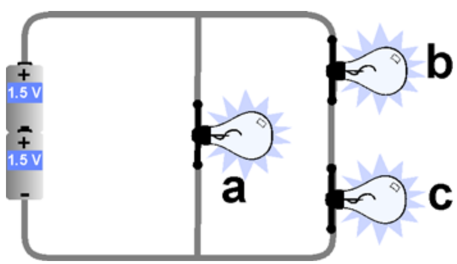


2. A student builds a circuit using three 1-ohm resistors in series. The current in the circuit is 1.5 amps. Use Ohm's law to determine the voltage of the circuit. (Hint: Draw the circuit described in the question.)

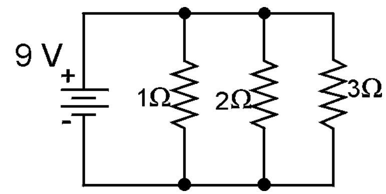
3. A student sets up a series circuit with four 1.5-volt batteries, a 5-ohm resistor, and two 1-ohm resistors. (Hint: Draw the circuit described in the question.)
    a. What is the total resistance in her circuit?
    b. Use Ohm's law to determine the value of current for the circuit.

4. A lab group was given a kit containing four 1.5-volt batteries, eight wires, and a resistor set containing three 1-ohm resistors and two 5-ohm resistors. They use all the batteries to build a series circuit. They use a meter to find that the current is 0.857 amps. What resistors did they use and what was the total resistance in the circuit?

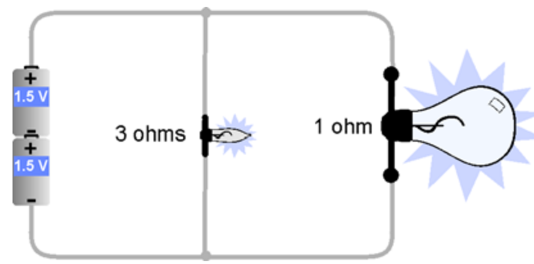
5. A lab group was asked to create two circuits with two 1.5-volt batteries. They are given three 1-ohm resistors and two 5-ohm resistors.
   a. The first circuit should have the highest possible current without creating a short circuit. Which resistor(s) should they use and what will the current in the circuit be?
   b. The second circuit should have a current of exactly 1 amp. Which resistor(s) should they use?
6. A circuit breaker in your house is set for 15 amps. You have plugged in a coffeemaker that uses 10 amps. You want to plug in four more things. Which of the four items will cause the circuit breaker to trip because the current is too high?
   a. A light that uses 1 amp.
   b. A can opener that uses 2 amps.
   c. A mixer that uses 6 amps.
   d. An electric knife that uses 1.5 amps.
7. Which of the following statements are **true** about the circuit drawn?



   a. Bulb **a** is brighter than bulb **b** or bulb **c**.
   b. Bulb **a** is dimmer than bulb **b** or bulb **c**.
   c. Bulb **b** is the same brightness as bulb **c**.
   d. Bulb **c** is brighter than bulb **b**.
8. Shown below is a parallel circuit with three branches. Branch 1 contains a 1-ohm resistor, branch 2 contains a 2-ohm resistor, and branch 3 contains a 3-ohm resistor. The circuit is powered by one 9-volt battery.

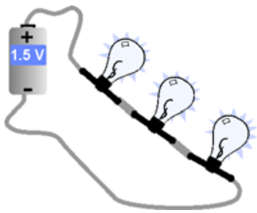


   a. Use Ohm's law to calculate the current in each branch of the circuit.
   b. Use Kirchhoff's current law to calculate the total current in the circuit.
   c. It is possible to replace all three resistors with a single resistor and have the total current in the circuit be the same. Use Ohm's law to calculate what the value of the single resistor should be to keep the total current the same.
   d. If someone were to add a fourth branch (containing a 4-ohm resistor) to the circuit, would the total current of the circuit decrease, increase, or stay the same?
9. Two 1.5-volt batteries are used to connect the circuit below.



   a. What is the total current in the circuit?
   b. Which bulb uses more current?

10. If one bulb is removed from the circuit below, the other bulbs will:



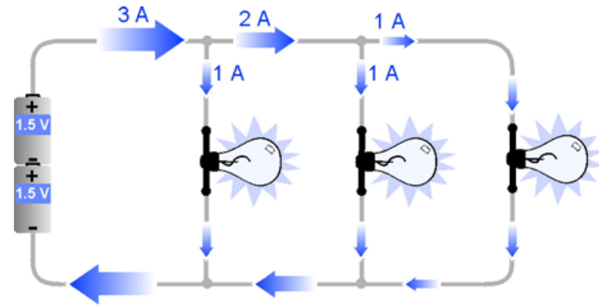
a. get brighter.

b. go out.

c. get dimmer.

d. stay at the same brightness.

11. The resistance of each of the three bulbs in the circuit below is:



a. 1 ohm.

b. 2 ohms.

c. 6 ohms.

d. 3 ohms.

Applying your knowledge

1. In an automobile, the warning bell turns on if you open the door while the key is in the ignition. The bell also turns on if you open the door while the headlights are on. A single circuit with three switches and a bell can be built to ring in both cases. One switch is attached to the door, one switch is attached to the ignition, and one switch is attached to the headlights. Figure out what circuit would make the bell ring at the right times and build or draw your circuit.

2. A burglar alarm system has switches in each door and window. If the door or window is opened, the switch opens a circuit. Draw a circuit that uses one battery and one light bulb to check five doors and windows. The bulb should go out if any of the five doors or windows is opened.

UNIT 3

Electricity and Magnetism

Chapter 10

Magnets and Motors

Introduction to Chapter 10

Electricity and magnetism are related to each other. As you will learn in this chapter, the interactions between electricity and magnetism are the core of many important technologies, from the generation of electricity to recording data on computer disks.

Investigations for Chapter 10

10.1	**Permanent Magnets**	*What effects do magnets have?*

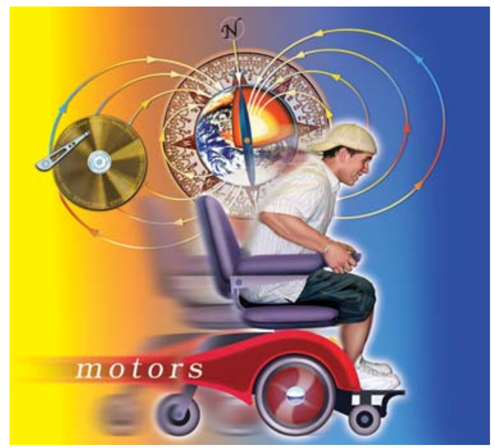
Like charges, magnets exert forces on each other. Every magnet has two distinct ends, called the north pole and the south pole. In this Investigation, you will explore how magnets affect each other, and discover which materials are attracted to magnets.

10.2	**Electromagnets**	*Can electric current create a magnet?*

In this Investigation, you will build an electromagnet and measure the electromagnet's strength as the current is varied.

10.3	**Electric Motors and Generators**	*How does an electric motor or generator work?*

In this Investigation, you will design and build different electric motors and evaluate them for speed and electric power. You will also build and test several designs of an electric generator.



Learning Goals

In this chapter, you will:

- ✔ Describe the properties of a permanent magnet.
- ✔ Describe the forces that magnets exert on other.
- ✔ Explain why materials like iron and steel are attracted to magnets.
- ✔ Explain why a compass points north.
- ✔ Build an electromagnet.
- ✔ Analyze how electric current affects the strength of the magnetic field in an electromagnet.
- ✔ List three ways that the strength of an electromagnet can be increased.
- ✔ Compare permanent magnets and electromagnets.
- ✔ List several applications of electromagnets.
- ✔ Explain electromagnetic induction.
- ✔ Describe how electric motors and generators work.

