Chapter 24

Magnetic Fields

What You'll Learn

- You will assign forces of attraction or repulsion between magnetic poles.
- You will relate magnetism to electric charge and electricity.
- You will describe how electromagnetism can be harnessed for practical applications.

Why It's Important

Magnetism is the basis for many technologies. Information on the hard drive of a computer is stored as a magnetic pattern.

Atom Smashers An accelerator tube, such as the one pictured, is surrounded by superconducting magnets. There is no magnetic field at the center of the tube where high-energy particles travel. If the particles stray from the center, they receive a magnetic push to keep them there.

Think About This ▶

How do forces applied by magnets cause particles to accelerate? Can any particle be accelerated?

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In which direction do magnetic fields act?

Question

What would be the direction of force on a magnetized object in a magnetic field?

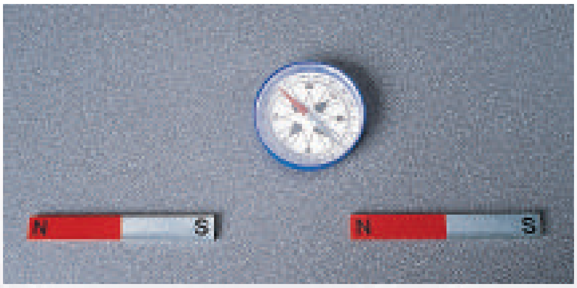
Procedure

1. Place a bar magnet horizontally in front of you so that the north pole faces left.
2. Place a second bar magnet horizontally next to, and 5.0 cm away from the first (you should be able to place the compass between the magnets). The north pole also should be facing the left.
3. Draw your setup on a sheet of paper. Be sure to label the poles.
4. Place a compass by the two magnets. Draw the direction the arrow is pointing.
5. Continue to move the compass to other positions, each time drawing the direction it points until you have drawn 15–20 arrows.
6. Repeat steps 3–5, this time with the two north poles facing each other.

Analysis

What did the red end of the compass needle typically point toward? Away from? Why might some of the arrows not point to either location stated in question 1?

Critical Thinking What you have diagrammed with your arrows is called a magnetic field. Recall what a gravitational field and an electric field are, and define *magnetic field.*



24.1 Magnets: Permanent and Temporary

The existence of magnets and magnetic fields has been known for more than 2000 years. Chinese sailors employed magnets as navigational compasses approximately 900 years ago. Throughout the world, early scientists studied magnetic rocks, called lodestones. Today, magnets play an increasingly important role in our everyday lives. Electric generators, simple electric motors, television sets, cathode-ray displays, tape recorders, and computer hard drives all depend on the magnetic effects of electric currents.

If you have ever used a compass or picked up tacks or paper clips with a magnet, you have observed some effects of magnetism. You even might have made an electromagnet by winding wire around a nail and connecting it to a battery. The properties of magnets become most obvious when you experiment with two of them. To enhance your study of magnetism, you can experiment with magnets, such as those shown in **Figure 24-1** on the next page.

▶ Objectives

- **Describe** the properties of magnets and the origin of magnetism in materials.
- **Compare and contrast** various magnetic fields.

▶ Vocabulary

polarized
magnetic fields
magnetic flux
first right-hand rule
solenoid
electromagnet
second right-hand rule
domain

■ **Figure 24-1** Common magnets are available in most hardware stores.

General Properties of Magnets

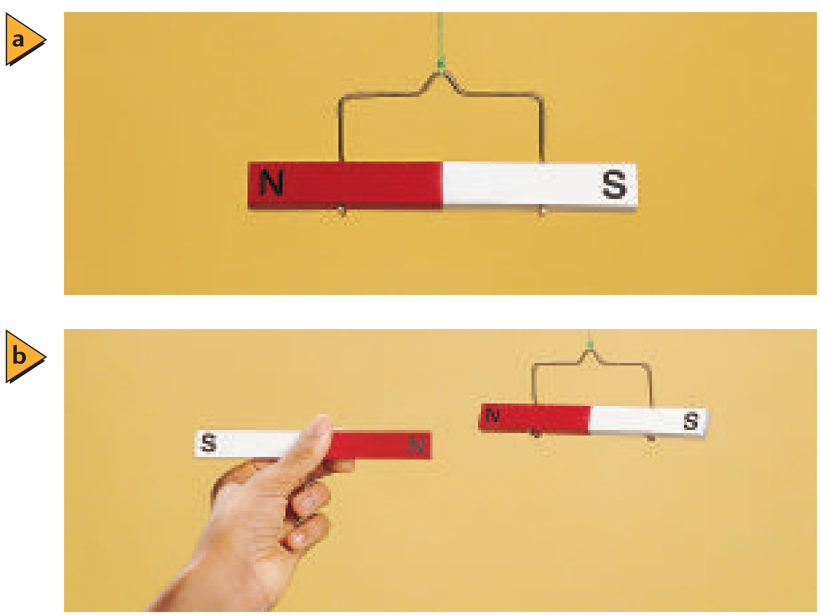
Suspend a magnet from a thread, as in **Figure 24-2a.** If you use a bar magnet, you might have to tie a yoke around it to keep it horizontal. When the magnet comes to rest, is it lined up in any particular direction? Now rotate the magnet so that it points in a different direction. When you release the magnet, does it come to rest in the same direction? If so, in which direction does it point?

You should have found that the magnet lined up in a north-south direction. Mark the end that points to the north with the letter *N* for reference. From this simple experiment, you can conclude that a magnet is **polarized;** that is, it has two distinct and opposite ends. One of the poles is the north-seeking pole; the other is the south-seeking pole. A compass is nothing more than a small magnet, mounted so that it is free to turn.

Suspend another magnet to determine the north end, and mark it as you did with the first magnet. While one magnet is suspended, observe the interaction of the two magnets by bringing the other magnet near, as in **Figure 24-2b.** What happens as you bring the two ends that were pointing north, the north poles, toward each other? Now try it with the south poles. Lastly, what happens as you bring opposite poles (the north pole of one magnet and the south pole of the other magnet) toward each other?

You should have observed that the two north poles repelled each other, as did the two south poles. However, the north pole of one magnet should have attracted the south pole of the other magnet. Like poles repel; unlike poles attract. Magnets always have two opposite magnetic poles. If you break a magnet in half, you create two smaller magnets, and each will have two poles. Scientists have tried to break magnets into separate north and south poles, called monopoles, but no one has succeeded, not even on the microscopic level.

Knowing that magnets always orient themselves in a north-south direction, it may occur to you that Earth itself is a giant magnet. Because opposite poles attract and the north pole of a compass magnet points north, the south pole of the Earth-magnet must be near Earth's geographic north pole.



■ **Figure 24-2** If you suspend a magnet by a thread, it will align itself with magnetic properties in Earth **(a).** The magnet's north pole will point north. If you then move the north pole of a second magnet toward the north pole of the suspended magnet, the suspended magnet will move away **(b).**

Horizons Companies

Figure 24-3 A common nail is attracted to a magnet. In the process, the nail itself becomes magnetized. Here you can see when a magnet is touching the nail, the nail is able to attract other metal objects. However, if you separate the magnet from the nail, some of the objects will drop off because the nail will have lost some of its magnetism.

How do magnets affect other materials? As you probably discovered as a child, magnets attract things besides other magnets, such as nails, tacks, paper clips, and many other metal objects. Unlike the interaction between two magnets, however, either end of a magnet will attract either end of a piece of metal. How can you explain this behavior? First, you can touch a magnet to a nail and then touch the nail to smaller metal pieces. The nail itself becomes a magnet, as shown in **Figure 24-3.** The magnet causes the nail to become polarized. The direction of polarization of the nail depends on the polarization of the magnet. If you pull away the magnet, the nail loses some of its magnetization and will no longer exhibit as much attraction for other metal objects.

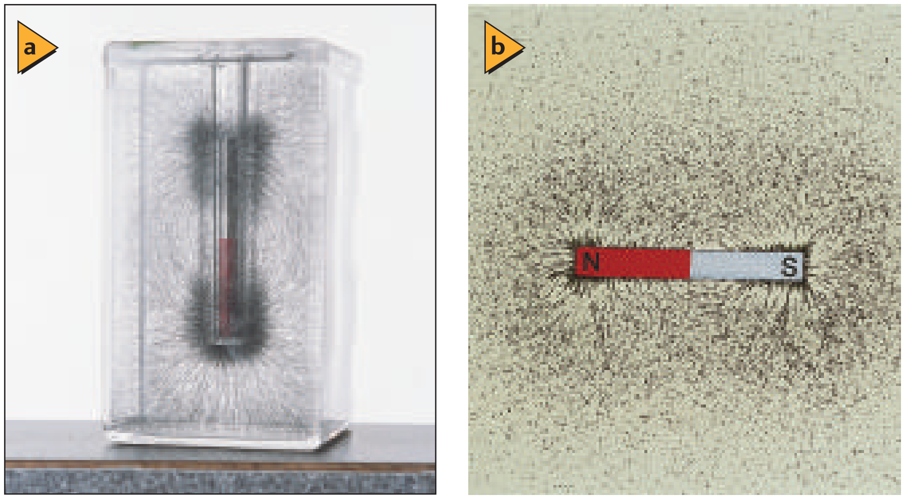
If you repeat the experiment shown in Figure 24-3 with a piece of soft iron (iron with a low carbon content) in place of a nail, you will notice that the iron loses all of its attraction for the other metal objects when the magnet is pulled away. This is because soft iron is a temporary magnet. A nail has other material in it to make it harder and allows it to retain some of its magnetism when a permanent magnet is pulled away.

Permanent magnets The magnetism of permanent magnets is produced in the same way in which you created the magnetism of the nail. Because of the microscopic structure of the magnet material, the induced magnetism becomes permanent. Many permanent magnets are made of an iron alloy called ALNICO V, that contains a mix of **al**uminum, **ni**ckel, and **co**balt. A variety of rare earth elements, such as neodymium and gadolinium, produce permanent magnets that are extremely strong for their size.

Magnetic Fields Around Permanent Magnets

When you experimented with two magnets, you noticed that the forces between magnets, both attraction and repulsion, occur not only when the magnets touch each other, but also when they are held apart. In the same way that long-range electric and gravitational forces can be described by electric and gravitational fields, magnetic forces can be described by the existence of fields around magnets. These **magnetic fields** are vector quantities that exist in a region in space where a magnetic force occurs.

Matt Meadows



■ **Figure 24-4** The magnetic field of a bar magnet shows up clearly in three dimensions when the magnet is suspended in glycerol with iron filings **(a).** It is, however, easier to set up a magnet on a sheet of paper covered with iron filings to see the pattern in two dimensions **(b).**

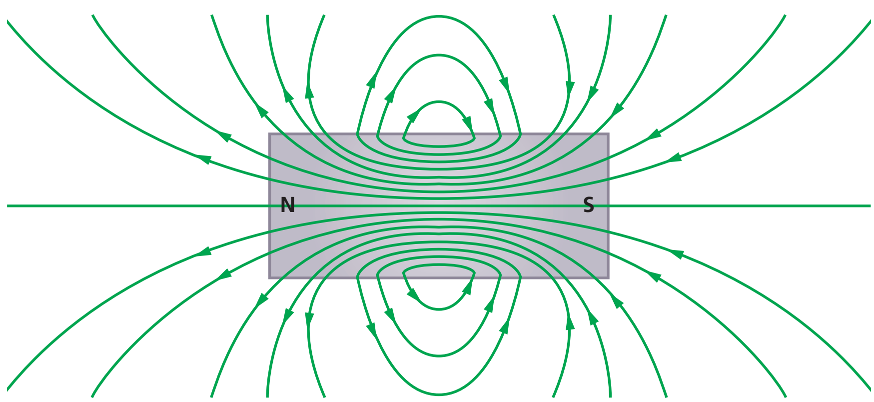
The presence of a magnetic field around a magnet can be shown using iron filings. Each long, thin, iron filing becomes a small magnet by induction. Just like a tiny compass needle, the iron filing rotates until it is parallel to the magnetic field. **Figure 24-4a** shows filings in a glycerol solution surrounding a bar magnet. The three-dimensional shape of the field is visible. In **Figure 24-4b,** the filings make up a two-dimensional plot of the field, which can help you visualize magnetic field lines. Filings also can show how the field can be distorted by an object.

Magnetic field lines Note that magnetic field lines, like electric field lines, are imaginary. They are used to help us visualize a field, and they also provide a measure of the strength of the magnetic field. The number of magnetic field lines passing through a surface is called the **magnetic flux.** The flux per unit area is proportional to the strength of the magnetic field. As you can see in Figure 24-4, the magnetic flux is most concentrated at the poles; thus, this is where the magnetic field strength is the greatest.

The direction of a magnetic field line is defined as the direction in which the north pole of a compass points when it is placed in the magnetic field. Outside the magnet, the field lines emerge from the magnet at its north pole and enter the magnet at its south pole, as illustrated in **Figure 24-5.** What happens inside the magnet? There are no isolated poles on which field lines can start or stop, so magnetic field lines always travel inside the magnet from the south pole to the north pole to form closed loops.

Color Convention

- Positive charges are **red.**
- Negative charges are **blue.**
- Electric field lines are **indigo.**
- Magnetic field lines are **green.**



■ **Figure 24-5** Magnetic field lines can be visualized as closed loops leaving the north pole of a magnet and entering the south pole of the same magnet.

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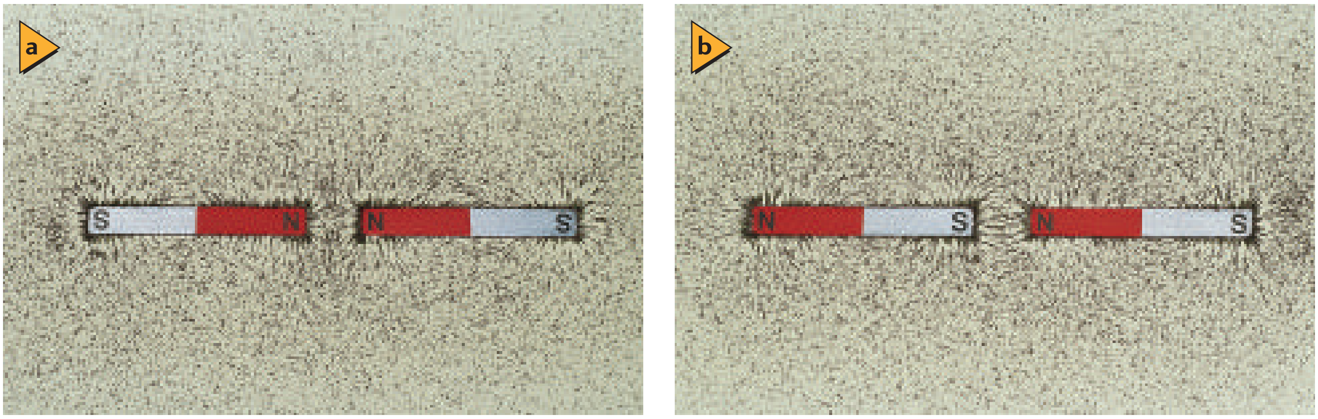


■ **Figure 24-6** The magnetic field lines indicated by iron filings on paper clearly show that like poles repel **(a)** and unlike poles attract **(b).** The iron filings do not form continuous lines between like poles. Between a north and a south pole, however, the iron filings show that field lines run directly between the two magnets.

What kinds of magnetic fields are produced by pairs of bar magnets? You can visualize these fields by placing two magnets on a sheet of paper, and then sprinkling the paper with iron filings. **Figure 24-6a** shows the field lines between two like poles. In contrast, two unlike poles (north and south) placed close together produce the pattern shown in **Figure 24-6b.** The filings show that the field lines between two unlike poles run directly from one magnet to the other.

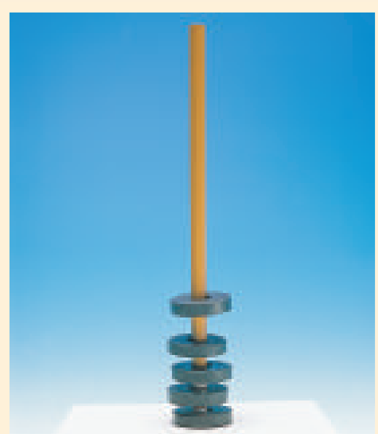
Forces on objects in magnetic fields Magnetic fields exert forces on other magnets. The field produced by the north pole of one magnet pushes the north pole of a second magnet away in the direction of the field line. The force exerted by the same field on the south pole of the second magnet is attractive in a direction opposite the field lines. The second magnet attempts to line up with the field, just like a compass needle.

When a sample made of iron, cobalt, or nickel is placed in the magnetic field of a permanent magnet, the field lines become concentrated within the sample. Lines leaving the north pole of the magnet enter one end of the sample, pass through it, and leave the other end. Thus, the end of the sample closest to the magnet's north pole becomes the sample's south pole, and the sample is attracted to the magnet.

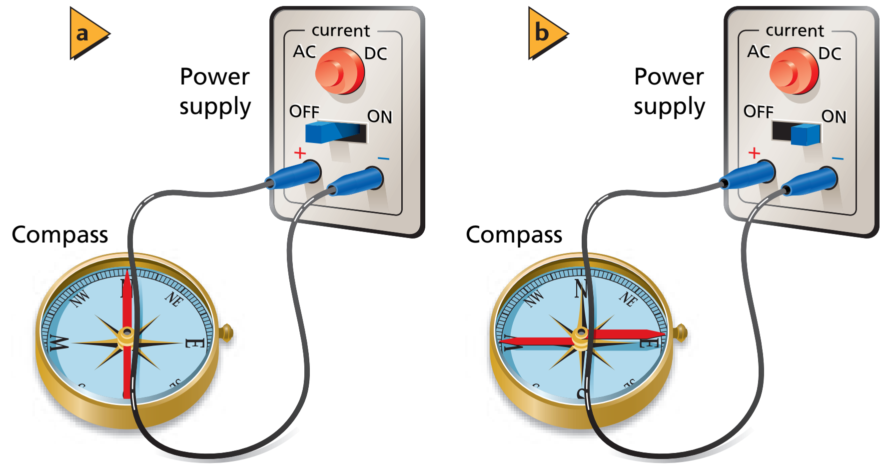
PRACTICE Problems

Additional Problems, Appendix B

1. If you hold a bar magnet in each hand and bring your hands close together, will the force be attractive or repulsive if the magnets are held in the following ways?
   a. the two north poles are brought close together
   b. a north pole and a south pole are brought together
2. **Figure 24-7** shows five disk magnets floating above each other. The north pole of the top-most disk faces up. Which poles are on the top side of each of the other magnets?
3. A magnet attracts a nail, which, in turn, attracts many small tacks, as shown in Figure 24-3 on page 645. If the north pole of the permanent magnet is the left end, as shown, which end of the nail is the south pole?
4. Why do magnetic compasses sometimes give false readings?



