

Magnetism



Chapter Preview

14.1 Magnets and Magnetic Fields

Magnets
Magnetic Fields

14.2 Magnetism from Electric Currents

Producing Magnetism from
Electric Currents
Electromagnetic Devices

14.3 Electric Currents from Magnetism

Electromagnetic Induction
and Faraday's Law
Transformers



The iron filings in the photo above are moved into a pattern by the magnetic force of the magnet. Maglev trains, like the one shown above, levitate above their tracks using magnetic force.

Focus ACTIVITY

Background Just as a magnet exerts a force on the iron filings in the small photo at left, a modern type of train called a *Maglev* train is levitated and accelerated by magnets. A Maglev train uses magnetic forces to lift the train off the track, reducing the friction and allowing the train to move faster. These trains, in fact, have reached speeds of more than 500 km/h (310 mi/h).

In addition to enabling the train to reach high speeds, the lack of contact with the track provides a smoother, quieter ride. With improvements in the technologies that produce the magnetic forces used in levitation, these trains may become more common in high-speed transportation.

Activity 1 You can see levitation in action with two ring-shaped magnets and a pencil.

Hold the pencil near the eraser with the tip pointing upward. Drop one of the ring magnets over the tip of the pencil so that it rests on your hand. Now drop the other magnet over the tip of the pencil. If the magnets are oriented correctly, the second ring will levitate above the other. If the magnets attract, remove the second ring, flip it over, and again drop it over the tip of the pencil.

The magnetic force exerted on the levitating magnet is equal to the magnet's weight. Use a scale to find the magnet's mass; then use the weight equation from Section 8.3 to calculate the magnetic force necessary to levitate this magnet.

Activity 2 The small photo at left shows how one magnet aligns iron filings. How does the pattern differ for two magnets?

Place two bar magnets flat on a table with the N poles about 2 cm apart. Cover the magnets with a sheet of plain paper. Sprinkle iron filings on the paper. Tap the paper gently until the filings line up. Make a sketch showing the orientation of the filings. Where does the magnetic force seem to be the strongest?



TOPIC: Maglev trains
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Magnets and Magnetic Fields

KEY TERMS

magnetic pole
magnetic field

OBJECTIVES

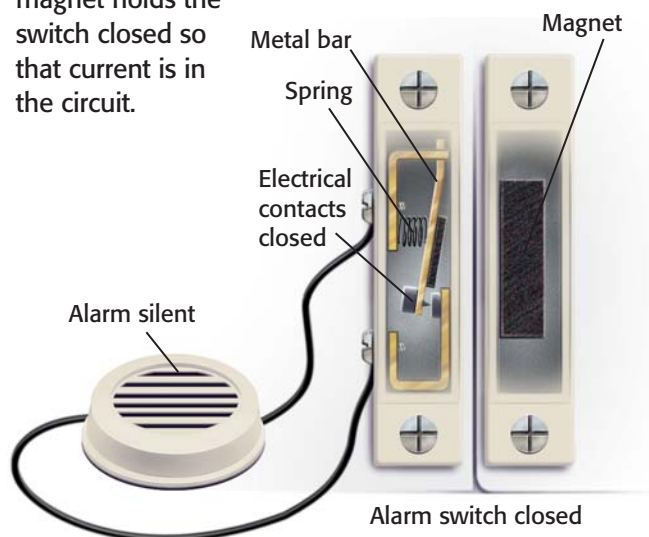
- ▶ Recognize that like magnetic poles repel and unlike poles attract.
- ▶ Describe the magnetic field around a permanent magnet.
- ▶ Explain how compasses work.
- ▶ Describe the orientation of Earth's magnetic field.

You may think of magnets as devices used to attach papers or photos to a refrigerator door. But magnets are involved in many different devices, such as alarm systems like the one in **Figure 14-1**. This type of alarm system uses the simple magnetic attraction between a piece of iron and a magnet to alert homeowners that a window or door has been opened.

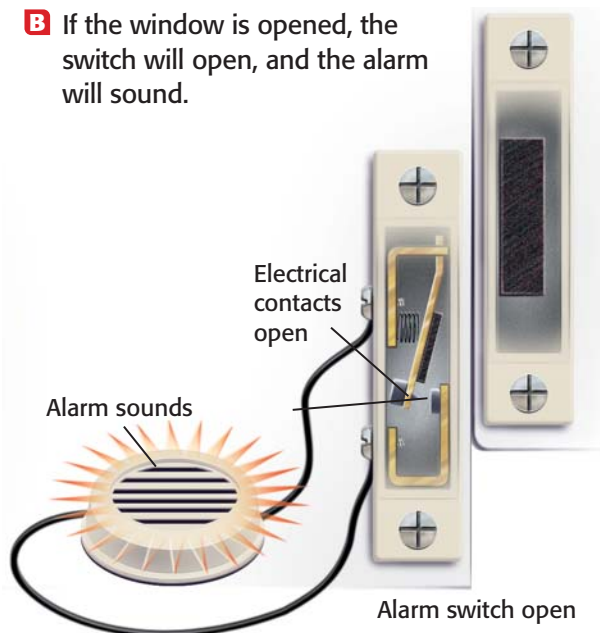
As shown in **Figure 14-1A**, when the window is closed, the iron switch is attracted to the magnet. Thus, the switch completes the circuit, and a current is in the system when it is turned on. When the window slides open, as shown in **Figure 14-1B**, the magnet is no longer close enough to the iron to attract it strongly. The spring pulls the switch open, and the circuit is broken. When this happens, the alarm sounds.

Figure 14-1

A When the window is closed, the magnet holds the switch closed so that current is in the circuit.



B If the window is opened, the switch will open, and the alarm will sound.



Magnets

Magnets got their name from the region of Magnesia, which is now part of modern-day Greece. The first naturally occurring magnetic rocks, called *lodestones*, were found in this region almost 3000 years ago. A lodestone, shown in **Figure 14-2**, is composed of an iron-based material called *magnetite*.

Some materials can be made into permanent magnets

Some substances, such as lodestones, are magnetic all the time. These types of magnets are called *permanent magnets*. You can change any piece of iron, such as a nail, into a permanent magnet by stroking it several times with a permanent magnet. A slower method is to place the piece of iron near a strong magnet. Eventually the iron will become magnetic and will remain magnetic even when the original magnet is removed.

Although a magnetized piece of iron is called a “permanent” magnet, its magnetism can be weakened or even removed. Possible ways to do this are to heat or hammer the piece of iron. Even when this is done, some materials retain their magnetism longer than others.

Scientists classify materials as either magnetically *hard* or magnetically *soft*. Iron is a soft magnetic material. Although a piece of iron is easily magnetized, it also tends to lose its magnetic properties easily. In contrast, hard magnetic materials, such as cobalt and nickel, are more difficult to magnetize. Once magnetized, however, they don’t lose their magnetism easily.

Magnets exert magnetic forces on each other

As shown in **Figure 14-3**, a magnet lowered into a bucket of nails will often pick up several nails. As soon as a nail touches the magnet, the nail acts as a magnet and attracts other nails. More than one nail is lifted because each nail in the chain becomes temporarily magnetized and exerts a *magnetic force* on the nail below it. This ability disappears when the chain of nails is no longer touching the magnet.

There is a limit to how long the chain of nails can be. The length of the chain depends on the ability of the nails to become magnetized and the strength of the magnet. The farther from the magnet each nail is, the smaller its magnetic force. Eventually, the magnetic force between the two lowest nails is not strong enough to overcome the force of gravity, and the bottom nail falls.

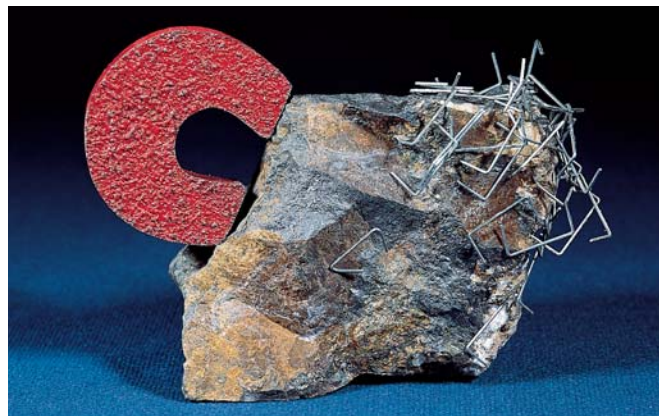


Figure 14-2

A naturally occurring magnetic rock, called a lodestone, will attract a variety of iron objects.