Vocabulary

electromagnet	magnetic field	magnetic north pole
electromagnetic induction	magnetic field intensity	magnetic south pole
generator	magnetic force	permanent magnet

10.1 Permanent Magnets

What effects do magnets have, both on each other and on other materials? What is magnetic force? What is a magnetic field? In this section you will learn about magnets, magnetic forces, and the magnetic field.

What is a magnet?

A magnet is a material that is magnetic

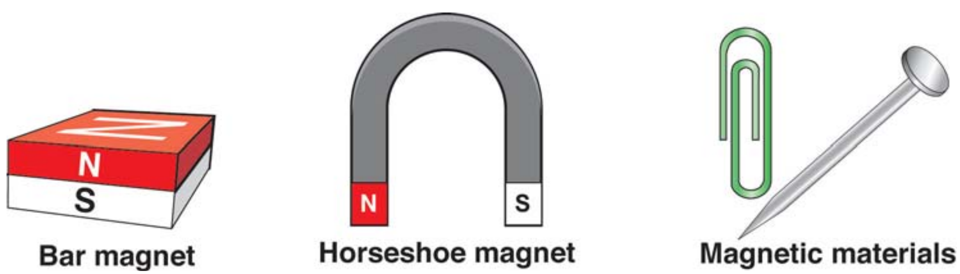
Magnetism has fascinated people since the earliest times. Up until the Renaissance, many people thought magnetism was a form of life-force since it could make rocks move. We know that magnets stick to refrigerators and pick up paper clips or pins. They are also part of electric motors, computer disc drives, burglar alarm systems, and many other common devices.

What does magnetic mean?

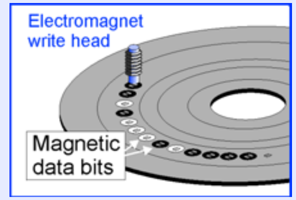
Magnetic means the ability to make forces on magnets or other magnetic materials. Some materials are actively magnetic, and we call them magnets. Other materials are attracted to nearby magnets but do not show magnetism otherwise. Iron and steel are in the second category because they are attracted by magnets but are not themselves magnetic.

Permanent magnets

A **permanent magnet** is a material that keeps its magnetic properties, even when it is not close to other magnets. Bar magnets, refrigerator magnets, and horseshoe magnets are good examples of permanent magnets.



How a computer disc works



Computer discs are coated with a material that can become magnetized by tiny electromagnets. By pulsing on and off, an *electromagnet* writes data by creating tiny north and south poles in the surface of the disc.

When reading data, a second electromagnet senses the north and south poles from the spinning disc. When a north pole changes to a south pole, these changes are converted to binary numbers used in programs and data.

A strong magnet can change the north and south poles on a disc surface. This removes the data just like an eraser removes pencil marks.

Properties of magnets

Magnets have common properties

All magnets have the following common properties:

- Magnets always have two opposite “poles,” called north and south.
- If divided, each part of a magnet has both north and south poles; we never see an unpaired north or south pole.
- When near each other, magnets exert magnetic forces on each other.
- The forces between magnets depend on the alignment of the poles; two unlike poles will attract each other and two like poles will repel each other.

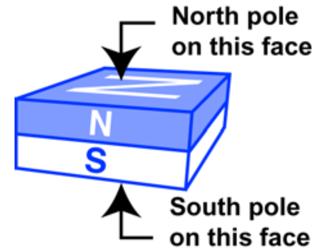


Figure 10.1: *The north and south poles of a small rectangular magnet.*

Why magnets attract a paperclip

The fact that magnets exert forces on each other explains why a permanent bar magnet is able to pick up a paperclip. When near the magnet, the paperclip becomes a temporary magnet. The two magnets are then attracted to each other. This magnetic force is so strong it easily overcomes the gravitational force that would otherwise cause the paperclip to fall down.

Exceptional scientists: Michael Faraday

Michael Faraday was born in London in 1791. After basic schooling, Faraday worked as a bookbinder and became very good at it. In fact, some of the books he bound are still in existence today!

Faraday often read the books he bound. From these books, he became interested in science and began to repeat the experiments that he read about. He was particularly interested in electricity and chemistry. At age 21, he decided to pursue further education in science.

At the age of 30, Faraday made his first electrical discovery. He then went on to became one of the great scientists of his time. He invented early motors using *electromagnets* (you will study these in the next section) and made many other discoveries in physics and chemistry.

Faraday loved to show children demonstrations of the exciting experiments of his day. He gave his demonstrations during an annual Christmas lecture at the Royal Institution where he worked. This tradition is still carried on today, and is televised. If you ever go to London you can still see Faraday’s laboratory at the Royal Institution’s museum.

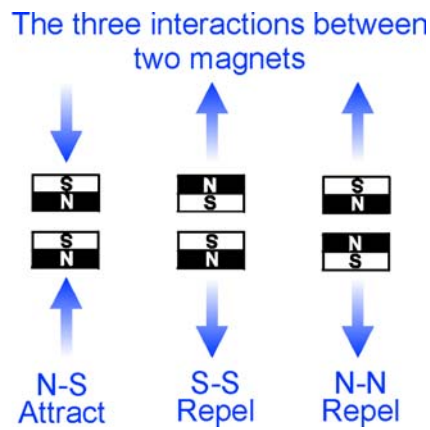


Figure 10.2: *Depending on their position, two magnets can either attract each other or repel each other.*

Discovering and using magnetism

Natural materials are magnetic

As early as 500 B.C. people discovered that some naturally occurring materials have magnetic properties. These materials include *lodestone* and *magnetite.* Ptolemy Philadelphos (367-283 B.C.) plated the entire surface of a temple in Egypt with magnetite, a magnetic mineral capable of attracting iron. He was hoping to suspend a statue of himself in midair!

Lodestone

In about 500 B.C., the Greeks discovered that a stone called lodestone had special properties. They observed that one end of a suspended piece of lodestone pointed north and the other end pointed south, helping sailors and travelers to find their way. This discovery was the first important application of magnetism, the *compass*.

The Chinese "south pointer"

The invention of the compass is also recorded in China, in 220 B.C. Writings from the Zheng dynasty tell stories of how people would use a "south pointer" when they went out to search for jade, so that they wouldn't lose their way home. The pointer was made of lodestone. It looked like a large spoon with a short, skinny handle. When balanced on a plate, the "handle" was aligned with magnetic south.

The first iron needle compass

By 1088 A.D., iron refining had developed to the point where the Chinese were making a small needle-like compass. Shen Kua recorded that a needle-shaped magnet was placed on a reed floating in a bowl of water. Chinese inventors also suspended a long, thin magnet in the air, realizing in both cases that the magnet ends were aligned with geographic north and south. Explorers from the Sung dynasty sailed their trading ships all the way to Saudi Arabia using compasses among their navigational tools. About 100 years later a similar design appeared in Europe and soon spread to the rest of the region.

The compass allows explorers to sail away from land

By 1200, explorers from Italy were using a compass to guide ocean voyages beyond the sight of land. The Chinese also continued exploring with compasses, and by the 1400s, they were traveling to the eastern coast of Africa. The compass, and the voyages that it made possible, led to many interactions among cultures.