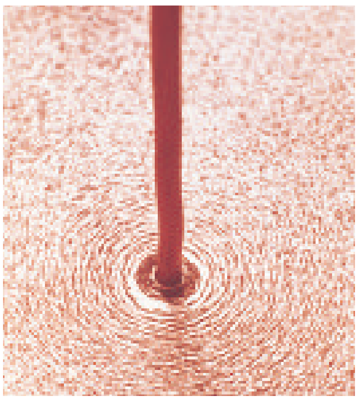
■ **Figure 24-7**



■ **Figure 24-8** Using an apparatus similar to the one shown **(a),** Oersted was able to demonstrate a connection between magnetism and electricity by applying current to the wire **(b).**

Electromagnetism

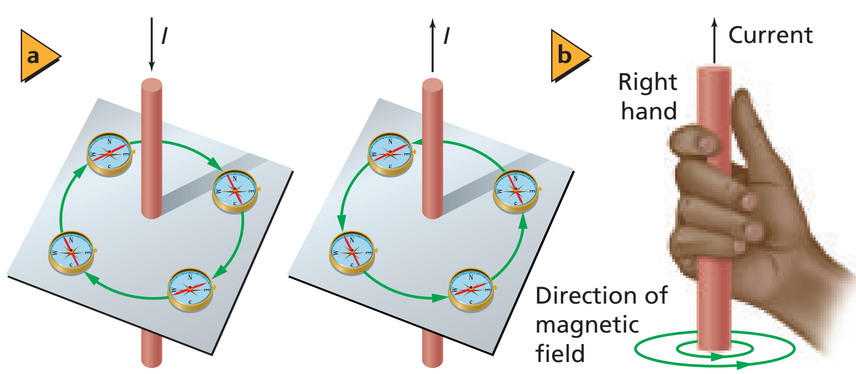
In 1820, Danish physicist Hans Christian Oersted was experimenting with electric currents in wires. Oersted laid a wire across the top of a small compass and connected the ends of the wire to complete an electrical circuit, as shown in **Figure 24-8a.** He had expected the needle to point toward the wire or in the same direction as the current in the wire. Instead, he was amazed to see that the needle rotated until it pointed perpendicular to the wire, as shown in **Figure 24-8b.** The forces on the compass magnet's poles were perpendicular to the direction of current in the wire. Oersted also found that when there was no current in the wire, no magnetic forces existed.



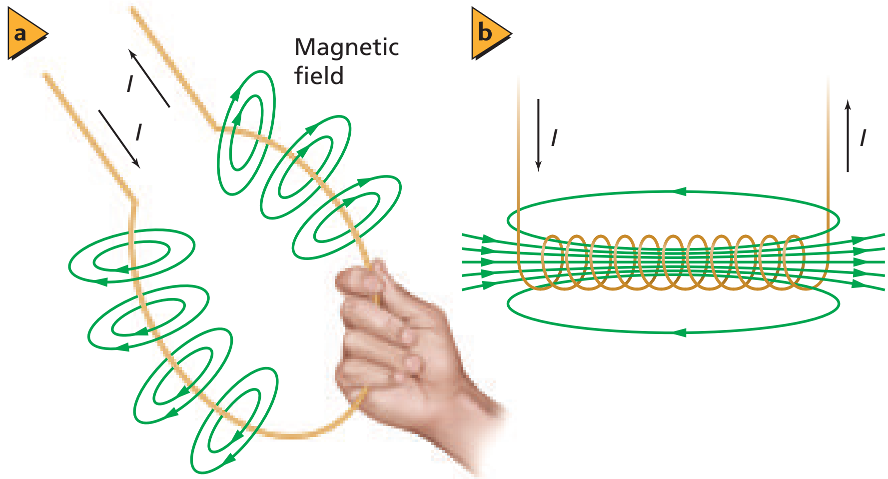
■ **Figure 24-9** The magnetic field produced by the current in a wire through a cardboard disk shows up as concentric circles of iron filings around the wire.

If a compass needle turns when placed near a wire carrying an electric current, it must be the result of a magnetic field created by the current. You easily can show the magnetic field around a current-carrying wire by placing a wire vertically through a horizontal piece of cardboard on which iron filings are sprinkled. When there is current through the wire, the filings will form a pattern of concentric circles, around the wire, as shown in **Figure 24-9.**

The circular lines indicate that magnetic field lines around current-carrying wires form closed loops in the same way that field lines about permanent magnets form closed loops. The strength of the magnetic field around a long, straight wire is proportional to the current in the wire. The strength of the field also varies inversely with the distance from the wire. A compass shows the direction of the field lines. If you reverse the direction of the current, the compass needle also reverses its direction, as shown in **Figure 24-10a.**



■ **Figure 24-10** The magnetic field produced by current in a straight-wire conductor reverses when the current in the wire is reversed **(a).** The first right-hand rule for a straight, current-carrying wire shows the direction of the magnetic field **(b).**



■ **Figure 24-11** The magnetic field around a circular loop of current-carrying wire can be modeled with the aid of the first right-hand rule **(a).** A current in a solenoid creates a magnetic field with the field from each coil adding to all the others **(b).**

The **first right-hand rule** is a method you can use to determine the direction of a magnetic field relative to the direction of conventional current. Imagine holding a length of insulated wire with your right hand. Keep your thumb pointed in the direction of the conventional (positive) current. The fingers of your hand circle the wire and point in the direction of the magnetic field, as illustrated in **Figure 24-10b.**

Magnetic field near a coil An electric current in a single circular loop of wire forms a magnetic field all around the loop. Applying the right-hand rule to any part of the wire loop, it can be shown that the direction of the field inside the loop is always the same. In **Figure 24-11a,** the field is always up, or out of the page. Outside the loop, it is always down, or into the page. When a wire is looped several times to form a coil and a current is allowed to flow through the coil, the field around all the loops is in the same direction, as shown in **Figure 24-11b.** A long coil of wire consisting of many loops is called a **solenoid.** The field from each loop in a solenoid adds to the fields of the other loops and creates a greater total field strength.

When there is an electric current in a coil of wire, the coil has a field similar to a permanent magnet. When this current-carrying coil is brought close to a suspended bar magnet, one end of the coil repels the north pole of the magnet. Thus, the current-carrying coil has a north and a south pole and is itself a magnet. This type of magnet, which is created when current flows through a wire coil, is called an **electromagnet.** The strength of the field is proportional to the current in the coil. The magnetic field produced by each loop is the same. Because these fields are in the same direction, increasing the number of loops increases the strength of the magnetic field.

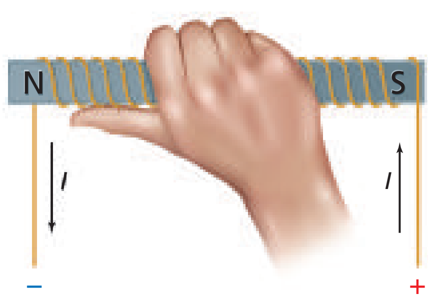
The strength of an electromagnet also can be increased by placing an iron rod or core inside the coil. The core supports the magnetic field better than air does. It increases the magnetic field because the field of the solenoid creates a temporary magnetic field in the core, just as a nearby permanent magnet does when brought near a metal object.

The **second right-hand rule** is a method you can use to determine the direction of the field produced by an electromagnet relative to the flow of conventional current. Imagine holding an insulated coil with your right hand. If you then curl your fingers around the loops in the direction of the conventional (positive) current, as in **Figure 24-12,** your thumb will point toward the north pole of the electromagnet.

APPLYING PHYSICS

▶ **Electromagnets** Cranes for moving iron and steel in industrial settings frequently use electromagnets. One such magnet, which operates at 230 V and draws 156 A, can lift over 11,300 kg! ◀

■ **Figure 24-12** The second right-hand rule can be used to determine the polarity of an electromagnet.



PRACTICE Problems

Additional Problems, Appendix B

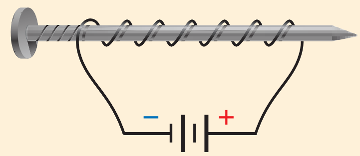
5. A long, straight, current-carrying wire runs from north to south.

- **a.** A compass needle placed above the wire points with its north pole toward the east. In what direction is the current flowing?
- **b.** If a compass is put underneath the wire, in which direction will the compass needle point?

6. How does the strength of a magnetic field, 1 cm from a current-carrying wire, compare with each of the following?

- **a.** the strength of the field that is 2 cm from the wire
- **b.** the strength of the field that is 3 cm from the wire

7. A student makes a magnet by winding wire around a nail and connecting it to a battery, as shown in **Figure 24-13.** Which end of the nail, the pointed end or the head, will be the north pole?



■ **Figure 24-13**

8. You have a spool of wire, a glass rod, an iron rod, and an aluminum rod. Which rod should you use to make an electromagnet to pick up steel objects? Explain.

9. The electromagnet in problem 8 works well, but you decide that you would like to make its strength adjustable by using a potentiometer as a variable resistor. Is this possible? Explain.

A Microscopic Picture of Magnetic Materials

Recall that when you put a piece of iron, nickel, or cobalt next to a magnet, the element also becomes magnetic, and it develops north and south poles. The magnetism, however, is only temporary. The creation of this temporary polarity depends on the direction of the external field. When you take away the external field, the element loses its magnetism. The three elements—iron, nickel, and cobalt—behave like electromagnets in many ways. They have a property called ferromagnetism.

In the early nineteenth century, French scientist André-Marie Ampère knew that the magnetic effects of an electromagnet are the result of electric current through its loops. He proposed a theory of magnetism in iron to explain this behavior. Ampère reasoned that the effects of a bar magnet must result from tiny loops of current within the bar.

Magnetic domains Although the details of Ampère's reasoning were wrong, his basic idea was correct. Each electron in an atom acts like a tiny electromagnet. When the magnetic fields of the electrons in a group of neighboring atoms are all aligned in the same direction, the group is called a **domain.** Although they may contain 10^{20} individual atoms, domains are still very small—usually from 10 to 1000 microns. Thus, even a small sample of iron contains a huge number of domains.

When a piece of iron is not in a magnetic field, the domains point in random directions, and their magnetic fields cancel one another out. If, however, a piece of iron is placed in a magnetic field, the domains tend to align with the external field, as shown in **Figure 24-14.** In the case of a temporary magnet, after the external field is removed, the domains return to their random arrangement. In a permanent magnet, the iron has been alloyed with other substances to keep the domains aligned after the external magnetic field is removed.

MINI LAB

3-D Magnetic Fields

Tie a string to the middle of a nail so that the nail will hang horizontally. Put a small piece of tape around the string where it wraps around the nail so that the string will not slip. Insert the nail into a coil and apply a voltage to the coil. Turn off the power and remove the nail from the coil. Now hold the string to suspend the nail.

1. Predict how the nail will behave in the presence of a permanent magnet.

2. Test your prediction.

Analyze and Conclude

3. Explain what evidence you have that the nail became magnetized.

4. Make a 3-D drawing that shows the magnetic field around the magnet.

Recording media Electromagnets make up the recording heads of audiocassette and videotape recorders. Recorders create electrical signals that represent the sounds or pictures being recorded. The electric signals produce currents in the recording head that create magnetic fields. When magnetic recording tape, which has many tiny bits of magnetic material bonded to thin plastic, passes over the recording head, the domains of the bits are aligned by the magnetic fields of the head. The directions of the domains' alignments depend on the direction of the current in the head and become a magnetic record of the sounds or pictures being recorded. The magnetic material on the tape allows the domains to keep their alignments until a strong enough magnetic field is applied to change them again. On a playback of the tape, the signal, produced by currents generated as the head passes over the magnetic particles, goes to an amplifier and a pair of loudspeakers or earphones. When a previously recorded tape is used to record new sounds, an erase head produces a rapidly alternating magnetic field that randomizes the directions of the domains on the tape.

A magnetic history of the Earth Rocks containing iron have recorded the history of the varying directions of Earth's magnetic field. Rocks on the seafloor were produced when molten rock poured out of cracks in the bottom of the oceans. As they cooled, the rocks were magnetized in the direction of Earth's field at the time. As a result of seafloor spreading, the rocks farther from the cracks are older than those near the cracks. Scientists who first examined seafloor rocks were surprised to find that the direction of the magnetization in different rocks varied. They concluded from their data that the north and south magnetic poles of Earth have exchanged places many times in Earth's history. The origin of Earth's magnetic field is not well understood. How this field might reverse direction is even more of a mystery.

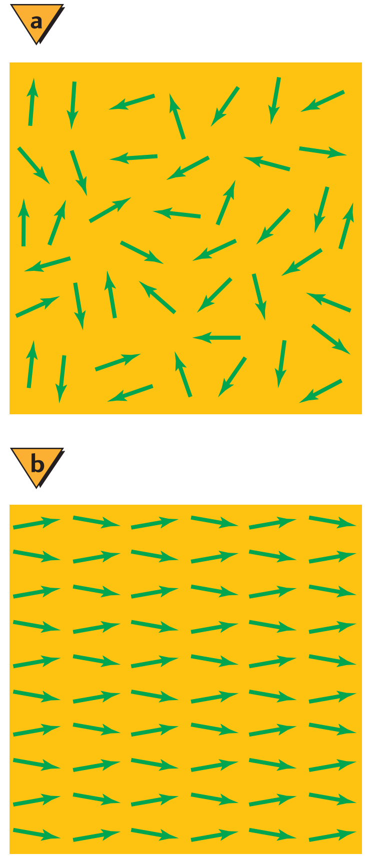


Figure 24-14 A piece of iron **(a)** becomes a magnet only when its domains align **(b).**

24.1 Section Review

10. Magnetic Fields Is a magnetic field real, or is it just a means of scientific modeling?

11. Magnetic Forces Identify some magnetic forces around you. How could you demonstrate the effects of those forces?

12. Magnetic Fields A current-carrying wire is passed through a card on which iron filings are sprinkled. The filings show the magnetic field around the wire. A second wire is close to and parallel to the first wire. There is an identical current in the second wire. If the two currents are in the same direction, how will the first magnetic field be affected? How will it be affected if the two currents are in opposite directions?

13. Direction of a Magnetic Field Describe the right-hand rule used to determine the direction of a magnetic field around a straight, current-carrying wire.

14. Electromagnets A glass sheet is placed over an active electromagnet, and iron filings sprinkled on the sheet create a pattern on it. If this experiment is repeated with the polarity of the power supply reversed, what observable differences will result? Explain.

15. Critical Thinking Imagine a toy containing two parallel, horizontal metal rods, one above the other. The top rod is free to move up and down.

a. The top rod floats above the lower one. If the top rod's direction is reversed, however, it falls down onto the lower rod. Explain why the rods could behave in this way.

b. Assume that the top rod was lost and replaced with another one. In this case, the top rod falls on top of the bottom rod no matter what its orientation is. What type of replacement rod must have been used?

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24.2 Forces Caused by Magnetic Fields

▶ **Objectives**

- **Relate** magnetic induction to the direction of the force on a current-carrying wire in a magnetic field.
- **Solve** problems involving magnetic field strength and the forces on current-carrying wires, and on moving, charged particles in magnetic fields.
- **Describe** the design and operation of an electric motor.

▶ **Vocabulary**

third right-hand rule
galvanometer
electric motor
armature

As you learned in the previous section, while Ampère was studying the behaviors of magnets, he noted that an electric current produces a magnetic field similar to that of a permanent magnet. Because a magnetic field exerts forces on permanent magnets, Ampère hypothesized that there is also a force on a current-carrying wire when it is placed in a magnetic field.

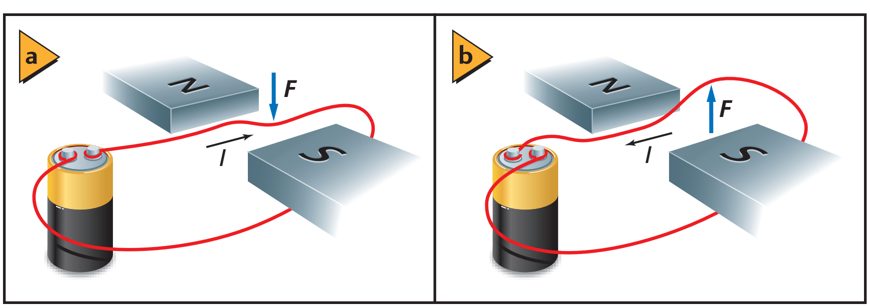
Forces on Currents in Magnetic Fields

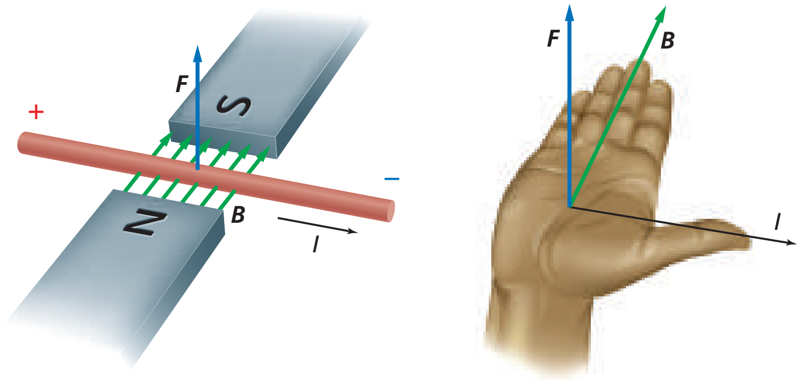
The force on a wire in a magnetic field can be demonstrated using the arrangement shown in **Figure 24-15.** A battery produces current in a wire directly between two bar magnets. Recall that the direction of the magnetic field between two magnets is from the north pole of one magnet to the south pole of the other magnet. When there is a current in the wire, a force is exerted on the wire. Depending on the direction of the current, the force on the wire either pushes it down, as shown in **Figure 24-15a,** or pulls it up, as shown in **Figure 24-15b.** Michael Faraday discovered that the force on the wire is at right angles to both the direction of the magnetic field and the direction of the current.

Determining the force's direction Faraday's description of the force on a current-carrying wire does not completely describe the direction because the force can be upward or downward. The direction of the force on a current-carrying wire in a magnetic field can be found by using **the third right-hand rule.** This technique is illustrated in **Figure 24-16.** The magnetic field is represented by the symbol $\boldsymbol{B}$, and its direction is represented by a series of arrows. To use the third right-hand rule, point the fingers of your right hand in the direction of the magnetic field, and point your thumb in the direction of the conventional (positive) current in the wire. The palm of your hand will be facing in the direction of the force acting on the wire. When drawing a directional arrow that is into or out of the page, direction is indicated with crosses and dots, respectively. Think of the crosses as the tail feathers of the arrow, and the dots as the arrowhead.