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Figure 14-3

When a magnet is lowered into a bucket of nails, it can pick up a chain of nails. Each nail is temporarily magnetized by the nail above it.



Quick ACTIVITY

Test Your Knowledge of Magnetic Poles

1. Tape the ends of a bar magnet so that its pole markings are covered.
2. Tie a piece of string to the center of the magnet and suspend it from a support stand, as shown in the figure at right.
3. Use another bar magnet to determine which pole of the hanging magnet is the north pole and which is the south pole. What happens when you bring one pole of your magnet near each end of the hanging magnet?
4. Now try to identify the poles of the hanging magnet using the other pole of your magnet.
5. After you have decided the identity of each pole, remove the tape to check. Can you determine which are north poles and which are south poles if you cover the poles on both magnets?



▶ **magnetic pole** an area of a magnet where the magnetic force appears to be the strongest

VOCABULARY Skills Tip

The word *pole* is used in physics for two related opposites that are separated by some distance along an axis. The word *polar*, used in chemistry, has the same origin.

Like poles repel, and opposite poles attract

As explained in Section 13.1, the closer two like electrical charges are brought together, the more they repel each other. The closer two opposite charges are brought together, the more they attract each other. A similar situation exists for **magnetic poles**.

Magnets have a pair of poles, a north pole and a south pole. The poles of magnets exert a force on one another. Two like poles, such as two south poles, repel each other. Two unlike poles, however, attract each other. Thus, the north pole of one magnet will attract the south pole of another magnet. Also, the north pole of one magnet repels the north pole of another magnet.

It is impossible to isolate a south magnetic pole from a north magnetic pole. If a magnet is cut, each piece will still have two poles. No matter how small the pieces of a magnet are, each piece still has both a north and a south pole.

Magnetic Fields

Try moving the south pole of one magnet toward the south pole of another that is free to move. As you do this, the magnet you are not touching will move away. A force is being exerted on the second magnet even though it never touches the magnet in your hand. The force is acting at a distance. This may seem unusual, but you are already familiar with other forces that act at a distance. Gravitational forces and the force between electric charges also act at a distance.

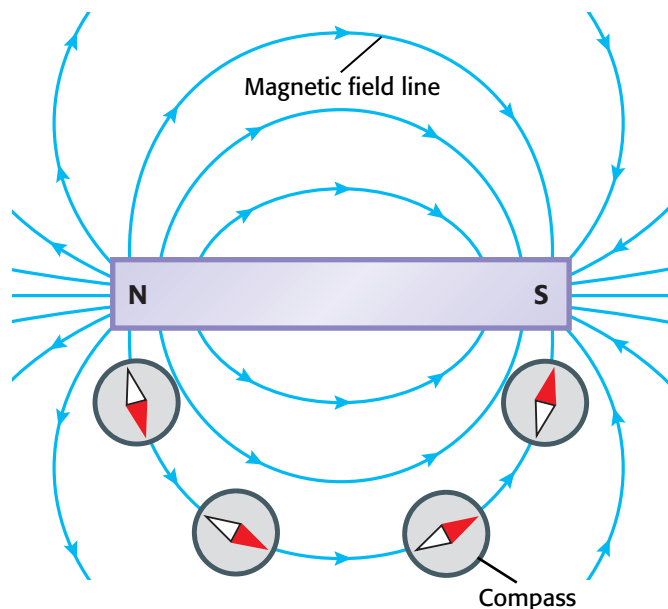


Figure 14-4

The magnetic field of a bar magnet can be traced with a compass. Note that the north pole of each compass points in the direction of the field lines from the magnet's north pole to its south pole.

Magnets are sources of magnetic fields

Magnetic force is a field force. When magnets repel or attract each other, it is due to the interaction of their **magnetic fields**.

All magnets produce a magnetic field. Some magnetic fields are stronger than others. The strength of the magnetic field depends on the material from which the magnet is made and the degree to which it has been magnetized.

Recall from Chapter 13 that electric field lines are used to represent an electric field. Similarly, magnetic field lines are used to represent the magnetic field of a bar magnet, as shown in **Figure 14-4**. These field lines all form closed loops. **Figure 14-4** shows only the field near the magnet. The field also exists within the magnet and farther away from the magnet. The magnetic field, however, gets weaker with distance from the magnet. Magnetic field lines that are close together indicate a strong magnetic field. Field lines that are farther apart indicate a weaker field. Knowing this, you can tell from **Figure 14-4** that a magnet's field is strongest near its poles.

Compasses can track magnetic fields

One way to analyze a magnetic field's direction is to use a compass, as shown in **Figure 14-4**. A compass is a magnet suspended on top of a pivot so that the magnet can rotate freely. You can make a simple compass by hanging a bar magnet from a support with a string tied to the magnet's midpoint.

► **magnetic field** a region where a magnetic force can be detected

Connection to SOCIAL STUDIES

With the invention of iron and steel ships in the late 1800s, it became necessary to develop a new type of compass. The *gyrocompass*, a device containing a spinning loop, was the solution. Because of inertia, the gyrocompass always points toward Earth's geographic North Pole, regardless of which way the ship turns.

Making the Connection

1. Why does the metal hull of a ship affect the function of magnetic compasses?
2. A gyrocompass contains a device called a gyroscope. Research gyroscopes, and briefly explain how they work.

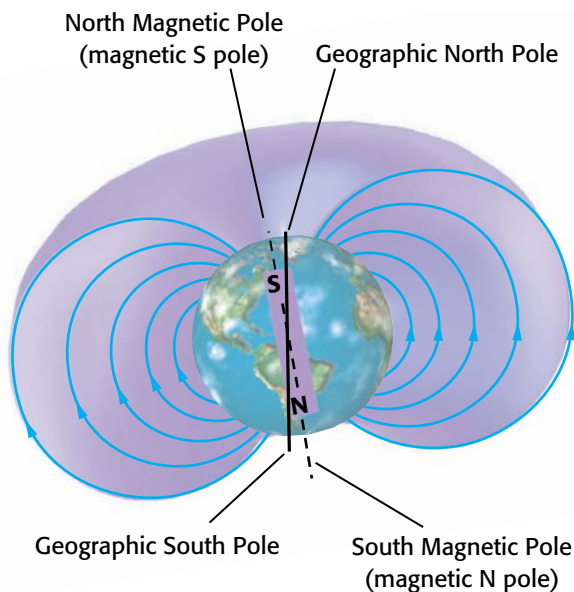


Figure 14-5
Earth's magnetic field is similar to that of a bar magnet.

A compass aligns with Earth's magnetic field just as iron filings align with the field of a bar magnet. The compass points in a direction that lies along, or is tangent to, the magnetic field at that point.

The first compasses were made using lodestones. A lodestone was placed on a small plank of wood and floated in calm water. Sailors then watched as the wood turned and pointed toward the north star. In this way, sailors could gauge their direction even during the day, when stars were not visible. Later, sailors found that a steel or iron needle rubbed with lodestone acted in the same manner.

Earth's magnetic field is like that of a bar magnet

A compass can be used to determine direction because Earth acts like a giant bar magnet. As shown in **Figure**

14-5, Earth's magnetic field has both direction and strength. If you were to move northward along Earth's surface with a compass whose needle could point up and down, the needle of the compass would slowly tilt forward. At a point in northeastern Canada, the needle would point straight down. This point is one of Earth's magnetic poles. There is an opposite magnetic pole in Antarctica.

The source of Earth's magnetism is a topic of scientific debate. Although Earth's core is made mostly of iron, the iron in the core is too hot to retain any magnetic properties. Instead, many researchers believe that the circulation of ions or electrons in the liquid layer of Earth's core may be the source of the magnetism. Others believe it is due to a combination of several factors.

Earth's magnetic field has changed direction throughout geologic time. Evidence of more than 20 reversals in the last 5 million years is preserved in the magnetization of sea-floor rocks.

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Quick ACTIVITY

Magnetic Field of a File Cabinet

1. Stand in front of a metal file cabinet, and hold a compass face up and parallel to the ground.
2. Move the compass from the top of the file cabinet to the bottom, and check to see if the direction of the compass needle changes. If the compass needle

- changes direction, the file cabinet is magnetized.
3. Can you explain what might have caused the file cabinet to become magnetized? Remember that Earth's magnetic field not only points horizontal to Earth but also points up and down.



Earth's magnetic poles are not the same as its geographic poles

One of the interesting things about Earth's magnetic poles is that they are not in the same place as the geographic poles, as shown in **Figure 14-5**. Another important distinction that should be made about Earth's magnetic poles is the orientation of the magnetic field. Earth's magnetic field points from the geographic South Pole to the geographic North Pole. This orientation is similar to an upside-down bar magnet, like the one shown in **Figure 14-5**. The magnetic pole in Antarctica is actually a magnetic N pole, and the magnetic pole in northern Canada is actually a magnetic S pole.