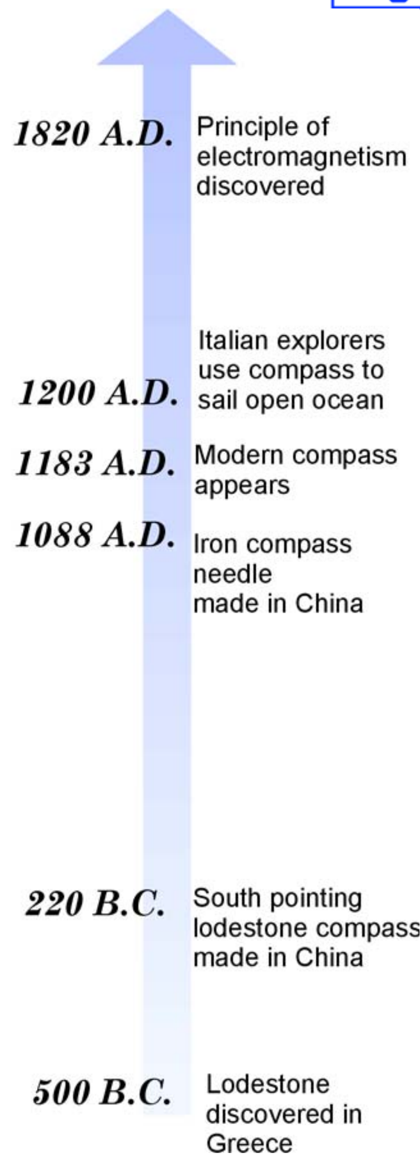


Figure 10.3: *Timeline of the discovery of lodestone and the development of the modern compass.*

How does a compass work?

The north pole of a magnet points north

A compass needle is a magnet that is free to spin until it lines up in the north-south direction. The origin of the terms "north pole" and "south pole" of a magnet come from the direction that a magnetized compass needle points. The end of the magnet that pointed north was called the north pole of the magnet and the end that pointed south was called the south pole.

Remember that two unlike poles of a magnet attract each other. So the north pole of the compass needle must point north because it is attracted by the south pole of another magnet. Where is this other magnet?

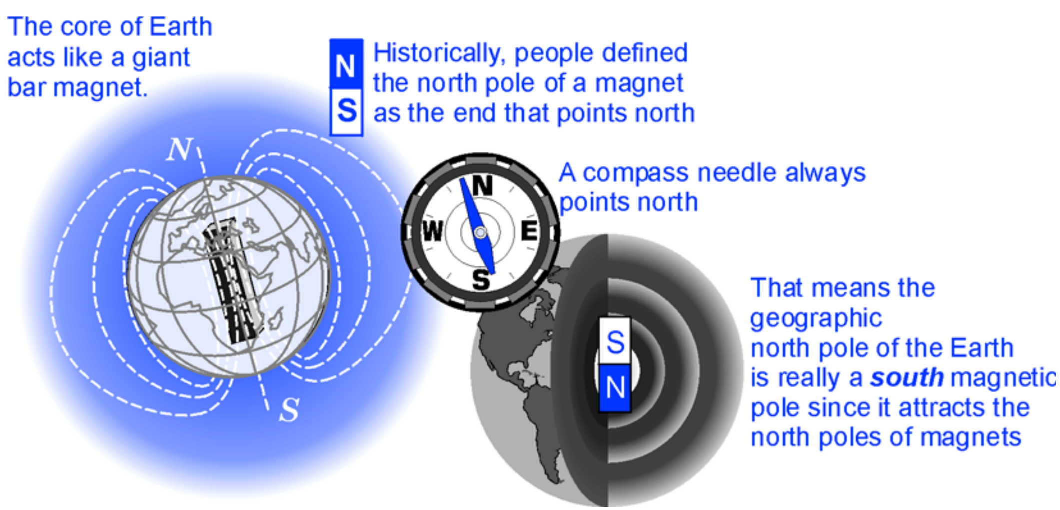


Figure 10.4: *A Chinese compass dating from 220 B.C., made of lodestone. The "handle" of the spoon points south.*

Figure 10.5: *A modern compass.*

The center of the Earth is a large magnet

It turns out that the core of our planet acts like a large magnet made of molten iron ores. This giant magnet is roughly aligned in the north-south direction. When the compass needle's north pole swings towards the *geographic north pole*, it is actually attracted by the *magnetic south pole* of Earth. The Earth's magnetic south pole is within a few degrees of geographic north!

The magnetic field

Why the magnetic field is a useful concept

People investigating magnetism needed a way to describe the forces between two magnets. They knew that the force depended on the direction and orientation of the two magnets and also on the distance between them. The model of a magnetic field was developed to describe how a magnet exerts magnetic force.

Imagine testing one magnet with another

Imagine you have a small test magnet (Figure 10.6) that you are moving around another magnet (the source magnet). The north pole of your test magnet feels a force everywhere in the space around the source magnet. To keep track of the force, imagine drawing an arrow in the direction your test magnet is pulled as you move it around.

What is a field?

The arrows that you draw show you the magnetic field. If you connect all the arrows from north to south, you get lines called *magnetic field lines*. In physics, the word “field” means that there is a quantity (such as force) that is associated with every point in space. There can be many other kinds of fields. For example, the “odor field” near a sewer would be strongest nearest the sewer and get weaker farther away!

The magnetic field

How do you interpret a drawing of a magnetic field? The number of field lines in a certain area indicates the relative strength of the source magnet in that area. The arrows on the field lines show where the north pole of a test magnet will point. Figure 10.7 shows the magnetic field lines around a small rectangular magnet.

Magnets interact through their fields

It is useful to think about the interactions between two magnets in two steps.

- First, every magnet creates an energy field, called the magnetic field, in the space around it.
- Second, the field (not the magnet directly) exerts forces on any other magnet that is within its range.

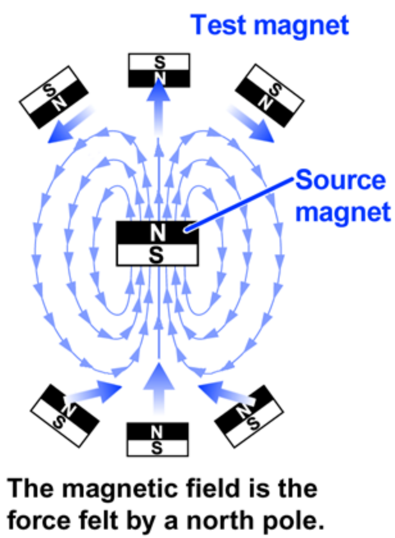


Figure 10.6: *The magnetic field is defined in terms of the force exerted on the north pole of another magnet.*

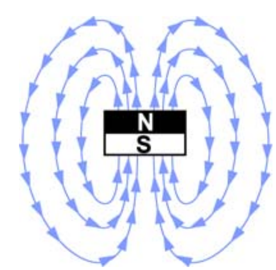


Figure 10.7: *Magnetic field lines around a magnet.*

10.2 Electromagnets

In the last section you learned about permanent magnets and magnetism. There is another type of magnet, one that is created by electric current. This type of magnet is called an electromagnet. What is an electromagnet? Why do magnets and electromagnets act the same way? In this section, you learn about electromagnets and how they helped scientists explain all magnetism.

What is an electromagnet?

Searching for a connection

For a long time, people thought about electricity and magnetism as different and unrelated effects. Starting about the 18th century, scientists suspected that the two were related. As scientists began to understand electricity better, they searched for relationships between electricity and magnetism.

The principle of an electromagnet

In 1819, Hans Christian Øersted, the Danish physicist and chemist (1777-1851), noticed that a current in a wire caused a compass needle to deflect. He had discovered that moving electric charges create a magnetic field! A dedicated teacher, he made this discovery while teaching his students at the University of Copenhagen. He suspected there might be an effect and did the experiment for the very first time in front of his class. With his discovery, Øersted was the first to identify the principle of an electromagnet.