Soon after Oersted announced his discovery that the direction of the magnetic field in a wire is perpendicular to the flow of electric current in the wire, Ampère was able to demonstrate the forces that current-carrying wires exert on each other. **Figure 24-17a** shows the direction of the magnetic field around each of the current-carrying wires, which is determined by the first right-hand rule. By applying the third right-hand rule to either wire, you can show why the wires attract each other. **Figure 24-17b** demonstrates the opposite situation. When currents are in opposite directions, the wires have a repulsive force between them.

■ **Figure 24-15** Current-carrying wires experience forces when they are placed in magnetic fields. In this case the force can be down **(a),** or up **(b),** depending on the direction of the current.





■ **Figure 24-16** The third right-hand rule can be used to determine the direction of force when the current and magnetic field are known.

Force on a wire resulting from a magnetic field It is possible to determine the force of magnetism exerted on a current-carrying wire passing through a magnetic field at right angles to the wire. Experiments show that the magnitude of the force, F, on the wire, is proportional to the strength of the field, B, the current, I, in the wire, and the length, L, of the wire in the magnetic field. The relationship of these four factors is as follows:

Force on a Current-Carrying Wire in a Magnetic Field $F = ILB$

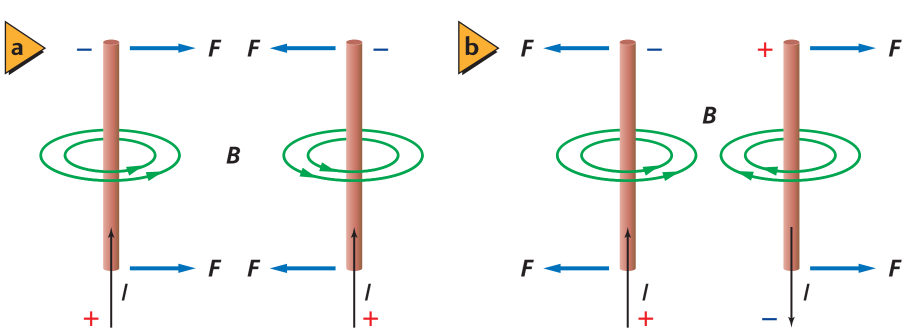
The force on a current-carrying wire in a magnetic field is equal to the product of magnetic field strength, the current, and the length of the wire.

The strength of a magnetic field, B, is measured in teslas, T. 1 T is equivalent to 1 N/A·m.

Note that if the wire is not perpendicular to the magnetic field, a factor of $\sin\theta$ is introduced in the above equation, resulting in $F = ILB \sin\theta$. As the wire becomes parallel to the magnetic field, the angle θ becomes zero, and the force is reduced to zero. When $\theta = 90°$, the equation is again $F = ILB$.

Loudspeakers

One use of the force on a current-carrying wire in a magnetic field is in a loudspeaker. A loudspeaker changes electric energy to sound energy using a coil of fine wire mounted on a paper cone and placed in a magnetic field. The amplifier driving the loudspeaker sends a current through the coil. The current changes direction between 20 and 20,000 times each second, depending on the pitch of the tone it represents. A force exerted on the coil, because it is in a magnetic field, pushes the coil either into or out of the field, depending on the direction of the current. The motion of the coil causes the cone to vibrate, thereby creating sound waves in the air.



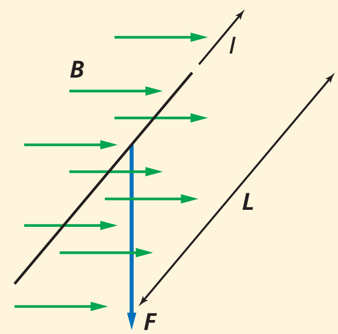
■ **Figure 24-17** Two current-carrying conductors are attracted when the currents are in the same direction **(a),** and are repelled when the currents are in opposite directions **(b).**

EXAMPLE Problem 1

Calculate the Strength of a Magnetic Field A straight wire carrying a 5.0-A current is in a uniform magnetic field oriented at right angles to the wire. When 0.10 m of the wire is in the field, the force on the wire is 0.20 N. What is the strength of the magnetic field, *B*?

1 Analyze and Sketch the Problem

- Sketch the wire and show the direction of the current with an arrow, the magnetic field lines labeled *B*, and the force on the wire, *F*.
- Determine the direction of the force using the third right-hand rule. The field, wire, and force are all at right angles.



Known:	Unknown:
$I = 5.0$ A	$B = ?$
$L = 0.10$ m	
$F = 0.20$ N	

2 Solve for the Unknown

B is uniform and because *B* and *I* are perpendicular to each other, $F = ILB$.

$$F = ILB$$

Solve for *B*.

$$B = \frac{F}{IL}$$

$$= \frac{0.20\ \text{N}}{(5.0\ \text{A})(0.10\ \text{m})}$$ Substitute $F = 0.20$ N, $I = 5.0$ A, $L = 0.10$ m

$$= 0.40\ \text{N/A·m} = 0.40\ \text{T}$$

B is 0.40 T from left to right and perpendicular to *I* and *F*.

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Operations with Significant Digits
pages 835–836

3 Evaluate the Answer

- **Are the units correct?** The answer is in teslas, the correct unit for a magnetic field.
- **Is the magnitude realistic?** The current and the length make the magnetic field fairly large, which is realistic.

PRACTICE Problems

Additional Problems, Appendix B

16. What is the name of the rule used to predict the direction of force on a current-carrying wire at right angles to a magnetic field? Identify what must be known to use this rule.

17. A wire that is 0.50 m long and carrying a current of 8.0 A is at right angles to a 0.40-T magnetic field. How strong is the force that acts on the wire?

18. A wire that is 75 cm long, carrying a current of 6.0 A, is at right angles to a uniform magnetic field. The magnitude of the force acting on the wire is 0.60 N. What is the strength of the magnetic field?

19. A 40.0-cm-long copper wire carries a current of 6.0 A and weighs 0.35 N. A certain magnetic field is strong enough to balance the force of gravity on the wire. What is the strength of the magnetic field?

20. How much current will be required to produce a force of 0.38 N on a 10.0 cm length of wire at right angles to a 0.49-T field?

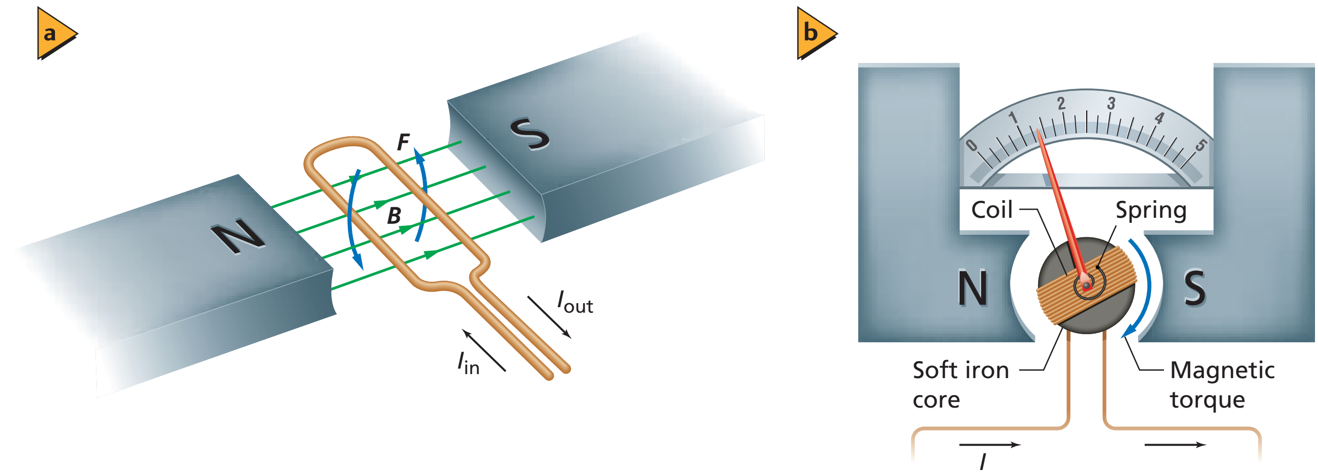


Figure 24-18 If a wire loop is placed in a magnetic field when there is a current, the loop will rotate **(a).** The coil in a galvanometer rotates in proportion to the magnitude of the current **(b).**

Galvanometers

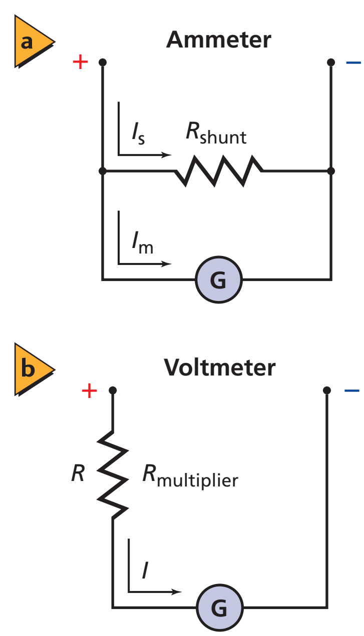
The forces exerted on a loop of wire in a magnetic field can be used to measure current. If a small loop of current-carrying wire is placed in the strong magnetic field of a permanent magnet, as in **Figure 24-18a,** it is possible to measure very small currents. The current passing through the loop goes in one end of the loop and out the other end. Applying the third right-hand rule to each side of the loop, note that one side of the loop is forced down, while the other side of the loop is forced up. The resulting torque rotates the loop, and the magnitude of the torque acting on the loop is proportional to the magnitude of the current. This principle is used in a galvanometer. A **galvanometer** is a device used to measure very small currents, and therefore, it can be used as a voltmeter or an ammeter.

A small spring in the galvanometer exerts a torque that opposes the torque that results from the flow of current through the wire loop; thus, the amount of rotation is proportional to the current. The meter is calibrated by finding out how much the coil turns when a known current is sent through it, as shown in **Figure 24-18b.** The galvanometer can then be used to measure unknown currents.

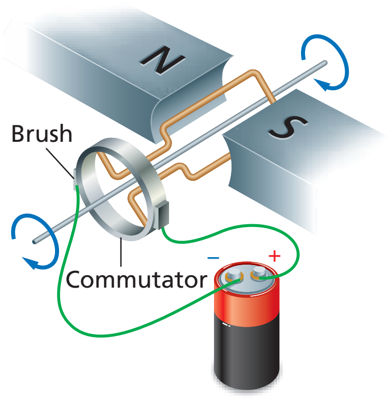
Many galvanometers produce full-scale deflections with as little as 50 μA (50×10^{-6} A) of current. The resistance of the coil of wire in a sensitive galvanometer is about 1000 Ω. To measure larger currents, a galvanometer can be converted into an ammeter by placing a resistor with resistance smaller than the galvanometer in parallel with the meter, as shown in **Figure 24-19a.** Most of the current, I_s, passes through the resistor, called the shunt, because the current is inversely proportional to resistance; whereas only a few microamps, I_m, flow through the galvanometer. The resistance of the shunt is chosen according to the desired deflection scale.

A galvanometer also can be connected as a voltmeter. To make a voltmeter, a resistor, called the multiplier, is placed in series with the meter, as shown in **Figure 24-19b.** The galvanometer measures the current through the multiplier. The current is represented by $I = V/R$, where V is the voltage across the voltmeter and R is the effective resistance of the galvanometer and the multiplier resistor. Now suppose you want the needle of a voltmeter to move across the entire scale when 10 V is placed across it. The resistor is chosen so that at 10 V, the meter is deflected full-scale by the current through the meter and the resistor.

Figure 24-19 A galvanometer is connected for use as an ammeter **(a),** and a galvanometer is connected for use as a voltmeter **(b).**



■ **Figure 24-20** In an electric motor, split-ring commutators allow the current in the wire loops to change direction and thus enable the loops in the motor to rotate 360°.



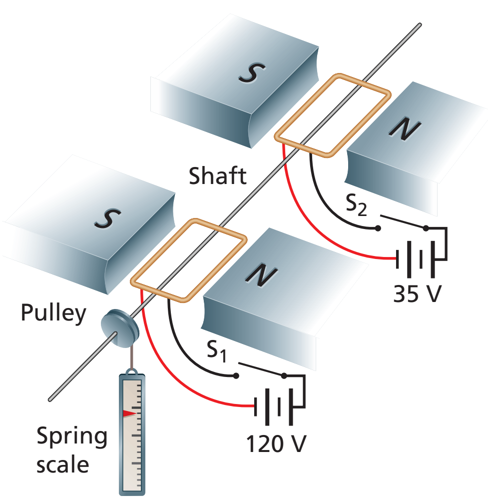
Electric motors You have seen how the simple loop of wire used in a galvanometer cannot rotate more than 180°. The forces push the right side of the loop up and the left side of the loop down until the loop reaches the vertical position. The loop will not continue to turn because the forces are still up and down, now parallel to the loop, and can cause no further rotation.

How can you allow the loop to continue to rotate? The current through the loop must reverse direction just as the loop reaches its vertical position. This reversal allows the loop to continue rotating, as illustrated in **Figure 24-20.** To reverse current direction, an electric connection is made between contacts, called brushes, and a ring that is split into two halves, called a split-ring commutator. Brushes, which are usually pieces of graphite, make contact with the commutator and allow current to flow into the loop. As the loop rotates, so does the commutator. The split ring is arranged so that each half of the commutator changes brushes just as the loop reaches the vertical position. Changing brushes reverse the current in the loop. As a result, the direction of the force on each side of the loop is reversed, and the loop continues to rotate. This process repeats at each half-turn, causing the loop to spin in the magnetic field. The result is an **electric motor,** which is an apparatus that converts electric energy into rotational kinetic energy.

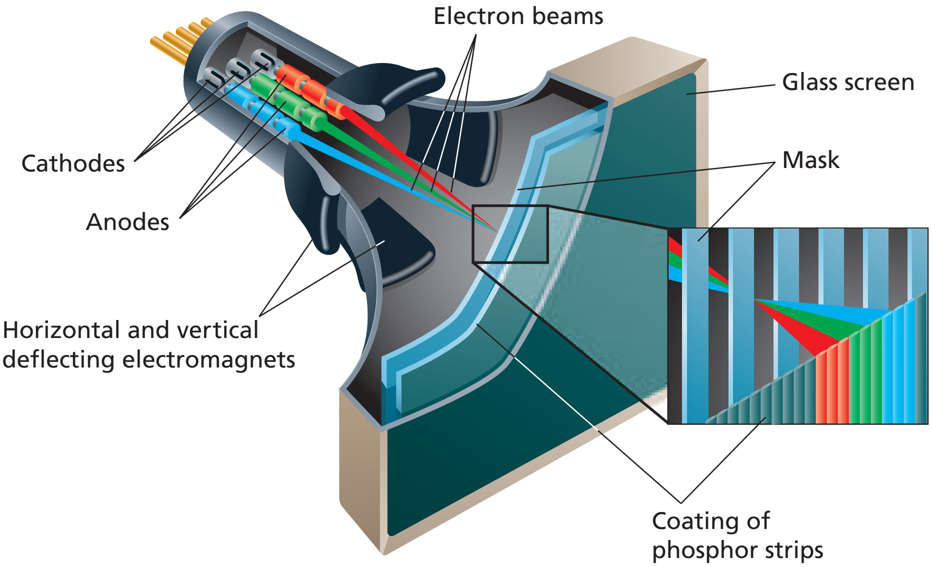
Although only one loop is indicated in Figure 24-20, in an electric motor, the wire coil, called the **armature,** is made of many loops mounted on a shaft or axle. The total force acting on the armature is proportional to $nILB$, where n is the total number of turns on the armature, B is the strength of the magnetic field, I is the current, and L is the length of wire in each turn that moves through the magnetic field. The magnetic field is produced either by permanent magnets or by an electromagnet, called a field coil. The torque on the armature, and, as a result, the speed of the motor, is controlled by varying the current through the motor.

CHALLENGE **PROBLEM**

The figure shows two identical motors with a common shaft. For simplicity, the commutators are not shown. Each armature coil consists of 48 turns of wire with rectangular dimensions of 17 cm wide by 35 cm deep. The armature resistance is 12 Ω. The red wire travels to the left (along half the width) and then back to the rear of the motor (along the depth). The magnetic field is 0.21 T. The diameter of the pulley is 7.2 cm. A rope fixed to the pulley and the floor prevents the motor shaft from turning.



1. Given $F = ILB$, derive an equation for the torque on the armature for the position shown.
2. With S_1 closed and S_2 open, determine the torque on the shaft and the force on the spring scale.
3. With both switches closed, determine the torque on the shaft and the force on the spring scale.
4. What happens to torque if the armature is in a different position?



■ **Figure 24-21** Pairs of magnets deflect the electron beam vertically and horizontally to form pictures for viewing.

The Force on a Single Charged Particle

Charged particles do not have to be confined to a wire. They also can move in a vacuum where the air particles have been removed to prevent collisions. A picture tube, also called a cathode-ray tube, in a computer monitor or television set uses electrons deflected by magnetic fields to form the pictures on the screen, as illustrated in **Figure 24-21.** Electric fields pull electrons off atoms in the negative electrode, or cathode. Other electric fields gather, accelerate, and focus the electrons into a narrow beam. Magnetic fields control the motion of the beam back-and-forth and up-and-down across the screen. The screen is coated with a phosphor that glows when it is struck by the electrons, thereby producing the picture.

The force produced by a magnetic field on a single electron depends on the velocity of the electron, the strength of the field, and the angle between directions of the velocity and the field. Consider a single electron moving in a wire of length L. The electron is moving perpendicular to the magnetic field. The current, I, is equal to the charge per unit time entering the wire, $I = q/t$. In this case, q is the charge of the electron and t is the time it takes to move the distance, L. The time required for a particle with speed v to travel distance L is found by using the equation of motion, $d = vt$, or, in this case, $t = L/v$. As a result, the equation for the current, $I = q/t$, can be replaced by $I = qv/L$. Therefore, the force on a single electron moving perpendicular to a magnetic field of strength B can be found.

Force of a Magnetic Field on a Charged, Moving Particle $F = qvB$

The force on a particle moving in a magnetic field is equal to the product of the field strength, the charge of the particle, and its velocity.

The particle's charge is measured in coulombs, C, its velocity in meters per second, m/s, and the strength of the magnetic field in teslas, T.