For historical reasons, the poles of magnets are named for the geographic pole they point toward. Thus, the end of the magnet labeled *N* is a "north-seeking" pole, and the end of the magnet labeled *S* is a "south-seeking" pole.

Did You Know?

For years scientists have speculated that some birds, such as geese and pigeons, use Earth's magnetic field to guide their migrations. Magnetic particles that seem to have a navigational role have been found in tissues from migrating animals such as birds, bees, and fish.

SECTION 14.1 REVIEW

SUMMARY

- ▶ All magnets have two poles that cannot be isolated.
- ▶ Like poles repel each other, and unlike poles attract each other.
- ▶ The magnetic force is the force due to interacting magnetic fields.
- ▶ The magnetic field of a magnet is strongest near its poles and gets weaker with distance.
- ▶ The direction of a magnetic field can be traced using a compass.
- ▶ Earth's magnetic field has both north and south poles.
- ▶ Earth's magnetic poles are not at the same location as the geographic poles. The magnetic N pole is in Antarctica, and the magnetic S pole is in northern Canada.

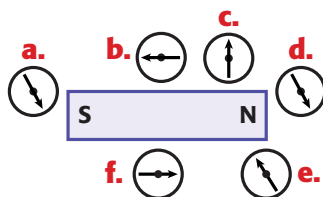
CHECK YOUR UNDERSTANDING

1. **Determine** whether the magnets will attract or repel each other in each of the following cases.



2. **State** how many poles each piece of a magnet will have when you break it in half.

3. **Identify** which of the compass-needle orientations in the figure below correctly describe the direction of the bar magnet's magnetic field.



4. **Describe** the direction a compass needle would point if you were in Australia.

5. **Critical Thinking** The north pole of a magnet is attracted to the geographic North Pole, yet like poles repel. Explain why.

Magnetism from Electric Currents

KEY TERMS

solenoid
electromagnet
domain
galvanometer
electric motor

OBJECTIVES

- ▶ Describe how magnetism is produced by electric currents.
- ▶ Interpret the magnetic field of a solenoid and of an electromagnet.
- ▶ Explain the magnetic properties of a material in terms of magnetic domains.
- ▶ Explain how galvanometers and electric motors work.

Figure 14-6

The iron filings show that the magnetic field of a current-carrying wire forms concentric circles around the wire.



During the eighteenth century, people noticed that a bolt of lightning could change the direction of a compass needle. They also noticed that iron pans sometimes became magnetized during lightning storms. Although these observations suggested a relationship between electricity and magnetism, it wasn't until 1820 that the relationship was understood.

Producing Magnetism from Electric Currents

In 1820, a Danish science teacher named Hans Christian Oersted first experimented with the effects of an electric current on the needle of a compass. He found that magnetism is produced by moving electric charges.

Electric currents produce magnetic fields

The experiment shown in **Figure 14-6** uses iron filings to demonstrate that a current-carrying wire creates a magnetic field. Because of this field, the iron filings make a distinct pattern around the wire.

As you learned in Section 14.1, pieces of iron will align with a magnetic field. The pattern of the filings in **Figure 14-6** suggests that the magnetic field around a current-carrying wire forms concentric circles around the wire. If you were to bring a compass close to a current-carrying wire, as Oersted did, you would find that the needle points in a direction tangent to the circles of iron filings.

Use the right-hand rule to find the direction of the magnetic field produced by a current

Is the direction of the wire's magnetic field clockwise or counterclockwise? Repeated measurements have shown an easy way to predict the direction: the *right-hand rule*. The right-hand rule is explained below.

If you imagine holding the wire in your right hand with your thumb pointing in the direction of the positive current, the direction your fingers would curl is in the direction of the magnetic field.

Figure 14-7 illustrates the right-hand rule. Pretend the wire is grasped with the right hand with the thumb pointing upward, in the direction of the current. When the hand holds the wire, the fingers encircle the wire with the fingertips pointing in the direction of the magnetic field, counterclockwise in this case. If the current were toward the bottom of the page, the thumb would point downward, and the magnetic field would point clockwise.

Remember—never grasp or touch an uninsulated wire. You could be electrocuted.

The magnetic field of a coil of wire resembles that of a bar magnet

As Oersted demonstrated, the magnetic field of a current-carrying wire exerts a force on a compass needle. This force causes the needle to turn in the direction of the wire's magnetic field. However, this force is very weak. One way to increase the force is to increase the current in the wire, but large currents can be fire hazards. A safer way to create a strong magnetic field that will provide a greater force is to wrap the wire into a coil, as shown in **Figure 14-8**. This device is called a **solenoid**.

In a solenoid, the magnetic field of each loop of wire adds to the strength of the magnetic field of the loop next to it. The result is a strong magnetic field similar to the magnetic field produced by a bar magnet. A solenoid even has a north and south pole, just like a magnet.

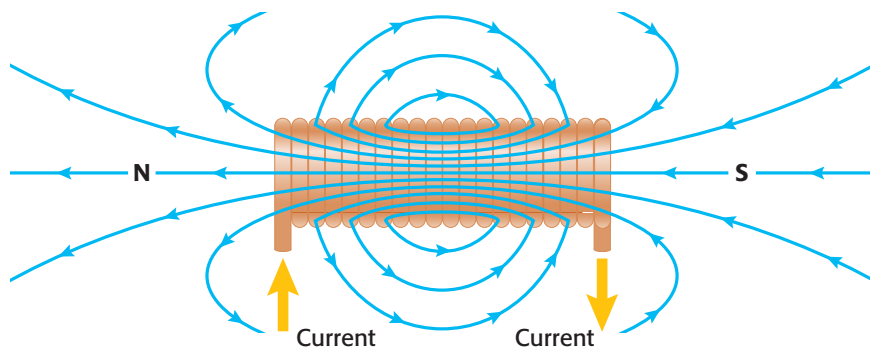


Figure 14-7 Use the right-hand rule to find the direction of the magnetic field around a current-carrying wire.



Disc Two, Module 17:

Magnetic Field of a Wire

Use the Interactive Tutor to learn more about this topic.

▶ **solenoid** a long, wound coil of insulated wire

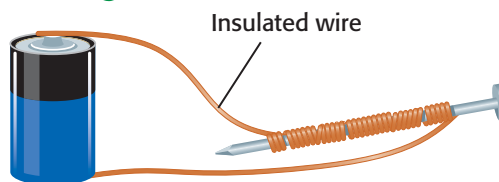
Figure 14-8 The magnetic field of a coil of wire resembles the magnetic field of a bar magnet.

Inquiry Lab

How can you make an electromagnet?

Materials

- ✓ D-cell
- ✓ 1 m length of insulated wire
- ✓ compass
- ✓ large iron or steel nail



Procedure

1. Wind the wire around the nail, as shown at right. Remove the insulation from the ends. Hold the insulated wire with the ends against the terminals.
2. Determine whether the nail is magnetized. If it is magnetized, the compass needle will spin to align with the nail's magnetic field.
3. Switch connections to the cell so the current is reversed. Again bring the compass toward the same part of the nail.

Analysis

1. What type of device have you produced? Explain your answer.
2. What happens to the direction of the compass needle after you reverse the direction of the current? Why does this happen?
3. After detaching the coil from the cell, what can you do to make the nail nonmagnetic?

▶ **electromagnet** a strong magnet created when an iron core is inserted into the center of a current-carrying solenoid

The strength of the magnetic field of a solenoid depends on the number of loops of wire and the amount of current in the wire. In particular, more loops or more current can create a stronger magnetic field.

The strength of a solenoid's magnetic field can be increased by inserting a rod made of iron (or some other potentially magnetic metal) through the center of the coils. The resulting device is called an **electromagnet**. The magnetic field of the solenoid causes the rod to become a magnet as well. The magnetic field of the rod then adds to the coil's field, creating a stronger magnet than the solenoid alone.

Magnetism is caused by moving charges

The movement of charges causes all magnetism. The magnetic properties of bar magnets, for instance, can be attributed to the movement of charged particles.

But what charges are moving in a bar magnet? Recall from Section 3.1 that electrons are negatively charged particles that move around the nuclei of atoms. All electrons have a property called *electron spin*. Electron spin produces a tiny magnetic field around every electron.