How to make an electromagnet

Electromagnets are magnets that are created when there is electric current flowing in a wire. The simplest electromagnet uses a coil of wire, often wrapped around some iron (Figure 10.8). Because iron is magnetic, it concentrates the magnetic field created by the current in the coil.

The north and south poles of an electromagnet

The north and south poles of an electromagnet are located at each end of the coil (Figure 10.8). Which end is the north pole depends on the direction of the electric current. When your fingers curl in the direction of current, your thumb points toward the magnet's north pole. This method of finding the magnetic poles is called the *right hand rule* (Figure 10.9). You can switch north and south by reversing the direction of the current. This is a great advantage over permanent magnets. You can't easily change the poles of a permanent magnet.

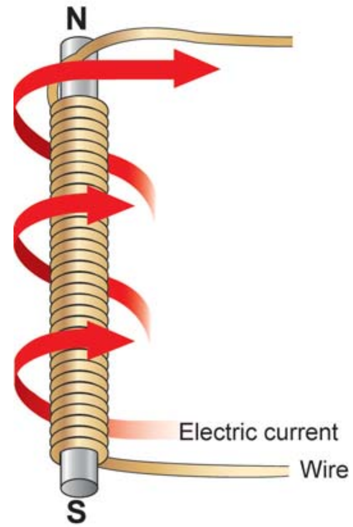


Figure 10.8: *The simplest electromagnet. In the picture, the arrows indicate the direction of current.*

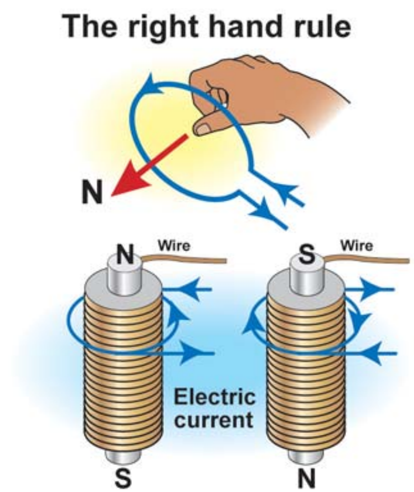


Figure 10.9: *The right hand rule: When your fingers curl in the direction of current, your thumb points toward the magnet's north pole.*

Applications of electromagnets

Current controls an electromagnet

By changing the amount of current, you can easily change the strength of an electromagnet or even turn its magnetism on and off. Electromagnets can also be much stronger than permanent magnets because the electric current can be large. For these reasons, electromagnets are used in many applications.

Magnetically levitated trains

Magnetically levitated (abbreviated to maglev) train technology uses electromagnetic force to lift a train a few inches above its track (Figure 10.10). By “floating” the train on a powerful magnetic field, the friction between wheels and rails is eliminated. Maglev trains achieve high speeds using less power than a normal train. In 1999, in Japan, a prototype five-car maglev train carrying 15 passengers reached a world-record speed of 552 kilometers (343 miles) per hour. Maglev trains are now being developed and tested in Germany, Japan, and the United States.

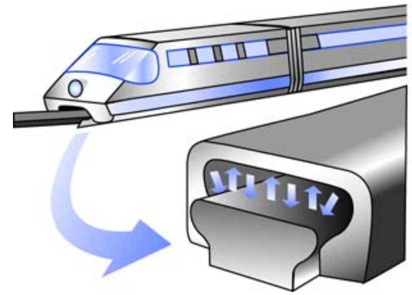


Figure 10.10: *A maglev train track has electromagnets in it that both lift the train and pull it forward.*

How does a toaster work?

The sliding switch on a toaster does several things: First, it turns the heating circuit on. Secondly, it activates an electromagnet that then attracts a spring-loaded metal tray to the bottom of the toaster. When a timing device signals that the bread has been toasting long enough, current to the electromagnet is cut off. This releases the spring-loaded tray that then pushes up on the bread so that it pops out of the toaster.

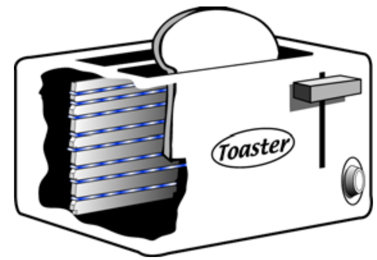
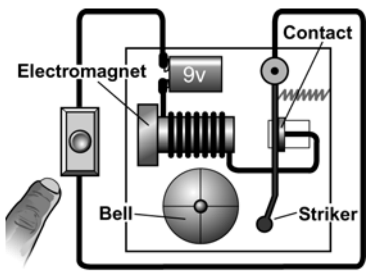


Figure 10.11: *A toaster tray is pulled down by an electromagnet while bread is toasting. When the toast is done, current is cut off and the tray pops up. The cutaway shows the heating element -- nichrome wires wrapped around a sheet of mica.*

How does an electric doorbell work?



A doorbell contains an electromagnet. When the button of the bell is pushed, it sends current through the electromagnet. The electromagnet attracts a piece of metal called the striker. The striker moves towards the electromagnet but hits a bell that is in the way. The movement of the striker away from the contact also breaks the circuit after it hits the bell. A spring pulls the striker back and reconnects the circuit. If your finger is still on the button, the cycle starts over again and the bell keeps ringing.

Building an electromagnet

Make an electromagnet from wire and a nail

You can easily build an electromagnet from wire and a piece of iron, such as a nail. Wrap the wire in many turns around the nail and connect a battery as shown in Figure 10.12. When current flows in the wire, the nail becomes a magnet. Use the right hand rule to figure out which end of the nail is the north pole and which is the south pole. To reverse north and south, reverse the connection to the battery, making the current flow the opposite way.

Increase the strength of an electromagnet

You might expect that more current would make an electromagnet stronger. You would be right, but there are two ways to increase the current.

1. You can apply more voltage by adding a second battery.
2. You can add more turns of wire around the nail.

Why adding turns works

The second method works because the magnetism in your electromagnet comes from the *total* amount of current flowing *around* the nail. If there is 1 amp of current in the wire, each loop of wire adds 1 amp to the total amount that flows around the nail. Ten loops of 1 amp each make 10 total amps flowing around. By adding more turns, you use the same current over and over to get stronger magnetism.

More turns also means more resistance

Of course, nothing comes for free. By adding more turns you also increase the resistance of your coil. Increasing the resistance makes the current a little lower and generates more heat. A good electromagnet is a balance between too much resistance and having enough turns to get a strong enough magnet.

Factors affecting the force

The magnetic force exerted by a simple electromagnet depends on three factors:

- The amount of electric current in the wire
- The amount of iron or steel in the electromagnet's core
- The number of turns in the coil

In more sophisticated electromagnets, the shape, size, material in the core and winding pattern of the coil also have an effect on the strength of the magnetic field produced.

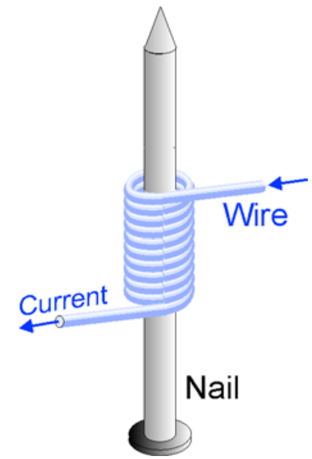


Figure 10.12: *Making an electromagnet from a nail and wire.*

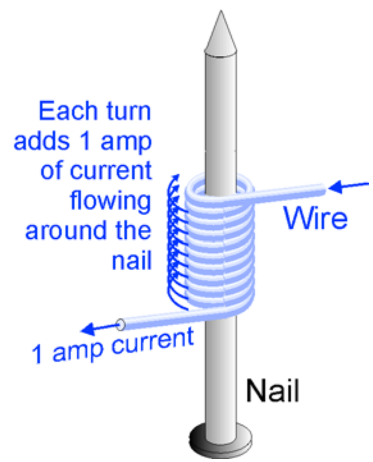


Figure 10.13: *Adding turns of wire increases the total current flowing around the electromagnet. The total current in all the turns is what determines the strength of the electromagnet.*

The relationship between permanent magnets and electromagnets

Electric currents cause all magnetism

Why do permanent magnets and electromagnets act the same way? The discovery of electromagnets helped scientists to determine why magnetism exists. Electric current through loops of wire creates an electromagnet. Atomic-scale electric currents create a permanent magnet.