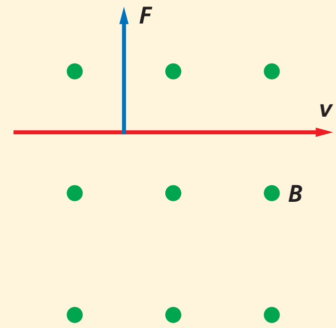
The direction of the force is perpendicular to both the velocity of the particle and the magnetic field. The direction given by the third right-hand rule is for positively charged particles. For electrons, the force is in the opposite direction.

▶ EXAMPLE Problem 2

Force on a Charged Particle in a Magnetic Field A beam of electrons travels at 3.0×10^{6} m/s through a uniform magnetic field of 4.0×10^{-2} T at right angles to the field. How strong is the force acting on each electron?

1 Analyze and Sketch the Problem

- Draw the beam of electrons and its direction of motion; the magnetic field of lines, labeled *B;* and the force on the electron beam, *F.* Remember that the force is opposite the force given by the third right-hand rule because of the electron's negative charge.



Known:

$v = 3.0\times10^{6}$ m/s

$B = 4.0\times10^{-2}$ T

$q = -1.60\times10^{-19}$ C

Unknown:

$F = ?$

2 Solve for the Unknown

$$F = qvB$$
$$= (-1.60\times10^{-19}\text{ C})(3.0\times10^{6}\text{ m/s})(4.0\times10^{-2}\text{ T})$$
$$= -1.9\times10^{-14}\text{ N}$$

Substitute $q = -1.60\times10^{-19}$ C, $v = 3.0\times10^{6}$ m/s, $B = 4.0\times10^{-2}$ T

3 Evaluate the Answer

- **Are the units correct?** T = N/(A·m), and A = C/s; so T = N·s/(C·m). Thus, (T·C·m)/s = N, the unit for force.
- **Does the direction make sense?** Use the third right-hand rule to verify that the directions of the forces are correct, recalling that the force on the electron is opposite the force given by the third right-hand rule.
- **Is the magnitude realistic?** Forces on electrons and protons are always small fractions of a newton.

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Operations with Scientific Notation pages 842–843

▶ PRACTICE Problems

Additional Problems, Appendix B

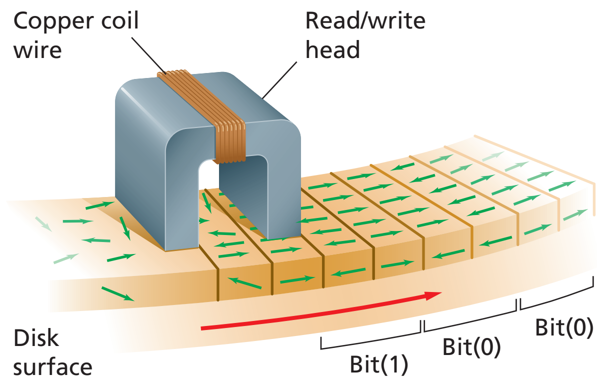
21. In what direction does the thumb point when using the third right-hand rule for an electron moving at right angles to a magnetic field?

22. An electron passes through a magnetic field at right angles to the field at a velocity of 4.0×10^{6} m/s. The strength of the magnetic field is 0.50 T. What is the magnitude of the force acting on the electron?

23. A stream of doubly ionized particles (missing two electrons, and thus, carrying a net charge of two elementary charges) moves at a velocity of 3.0×10^{4} m/s perpendicular to a magnetic field of 9.0×10^{-2} T. What is the magnitude of the force acting on each ion?

24. Triply ionized particles in a beam carry a net positive charge of three elementary charge units. The beam enters a magnetic field of 4.0×10^{-2} T. The particles have a speed of 9.0×10^{6} m/s. What is the magnitude of the force acting on each particle?

25. Doubly ionized helium atoms (alpha particles) are traveling at right angles to a magnetic field at a speed of 4.0×10^{4} m/s. The field strength is 5.0×10^{-2} T. What force acts on each particle?



■ **Figure 24-22** Information is written to a computer disk by changing the magnetic field in a read/write head as the media passes beneath it. This causes magnetic particles in the media to align themselves in a pattern that represents the stored information.

Storing Information with Magnetic Media

Data and software commands for computers are processed digitally in bits. Each bit is identified as either a 0 or a 1. How are these bits stored? The surface of a computer storage disk is covered with an even distribution of magnetic particles within a film. The direction of the particles' domains changes in response to a magnetic field. During recording onto the disk, current is routed to the disk drive's read/write head, which is an electromagnet composed of a wire-wrapped iron core. The current through the wire induces a magnetic field in the core.

When the read/write head passes over the spinning storage disk, as in **Figure 24-22,** the domains of atoms in the magnetic film line up in bands. The orientation of the domains depends on the direction of the current.

Two bands code for one bit of information. Two bands magnetized with the poles oriented in the same direction represent 0. Two bands represent 1 with poles oriented in opposite directions. The recording current always reverses when the read/write head begins recording the next data bit.

To retrieve data, no current is sent to the read/write head. Rather, the magnetized bands in the disk induce current in the coil as the disk spins beneath the head. Changes in the direction of the induced current are sensed by the computer and interpreted as 0's and 1's.

24.2 Section Review

26. **Magnetic Forces** Imagine that a current-carrying wire is perpendicular to Earth's magnetic field and runs east-west. If the current is east, in which direction is the force on the wire?

27. **Deflection** A beam of electrons in a cathode-ray tube approaches the deflecting magnets. The north pole is at the top of the tube; the south pole is on the bottom. If you are looking at the tube from the direction of the phosphor screen, in which direction are the electrons deflected?

28. **Galvanometers** Compare the diagram of a galvanometer in Figure 24-18 on page 655 with the electric motor in Figure 24-20 on page 656. How is the galvanometer similar to an electric motor? How are they different?

29. **Motors** When the plane of the coil in a motor is perpendicular to the magnetic field, the forces do not exert a torque on the coil. Does this mean that the coil does not rotate? Explain.

30. **Resistance** A galvanometer requires 180 μA for full-scale deflection. What is the total resistance of the meter and the multiplier resistor for a 5.0-V full-scale deflection?

31. **Critical Thinking** How do you know that the forces on parallel current-carrying wires are a result of magnetic attraction between wires, and not a result of electrostatics? *Hint: Consider what the charges are like when the force is attractive. Then consider what the forces are when three wires carry currents in the same direction.*

Physics Online physicspp.com/self_check_quiz

PHYSICS LAB • Design Your Own

Creating an Electromagnet

An electromagnet uses the magnetic field generated by a current to magnetize a piece of metal. In this activity, you will construct an electromagnet and test one variable that you think might affect the strength of it.

QUESTION

What is one variable that determines the strength of an electromagnet?

Objectives

- **Hypothesize** which variables might affect the strength of an electromagnet.
- **Observe** the effects on an electromagnet's strength.
- **Collect and organize data** comparing the chosen variable and magnet strength.
- **Make and use graphs** to help identify a relationship between a controlling variable and a responding variable.
- **Analyze and conclude** what the effect is of the chosen variable on magnet strength.

Safety Precautions

Possible Materials

large paper clips
small paper clips
steel BBs
wire
steel nail
6-V lantern batteries
9-V batteries
DC power source

Procedure

1. List the materials you will use to make your electromagnet.
2. List all the possible variables you think could affect the strength of an electromagnet.
3. Choose the one variable you will vary to determine whether it does, in fact, affect the strength of an electromagnet.
4. Determine a method to detect the strength of the magnetic field produced by the electromagnet.
5. Have your teacher approve your lists before continuing.
6. Write a brief procedure for your experiment. Be sure to include all the values for the variables you will be keeping constant.
7. Create a data table like the one on the following page that displays the two quantities you will measure.
8. Build your electromagnet by using a nail and a length of wire. Wrap the wire around the nail. Be sure to leave several inches from both ends of the wire sticking out from your coil to allow attachment to the power source. ***CAUTION: The end of the nail or wire may be sharp. Exercise care when handling these materials to avoid being cut or scraped.***

Horizons Companies
CONTENTS

Data Table	
Number of ________________	Number of ________________

9. Have your teacher inspect your magnet before continuing.
10. Perform your experiment and record your data. ***CAUTION: If you are using BBs in your experiment, avoid possible injury by immediately picking up any BBs that should happen to fall to the floor.***

Analyze

1. **Make and Use Graphs** Create a graph showing the relationship between your two variables.
2. What were the variables that you attempted to control in this experiment? Were there any you were unable to control?
3. If you evaluated the strength of the electromagnet by the amount of material it could pick up, how did you try to control any error from the magnet attracting only whole numbers of objects?

Conclude and Apply

1. What is the relationship between your chosen variable and the strength of a magnet?
2. What variables did other students in your class find that also affected the strength of an electromagnet?
3. Were there any variables, by any group, that were found not to affect the strength of the electromagnet?

Going Further

1. Compare the various variables students found that affected magnet strength. Did any of the variables appear to greatly increase strength without much change in the independent variable? If so, which ones?
2. If you wanted to increase magnet strength, which method seems the most cost effective? Explain.
3. If you need to easily vary the strength of an electromagnet, how would you suggest that be done?

Real-World Physics

1. If you needed to create a stronger electromagnet for use in a small space, such as inside a laptop computer, what method would you use to increase the electromagnetic strength, given the size constraints?
2. Some buildings have electromagnets to hold fire doors open when the building is occupied. These magnets are mounted to the wall, like a door stop, behind the door. Thinking about the actions a fire alarm system would need to perform to control a fire, what is the advantage of using a system like this to hold the doors? How might a system like this be an advantage, or a disadvantage, in the event of a natural disaster?
3. Some electric bells work by having an arm strike the side of a metal dome-shaped bell. How might an electromagnet be used to make this bell work? How might the bell be wired to allow the arm to strike repeatedly (continual ringing) until the power supply is removed?

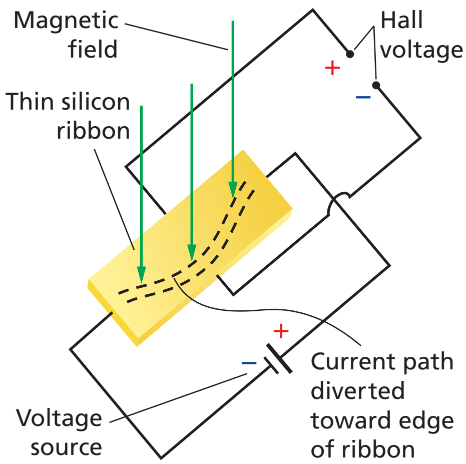
Physics Online

To find out more about magnetic fields, visit the Web site: **physicspp.com**

eXtreme physics

The Hall Effect

Something as simple as magnetic fields deflecting charged particles has led to a revolution in how we measure or detect the movement of things, such as bicycle wheels and automotive crankshafts. It all starts when current passes through a wide, flat conductor, in the presence of a magnetic field.



A magnetic field forces more electrons to the edge of a thin metal strip. This creates the Hall voltage.

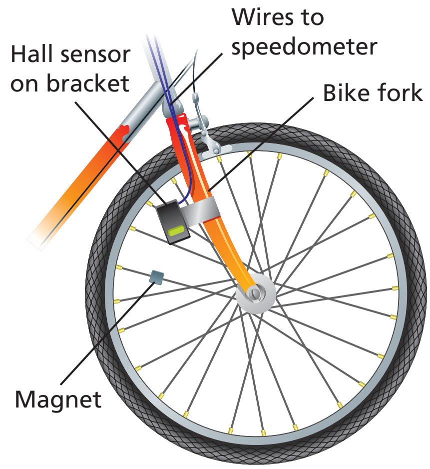
The magnetic lines of force are perpendicular to the ribbon's broad surface. This makes the flowing electrons crowd into one side of the ribbon. Because there are more electrons on one edge of the ribbon than on the other, a voltage, called the *Hall voltage,* is generated across the width of the ribbon. The magnitude of the Hall voltage is dependent upon the strength of the magnetic field.

E.H. Hall discovered this effect in 1879. Its industrial and scientific significance were discovered only recently because the Hall voltage is small in ribbons of conventional metals. Now, very thin layers of semiconducting silicon yield substantial Hall voltages.

The Hall effect can be used to explore conduction in different types of materials. The sign of the Hall-effect voltage gives the sign of the moving charge, and the magnitude of the voltage tells us about the density and velocity of the charge. Such experiments have shown that in copper and most other metals, electrons carry the charge, but in zinc it is the positive charges that move.

A Useful Sensor Engineers have developed the Hall-effect sensor. These tiny black plastic devices contain a thin film of silicon with wires connected, as shown in the diagram. The Hall voltage wires are connected to a tiny amplifier so that other instruments can detect it.

If a permanent magnet is moved near a Hall-effect sensor, the voltage from the amplifier will increase. Thus, the sensor can be used to detect the proximity of the magnet.



Bicycle speedometers use a Hall-effect sensor to display the speed at which a bicycle is moving.

Everyday Applications Bicycle speedometers use a permanent magnet attached to the front wheel. Each revolution of the wheel brings the magnet close to a Hall-effect sensor. The resulting pulses are counted and timed. Hall-effect sensors also are used to time the spark in automobile engines. When a magnet mounted on the crankshaft or distributor rotor moves near a sensor, a voltage pulse is produced, and the ignition system instantly fires the spark plug.

Going Further

1. **Analyze** Why are the Hall-voltage electrodes positioned directly across from each other? What if they weren't?
2. **Critical Thinking** Might a strong magnetic field applied across a conducting ribbon change the resistance of that ribbon as a result of the Hall effect? Consider what you learned about the cross-sectional areas of wires.

Chapter 24

Study Guide

24.1 Magnets: Permanent and Temporary

Vocabulary

- polarized (p. 644)
- magnetic field (p. 645)
- magnetic flux (p. 646)
- first right-hand rule (p. 649)
- solenoid (p. 649)
- electromagnet (p. 649)
- second right-hand rule (p. 649)
- domain (p. 650)

Key Concepts

- Like magnetic poles repel; unlike magnetic poles attract.
- Magnetic fields exit from the north pole of a magnet and enter its south pole.
- Magnetic field lines always form closed loops.
- A magnetic field exists around any carrying-current wire.
- A coil of wire carrying a current has a magnetic field. The field about the coil is like the field about a permanent magnet.

24.2 Forces Caused by Magnetic Fields

Vocabulary

- third right-hand rule (p. 652)
- galvanometer (p. 655)
- electric motor (p. 656)
- armature (p. 656)

Key Concepts

- The strength of a magnetic field is measured in teslas.
- When a current-carrying wire is placed in a magnetic field, there exists a force on the wire, perpendicular to both the field and the wire.
- The force on a current-carrying wire in a magnetic field is proportional to the field strength, the current flow, and the length of the wire.

$$F = ILB$$

- A galvanometer consists of a loop of wire in a magnetic field, and is used to measure small currents. When current is passed through the loop, a force on the wire loop results in a deflection of the loop.
- A galvanometer can be used as an ammeter by adding a shunt resistor in parallel with the galvanometer.
- A galvanometer can be used as a voltmeter by adding a multiplier resistor in series with the galvanometer.
- A loudspeaker functions by varying the current through a coil that is placed in a magnetic field. The coil is attached to a paper cone that moves when the coil moves. As the current varies, the cone vibrates, thereby producing sound.
- An electric motor consists of a coil of wire placed in a magnetic field. When there is a current in the coil, the coil rotates as a result of the force on the wire in the magnetic field. Complete 360° rotation is achieved by using a commutator to switch the direction of the current in the coil as the coil rotates.
- The force that a magnetic field exerts on a charged particle depends on three factors: the velocity of the particle, the charge of the particle, and the strength of the field. The direction of the force is perpendicular to both the field and the particle's velocity.

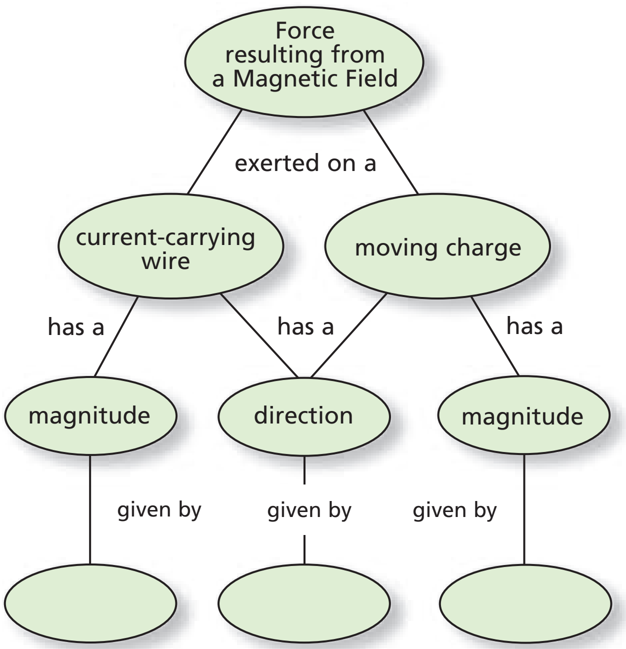
$$F = qvB$$

- Computer monitors and television screens function by using magnets to focus and direct particles on phosphor screens. When particles strike the screen, light is emitted, and produces images on the screen.

Chapter 24 Assessment

Concept Mapping

32. Complete the following concept map using the following: *right-hand rule*, $F = qvB$, and $F = ILB$.



Mastering Concepts

33. State the rule for magnetic attraction and repulsion. (24.1)

34. Describe how a temporary magnet differs from a permanent magnet. (24.1)

35. Name the three most important common magnetic elements. (24.1)

36. Draw a small bar magnet and show the magnetic field lines as they appear around the magnet. Use arrows to show the direction of the field lines. (24.1)

37. Draw the magnetic field between two like magnetic poles and then between two unlike magnetic poles. Show the directions of the fields. (24.1)

38. If you broke a magnet in two, would you have isolated north and south poles? Explain. (24.1)

39. Describe how to use the first right-hand rule to determine the direction of a magnetic field around a straight current-carrying wire. (24.1)

40. If a current-carrying wire is bent into a loop, why is the magnetic field inside the loop stronger than the magnetic field outside? (24.1)

41. Describe how to use the second right-hand rule to determine the polarity of an electromagnet. (24.1)

42. Each electron in a piece of iron is like a tiny magnet. The iron, however, may not be a magnet. Explain. (24.1)

43. Why will dropping or heating a magnet weaken it? (24.1)

44. Describe how to use the third right-hand rule to determine the direction of force on a current-carrying wire placed in a magnetic field. (24.2)

45. A strong current suddenly is switched on in a wire. No force acts on the wire, however. Can you conclude that there is no magnetic field at the location of the wire? Explain. (24.2)

46. What kind of meter is created when a shunt is added to a galvanometer? (24.2)

Applying Concepts

47. A small bar magnet is hidden in a fixed position inside a tennis ball. Describe an experiment that you could do to find the location of the north pole and the south pole of the magnet.