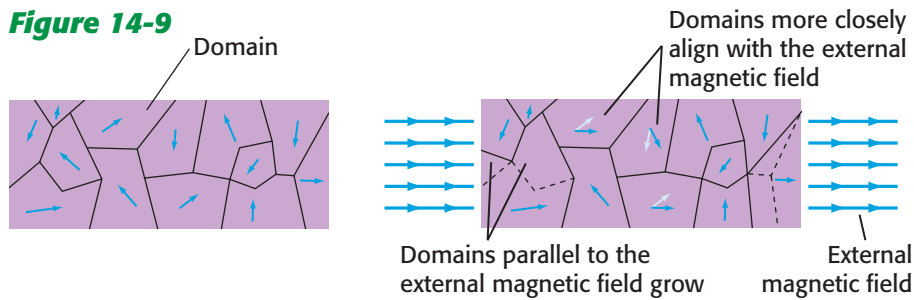
In some cases, the magnetic fields of the electrons in an atom cancel each other and the material is not magnetic. However, in materials such as iron, nickel, and cobalt, not all of the magnetic fields of the electrons cancel. Thus, each atom in those metals has its own magnetic field.

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Figure 14-9



A When a potentially magnetic substance is unmagnetized, its domains are randomly oriented.

B When in an external magnetic field, the direction of the domains becomes more uniform, and the material becomes magnetized.

Just as a compass needle rotates to align with a magnetic field, magnetic atoms rotate to align with the magnetic fields of nearby atoms. The result is small regions within the material called **domains**. The magnetic fields of atoms in a domain point in the same direction.

As shown in **Figure 14-9A**, the magnetic fields of the domains inside an unmagnetized piece of iron are not aligned. When a strong magnet is brought nearby, the domains line up more closely with the magnetic field. **Figure 14-9B** shows the two ways this can happen. The result of the reorientation of the domains is an overall magnetization of the iron.

▶ **domain** a microscopic magnetic region composed of a group of atoms whose magnetic fields are aligned in a common direction

▶ **galvanometer** an instrument that measures the amount of current in a circuit

Electromagnetic Devices

Many modern devices make use of the magnetic field produced by coils of current-carrying wire. Devices as different as hair dryers and stereo speakers function because of the magnetic field produced by these current-carrying conductors.

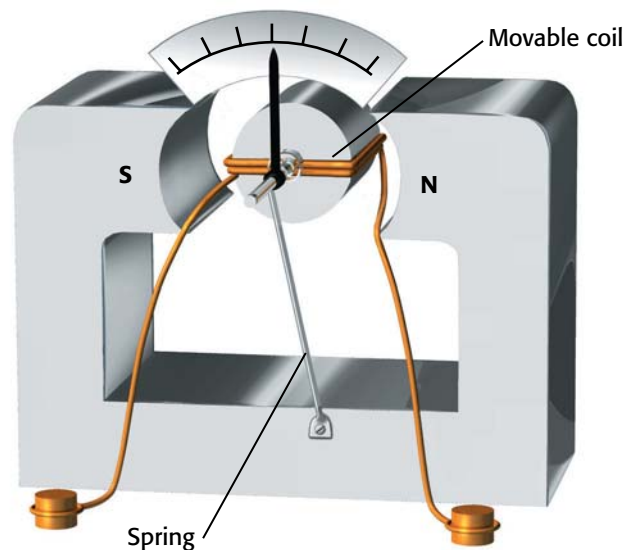
Galvanometers detect current

Galvanometers are devices used to measure current in *ammeters* and voltage in *voltmeters*. The basic construction of a galvanometer is shown in **Figure 14-10**. In all cases, a galvanometer detects current, or the movement of charges in a circuit.

As shown in **Figure 14-10**, a galvanometer consists of a coil of insulated wire wrapped around an iron core that can spin between the poles of a permanent magnet. When the galvanometer is attached to a circuit, a current will

Figure 14-10

When there is current in the coil of a galvanometer, magnetic repulsion between the coil and the magnet causes the coil to twist.



be in the coil of wire. The coil and iron core will act as an electromagnet and produce a magnetic field. This magnetic field will interact with the magnetic field of the surrounding permanent magnet. The resulting forces will turn the core.

As stated earlier in this section, the greater the current in the electromagnet, the stronger its magnetic field. If the core's magnetic field is strong, the force on the core will be great, and the core will rotate through a large angle. A needle extends upward from the core to a scale. As the core rotates, the needle moves across the scale. The greater the movement across the scale, the larger the current.

▶ **electric motor** a device that converts electrical energy to mechanical energy

Electric motors convert electrical energy to mechanical energy

Electric motors are another type of device that uses magnetic force to cause motion. **Figure 14-11** is an illustration of a simple direct current, or DC, motor.

As shown by the arrow in **Figure 14-11**, the coil of wire in a motor turns when a current is in the wire. But unlike the coil and core in a galvanometer, the coil in an electric motor keeps spinning. If the coil is attached to a shaft, it can do work. The end of the shaft is connected to some other device, such as a propeller or wheel. This design is often used in mechanical toys.

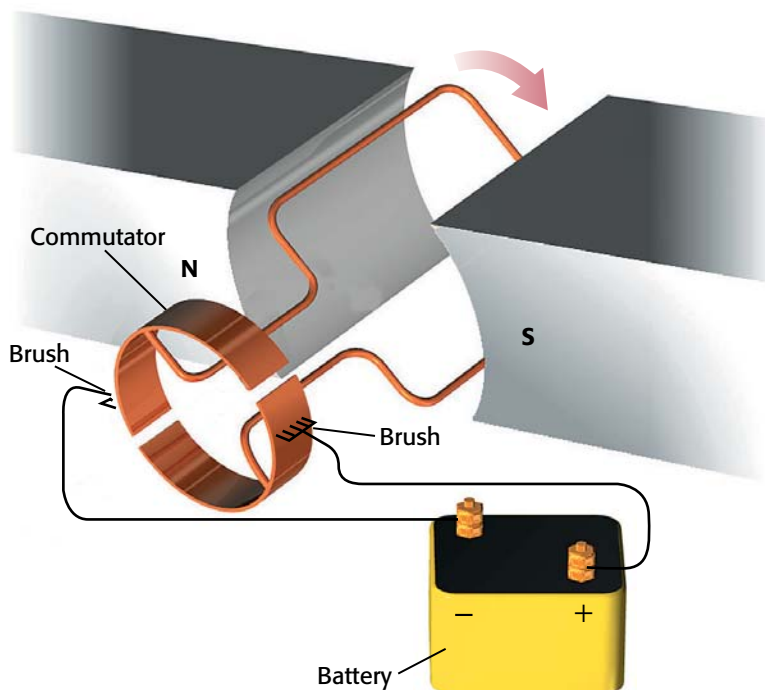
A device called a *commutator* is used to make the current change direction every time the flat coil makes a half revolution. This commutator is two half rings of metal. Devices called *brushes* connect the wires to the commutator. Because of the slits in the commutator, charges must move through the coil of wire

to reach the opposite half of the ring. As the coil and commutator spin, the current in the coil changes direction every time the brushes come in contact with a different side of the ring.

So the magnetic field of the coil changes direction as the coil spins. In this way, the coil is repelled by both the north and south poles of the magnet surrounding it. Because the current keeps reversing, the loop rotates in one direction. If the current did not keep changing direction, the loop would just bounce back and forth in the magnetic field until the force of friction caused it to come to rest.

Figure 14-11

In an electric motor, the current in the coil produces a magnetic field that interacts with the magnetic field of the surrounding magnet, causing the coil to turn.



Stereo speakers use magnetic force to produce sound

Motion caused by magnetic force can even be used to produce sound waves. This is how most stereo speakers work. The speaker shown in **Figure 14-12** consists of a permanent magnet and a coil of wire attached to a flexible paper cone. When a current is in the coil, a magnetic field is produced. This field interacts with the field of the permanent magnet, causing the coil and cone to move in one direction. When the current reverses direction, the magnetic force on the coil also reverses direction. As a result, the cone accelerates in the opposite direction.

This alternating force on the speaker cone makes it vibrate. Varying the magnitude of the current changes how much the cone vibrates. These vibrations produce sound waves. In this way, an electric signal is converted to a sound wave.