Electrons move, creating small loops of current

Remember, atoms contain two types of charged particles, protons (positive) and electrons (negative). The charged electrons in atoms behave like small loops of current. These small loops of current mean that atoms themselves act like tiny electromagnets with north and south poles!

We don't usually see the magnetism from atoms for two reasons.

1 Atoms are very tiny and the magnetism from a single atom is far too small to detect without very sensitive instruments.

2 The alignment of the atomic north and south poles changes from one atom to the next. On average the atomic magnets cancel each other out (Figure 10.14).

How permanent magnets work

If all the atomic magnets are lined up in a similar direction, the magnetism of each atom adds to that of its neighbors and we observe magnetic properties on a large scale. This is what makes a permanent magnet. On average, permanent magnets have the magnetic fields of individual atoms aligned in a similar direction.

Why iron always attracts magnets and never repels them

In magnetic materials (like iron) the atoms are free to rotate and align their individual north and south poles. If you bring the north pole of a magnet near iron, the south poles of all the iron atoms are attracted. Because they are free to move, the iron near your magnet becomes a south pole and it attracts your magnet.

If you bring a south pole near iron, the opposite happens. The iron atoms nearest your magnet align themselves to make a north pole, which also attracts your magnet. This is why magnetic materials like iron always attract your magnet, and never repel, regardless of whether your test magnet approaches with its north or south pole.

Non-magnetic materials

The atoms in non-magnetic materials, like plastic, are not free to move and change their magnetic orientation. That is why most objects are not affected by magnets.

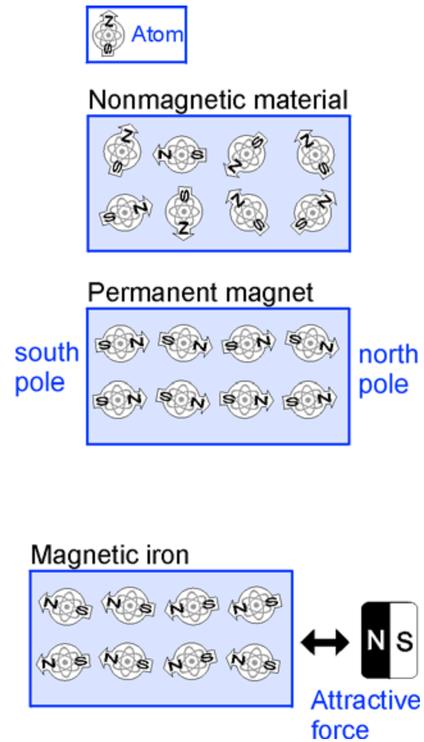


Figure 10.14: *Atoms act like tiny magnets. Permanent magnets have their atoms partially aligned, creating the magnetic forces we observe.*

The magnetic properties of iron occur because iron atoms can easily adjust their orientation in response to an outside magnetic field.

10.3 Electric Motors and Generators

Permanent magnets and electromagnets work together to make electric motors and generators. In this section you will learn about how a real electric motor works. The secret is in the ability of an electromagnet to reverse form north to south. By changing the direction of electric current, the electromagnet changes from attract to repel, and spins the motor! Electric motors convert electrical energy into mechanical energy.

Using magnets to spin a disk

Imagine a spinning disk with magnets

Imagine you have a disk that can spin. Around the edge of the disk are magnets. You have cleverly arranged the magnets so they alternate north and south. Figure 10.15 shows a picture of your rotating disk.

How to make the disk spin

To make your disk spin, you bring a magnet near the edge. The magnet attracts one of the magnets in the disk and repels the next one. These forces make the disk spin a little way (Figure 10.15)

Reversing the magnet is the key

To keep the disk spinning, you need to reverse the magnet in your fingers as soon as each magnet comes by. This way you first attract a magnet, then reverse your magnet to repel it away again. You make the disk spin by using your magnet to alternately attract and repel the magnets on the disk.

Knowing when to reverse the magnet

The disk is called the *rotor* because it can rotate. The key to making the rotor spin smoothly is to reverse your magnet when the disk is at the right place. You want the reversal to happen just as a magnet passes by. If you reverse too early, you will repel the magnet in the rotor backwards before it reaches your magnet. If you reverse too late, you attract the magnet backwards after it has passed. For it to work best, you need to change your magnet from north to south just as the magnet on the rotor passes by.

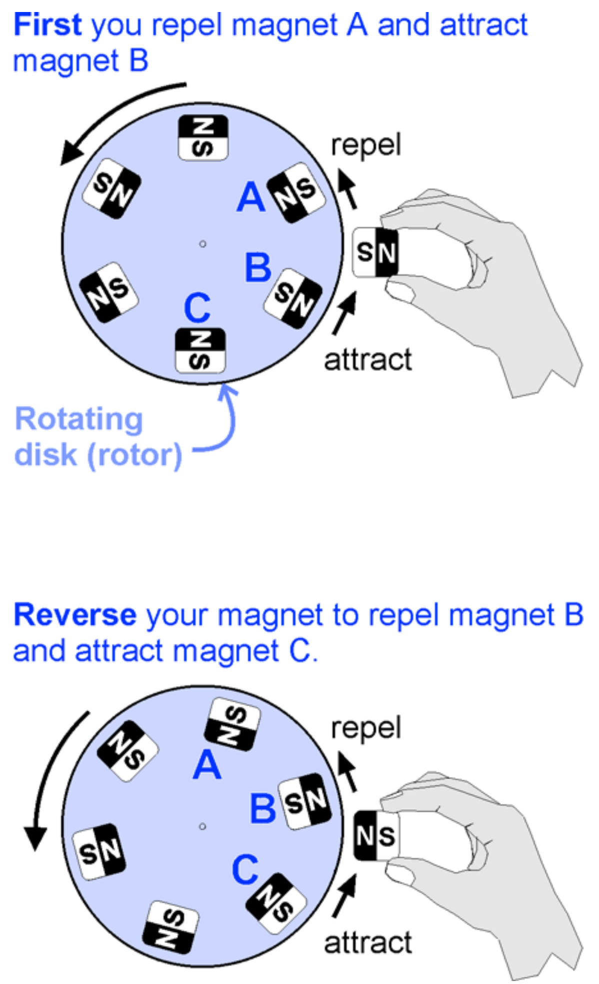
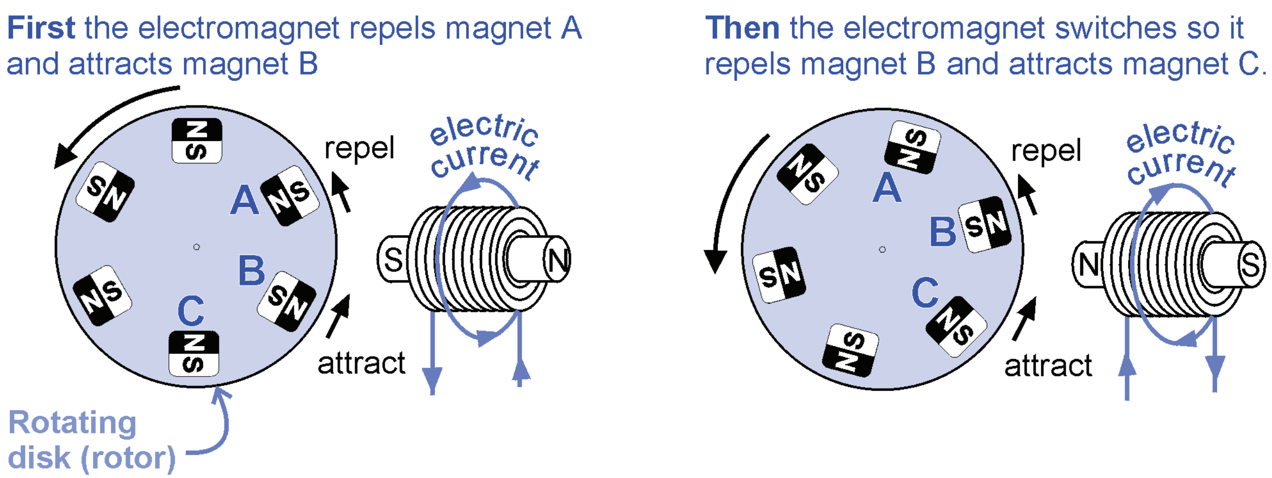