48. A piece of metal is attracted to one pole of a large magnet. Describe how you could tell whether the metal is a temporary magnet or a permanent magnet.

49. Is the magnetic force that Earth exerts on a compass needle less than, equal to, or greater than the force that the compass needle exerts on Earth? Explain.

50. **Compass** Suppose you are lost in the woods but have a compass with you. Unfortunately, the red paint marking the north pole of the compass needle has worn off. You have a flashlight with a battery and a length of wire. How could you identify the north pole of the compass?

51. A magnet can attract a piece of iron that is not a permanent magnet. A charged rubber rod can attract an uncharged insulator. Describe the different microscopic processes producing these similar phenomena.

52. A current-carrying wire runs across a laboratory bench. Describe at least two ways in which you could find the direction of the current.

53. In which direction, in relation to a magnetic field, would you run a current-carrying wire so that the force on it, resulting from the field, is minimized, or even made to be zero?

 For more problems, go to Additional Problems, Appendix B.

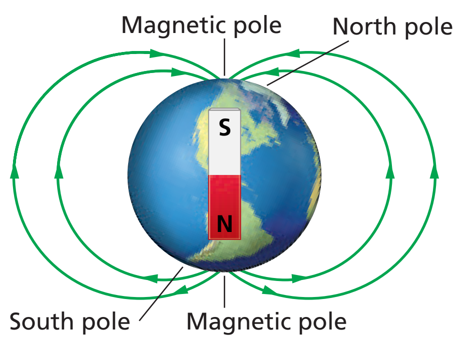
54. Two wires carry equal currents and run parallel to each other.
  a. If the two currents are in opposite directions, where will the magnetic field from the two wires be larger than the field from either wire alone?
  b. Where will the magnetic field from both be exactly twice as large as from one wire?
  c. If the two currents are in the same direction, where will the magnetic field be exactly zero?

55. How is the range of a voltmeter changed when the resistor's resistance is increased?

56. A magnetic field can exert a force on a charged particle. Can the field change the particle's kinetic energy? Explain.

57. A beam of protons is moving from the back to the front of a room. It is deflected upward by a magnetic field. What is the direction of the field causing the deflection?

58. Earth's magnetic field lines are shown in **Figure 24-23.** At what location, poles or equator, is the magnetic field strength greatest? Explain.

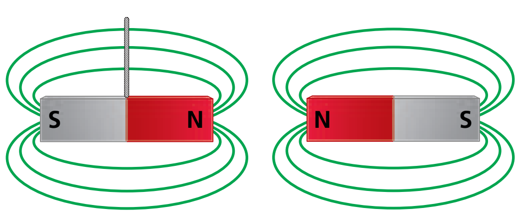


■ **Figure 24-23**

Mastering Problems

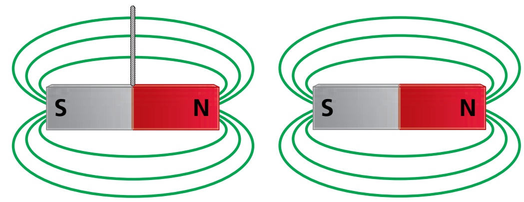
24.1 Magnets: Permanent and Temporary

59. As the magnet below in **Figure 24-24** moves toward the suspended magnet, what will the magnet suspended by the string do?



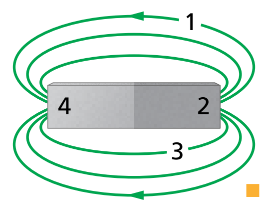
■ **Figure 24-24**

60. As the magnet in **Figure 24-25** moves toward the suspended magnet, what will the magnet that is suspended by the string do?



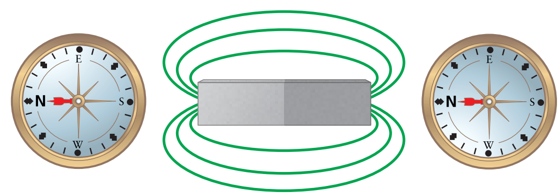
■ **Figure 24-25**

61. Refer to **Figure 24-26** to answer the following questions.
  a. Where are the poles?
  b. Where is the north pole?
  c. Where is the south pole?



■ **Figure 24-26**

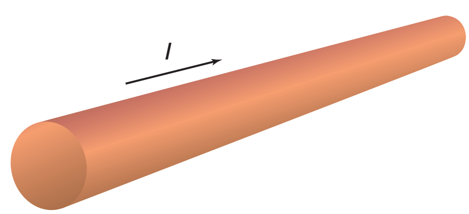
62. **Figure 24-27** shows the response of a compass in two different positions near a magnet. Where is the south pole of the magnet located?



■ **Figure 24-27**

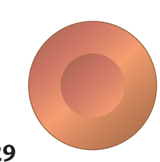
63. A wire that is 1.50 m long and carrying a current of 10.0 A is at right angles to a uniform magnetic field. The force acting on the wire is 0.60 N. What is the strength of the magnetic field?

64. A conventional current flows through a wire, as shown in **Figure 24-28.** Copy the wire segment and sketch the magnetic field that the current generates.



■ **Figure 24-28**

65. The current is coming straight out of the page in **Figure 24-29.** Copy the figure and sketch the magnetic field that the current generates.



■ **Figure 24-29**

66. **Figure 24-30** shows the end view of an electromagnet with current flowing through it.
a. What is the direction of the magnetic field inside the loops?
b. What is the direction of the magnetic field outside the loops?

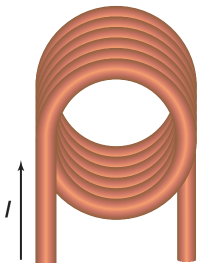


Figure 24-30

67. **Ceramic Magnets** The repulsive force between two ceramic magnets was measured and found to depend on distance, as given in **Table 24-1.**
a. Plot the force as a function of distance.
b. Does this force follow an inverse square law?

Table 24-1

Separation, *d* (cm)	Force, *F* (N)
1.0	3.93
1.2	0.40
1.4	0.13
1.6	0.057
1.8	0.030
2.0	0.018
2.2	0.011
2.4	0.0076
2.6	0.0053
2.8	0.0038
3.0	0.0028

24.2 Forces Caused by Magnetic Fields

68. The arrangement shown in **Figure 24-31** is used to convert a galvanometer to what type of device?

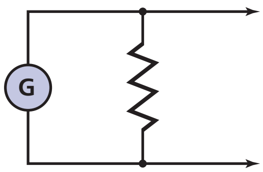


Figure 24-31

69. What is the resistor shown in Figure 24-31 called?

70. The arrangement shown in **Figure 24-32** is used to convert a galvanometer to what type of device?

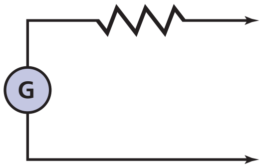


Figure 24-32

71. What is the resistor shown in Figure 24-32 called?

72. A current-carrying wire is placed between the poles of a magnet, as shown in **Figure 24-33.** What is the direction of the force on the wire?

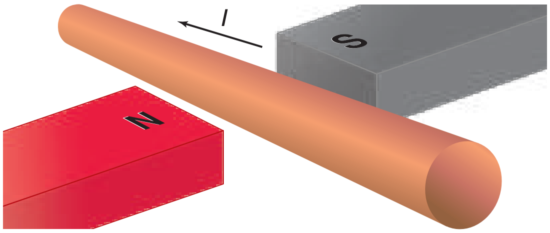


Figure 24-33

73. A wire that is 0.50 m long and carrying a current of 8.0 A is at right angles to a uniform magnetic field. The force on the wire is 0.40 N. What is the strength of the magnetic field?

74. The current through a wire that is 0.80 m long is 5.0 A. The wire is perpendicular to a 0.60-T magnetic field. What is the magnitude of the force on the wire?

75. A wire that is 25 cm long is at right angles to a 0.30-T uniform magnetic field. The current through the wire is 6.0 A. What is the magnitude of the force on the wire?

76. A wire that is 35 cm long is parallel to a 0.53-T uniform magnetic field. The current through the wire is 4.5 A. What force acts on the wire?

77. A wire that is 625 m long is perpendicular to a 0.40-T magnetic field. A 1.8-N force acts on the wire. What current is in the wire?

78. The force on a 0.80-m wire that is perpendicular to Earth's magnetic field is 0.12 N. What is the current in the wire? Use 5.0×10^{-5}T for Earth's magnetic field.

79. The force acting on a wire that is at right angles to a 0.80-T magnetic field is 3.6 N. The current in the wire is 7.5 A. How long is the wire?

 For more problems, go to Additional Problems, Appendix B.

80. A power line carries a 225-A current from east to west, parallel to the surface of Earth.
  a. What is the magnitude of the force resulting from Earth's magnetic field acting on each meter of the wire? Use $B_{Earth}=5.0\times10^{-5}$T.
  b. What is the direction of the force?
  c. In your judgment, would this force be important in designing towers to hold this power line? Explain.

81. Galvanometer A galvanometer deflects full-scale for a 50.0-μA current.
  a. What must be the total resistance of the series resistor and the galvanometer to make a voltmeter with 10.0-V full-scale deflection?
  b. If the galvanometer has a resistance of 1.0 kΩ, what should be the resistance of the series (multiplier) resistor?

82. The galvanometer in problem 81 is used to make an ammeter that deflects full-scale for 10 mA.
  a. What is the potential difference across the galvanometer (1.0 kΩ resistance) when a current of 50 μA passes through it?
  b. What is the equivalent resistance of parallel resistors having the potential difference calculated in a circuit with a total current of 10 mA?
  c. What resistor should be placed parallel with the galvanometer to make the resistance calculated in part b?

83. A beam of electrons moves at right angles to a magnetic field of 6.0×10^{-2} T. The electrons have a velocity of 2.5×10^{6} m/s. What is the magnitude of the force on each electron?

84. Subatomic Particle A muon (a particle with the same charge as an electron) is traveling at 4.21×10^{7} m/s at right angles to a magnetic field. The muon experiences a force of 5.00×10^{-12} N.
  a. How strong is the magnetic field?
  b. What acceleration does the muon experience if its mass is 1.88×10^{-28} kg?

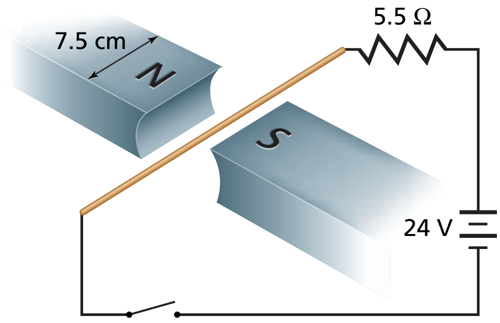
85. A singly ionized particle experiences a force of 4.1×10^{-13} N when it travels at right angles through a 0.61-T magnetic field. What is the velocity of the particle?

86. A room contains a strong, uniform magnetic field. A loop of fine wire in the room has current flowing through it. Assume that you rotate the loop until there is no tendency for it to rotate as a result of the field. What is the direction of the magnetic field relative to the plane of the coil?

87. A force of 5.78×10^{-16} N acts on an unknown particle traveling at a 90° angle through a magnetic field. If the velocity of the particle is 5.65×10^{4} m/s and the field is 3.20×10^{-2} T, how many elementary charges does the particle carry?

Mixed Review

88. A copper wire of insignificant resistance is placed in the center of an air gap between two magnetic poles, as shown in **Figure 24-34.** The field is confined to the gap and has a strength of 1.9 T.
  a. Determine the force on the wire (direction and magnitude) when the switch is open.
  b. Determine the force on the wire (direction and magnitude) when the switch is closed.
  c. Determine the force on the wire (direction and magnitude) when the switch is closed and the battery is reversed.
  d. Determine the force on the wire (direction and magnitude) when the switch is closed and the wire is replaced with a different piece having a resistance of 5.5 Ω.



■ **Figure 24-34**

89. Two galvanometers are available. One has 50.0-μA full-scale sensitivity and the other has 500.0-μA full-scale sensitivity. Both have the same coil resistance of 855 Ω. Your challenge is to convert them to measure a current of 100.0 mA, full-scale.
  a. Determine the shunt resistor for the 50.0-μA meter.
  b. Determine the shunt resistor for the 500.0-μA meter.
  c. Determine which of the two is better for actual use. Explain.

90. Subatomic Particle A beta particle (high-speed electron) is traveling at right angles to a 0.60-T magnetic field. It has a speed of 2.5×10^{7} m/s. What size force acts on the particle?

91. The mass of an electron is 9.11×10^{-31} kg. What is the magnitude of the acceleration of the beta particle described in problem 90?

92. A magnetic field of 16 T acts in a direction due west. An electron is traveling due south at 8.1×10^5 m/s. What are the magnitude and the direction of the force acting on the electron?

93. Loudspeaker The magnetic field in a loudspeaker is 0.15 T. The wire consists of 250 turns wound on a 2.5-cm-diameter cylindrical form. The resistance of the wire is 8.0 Ω. Find the force exerted on the wire when 15 V is placed across the wire.

94. A wire carrying 15 A of current has a length of 25 cm in a magnetic field of 0.85 T. The force on a current-carrying wire in a uniform magnetic field can be found using the equation $F = ILB \sin\theta$. Find the force on the wire when it makes the following angles with the magnetic field lines of

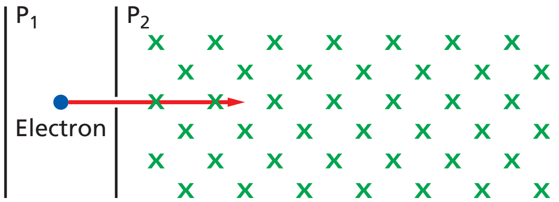
a. 90° **b.** 45° **c.** 0°

95. An electron is accelerated from rest through a potential difference of 20,000 V, which exists between plates P_1 and P_2, shown in **Figure 24-35.** The electron then passes through a small opening into a magnetic field of uniform field strength, *B*. As indicated, the magnetic field is directed into the page.

a. State the direction of the electric field between the plates as either P_1 to P_2 or P_2 to P_1.

b. In terms of the information given, calculate the electron's speed at plate P_2.

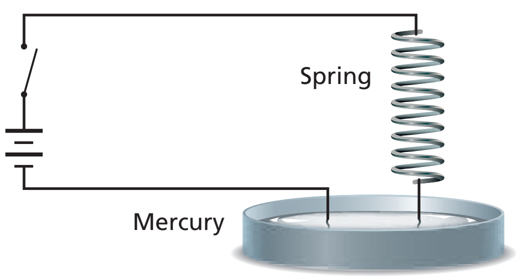
c. Describe the motion of the electron through the magnetic field.



■ **Figure 24-35**

Thinking Critically

96. Apply Concepts A current is sent through a vertical spring, as shown in **Figure 24-36.** The end of the spring is in a cup filled with mercury. What will happen? Why?



■ **Figure 24-36**

97. Apply Concepts The magnetic field produced by a long, current-carrying wire is represented by $B = (2\times10^{-7}\ \text{T·m/A})(I/d)$, where *B* is the field strength in teslas, *I* is the current in amps, and *d* is the distance from the wire in meters. Use this equation to estimate some magnetic fields that you encounter in everyday life.

a. The wiring in your home seldom carries more than 10 A. How does the magnetic field that is 0.5 m from such a wire compare to Earth's magnetic field?

b. High-voltage power transmission lines often carry 200 A at voltages as high as 765 kV. Estimate the magnetic field on the ground under such a line, assuming that it is about 20 m high. How does this field compare with a magnetic field in your home?

c. Some consumer groups have recommended that pregnant women not use electric blankets in case the magnetic fields cause health problems. Estimate the distance that a fetus might be from such a wire, clearly stating your assumptions. If such a blanket carries 1 A, find the magnetic field at the location of the fetus. Compare this with Earth's magnetic field.

98. Add Vectors In almost all cases described in problem 97, a second wire carries the same current in the opposite direction. Find the net magnetic field that is a distance of 0.10 m from each wire carrying 10 A. The wires are 0.01 m apart. Make a scale drawing of the situation. Calculate the magnitude of the field from each wire and use a right-hand rule to draw vectors showing the directions of the fields. Finally, find the vector sum of the two fields. State its magnitude and direction.

Writing In Physics

99. Research superconducting magnets and write a one-page summary of proposed future uses for such magnets. Be sure to describe any hurdles that stand in the way of the practical application of these magnets.

Cumulative Review

100. How much work is required to move a charge of 6.40×10^{-3} C through a potential difference of 2500 V? (Chapter 21)

101. The current flow in a 120-V circuit increases from 1.3 A to 2.3 A. Calculate the change in power. (Chapter 22)

102. Determine the total resistance of three, 55-Ω resistors connected in parallel and then series-connected to two 55-Ω resistors connected in series. (Chapter 23)

Standardized Test Practice

Multiple Choice

1. A straight wire carrying a current of 7.2 A has a field of 8.9×10^{-3} T perpendicular to it. What length of wire in the field will experience a force of 2.1 N?

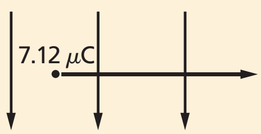
- (A) 2.6×10^{-3} m
- (B) 3.1×10^{-2} m
- (C) 1.3×10^{-1} m
- (D) 3.3×10^{1} m

2. Assume that a 19-cm length of wire is carrying a current perpendicular to a 4.1-T magnetic field and experiences a force of 7.6 mN. What is the current in the wire?

- (A) 3.4×10^{-7} A
- (B) 9.8×10^{-3} A
- (C) 1.0×10^{-2} A
- (D) 9.8 A

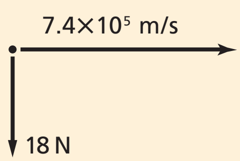
3. A 7.12-μC charge is moving at the speed of light in a magnetic field of 4.02 mT. What is the force on the charge?

- (A) 8.59 N
- (B) 2.90×10^{1} N
- (C) 8.59×10^{12} N
- (D) 1.00×10^{16} N



4. An electron is moving at 7.4×10^{5} m/s perpendicular to a magnetic field. It experiences a force of 18 N. What is the strength of the magnetic field?