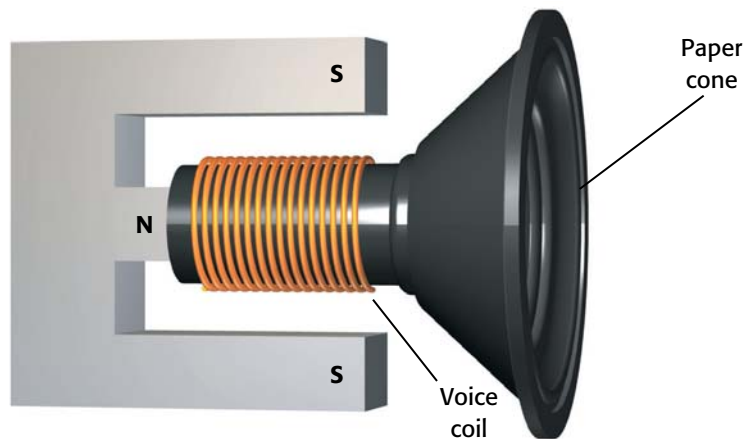


Figure 14-12

In a speaker, when the direction of the current in the coil of wire changes, the paper cone attached to the coil moves, producing sound waves.

SECTION 14.2 REVIEW

SUMMARY

- ▶ A magnetic field is produced around a current-carrying wire.
- ▶ A current-carrying solenoid has a magnetic field similar to that of a bar magnet.
- ▶ An electromagnet consists of a current-carrying solenoid with an iron core.
- ▶ A domain is a group of atoms whose magnetic fields are aligned.
- ▶ Galvanometers measure the current in a circuit using the magnetic field produced by a current in a coil.
- ▶ Electric motors convert electrical energy to mechanical energy.

CHECK YOUR UNDERSTANDING

- 1. Describe** the shape of the magnetic field produced by a straight current-carrying wire.
- 2. Determine** the direction in which a compass needle will point when held above a wire with positive charges moving west. (**Hint:** Use the right-hand rule.)
- 3. Identify** which of the following would have the strongest magnetic field. Assume the current in each is the same.
 - a. a straight wire
 - b. an electromagnet with 30 coils
 - c. a solenoid with 20 coils
 - d. a solenoid with 30 coils
- 4. Explain** why a very strong magnet attracts both poles of a weak magnet. Use the concept of magnetic domains in your explanation.
- 5. Predict** whether a solenoid suspended by a string could be used as a compass.
- 6. Critical Thinking** A friend claims to have built a motor by attaching a shaft to the core of a galvanometer and removing the spring. Can this motor rotate through a full rotation? Explain your answer.

Electric Currents from Magnetism

KEY TERMS

electromagnetic induction
generator
alternating current
transformer

electromagnetic induction the production of a current in a conducting circuit by a change in the strength, position, or orientation of an external magnetic field

OBJECTIVES

- ▶ Describe the conditions required for electromagnetic induction.
- ▶ Apply the concept of electromagnetic induction to generators.
- ▶ Explain how transformers increase or decrease voltage across power lines.

Can you have current in a wire without a battery or some other source of voltage? In 1831, Michael Faraday discovered that a current can be produced by pushing a magnet through a coil of wire. In other words, moving a magnet in and out of a coil of wire causes charges in the wire to move. This process is called **electromagnetic induction**.

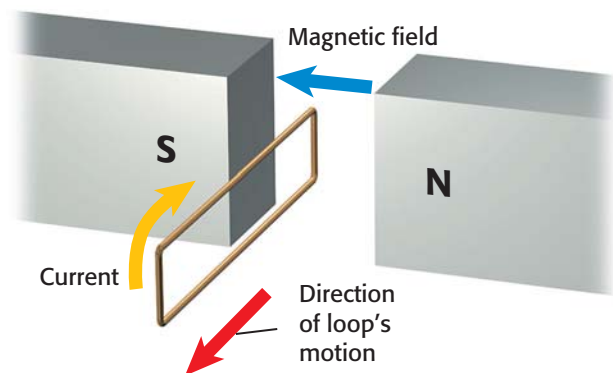
Electromagnetic Induction and Faraday's Law

Electromagnetic induction is so fundamental that it has become one of the laws of physics—*Faraday's law*. Faraday's law states the following:

An electric current can be produced in a circuit by a changing magnetic field.

Figure 14-13

When the loop moves in or out of the magnetic field, a current is induced in the wire.



Consider the loop of wire moving between the two magnetic poles in **Figure 14-13**. As the loop moves in and out of the magnetic field of the magnet, a current is *induced* in the circuit. As long as the wire continues to move in or out of the field in a direction that is not parallel to the field, an induced current will exist in the circuit.

Rotating the circuit or changing the strength of the magnetic field will also induce a current in the circuit. In each case, there is a changing magnetic field passing through the loop. You can predict whether a current will be induced using the concept of magnetic field lines. A current will be induced if the number of field lines that pass through the loop changes.

It would seem that electromagnetic induction creates energy from nothing, but this is not true. Electromagnetic induction does not violate the law of conservation of energy. Pushing a loop through a magnetic field requires work. The greater the magnetic field, the stronger the force required to push the loop through the field. The energy required for this work comes from an outside source, such as your muscles pushing the loop through the magnetic field. So while electrical energy is produced by electromagnetic induction, energy is required to move the loop.

Moving electric charges experience a magnetic force when in a magnetic field

When studying electromagnetic induction, it is helpful to imagine the individual charges in a wire. A charged particle moving in a magnetic field will experience a force due to the magnetic field. Experiments have shown that this magnetic force is zero when the charge moves along or opposite the direction of the magnetic field lines. The force is at its maximum value when the charge moves perpendicular to the field. As the angle between the charge's direction and the direction of the magnetic field decreases, the force on the charge decreases.

INTEGRATING



BIOLOGY

Many types of bacteria contain magnetic particles of iron oxide and iron sulfide. These particles are encased in a membrane within the cell, forming a magnetosome. The magnetosomes in a bacterium spread out in a line and align with Earth's magnetic field. In this way, as the cell uses its flagella to swim, it travels along a north-south axis. Recently, magnetite crystals have been found in human brain cells, but the role these particles play remains uncertain.

Inquiry

Lab

Can you demonstrate electromagnetic induction?

- Materials**
- ✓ galvanometer
 - ✓ 2 insulated wire leads
 - ✓ solenoid
 - ✓ 2 bar magnets

Procedure

1. Set up the apparatus as shown in the photo at right. With this arrangement, current induced in the solenoid will pass through the galvanometer.
2. Holding one of the bar magnets, insert its north pole into the solenoid while observing the galvanometer needle. What happens?
3. Pull the magnet out of the solenoid, and record the movement of the galvanometer needle.
4. Turn the magnet around, and move the south pole in and out of the solenoid. What happens?
5. Vary the speed of the magnet. What happens if you do not move the magnet at all?
6. Try again using two magnets alongside each other with north poles and south poles together. How does the amount of current induced depend on the strength of the magnetic field?

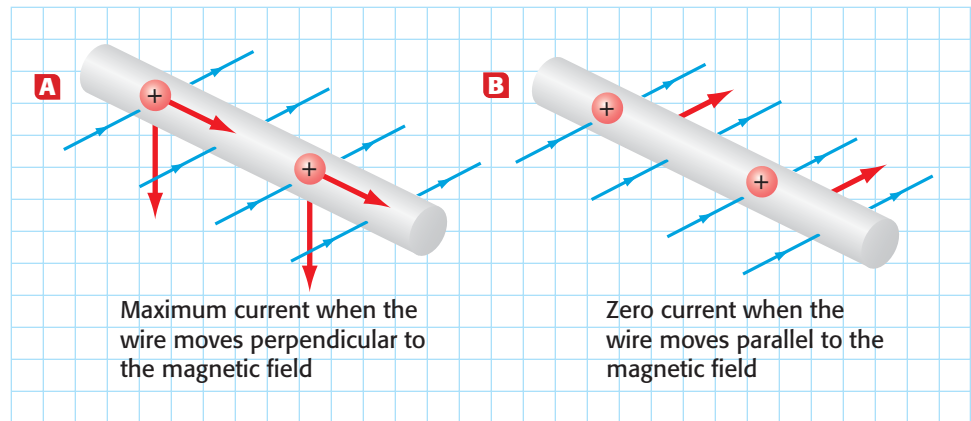


Analysis

1. What evidence did you find that current is induced by a changing magnetic field?
2. Compare the current induced by a south pole with that induced by a north pole.
3. What two observations did you make that show that more current is induced if the magnetic field changes rapidly?

Figure 14-14

(A) When the wire in a circuit moves perpendicular to a magnetic field, the current induced in the wire is at a maximum. (B) When the wire moves parallel to a magnetic field, there is zero current induced in the wire.



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Now apply this concept to current. Imagine the wire in a circuit as a tube full of charges, as shown in **Figure 14-14**. When the wire is moving perpendicular to a magnetic field, the force on the charges is at a maximum. In this case, there will be a current in the wire and circuit, as shown in **Figure 14-14A**. When a wire is moving parallel to the field, as in **Figure 14-14B**, no current is induced in the wire. Because the charges are moving parallel to the field, they experience no magnetic force.