Figure 10.15: *Using a single magnet to spin a disk of magnets. Reversing the magnet in your fingers attracts and repels the magnets in the rotor, making it spin.*

Using electricity to reverse the magnet

How electromagnets are used in electric motors

The spinning disk of magnets is like the rotor of a real electric motor. In a real electric motor, the magnet you reversed with your fingers becomes an electromagnet. The switch from north to south is done by reversing the electric current in a coil. The sketch below shows how the electromagnets switch to make the rotor keep turning.



The commutator is a kind of switch

Just as with the finger magnet, the electromagnet must switch from north to south as each rotor magnet passes by to keep the rotor turning. The switch that makes this happen is called a *commutator*. As the rotor spins, the commutator switches the direction of current in the electromagnet. This makes the electromagnet change from north to south, and back again. The electromagnet attracts and repels the magnets in the rotor, and the motor turns.

The three things you need to make a motor

All types of electric motors must have three things to work. The three things are:

1. A rotating element (rotor) with magnets.
2. A stationary magnet that surrounds the rotor.
3. A commutator that switches the electromagnets from north to south at the right place to keep the rotor spinning.

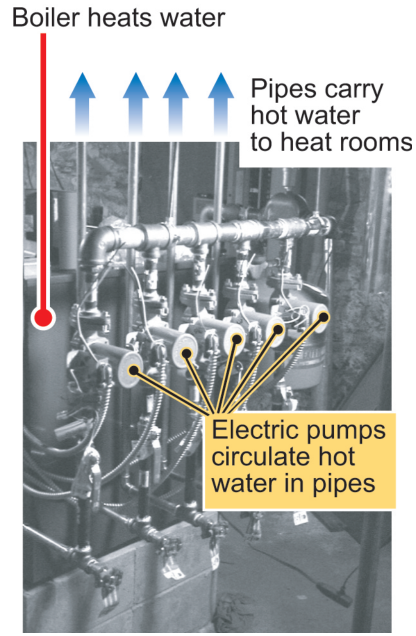
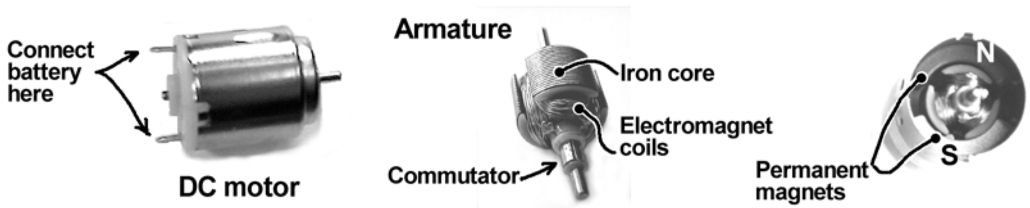


Figure 10.16: *There are electric motors all around you, even where you don't see them. The heating system in your house or school uses electric motors to move hot air or water to heat rooms.*

How a battery-powered electric motor works

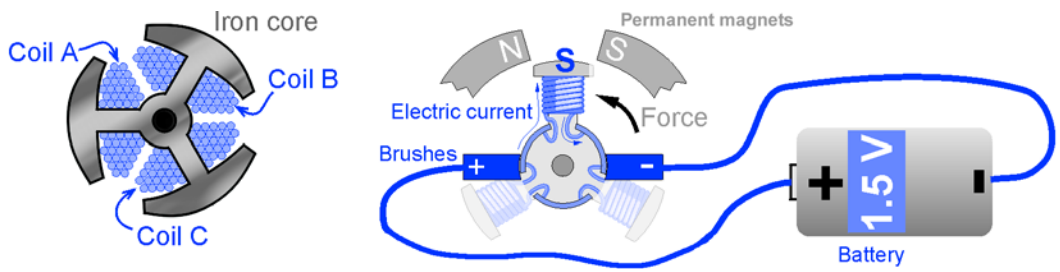
Inside a small electric motor

If you take apart an electric motor that runs from batteries, it doesn't look like the motor you built in the lab. But the same three mechanisms are still there. The difference is in the arrangement of the electromagnets and permanent magnets. The picture below shows a small battery-powered electric motor and what it looks like inside with one end of the motor case removed. The permanent magnets are on the outside, and they stay fixed in place.



Electromagnets and the armature

The electromagnets are in the rotor, and they turn. The rotating part of the motor, including the electromagnets, is called the *armature*. The armature in the picture has three electromagnets, corresponding to the three coils (A, B, and C) in the sketch below.

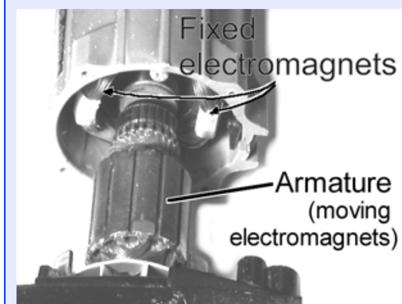


How the switching happens

The wires from each of the three coils are attached to three metal plates (commutator) at the end of the armature. As the rotor spins, the three plates come into contact with the positive and negative *brushes*. Electric current flows through the brushes into the coils. As the motor turns, the plates rotate past the brushes, switching the electromagnets from north to south by reversing the positive and negative connections to the coils. The turning electromagnets are attracted and repelled by the permanent magnets and the motor turns.

AC and DC motors

Almost all the electric motors you find around your house use AC electricity. Remember, AC means alternating current, so the current switches back and forth as it comes out of the wall socket. This makes it easier to build motors.

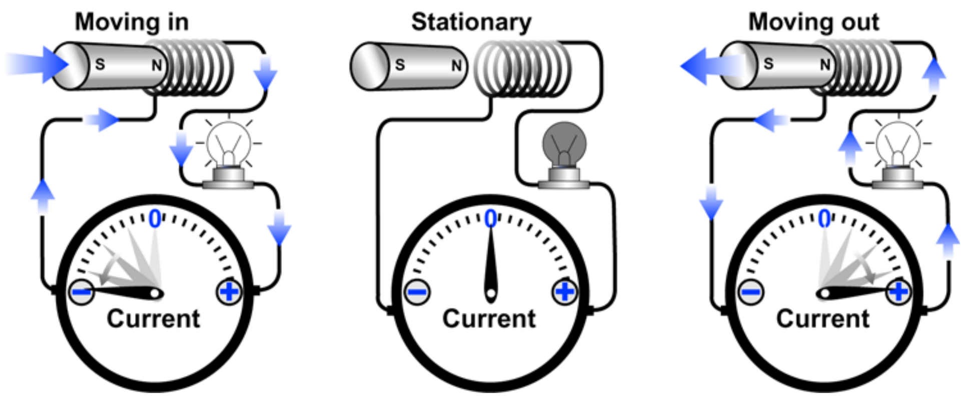


Most AC motors use electromagnets for the rotating magnets on the armature, and also for the stationary magnets around the outside. The attract-repel switching happens in both sets of electromagnets.