- (A) 6.5×10^{-15} T
- (B) 2.4×10^{-5} T
- (C) 1.3×10^{7} T
- (D) 1.5×10^{14} T



5. Which factor will not affect the strength of a solenoid?

- (A) number of wraps
- (B) strength of current
- (C) thickness of wire
- (D) core type

6. Which statement about magnetic monopoles is false?

- (A) A monopole is a hypothetical separate north pole.
- (B) Research scientists use them for internal medical testing applications.
- (C) A monopole is a hypothetical separate south pole.
- (D) They don't exist.

7. A uniform magnetic field of 0.25 T points vertically downward. A proton enters the field with a horizontal velocity of 4.0×10^{6} m/s. What are the magnitude and direction of the instantaneous force exerted on the proton as it enters the magnetic field?

- (A) 1.6×10^{-13} N to the left
- (B) 1.6×10^{-13} N downward
- (C) 1.0×10^{6} N upward
- (D) 1.0×10^{6} N to the right

Extended Answer

8. Derive the units of teslas in kilograms, meters, seconds, and coulombs using dimensional analysis and the formulas $F = qvB$ and $F = ILB$.

9. A wire attached to a 5.8-V battery is in a circuit with 18 Ω. 14 cm of the wire is in a magnetic field of 0.85 T and the force on the wire is 22 mN. What is the angle of the wire in the field given that the formula for angled wires in fields is $F = ILB \sin \theta$?

✓ Test-Taking TIP

Read the Directions

No matter how many times you've taken a particular test or practiced for an exam, it's always a good idea to read through the directions provided at the beginning of each section. It only takes a moment and could prevent you from making a simple mistake throughout the test that could cause you to do poorly.

Chapter 25

Electromagnetic Induction

What You'll Learn

- You will describe how changing magnetic fields can generate electric potential differences.
- You will apply this phenomenon to the construction of generators and transformers.

Why It's Important

The relationship between magnetic fields and current makes possible the three cornerstones of electrical technology: motors, generators, and transformers.

Hydroelectric Generators Dams commonly are built on rivers to provide a source of power for nearby communities. Within the dam, the potential and kinetic energy of water is turned into electric energy.

Think About This ▶

How do the generators located inside the dam convert the kinetic and potential energy of the water into electric energy?

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Think About This ►

How do the generators located inside the dam convert the kinetic and potential energy of the water into electric energy?

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Tom Pantages, (inset)Robert Cameron/Getty Images

CONTENTS

LAUNCH Lab

What happens in a changing magnetic field?

Question

How does a changing magnetic field affect a coil of wire passed through it?

Procedure

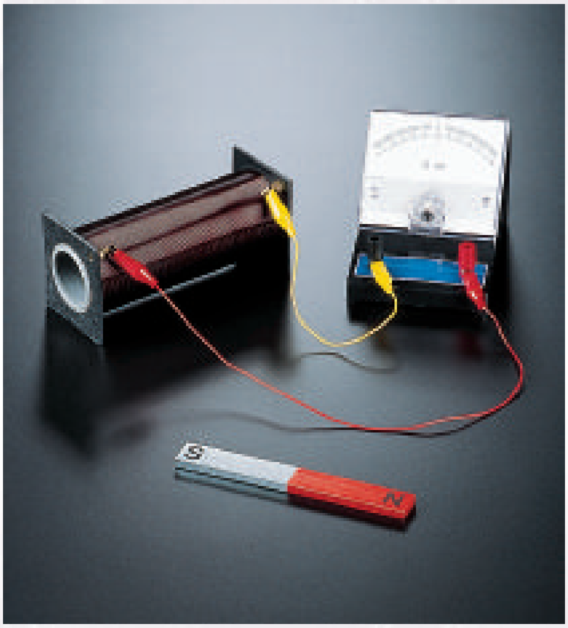
1. Place two bar magnets about 8 cm apart.
2. Attach a sensitive galvanometer to either end of a piece of coiled copper wire.
3. Slowly move the wire between the magnets. Note the galvanometer reading.
4. Vary the angle of the movement of the copper wire and the velocity of the wire. Note your results.

Analysis

What causes the galvanometer to move?

What situation makes the galvanometer deflect the most?

Critical Thinking When the wire is moved between the magnets, what is happening to the wire?



25.1 Electric Current from Changing Magnetic Fields

In Chapter 24, you learned how Hans Christian Oersted discovered that an electric current produces a magnetic field. Michael Faraday thought that the reverse must also be true: that a magnetic field produces an electric current. In 1822, Michael Faraday wrote a goal in his notebook: "Convert magnetism into electricity." Faraday tried many combinations of magnetic fields and wires without success. After nearly ten years of unsuccessful experiments, Faraday found that he could induce electric current by moving a wire through a magnetic field. In the same year, Joseph Henry, an American high-school teacher, also showed that a changing magnetic field could produce electric current. Henry took an idea developed by another scientist and broadened the application to other educational demonstration devices to make them more sensitive or powerful. Henry's versions of these devices were not new discoveries, but he made the devices more dramatic and effective as educational aids. However, Henry, unlike Faraday, chose not to publish his discoveries.

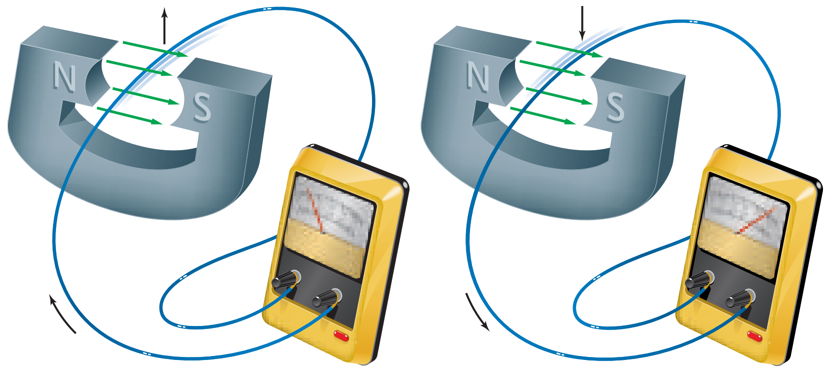
▶ Objectives

- **Explain** how a changing magnetic field produces an electric current.
- **Define** electromotive force.
- **Solve** problems involving wires moving in magnetic fields.

▶ Vocabulary

electromagnetic induction
fourth right-hand rule
electromotive force
electric generator
average power

Horizons Companies



■ **Figure 25-1** When a wire is moved in a magnetic field, there is an electric current in the wire, but only while the wire is moving. The direction of the current depends on the direction in which the wire is moving through the field. The arrows indicate the direction of conventional current.

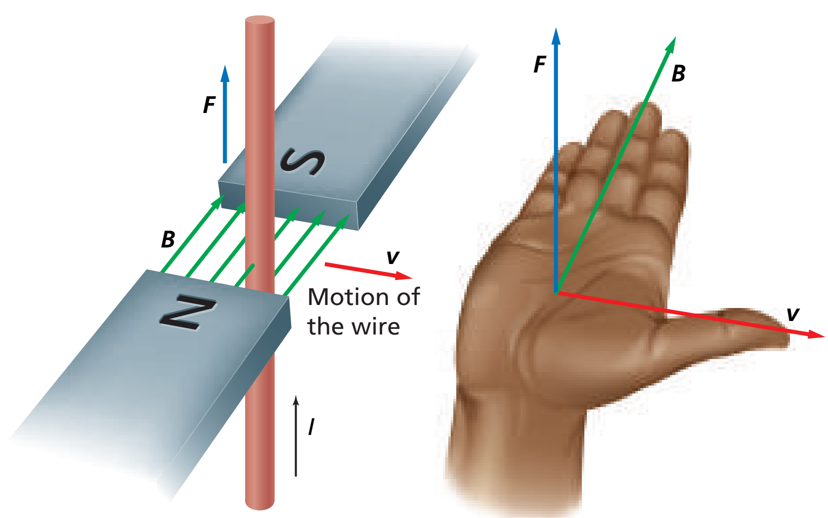
Electromagnetic Induction

Figure 25-1 shows one of Faraday's experiments, in which a wire loop that is part of a closed circuit is placed in a magnetic field. When the wire is held stationary or is moved parallel to the magnetic field, there is no current, but when the wire moves up through the field, the current is in one direction. When the wire moves down through the field, the current is in the opposite direction. An electric current is generated in a wire only when the wire cuts magnetic field lines.

Faraday found that to generate current, either the conductor can move through a magnetic field or a magnetic field can move past the conductor. It is the relative motion between the wire and the magnetic field that produces the current. The process of generating a current through a circuit in this way is called **electromagnetic induction.**

How can you tell the direction of the current? To find the force on the charges in the wire, use the **fourth right-hand rule** to hold your right hand so that your thumb points in the direction in which the wire is moving and your fingers point in the direction of the magnetic field. The palm of your hand will point in the direction of the conventional (positive) current, as illustrated in **Figure 25-2.**

■ **Figure 25-2** The fourth right-hand rule can be used to find the direction of the forces on the charges in a conductor that is moving in a magnetic field.



Electromotive Force

When you studied electric circuits, you learned that a source of electrical energy, such as a battery, is needed to produce a continuous current. The potential difference, or voltage, given to the charges by a battery is called the **electromotive force,** or *EMF*. Electromotive force, however, is not actually a force; instead, it is a potential difference and is measured in volts. Thus, the term electromotive force is misleading. Like many other historical terms still in use, it originated before the related principles—in this case, those of electricity—were well understood. The *EMF* is the influence that makes current flow from lower to higher potential, like a water pump in a water fountain.

What created the potential difference that caused an induced current in Faraday's experiment? When you move a wire through a magnetic field, you exert a force on the charges and they move in the direction of the force. Work is done on the charges. Their electrical potential energy, and thus their potential, is increased. The difference in potential is called the induced *EMF*. *EMF* depends on the magnetic field, *B*, the length of the wire in the magnetic field, *L*, and the velocity of the wire in the field that is perpendicular to the field, $v(\sin \theta)$.

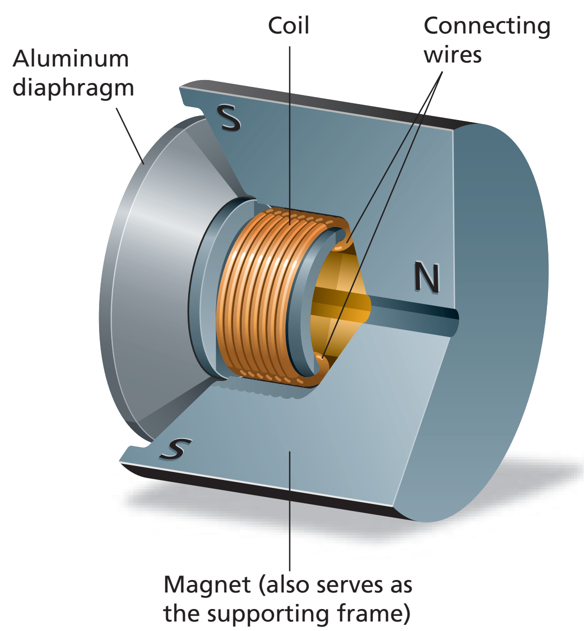
Electromotive Force $EMF = BLv(\sin \theta)$

Electromotive force is equal to the magnitude of the magnetic field, times the length of the wire times the component of the velocity of the wire in the field perpendicular to the field.

If a wire moves through a magnetic field at an angle to the field, only the component of the wire's velocity that is perpendicular to the direction of the magnetic field generates *EMF*. If the wire moves through the field with a velocity that is exactly perpendicular to the field, then the above equation reduces to $EMF = BLv$, because $\sin 90° = 1$. Checking the units of the *EMF* equation will help you work algebra correctly in related problems. The unit for measuring *EMF* is the volt, V. In Chapter 24, *B* was defined as F/IL; therefore, the units for *B* are N/A·m. Velocity is measured in m/s. Using dimensional analysis, $(\text{N/A·m})(\text{m})(\text{m/s}) = \text{N·m/A·s} = \text{J/C} = \text{V}$. Recall from previous chapters that J = N·m, A = C/s, and V = J/C.

Application of induced *EMF* A microphone is a simple application that depends on an induced *EMF*. A dynamic microphone is similar in construction to a loudspeaker. The microphone shown in **Figure 25-3** has a diaphragm attached to a coil of wire that is free to move in a magnetic field. Sound waves vibrate the diaphragm, which moves the coil in the magnetic field. The motion of the coil, in turn, induces an *EMF* across the ends of the coil. The induced *EMF* varies as the frequency of the sound varies. In this way, the sound wave is converted to an electrical signal. The voltage generated is small, typically 10^{-3} V, but it can be increased, or amplified, by electronic devices.

■ **Figure 25-3** In this drawing of a moving coil microphone, the aluminum diaphragm is connected to a coil in a magnetic field. When sound waves vibrate the diaphragm, the coil moves in the magnetic field and generates a current that is proportional to the sound wave.



EXAMPLE Problem 1

Induced *EMF* A straight wire, 0.20 m long, moves at a constant speed of 7.0 m/s perpendicular to a magnetic field of strength 8.0×10^{-2} T.

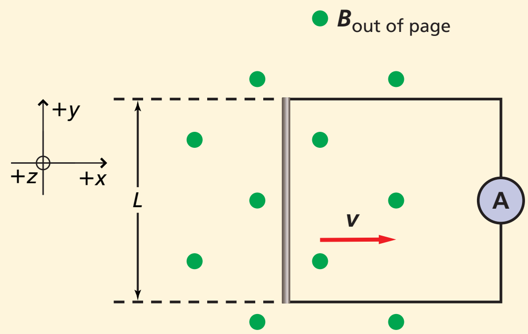
a. What *EMF* is induced in the wire?

b. The wire is part of a circuit that has a resistance of 0.50 Ω. What is the current through the wire?

c. If a different metal was used for the wire, which has a resistance of 0.78 Ω, what would the new current be?

1 Analyze and Sketch the Problem

- Establish a coordinate system.
- Draw a straight wire of length *L*. Connect an ammeter to the wire to represent a measurement of current.
- Choose a direction for the magnetic field that is perpendicular to the length of wire.
- Choose a direction for the velocity that is perpendicular to both the length of the wire and the magnetic field.



Known:	**Unknown:**
$v = 7.0$ m/s	$EMF = ?$
$L = 0.20$ m	$I = ?$
$B = 8.0\times10^{-2}$ T	
$R_1 = 0.50\ \Omega$	
$R_2 = 0.78\ \Omega$	

2 Solve for the Unknown

a. $EMF = BLv$

$= (8.0\times10^{-2}\ \text{T})(0.20\ \text{m})(7.0\ \text{m/s})$ Substitute $B = 8.0\times10^{-2}$, $L = 0.20$ m, $v = 7.0$ m/s

$= 0.11\ \text{T·m}^2/\text{s}$

$= 0.11$ V

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

$= \frac{EMF}{R}$ Substitute $V = EMF$

$= \frac{0.11\ \text{V}}{0.50\ \Omega}$ Substitute $EMF = 0.11$ V, $R_1 = 0.50\ \Omega$

$= 0.22$ A

Using the fourth right-hand rule, the direction of the current is counterclockwise.

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c. $I = \frac{EMF}{R}$

$= \frac{0.11\ \text{V}}{0.78\ \Omega}$ Substitute $EMF = 0.11$ V, $R_2 = 0.78\ \Omega$

$= 0.14$ A

The current is counterclockwise.

3 Evaluate the Answer

- **Are the units correct?** Volt is the correct unit for *EMF*. Current is measured in amperes.
- **Does the direction make sense?** The direction obeys the fourth right-hand rule: *v* is the direction of the thumb, *B* is the same direction as the fingers, and *F* is the direction that the palm faces. Current is in the same direction as the force.
- **Is the magnitude realistic?** The answers are near 10^{-1}. This agrees with the quantities given and the algebra performed.

PRACTICE Problems

Additional Problems, Appendix B

1. A straight wire, 0.5 m long, is moved straight up at a speed of 20 m/s through a 0.4-T magnetic field pointed in the horizontal direction.
   a. What *EMF* is induced in the wire?
   b. The wire is part of a circuit of total resistance of 6.0 Ω. What is the current in the circuit?
2. A straight wire, 25 m long, is mounted on an airplane flying at 125 m/s. The wire moves in a perpendicular direction through Earth's magnetic field ($B = 5.0\times10^{-5}$ T). What *EMF* is induced in the wire?
3. A straight wire, 30.0 m long, moves at 2.0 m/s in a perpendicular direction through a 1.0-T magnetic field.
   a. What *EMF* is induced in the wire?
   b. The total resistance of the circuit of which the wire is a part is 15.0 Ω. What is the current?
4. A permanent horseshoe magnet is mounted so that the magnetic field lines are vertical. If a student passes a straight wire between the poles and pulls it toward herself, the current flow through the wire is from right to left. Which is the north pole of the magnet?

Electric Generators

The **electric generator,** invented by Michael Faraday, converts mechanical energy to electrical energy. An electric generator consists of a number of wire loops placed in a strong magnetic field. The wire is wound around an iron core to increase the strength of the magnetic field. The iron and wires are called the armature, which is similar to that of an electric motor.

The armature is mounted so that it can rotate freely in the magnetic field. As the armature turns, the wire loops cut through the magnetic field lines and induce an *EMF*. Commonly called the voltage, the *EMF* developed by the generator depends on the length of wire rotating in the field. Increasing the number of loops in the armature increases the wire length, thereby increasing the induced *EMF*. Note that you could have a length of wire with only part of it in the magnetic field. Only the portion within the magnetic field induces an *EMF*.

Current from a generator When a generator is connected in a closed circuit, the induced *EMF* produces an electric current. **Figure 25-4** shows a single-loop generator without an iron core. The direction of the induced current can be found from the third right-hand rule. As the loop rotates, the strength and the direction of the current change.