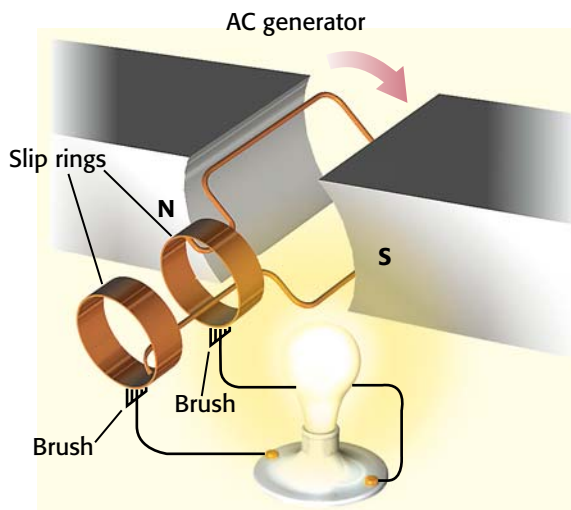
- ▶ **generator** a device that uses electromagnetic induction to convert mechanical energy to electrical energy
- ▶ **alternating current** an electric current that changes direction at regular intervals; also called AC

Generators convert mechanical energy to electrical energy

Generators are similar to motors except that they convert mechanical energy to electrical energy. If you exert energy to do work on a simple generator, like the one in **Figure 14-15**, the loop of wire inside turns within a magnetic field and current is produced. For each half rotation of the loop, the current produced by the generator reverses direction. This type of generator is therefore called an **alternating current**, or AC, generator. The generators that produce the electrical energy that you use at

Figure 14-15

In an alternating current generator, the mechanical energy of the loop's rotation is converted to electrical energy when a current is induced in the wire. The current lights the light bulb.



home are alternating current generators. The current supplied by the outlets in your home and in most of the world is alternating current.

As can be seen by the glowing light bulb in **Figure 14-15**, the coil turning in the magnetic field of the magnet creates a current. The magnitude and direction of the current that results from the coil's rotation vary depending on the orientation of the loop in the field.

Table 14-1 Induced Current in a Generator

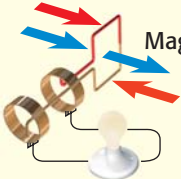
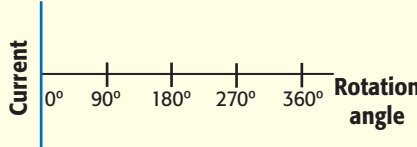
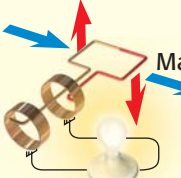
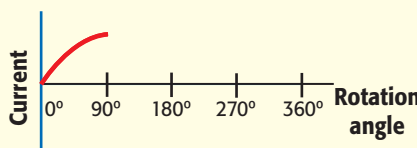
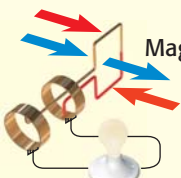
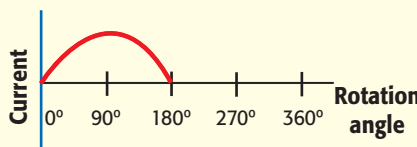
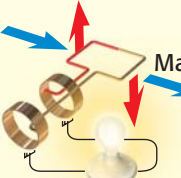
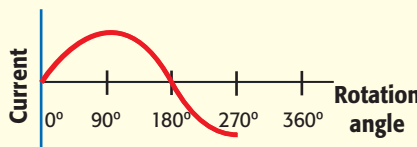
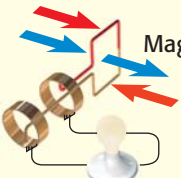
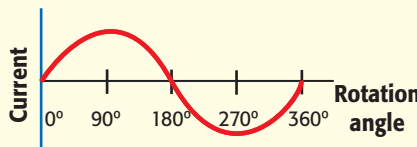
Position of loop	Amount of current	Graph of current versus angle of rotation
 <p>Magnetic field</p>	Zero current	
 <p>Magnetic field</p>	Maximum current	
 <p>Magnetic field</p>	Zero current	
 <p>Magnetic field</p>	Maximum current (opposite direction)	
 <p>Magnetic field</p>	Zero current	

Table 14-1 shows how the magnitude of the current produced by an alternating current generator varies with time. When the loop is perpendicular to the field, the current is zero. Recall that a charge moving parallel to a magnetic field experiences no magnetic force. This is the case here. The charges in the wire experience no magnetic force, so no current is induced in the wire.

As the loop continues to turn, the current increases until it reaches a maximum. When the loop is parallel to the field, charges on either side of the wire move perpendicular to the magnetic field. Thus, the charges experience the maximum magnetic force, and the current is large. Current decreases as the loop rotates, reaching zero when it is again perpendicular to the magnetic field. As the loop continues to rotate, the direction of the current reverses.

Did You Know?

Although the light from an incandescent light bulb appears to be constant, the current in the bulb actually varies, changing direction 60 times each second. The light appears to be steady because the changes are too rapid for our eyes to perceive.

Generators produce the electrical energy you use in your home

Large power plants use generators to convert mechanical energy to electrical energy. The mechanical energy used in a commercial power plant comes from a variety of sources. One of the most common sources is running water. Dams are built to harness the kinetic energy of falling water. Water is forced through small channels at the top of the dam. As the water falls to the base of the dam, it turns the blades of large turbine fans. The fans are attached to a core wrapped with many loops of wire that rotate within a strong magnetic field. The end result is electrical energy.

Coal power plants use the heat from burning coal to make steam that eventually turns the blades of the turbines. Other sources of energy are nuclear fission, wind, hot water from geysers (geothermal), and solar power.

Unfortunately, much of the electrical energy produced by generators is lost to external sources. Many power plants are not very efficient. More-efficient and safer methods of producing energy are continually being sought.

Electricity and magnetism are two aspects of a single electromagnetic force

So far you've read that a moving charge produces a magnetic field and that a changing magnetic field causes an electric charge to move. The energy that results from these two forces is called electromagnetic energy.

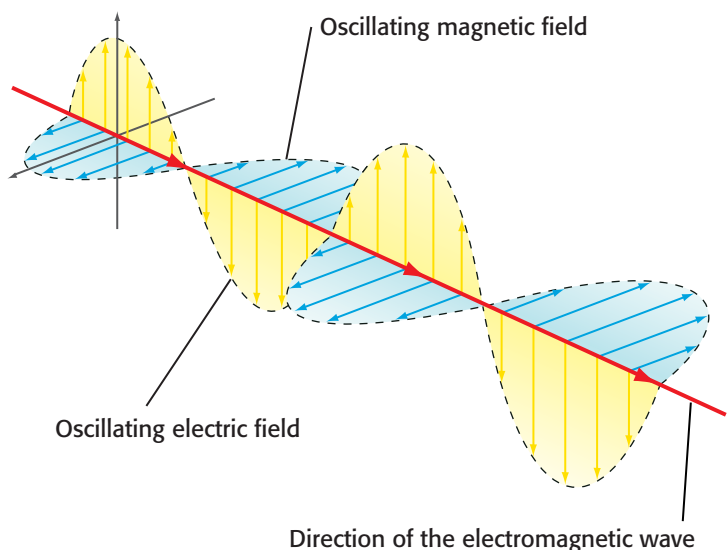
You learned in Section 12.2 that light is a form of electromagnetic energy. Visible light travels as electromagnetic waves, or *EM* waves, as do other forms of radiation, such as radio signals and X rays. These waves are also called *EMF* (electromagnetic

frequency) waves. As shown in **Figure 14-16**, EM waves are made up of oscillating electric and magnetic fields that are perpendicular to each other. This is true of any type of EM wave, regardless of the frequency.

Both the electric and magnetic fields in an EM wave are perpendicular to the direction the wave travels. So EM waves are transverse waves. As the wave moves along, the changing electric field generates the magnetic field. The changing magnetic field generates the electric field. Each field regenerates the other, allowing EM waves to travel through empty space.

Figure 14-16

An electromagnetic wave consists of electric and magnetic field waves at right angles to each other.