Electromagnetic force and electromagnetic induction

Electromagnetic force

Both electrical force and magnetic force exist between electric charges. Scientists now believe both forces are two aspects of one force, the electromagnetic force. Many laws in physics display an elegant kind of symmetry. This symmetry is seen in the interactions between magnetism and electricity. A current through a wire creates a magnet. The reverse is also true: If you move a magnet through a coil of wire, then electric current is created. This process is called electromagnetic induction (Figure 10.17) because a moving magnet *induces* electric current to flow.



Moving magnets make current flow

When a magnet moves into a coil of wire, it induces electric current to flow in the coil (diagram above). The current stops if the magnet stops moving. If you pull the magnet back out again, the current flows in the opposite direction. A changing magnetic field is what makes the electricity flow. If the magnetic field does not change, no electricity flows. As you might expect, the faster we make the magnetic field change, the greater the amount of electric current we generate.

Induction and energy transformations

Electromagnetic induction enables us to transform mechanical energy (moving magnets) into electrical energy. Any machine that causes magnets to move past wire coils generates electric currents. These machines include giant electric power plants and computer disk drives. Tiny sensors on the disk drive read data on a magnetic disk by looking at the pulses of current that are generated as a high-speed disk spins past the coil of wire in the drive's sensor head (Figure 10.18).

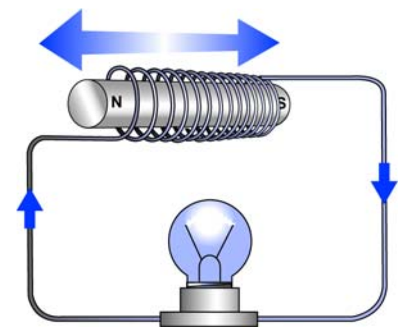


Figure 10.17: *Electromagnetic induction: Moving a magnet in loops of wire generates current in the wire.*

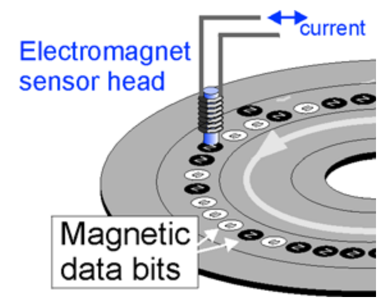


Figure 10.18: *A computer hard drive uses induction to read data from the magnetic writing on a spinning disk.*

Generating electricity

What is a generator?
Power plants use electromagnetic induction to create electricity. A **generator** is a combination of mechanical and electrical systems that converts kinetic energy into electrical energy (Figure 10.19).

Batteries are not powerful enough
Although batteries can convert energy from chemical reactions into electrical energy, batteries are not practical for creating large amounts of electric current. Power plants, which supply current to homes and businesses, use generators.

How a generator works
As an example of how the electricity is made, consider a disk with magnets in it (Figure 10.20). As the disk rotates, first a north pole and then a south pole passes the coil. When the north pole is approaching, the current flows one way. When the north pole passes and a south pole approaches, the current flows the other way. As long as the disk is spinning, there is a changing magnetic field near the coil and electric current is induced to flow.

Generators make alternating current
Because the magnetic field alternates from north to south as the disk spins, generators produce *alternating current* (AC). Alternating current is used in the electrical system in your home and school.

Energy is conserved
The electrical energy created from a generator isn't free. You have to do work to turn the disk and make the electric current flow. Power plants contain a rotating machine called a *turbine*. The turbine is kept turning by a flow of air heated by gas, oil, coal, or nuclear energy. One kind of energy is transformed into another and energy is conserved. The energy stored in the gas, oil, coal, or nuclear fuel is transformed into the movement of the turning turbine, which is then transformed into electrical energy.

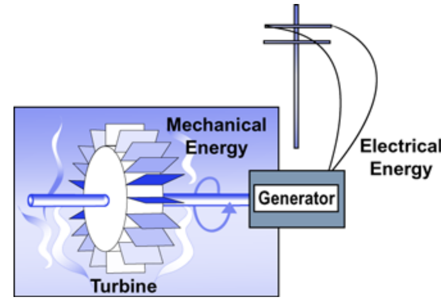


Figure 10.19: *A power plant generator contains a turbine that turns magnets inside loops of wire, generating electricity.*

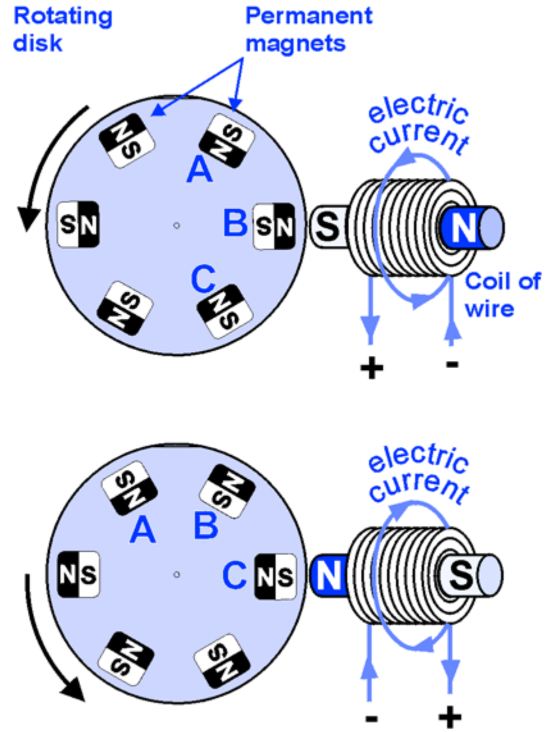


Figure 10.20: *How a generator works. In the top sketch the north pole on the disk induces a south pole in the electromagnet, causing current to flow one way. When the disk rotates, the magnetism in the coil is reversed, and the electric current generated also reverses.*

Chapter 10 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. permanent magnet
2. magnetic north pole
3. magnetic south pole
4. magnetic forces
5. lodestone

a. A naturally occurring magnetic material
b. A material that is magnetic; it has a north and a south pole, and interacts with other magnets
c. The large magnet located inside the Earth
d. The end of a magnet that will point north if suspended in air near the surface of the Earth
e. The end of a magnet that will point south if suspended in air near the surface of the Earth
f. The forces that magnets exert on each other

Set Two

1. compass
2. magnetic field
3. electromagnet
4. electric motor
5. commutator

a. A device that uses electricity and magnets to turn electrical energy into rotating mechanical energy
b. The movement of electrons that causes them to act like tiny atomic magnets
c. A magnet that is created from current through a wire
d. The part of an electric motor that switches the electromagnets from north to south
e. Magnets create this in the space around them and it exerts forces on other magnets
f. A device that uses magnets to tell direction

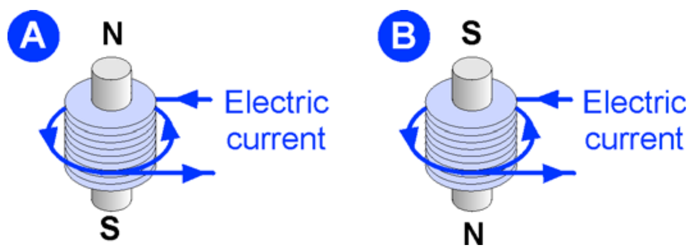
Set Three

1. generator
2. electromagnetic force
3. electromagnetic induction
4. alternating current
5. turbine