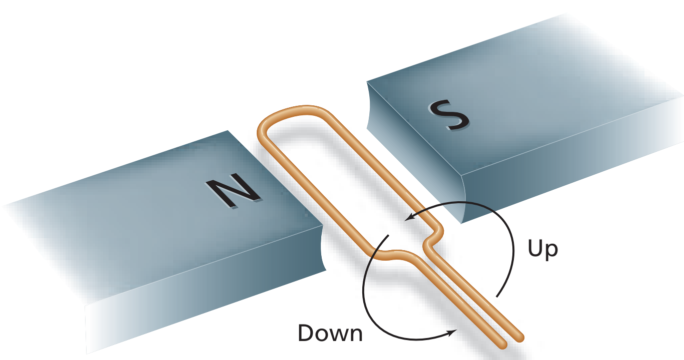
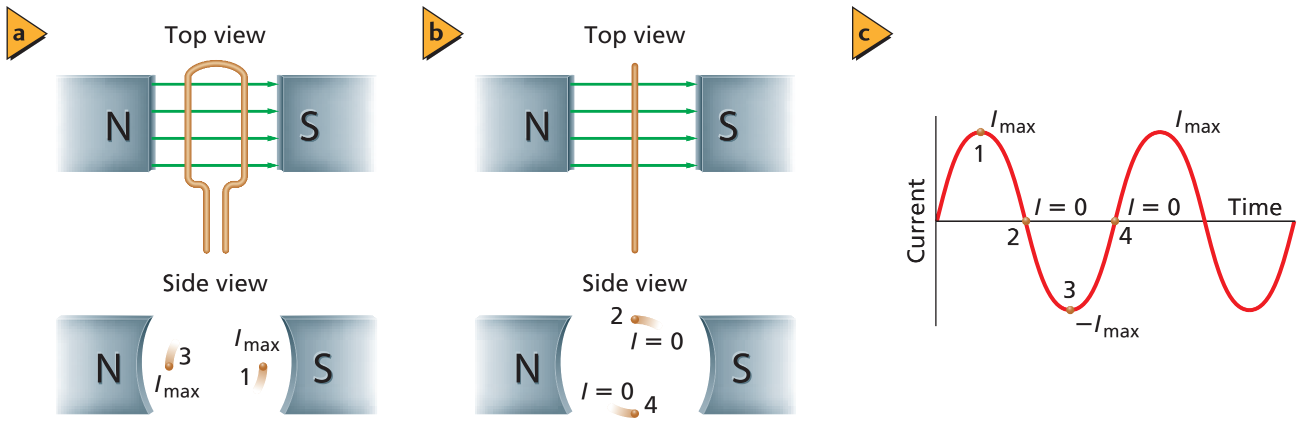


Figure 25-4 An electric current is generated in a wire loop as the loop rotates.



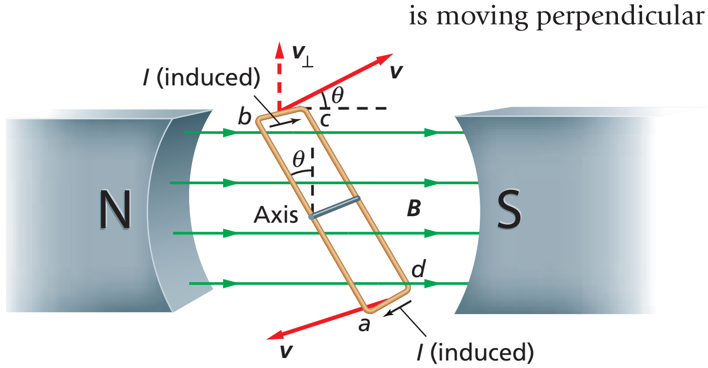
■ **Figure 25-5** The cross-sectional view of a rotating wire loop shows the position of the loop when maximum current is generated **(a).** When the loop is vertical, the current is zero **(b).** The current varies with time as the loop rotates **(c).** The variation of *EMF* with time can be shown with a similar graph.

The current is greatest when the motion of the loop is perpendicular to the magnetic field; that is, when the loop is in the horizontal position, as shown in **Figure 25-5a.** In this position, the component of the loop's velocity perpendicular to the magnetic field is greatest. As the loop rotates from the horizontal to the vertical position, as shown in **Figure 25-5b,** it moves through the magnetic field lines at an ever-increasing angle. Thus, it cuts through fewer magnetic field lines per unit of time, and the current decreases. When the loop is in the vertical position, the wire segments move parallel to the field and the current is zero. As the loop continues to turn, the segment that was moving up begins to move down and reverses the direction of the current in the loop. This change in direction takes place each time the loop turns through 180°. The current changes smoothly from zero to some maximum value and back to zero during each half-turn of the loop. Then it reverses direction. A graph of current versus time is shown in **Figure 25-5c.**

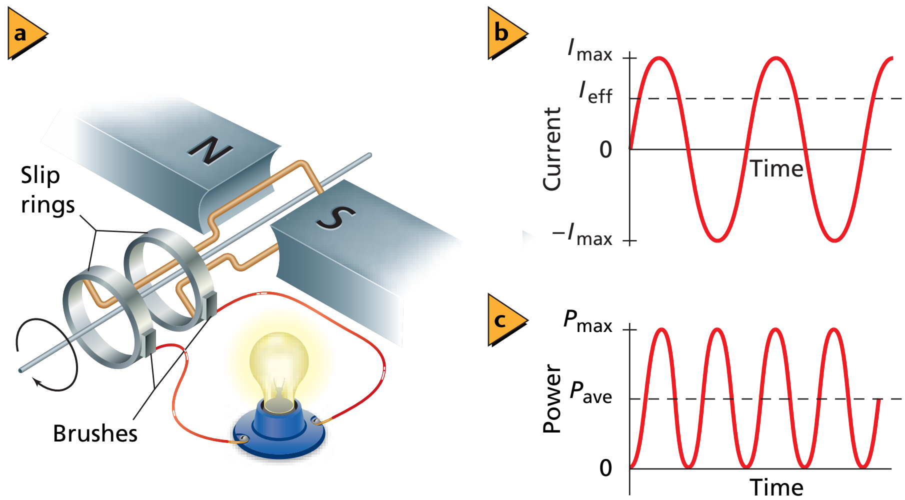
Does the entire loop contribute to the induced *EMF*? Look at **Figure 25-6,** where all four sides of the loop are depicted in the magnetic field. If the fourth right-hand rule is applied to segment *ab*, the direction of the induced current is toward the side of the wire. The same applies to segment *cd*. Thus, no current is induced along the length of the wire in *ab* or *cd*. But in segment *bc*, the direction of the induced current is from *b* to *c*, and in segment *ad*, the current is from *d* to *a*.

Because the conducting loop is rotating in a circular motion, the relative angle between a point on the loop and the magnetic field constantly changes. The electromotive force can be calculated by the electromotive force equation given earlier, $EMF = BLv(\sin\theta)$, except that L is now the length of segment *bc*. The maximum voltage is induced when a conductor is moving perpendicular to the magnetic field and thus $\theta = 90°$.

■ **Figure 25-6** Only the segments *bc* and *ad* have current induced through them. This can be shown using the fourth right-hand rule.



Generators, such as those in the chapter opening image, work in a similar fashion. Potential energy from water stored behind a dam is converted to kinetic energy, which spins the turbines. The turbines, in turn, turn coils of conductors in a magnetic field, thereby inducing an *EMF*. Generators and motors are almost identical in construction, but



■ **Figure 25-7** An alternating-current generator transmits current to an external circuit by way of a brush-slip-ring arrangement **(a).** The alternating current produced varies with time **(b).** The resulting power is always positive and also is sinusoidal **(c).**

they convert energy in opposite directions. A generator converts mechanical energy to electrical energy, while a motor converts electrical energy to mechanical energy.

Alternating-Current Generators

An energy source turns the armature of a generator in a magnetic field at a fixed number of revolutions per second. In the United States, electric utilities use a 60-Hz frequency, in which the current goes from one direction to the other and back to the first 60 times per second. **Figure 25-7a** shows how an alternating current, AC, in an armature is transmitted to the rest of the circuit. The brush-slip-ring arrangement permits the armature to turn freely while still allowing the current to pass into the external circuit. As the armature turns, the alternating current varies between some maximum value and zero, as shown in the graph in **Figure 25-7b.**

Average power The power produced by a generator is the product of the current and the voltage. Because both current and voltage vary, the power associated with an alternating current varies. **Figure 25-7c** shows a graph of the power produced by an AC generator. Note that power is always positive because I and V are either both positive or both negative. **Average power,** P_{AC}, is half the maximum power; thus, $P_{AC} = \frac{1}{2}P_{AC\ max}$.

Effective voltage and current It is common to describe alternating current and voltage in terms of effective current and voltage, rather than referring to their maximum values. Recall from Chapter 22 that $P = I^2R$. Thus, you can express effective current, I_{eff}, in terms of the average AC power as $P_{AC} = I_{eff}{}^2R$. To determine I_{eff} in terms of maximum current, I_{max}, start with the power relationship, $P_{AC} = \frac{1}{2}P_{AC\ max}$, and substitute in I^2R. Then solve for I_{eff}.

Effective Current $I_{eff} = \frac{\sqrt{2}}{2}I_{max} = 0.707\ I_{max}$

Effective current is equal to $\frac{\sqrt{2}}{2}$ times the maximum current.

Similarly, the following equation can be used to express effective voltage.

Effective Voltage $V_{eff} = \left(\frac{\sqrt{2}}{2}\right)V_{max} = 0.707\ V_{max}$

Effective voltage is equal to $\frac{\sqrt{2}}{2}$ times the maximum voltage.

Effective voltage, also is commonly referred to as RMS (root mean square) voltage. In the United States, the voltage generally available at wall outlets is described as 120 V, where 120 V is the magnitude of the effective voltage, not the maximum voltage. The frequency and effective voltage that are used vary in different countries.

PRACTICE Problems

Additional Problems, Appendix B

5. A generator develops a maximum voltage of 170 V.

a. What is the effective voltage?

b. A 60-W lightbulb is placed across the generator with an I_{max} of 0.70 A. What is the effective current through the bulb?

c. What is the resistance of the lightbulb when it is working?

6. The RMS voltage of an AC household outlet is 117 V. What is the maximum voltage across a lamp connected to the outlet? If the RMS current through the lamp is 5.5 A, what is the maximum current in the lamp?

7. An AC generator delivers a peak voltage of 425 V.

a. What is the V_{eff} in a circuit placed across the generator?

b. The resistance is $5.0\times10^2\ \Omega$. What is the effective current?

8. If the average power dissipated by an electric light is 75 W, what is the peak power?

In this section you have explored how moving wires in magnetic fields can induce current. However, as Faraday discovered, changing magnetic fields around a conductor also can induce current in the conductor. In the next section, you will explore changing magnetic fields and the applications of induction by changing magnetic fields.

25.1 Section Review

9. Generator Could you make a generator by mounting permanent magnets on a rotating shaft and keeping the coil stationary? Explain.

10. Bike Generator A bike generator lights the headlamp. What is the source of the energy for the bulb when the rider travels along a flat road?

11. Microphone Consider the microphone shown in Figure 25-3. When the diaphragm is pushed in, what is the direction of the current in the coil?

12. Frequency What changes to the generator are required to increase the frequency?

13. Output Voltage Explain why the output voltage of an electric generator increases when the magnetic field is made stronger. What else is affected by strengthening the magnetic field?

14. Generator Explain the fundamental operating principle of an electric generator.

15. Critical Thinking A student asks, "Why does AC dissipate any power? The energy going into the lamp when the current is positive is removed when the current is negative. The net is zero." Explain why this reasoning is wrong.

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CONTENTS

25.2 Changing Magnetic Fields Induce *EMF*

In a generator, current is produced when the armature turns through a magnetic field. The act of generating current produces a force on the wires in the armature. In what direction is the force on the wires of an armature?

Lenz's Law

Consider a section of one loop that moves through a magnetic field, as shown in **Figure 25-8a.** An *EMF*, equal to *BLv*, will be induced in the wire. If the magnetic field is out of the page and velocity is to the right, then the fourth right-hand rule shows a downward *EMF*, as illustrated in **Figure 25-8b,** and consequently a downward current is produced. In Chapter 24, you learned that a wire carrying a current through a magnetic field will experience a force acting on it. This force results from the interaction between the existing magnetic field and the magnetic field generated around all currents. To determine the direction of this force, use the third right-hand rule: if current, *I*, is down and the magnetic field, *B*, is out, then the resulting force is to the left, as shown in **Figure 25-8c.** This means that the direction of the force on the wire opposes the original motion of the wire, *v*. That is, the force acts to slow down the rotation of the armature. The method of determining the direction of a force was first demonstrated in 1834 by H.F.E. Lenz and is therefore called Lenz's law.

Lenz's law states that the direction of the induced current is such that the magnetic field resulting from the induced current opposes the change in the field that caused the induced current. Note that it is the change in the field and not the field itself that is opposed by the induced magnetic effects.

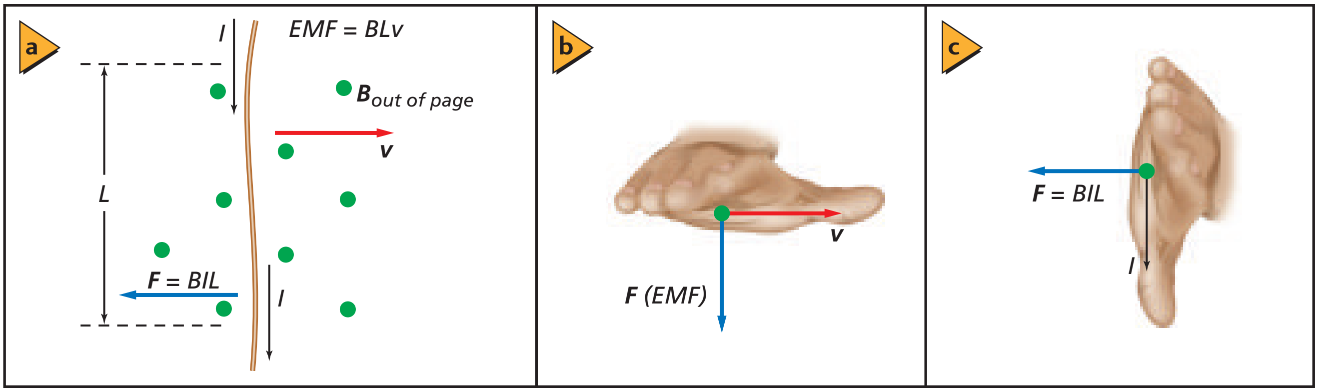
Opposing change **Figure 25-9,** on the next page, is an example of how Lenz's law works. The north pole of a magnet is moved toward the left end of a coil of wire. To create a force that will oppose the approach of the north pole, the left end of the coil also must become a north pole. In other words, the magnetic field lines must emerge from the left end of the coil. Using the second right-hand rule, which you learned in Chapter 24, you will see that if Lenz's law is correct, the induced current must be in a counterclockwise direction as viewed from the end of the coil where the magnet is inserted. Experiments have shown that this is so. If the magnet is turned so that a south pole approaches the coil, the induced current will flow in a clockwise direction.

▶ Objectives

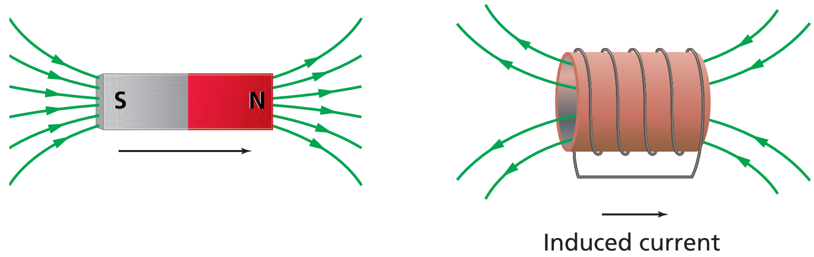
- **Apply** Lenz's law.
- **Explain** back-*EMF* and how it affects the operation of motors and generators.
- **Explain** self-inductance and how it affects circuits.
- **Solve** transformer problems involving voltage, current, and turn ratios.

▶ Vocabulary

Lenz's law
eddy current
self-inductance
transformer
primary coil
secondary coil
mutual inductance
step-up transformer
step-down transformer



■ **Figure 25-8** A wire, length *L*, moving through a magnetic field, *B*, induces an electromotive force. If the wire is part of a circuit, then there will be a current, *I*. This current will interact with the magnetic field and produce a force, *F*. Notice that the resulting force opposes the motion, *v*, of the wire.



■ **Figure 25-9** The magnet approaching the coil causes an induced current to flow. Lenz's law predicts the direction of flow shown.

If a generator produces only a small current, then the opposing force on the armature will be small, and the armature will be easy to turn. If the generator produces a larger current, the force on the larger current will be greater, and the armature will be more difficult to turn. A generator supplying a large current is producing a large amount of electric energy. The opposing force on the armature means that mechanical energy must be supplied to the generator to produce the electric energy, consistent with the law of conservation of energy.

Motors and Lenz's law Lenz's law also applies to motors. When a current-carrying wire moves in a magnetic field, an *EMF* is generated. This *EMF*, called the back-*EMF*, is in a direction that opposes the current. When a motor is first turned on, there is a large current because of the low resistance of the motor. As the motor begins to turn, the motion of the wires across the magnetic field induces a back-*EMF* that opposes the current. Therefore, the net current through the motor is reduced. If a mechanical load is placed on the motor, as in a situation in which work is being done to lift a weight, the rotation of the motor will slow. This slowing down will decrease the back-*EMF*, which will allow more current through the motor. Note that this is consistent with the law of conservation of energy: if current increases, so does the rate at which electric power is being sent to the motor. This power is delivered in mechanical form to the load. If the mechanical load stops the motor, current can be so high that wires overheat.

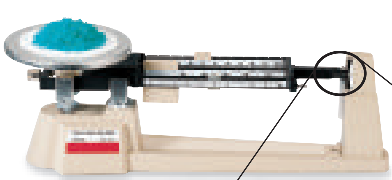
As current draw varies with the changing speed of an electric motor, the voltage drop across the resistance of the wires supplying the motor also varies. Another device, such as a lightbulb, that is in parallel with the motor, also would experience the drop in voltage. This is why you may have noticed some lights in a house dimming when a large motorized appliance, such as an air conditioner or a table saw, starts operating.

When the current to the motor is interrupted by a switch in the circuit being turned off or by the motor's plug being pulled from a wall outlet, the sudden change in the magnetic field generates a back-*EMF*. This reverse voltage can be large enough to cause a spark across the switch or between the plug and the wall outlet.

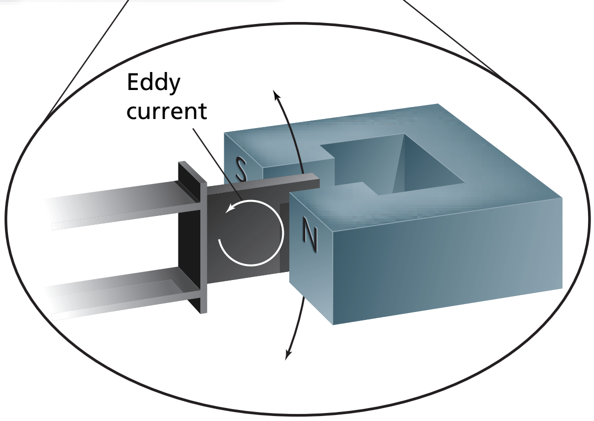
Application of Lenz's law A sensitive balance, such as the kind used in laboratories, uses Lenz's law to stop its oscillation when an object is placed on the pan. As shown in **Figure 25-10,** a piece of metal attached to the balance arm is located between the poles of a horseshoe magnet.