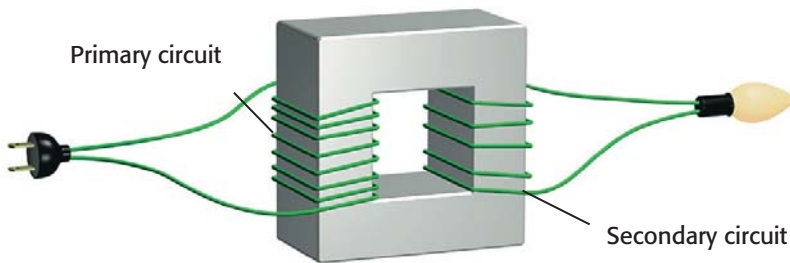


Figure 14-17

A transformer uses the alternating current in the primary circuit to induce an alternating current in the secondary circuit.

Transformers

You may have seen metal cylinders on power line poles in your neighborhood. These cylinders hold electromagnetic devices called **transformers**. **Figure 14-17** is a simple representation of a transformer. Two wires are coiled around opposite sides of a closed iron loop. In this transformer, one wire is attached to a source of alternating current, such as a power outlet in your home. The other wire is attached to an appliance, such as a lamp.

When there is current in the primary wire, this current creates a changing magnetic field that magnetizes the iron core. The changing magnetic field of the iron core then induces a current in the secondary coil. The direction of the current in the secondary coil changes every time the direction of the current in the primary coil changes.

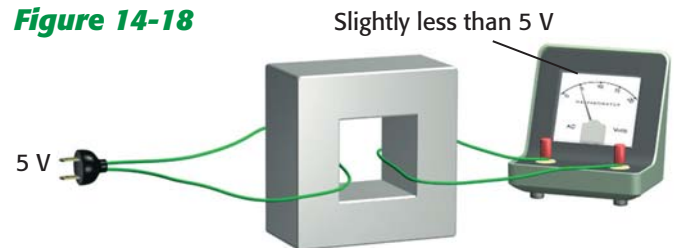
Transformers can increase or decrease voltage

The voltage induced in the secondary coil of a transformer depends on the number of loops, or *turns*, in the coil. As shown in **Figure 14-18A**, both the primary and secondary wires are coiled only once around the iron core. If the incoming current has a voltage of 5 V, then the voltage measured in the other circuit will be close to 5 V. When the number of turns in the two coils is equal, the voltage induced in the secondary coil is about the same as the voltage in the primary coil.

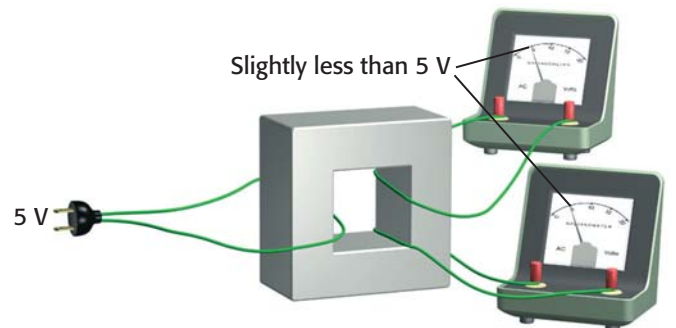
In **Figure 14-18B**, two secondary coils with just one turn each are placed on the iron core. In this case, a voltage of slightly less than 5 V is induced in each coil. If these turns are joined together to form one coil with two turns, as shown in **Figure 14-18C**, the voltmeter

▶ **transformer** a device that can change one alternating-current voltage to a different alternating-current voltage

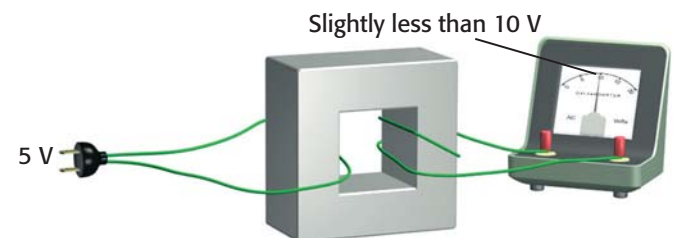
Figure 14-18



A When the primary and secondary circuits in a transformer each have one turn, the voltage across each is about equal.



B When an additional secondary circuit is added, the voltage across each is again about equal.



C When the two secondary circuits are combined, the secondary circuit has about twice the voltage of the primary circuit. Actual transformers have thousands of turns.



Figure 14-19

Step-down transformers like this one are used to reduce the voltage across power lines so that the electrical energy supplied to homes and businesses is safer to use.

will measure an induced voltage of slightly less than twice as much as the voltage produced by one coil. Thus, the voltage across the secondary coil is about twice as large as the voltage across the primary coil. This device is called a *step-up transformer* because the voltage across the secondary coil is greater than the voltage across the primary coil.

If the secondary coil has fewer loops than the primary coil, then the voltage is lowered by the transformer. This type of transformer is called a *step-down transformer*.

Step-up and step-down transformers are used in the transmission of electrical energy from power plants to homes and businesses. A step-up transformer is used at or near the power plant to increase the voltage of the current to about 120 000 V. At this high voltage, less energy is lost due to the resistance of the transmission wires. A step-down transformer, like the one shown in **Figure 14-19**, is then used near your home to reduce the voltage of the current to about 120 V. This lower voltage is much safer. Many appliances in the United States operate at 120 V.

SECTION 14.3 REVIEW

SUMMARY

- ▶ A current is produced in a circuit by a changing magnetic field.
- ▶ In a generator, mechanical energy is converted to electrical energy by a conducting loop turning in a magnetic field.
- ▶ Electromagnetic waves consist of magnetic and electric fields oscillating at right angles to each other.
- ▶ In a transformer, the magnetic field produced by a primary coil induces a current in a secondary coil.
- ▶ The voltage across the secondary coil of a transformer is proportional to the number of loops, or turns, it has relative to the number of turns in the primary coil.

CHECK YOUR UNDERSTANDING

- 1. Identify** which of the following will *not* increase the current induced in a wire loop moving through a magnetic field.
 - a. increasing the strength of the magnetic field
 - b. increasing the speed of the wire
 - c. rotating the loop until it is perpendicular to the field
- 2. Explain** how hydroelectrical power plants use moving water to produce electricity.
- 3. Determine** whether the following statement describes a step-up transformer or a step-down transformer: The primary coil has 7000 turns, and the secondary coil has 500 turns.
- 4. Predict** the movement of the needle of a galvanometer attached to a coil of wire for each of the following actions. Assume that the north pole of a bar magnet has been inserted into the coil, causing the needle to deflect to the right.
 - a. pulling the magnet out of the coil
 - b. letting the magnet rest in the coil
 - c. thrusting the south pole of the magnet into the coil
- 5. Critical Thinking** A spacecraft orbiting Earth has a coil of wire in it. An astronaut measures a small current in the coil, even though there is no battery connected to it and there are no magnets on the spacecraft. What is causing the current?

Chapter Highlights

Before you begin, review the summaries of the key ideas of each section, found on pages 467, 473, and 480. The key vocabulary terms are listed on pages 462, 468, and 474.

UNDERSTANDING CONCEPTS

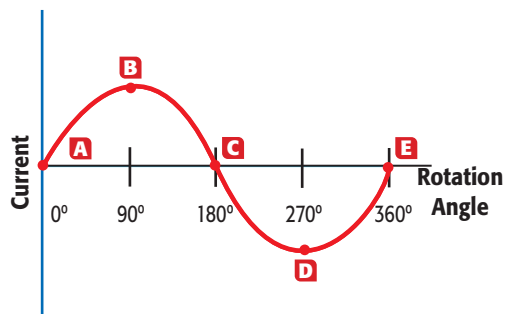
- If the poles of two magnets repel each other, _____.
 - both poles must be south poles
 - both poles must be north poles
 - one pole is a south pole and the other is a north pole
 - the poles are the same type
- The part of a magnet where the magnetic field and forces are strongest is called a magnetic _____.
 - field
 - pole
 - attraction
 - repulsion
- A _____ magnetic material is easy to magnetize but loses its magnetism easily.
 - hard
 - magnetically unstable
 - soft
 - No such material exists.
- An object's ability to generate a magnetic field depends on its _____.
 - size
 - location
 - composition
 - direction
- A straight current-carrying wire produces _____.
 - an electric field
 - a magnetic field
 - beams of white light
 - All of the above
- A compass held directly below a current-carrying wire with a positive current moving north will point _____.
 - east
 - north
 - south
 - west
- An electric motor uses an electromagnet to change _____.
 - mechanical energy to electrical energy
 - magnetic fields in the motor
 - magnetic poles in the motor
 - electrical energy to mechanical energy
- An electric generator is a device that converts _____.
 - nuclear energy to electrical energy
 - wind energy to electrical energy
 - energy from burning coal to electrical energy
 - All of the above
- The process of producing an electrical current by moving a magnet in and out of a coil of wire is called _____.
 - magnetic deduction
 - electromagnetic induction
 - magnetic reduction
 - magnetic production
- In a generator, the current produced is _____ when the loop is parallel to the surrounding magnetic field.
 - at a maximum
 - very small
 - zero
 - none of the above

Using Vocabulary

- Use the terms *magnetic pole* and *magnetic field* to explain why the N pole of a compass points toward northern Canada.
- What is made by inserting an iron core into a *solenoid*?
- Use the terms *generator* and *electromagnetic induction* to explain how *electrical energy* can be produced using the *kinetic energy* of falling water.
- What does the abbreviation *EM* stand for?
- What is used to increase or decrease the voltage across a power line?