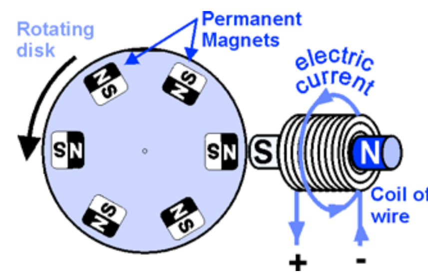
a. The process by which a moving magnet creates voltage and current in a loop of wire
b. A device to float a train above the track
c. A mechanical wheel that might work with steam or water to turn a generator
d. The force that exists between electric charges; often described as electrical force or magnetic force depending on how charges interact
e. Electrical current flowing back and forth
f. A device that uses electromagnetic induction to make electricity

Concept review

1. Name two examples of naturally occurring magnetic materials.
2. What is the first known application of magnetism?
3. Explain the origin of the terms “north pole” and “south pole” used to describe the two ends of a magnet.
4. Explain why a compass points north.
5. Describe the types of forces that magnetic poles exert on each other.
6. What are three ways you can increase the strength of an electromagnet?
7. Explain why an electromagnet usually has a core of iron or steel.
8. Name two examples of machines that use electromagnets. Explain the purpose of the electromagnet in each machine.
9. In your own words, explain how atoms give rise to magnetic properties in certain materials.
10. Which picture shows the correct location of the north and south poles of the electromagnet? Choose A or B and explain how you arrived at your choice.



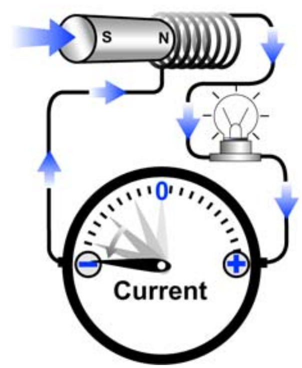
11. An electric generator is constructed that uses a rotating disk of magnets that spin past a coil of wire as shown in the diagram. Which of the following statements are TRUE?



    a. Turning the disk 2 times faster generates 4 times as much electricity.
    b. Turning the disk 2 times faster generates 2 times as much electricity.
    c. Doubling the number of magnets generates 2 times as much electricity.
    d. Doubling the number of magnets and spinning twice as fast generates 4 times as much electricity.

12. The amount of electricity generated by a magnet moving through a coil of wire can be INCREASED by:

    a. Using a stronger magnet and holding the magnet stationary in the coil.
    b. Moving the magnet through the coil faster.
    c. Adding more turns of wire to the coil.
    d. Moving the magnet more slowly through the coil so the coil has time to feel the effects of the magnetic force.



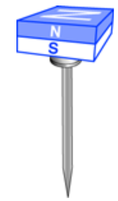
Problems

1. A student knocked a ceramic magnet off her desk and it shattered when it hit the floor. Copy the broken pieces and label the north and south poles on each one.

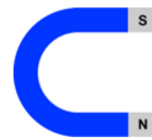
2. A student placed two magnets with opposite poles facing each other. He slowly brought the two magnets closer and observed the distance at they first interacted with each other. The student observed that one magnet could move the other at a distance of 33 millimeters.
   a. Next, he placed the two north poles facing one another. Predict the distance at which he would observe one magnet moving the other through repelling forces.
   b. The student put one of his magnets on his wooden desk with the north pole down. If the desk top is 2.5 centimeters thick, do you think he could move the top magnet by sliding another magnet under the desk? Explain how the observed data supports your answer.

3. The atoms of a permanent magnet can't move, and the electrons in the atoms are lined up so that a magnetic field is created around the magnet. The atoms in iron or steel can move. Describe what you think happens to the atoms of a steel paperclip when the paperclip is near a permanent magnet.

4. A magnet attracts a pin, as shown in the picture. The pin has become a temporary magnet. Copy the picture and then, using what you know about magnetic forces, label the north and south poles of the pin.



5. A horseshoe magnet is shown at right. Copy the picture and then draw the magnetic field lines between the north and south poles of the magnet.



6. Draw an electromagnet. Label all parts including the magnetic poles.

7. What property of matter gives rise to both electricity and magnetism?

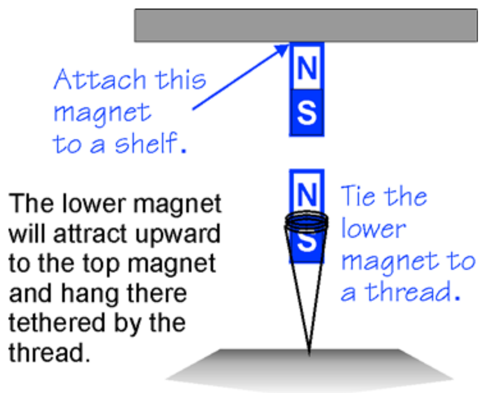
8. A working electric motor needs to have three things. Which of the following are the three?
   a. A device to switch the electromagnets at the right time.
   b. A moving element with magnets.
   c. An even number of magnets.
   d. A stationary element with magnets.

9. An electric motor running from a single 1.5-volt battery draws a current of 1 amp. How much electric power does the motor use in watts?

10. Describe the function of the commutator in an electric motor.

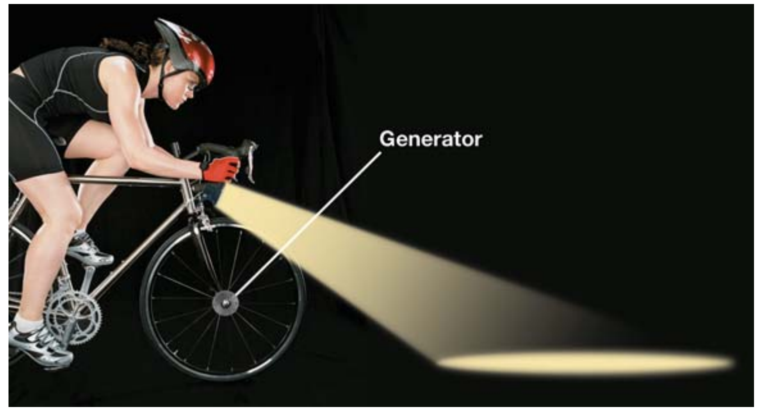
Applying your knowledge

1. You read that Ptolemy Philadelphos (367-283 BC) covered the entire surface of a temple in Egypt with magnetite, a magnetic stone capable of attracting iron. He was hoping to suspend a statue of himself in midair. Ptolemy's experiment did not work, but you can suspend something using magnets. Build a device like the diagram below and see if you can make the lower magnet float. See how much weight you can hang from the lower magnet by changing the distance between the upper and lower magnets.



2. Speakers and microphones use electromagnets to turn electric currents into sound, and vice versa. Research how electromagnets are used in sound systems. Draw a diagram that shows the location of permanent magnets and electromagnets in a speaker. How does the electromagnet produce vibrations that create sound?

3. A bicycle light generator is a device that you place on the wheel of your bike. When you turn the wheel, the generator powers a light. When you stop, the light goes out. Explain how you think the bike generator makes electricity.



4. A clever inventor claims to be able to make an electric car that makes its own electricity and never needs gas or recharging. The inventor claims that as the car moves, the wind created by its motion spins a propeller that turns a generator to make electricity and power the wheels. Do you believe the car can work, and why (or why not)? (Hint: Think about conservation of energy.)