BUILDING MATH SKILLS

- 16. Graphing** The figure below is a graph of current versus rotation angle for the output of an alternating-current generator.
- At what point(s) does the generator produce no current?
 - Is less or more current being produced at point *B* than at points *C* and *E*?
 - Is less or more current being produced at point *D* than at points *C* and *E*?
 - What does the negative value for the current at *D* signify?

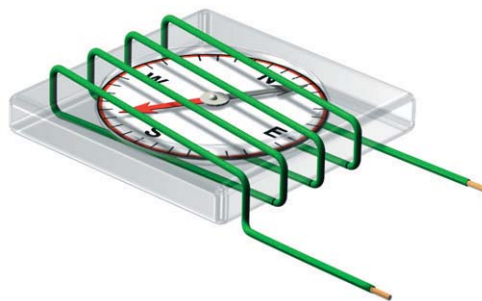


- 17. Interpreting Graphics** If the coil of the generator referred to in item 16 were like the one shown in **Table 14-1**, what would the coil orientation be relative to the magnetic field in order to produce the maximum current at *B*?

THINKING CRITICALLY

- 18. Problem Solving** How could you use a compass with a magnetized needle to determine if a steel nail were magnetized?
- 19. Applying Knowledge** If you place a stethoscope on an unmagnetized iron nail and then slowly move a strong magnet toward the nail, you can hear a faint crackling sound. Use the concept of domains to explain this sound.

- 20. Problem Solving** You walk briskly into a strong magnetic field while wearing a copper bracelet. How should you hold your wrist relative to the magnetic field lines to avoid inducing a current in the bracelet?
- 21. Understanding Systems** Transformers are usually used to raise or lower the voltage across an alternating-current circuit. Could a transformer be used in a direct-current circuit? How about if the direct current were pulsating (turning on and off)?
- 22. Understanding Systems** Which of the following might be the purpose of the device shown below?
- to measure the amount of voltage across the wire
 - to determine the direction of the current in the wire
 - to find the resistance of the wire



DEVELOPING LIFE/WORK SKILLS

- 23. Working Cooperatively** During a field trip, you find a round chunk of metal that attracts iron objects. In groups of three, design a procedure to determine whether the object is magnetic and, if so, to locate its poles. What materials would you need? How would you draw your conclusions? List all the possible results and the conclusions you could draw from each result.

24. Applying Technology Use your imagination and your knowledge of electromagnetism to invent a useful electromagnetic device. Use a computer-drawing program to make sketches of your invention, and write a description of how it works.

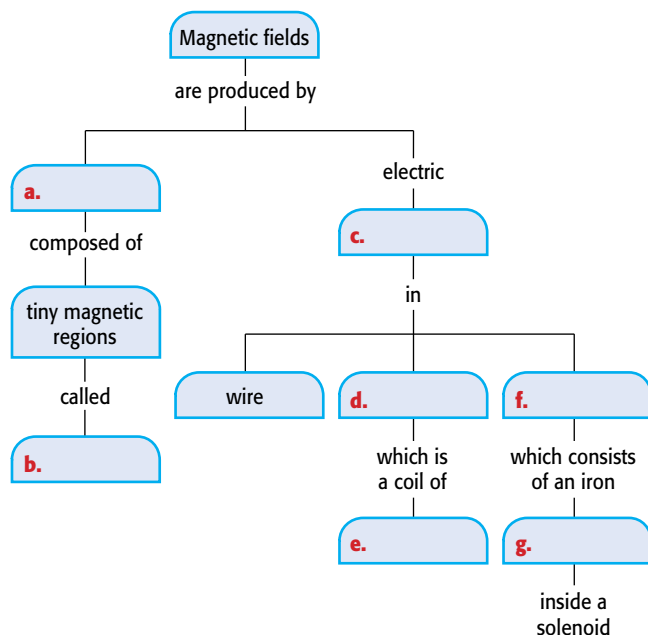


25. Interpreting and Communicating Research one of the following electromagnetic devices. Write a half-page description of how electromagnetism is used in the device, using diagrams where appropriate.

- a. hair dryer
- b. electric guitar
- c. doorbell
- d. tape recorder

INTEGRATING CONCEPTS

26. Concept Mapping Copy the unfinished concept map below onto a sheet of paper. Complete the map by writing the correct word or phrase in the lettered boxes.



27. Connection to Social Studies Why was the discovery of lodestones in Greece important to navigators hundreds of years later?

28. Connection to Health Some studies indicate that magnetic fields produced by power lines may contribute to leukemia among children who grow up near high-voltage power lines. Research the history of scientific studies of the connection between leukemia and power lines. What experiments show that growing up near power lines increases risk of leukemia? What evidence is there that there is no relation between leukemia and the magnetic fields produced by power lines?

29. Connection to Physics Find out how electromagnetism is used in containing nuclear fusion reactions. Write a report on your findings.



30. Connection to Social Studies Research the debate between proponents of alternating current and proponents of direct current in the 1880s and 1890s. How were Thomas Edison and George Westinghouse involved in the debate? What advantages and disadvantages did each side claim? What kind of current was finally generated in the Niagara Falls hydroelectric plant? If you had been in a position to fund the projects at that time, which projects would you have funded? Prepare your arguments so that you can reenact a meeting of businesspeople in Buffalo in 1887.

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Design Your Own Lab

Introduction

How can you build the strongest electromagnet from a selection of batteries, wires, and metal rods?

Objectives

- ▶ **Build** several electromagnets.
- ▶ **Identify** the features of a strong electromagnet.
- ▶ **Determine** how many paper clips each electromagnet can lift.

Materials

2 D-cell batteries
2 battery holders
1 m thick insulated wire
1 m thin insulated wire
extra insulated wire
4 metal rods
(iron, tin, aluminum, and nickel)
wire stripper
electrical tape
box of small paper clips



Safety Needs



safety goggles
heat-resistant gloves

Making a Better Electromagnet

▶ Building an Electromagnet

1. Review the Inquiry Lab in Section 14.2 on the basic steps in making an electromagnet.  
2. On a blank sheet of paper, prepare a table like the one shown at right.
3. Wind the thin wire around the thickest metal core. Carefully pull the core out of the center of the thin wire coil. Repeat the above steps with the thick wire. You now have two wire coils that can be used to make electromagnets.

SAFETY CAUTION Handle the wires only where they are insulated.

▶ Designing Your Experiment

4. With your lab partners, decide how you will determine what features combine to make a strong electromagnet. Think about the following before you predict the features that the strongest electromagnet would have.
 - a. Which metal rod would make the best core?
 - b. Which of the two wires would make a stronger electromagnet?
 - c. How many coils should the electromagnet have?
 - d. Should the batteries be connected in series or in parallel?



Electromagnet number	Wire (thick or thin)	# of coils	Core (iron, tin, alum., or nickel)	Batteries (series or parallel)	# of paper clips lifted
1					
2					
3					
4					
5					
6					

- In your lab report, list each step you will perform in your experiment.
- Before you carry out your experiment, your teacher must approve your plan.

▶ Performing Your Experiment

- After your teacher approves your plan, carry out your experiment. You should test all four metal rods, both thicknesses of wire, and both series and parallel battery connections. Count the number of coils of wire in each electromagnet you build.
- Record your results in your data table.

▶ Analyzing Your Results

- Did the thick wire or the thin wire make a stronger electromagnet? How can you explain this result?
- Which metal cores made the strongest electromagnets? Why?
- Could your electromagnet pick up more paper clips when the batteries were connected in series or in parallel? Explain why.
- What combination of wire, metal core, and battery connection made the strongest electromagnet?



▶ Defending Your Conclusions

- Suppose someone tells you that your conclusion is invalid because each time you tested a magnet on the paper clips, the paper clips themselves became more and more magnetized. How could you show that your conclusion is valid?