■ **Figure 25-10** Sensitive balances use eddy-current damping to control oscillations of the balance beam **(a).** As the metal plate on the end of the beam moves through the magnetic field, a current is generated in the metal. This current, in turn, produces a magnetic field that opposes the motion that caused it, and the motion of the beam is dampened **(b).**

a



b



Matt Meadows

When the balance arm swings, the metal moves through the magnetic field. Currents called **eddy currents** are generated in the metal and produce a magnetic field that acts to oppose the motion that caused the currents. Thus, the metal piece is slowed down. The force opposes the motion of the metal in either direction but does not act if the metal is still. Thus, the force does not change the mass read by the balance. This effect is called eddy-current damping. A practical motor or transformer core is constructed from thin laminations, or layers, each one insulated from the other, to reduce the circulation of eddy currents.

Eddy currents are generated when a piece of metal moves through a magnetic field. The reverse is also true: a current is generated when a metal loop is placed in a changing magnetic field. According to Lenz's law, the current generated will oppose the changing magnetic field. The current generates a magnetic field of its own in the opposite direction that causes the uncut, aluminum ring in **Figure 25-11** to float. An AC current is in the coil, so a constantly changing magnetic field is generated. This changing magnetic field induces an *EMF* in the rings. If these rings were constructed from a nonconducting material such as nylon or brass, an *EMF* could not be induced. For the uncut ring, the *EMF* causes a current that produces a magnetic field that will oppose the change in the generating magnetic field. The interaction of these two magnetic fields causes the ring to push away from the coil, similar to the way in which the north poles of two magnets push away from each other. For the lower ring, which has been sawed through, an *EMF* is generated, but no current can result because of an incomplete path. Hence, no opposing magnetic field is produced by the ring.

Figure 25-11 Current is induced in the continuous metal ring, while there is no current in the cut ring.

Self-Inductance

Back-*EMF* can be explained in another way. As Faraday showed, *EMF* is induced whenever a wire cuts the lines of a magnetic field. The current through the wire shown in **Figure 25-12** increases from **Figure 25-12a** to **Figure 25-12c.** The current generates a magnetic field, shown by magnetic field lines. As the current and magnetic field increase, new lines are created. As more lines are added, they cut through the coil wires and generate an *EMF* to oppose the current changes. The *EMF* will make the potential of the top of the coil more negative than the bottom. This induction of *EMF* in a wire carrying changing current is called **self-inductance.**

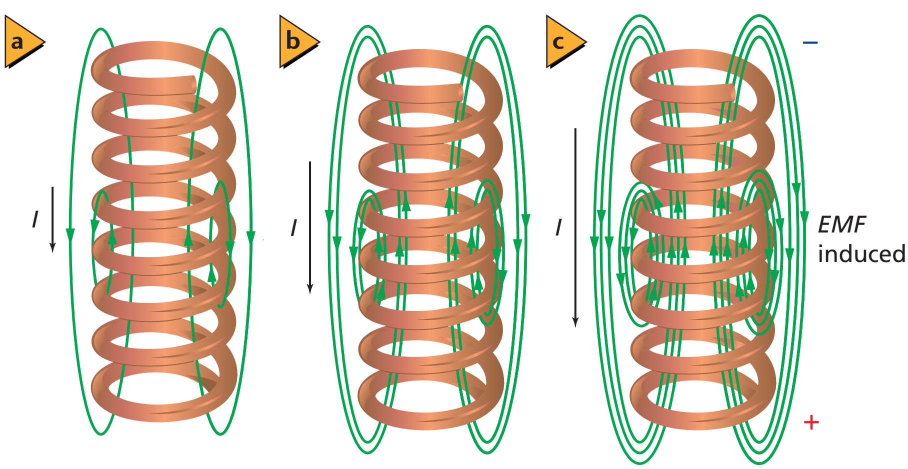


Figure 25-12 As the current in the coil increases from **(a)** on the left to **(c)** on the right, the magnetic field generated by the current also increases. This increase in the magnetic field produces an *EMF* that opposes the current direction.

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Motor and Generator

Motors and generators differ, mainly in the way they convert energy—electric to mechanical compared to mechanical to electric.

1. Make a series circuit with an efficient DC motor, a miniature lamp, and an ammeter.

2. Rotate the handle, or motor shaft, to try to light the lamp.

Analyze and Conclude

3. What happens if you vary the speed at which you rotate the handle?

4. Predict what will happen if you connect your motor to a second motor.

The size of the induced *EMF* is proportional to the rate at which field lines cut through the wires. The faster the current is changed, the larger the opposing *EMF*. If the current reaches a steady value, the magnetic field is constant, and the *EMF* is zero. When the current is decreased, an *EMF* is generated that tends to prevent the reduction in the magnetic field and current. Because of self-inductance, work has to be done to increase the current flowing through the coil. Energy is stored in the magnetic field. This is similar to the way in which a charged capacitor stores energy in the electric field between its plates.

Transformers

Transformers are used to increase or decrease AC voltages. Usage of transformers is common because they change voltages with relatively little loss of energy. In fact, many of the devices in your home, such as game systems, printers, and stereos, have transformers inside their casings or as part of their cords.

How transformers work Self-inductance produces an *EMF* when current changes in a single coil. A transformer has two coils, electrically insulated from each other, but wound around the same iron core. One coil is called the **primary coil.** The other coil is called the **secondary coil.** When the primary coil is connected to a source of AC voltage, the changing current creates a changing magnetic field, which is carried through the core to the secondary coil. In the secondary coil, the changing field induces a varying *EMF*. This effect is called **mutual inductance.**

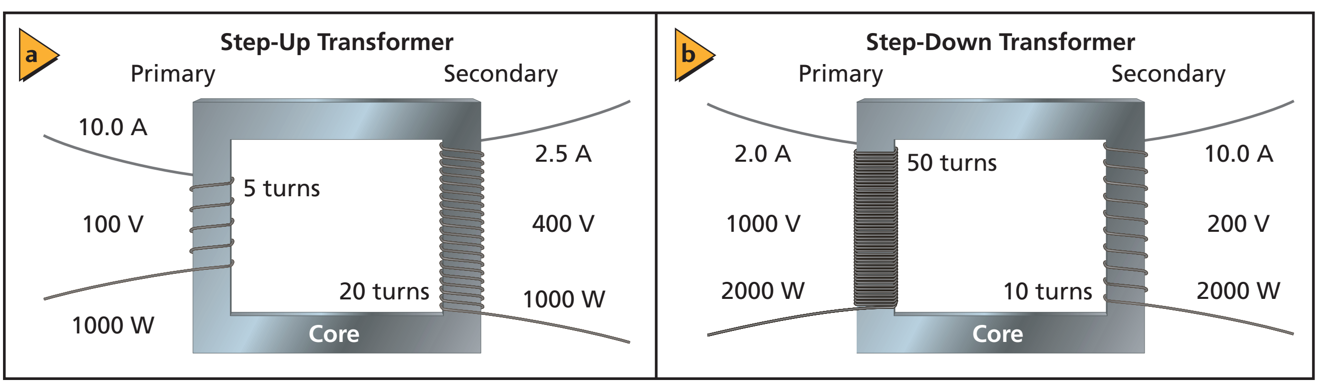
The *EMF* induced in the secondary coil, called the secondary voltage, is proportional to the primary voltage. The secondary voltage also depends on the ratio of the number of turns on the secondary coil to the number of turns on the primary coil, as shown by the following expressions.

$$\frac{\text{secondary voltage}}{\text{primary voltage}} = \frac{\text{number of turns on secondary coil}}{\text{number of turns on primary coil}}$$

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

If the secondary voltage is larger than the primary voltage, the transformer is called a **step-up transformer,** as shown in **Figure 25-13a.** If the voltage coming out of the transformer is smaller than the voltage put in, then it is called a **step-down transformer,** as shown in **Figure 25-13b.**

Figure 25-13 In a transformer, the ratio of input voltage to output voltage depends upon the ratio of the number of turns on the primary coil to the number of turns on the secondary coil. The output voltage can be the same as the input, greater than the input **(a),** or less than the input **(b)**.



In an ideal transformer, the electric power delivered to the secondary circuit equals the power supplied to the primary circuit. An ideal transformer dissipates no power itself, and can be represented by the following equations:

$$P_p = P_s$$

$$V_p I_p = V_s I_s$$

Rearranging the equation to find the ratio V_p/V_s shows that the current in the primary circuit depends on how much current is required by the secondary circuit. This relationship can be combined with the relationship shown earlier between voltage and the number of turns to result in the following.

Transformer Equation $\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}$

The ratio of the current in the secondary coil to the current in the primary coil is equal to the ratio of the voltage in the primary coil to the secondary coil, which is also equal to the ratio of the number of turns on the voltage in the primary coil to the number of turns on the secondary coil.

As mentioned previously, a step-up transformer increases voltage. Because transformers cannot increase the power output, there must be a corresponding decrease in current through the secondary circuit. Similarly, in a step-down transformer, the current is greater in the secondary circuit than it is in the primary circuit. A voltage decrease corresponds to a current increase, as shown in the Connecting Math to Physics. Another way to understand this is to consider a transformer as 100 percent efficient, as is typically assumed in industry. Therefore, in most cases, it may be assumed that the input power and the output power are the same. Figure 25-13 illustrates the principles of step-up and step-down transformers. As shown in **Figure 25-14,** some transformers can function either as step-up transformers or step-down transformers, depending on how they are hooked up.

▶ Connecting Math to Physics

Inequalities Study the following expressions to help you understand the relationships among voltage, current, and the number of coils in step-up and step-down transformers.

Step-Up Transformer	Step-Down Transformer
$V_p < V_s$	$V_p > V_s$
$I_p > I_s$	$I_p < I_s$
$N_p < N_s$	$N_p > N_s$

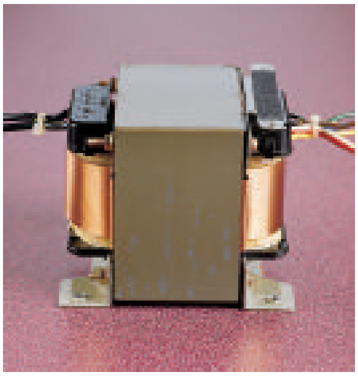


Figure 25-14 If the input voltage is connected to the coils on the left, where there is a larger number of turns, the transformer functions as a step-down transformer. If the input voltage is connected at the right, the transformer functions as a step-up transformer.

APPLYING PHYSICS

▶ **Common Units** Transformers typically are rated in volt-amps reactive (VA, kilo-VA, mega-VA). Technically, only pure resistive-type loads have their power expressed in watts and reactive loads in volt-amps. ◀

CONTENTS

EXAMPLE Problem 2

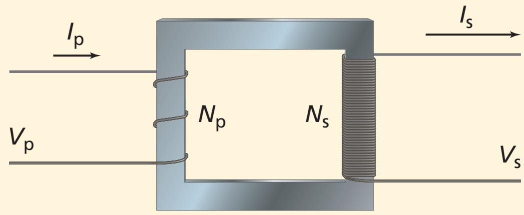
Step-Up Transformers A step-up transformer has a primary coil consisting of 200 turns and a secondary coil consisting of 3000 turns. The primary coil is supplied with an effective AC voltage of 90.0 V.

a. What is the voltage in the secondary circuit?

b. The current in the secondary circuit is 2.0 A. What is the current in the primary circuit?

1 Analyze and Sketch the Problem

- Draw an iron core with turns of wire.
- Label the variables *I*, *V*, and *N*.



Known:		Unknown:
$N_p = 200$	$V_p = 90.0$ V	$V_s = ?$
$N_s = 3000$	$I_s = 2.0$ A	$I_p = ?$

2 Solve for the Unknown

a. Solve for V_s.

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$V_s = \frac{N_s V_p}{N_p}$$

$$= \frac{(3000)(90.0\text{ V})}{200}$$

Substitute $N_s = 3000$, $V_p = 90.0$ V, $N_p = 200$

$$= 1350\text{ V}$$

b. The power in the primary and secondary circuits are equal assuming 100 percent efficiency.

$$P_p = P_s$$

$$V_p I_p = V_s I_s$$

Substitute $P_p = V_p I_p$, $P_s = V_s I_s$

Solve for I_p.

$$I_p = \frac{V_s I_s}{V_p}$$

$$= \frac{(1350\text{ V})(2.0\text{ A})}{90.0\text{ V}}$$

Substitute $V_s = 1350$ V, $I_s = 2.0$ A, $V_p = 90.0$ V

$$= 3.0\times10^{1}\text{ A}$$

Math Handbook
Significant Digits
pages 833–834

3 Evaluate the Answer

- **Are the units correct?** Voltage should be in volts and current in amps.
- **Is the magnitude realistic?** A large step-up ratio of turns results in a large secondary voltage yet a smaller secondary current. The answers agree with this.

PRACTICE Problems

Additional Problems, Appendix B

For the following problems, effective currents and voltages are indicated.

16. A step-down transformer has 7500 turns on its primary coil and 125 turns on its secondary coil. The voltage across the primary circuit is 7.2 kV. What voltage is being applied across the secondary circuit? If the current in the secondary circuit is 36 A, what is the current in the primary circuit?

17. A step-up transformer has 300 turns on its primary coil and 90,000 turns on its secondary coil. The *EMF* of the generator to which the primary circuit is attached is 60.0 V. What is the *EMF* in the secondary circuit? The current in the secondary circuit is 0.50 A. What current is in the primary circuit?

CHALLENGE PROBLEM

A distribution transformer (T_1) has its primary coil connected to a 3.0-kV AC source. The secondary coil is connected to the primary coil of a second transformer (T_2) by copper conductors. Finally, the secondary coil of transformer T_2 connects to a load that uses 10.0 kW of power. Transformer T_1 has a turn ratio of 5:1, and T_2 has a load voltage of 120 V. The transformer efficiencies are 100.0 percent and 97.0 percent, respectively.

1. Calculate the load current.
2. How much power is being dissipated by transformer T_2?
3. What is the secondary current of transformer T_1?
4. How much current is the AC source supplying to T_1?

Everyday uses of transformers As you learned in Chapter 22, long-distance transmission of electrical energy is economical only if low currents and very high voltages are used. Step-up transformers are used at power sources to develop voltages as high as 480,000 V. High voltages reduce the current required in the transmission lines, keeping the energy lost to resistance low. When the energy reaches the consumer, step-down transformers, such as those shown in **Figure 25-15,** provide appropriately low voltages for consumer use.

Transformers in home appliances further adjust voltages to useable levels. If you have ever had to charge a toy or operate a personal electronic device, you probably had to plug a large "block" into the wall outlet. A transformer of the type discussed in this chapter is contained inside of that block. In this case, it is probably reducing the household voltage of about 120 V to something in the 3-V to 26-V range.

Not all transformers are step-up or step-down. Transformers can be used to isolate one circuit from another. This is possible because the wire of the primary coil never makes direct contact with the wire of the secondary coil. This type of transformer would most likely be found in some small electronic devices.

Figure 25-15 Step-down transformers are used to reduce the high voltages in transmission lines to levels appropriate for consumers at the points of use.

25.2 Section Review

18. **Coiled Wire and Magnets** You hang a coil of wire with its ends joined so that it can swing easily. If you now plunge a magnet into the coil, the coil will swing. Which way will it swing relative to the magnet and why?

19. **Motors** If you unplugged a running vacuum cleaner from a wall outlet, you would be much more likely to see a spark than you would be if you unplugged a lighted lamp from the wall. Why?

20. **Transformers and Current** Explain why a transformer may only be operated on alternating current.

21. **Transformers** Frequently, transformer coils that have only a few turns are made of very thick (low-resistance) wire, while those with many turns are made of thin wire. Why?

22. **Step-Up Transformers** Refer to the step-up transformer shown in Figure 25-13. Explain what will happen to the primary current if the secondary coil is short-circuited.

23. **Critical Thinking** Would permanent magnets make good transformer cores? Explain.

Matt Meadows

PHYSICS LAB

Induction and Transformers

A transformer is an electric device without any moving components. It is made of two electric circuits interlinked by a magnetic field. A transformer is used to increase or decrease an AC potential difference, which often is called *voltage.* Transformers can be found everywhere. Every electronic device that plugs into your household electric circuits incorporates a transformer, usually to lower the voltage going to the device. Televisions that have standard cathode-ray picture tubes incorporate high-voltage transformers, which raise the standard household voltage to tens of thousands of volts. This accelerates electrons from the rear of the tube to the screen. In this experiment, you will use two coils with a removable iron core. One coil is called the primary coil, the other the secondary coil. When an AC voltage is applied to the primary coil, the changing magnetic field induces a current, and thus, a voltage in the secondary coil. This induced voltage is expressed by $V_s/V_p = N_s/N_p$, where N refers to the number of turns in the coils.

QUESTION

What is the relationship between voltages in the two coils of a transformer?

Objectives

- **Describe** how a transformer works.
- **Observe** the effect of DC voltage on a transformer.
- **Observe** the effect of AC voltage on a transformer.

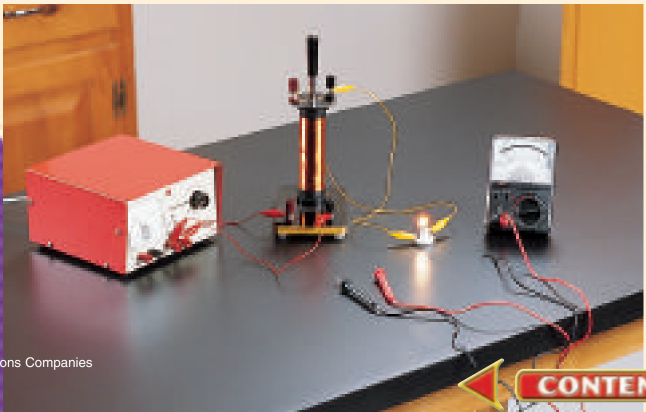
Safety Precautions

Materials

primary and secondary coil apparatus
small AC power supply
AC voltmeter
DC power supply (0-6V, 0-5A)
connecting wires with alligator clips
small lightbulb with wires

Procedure

1. Estimate the number of coils of wire on the primary and secondary coils. Do this by counting the number of coils in 1 cm and multiplying by the coil's length in centimeters. The primary coil has one layer. The secondary coil has two layers of wire, so double the value for it. Record your results in the data table.
2. Place a small lightbulb across the contacts of the secondary coil. Carefully place the secondary coil into the primary coil. Slowly insert the iron core into the center of the secondary coil.
3. Attach two wires to the output of the DC power supply. Attach the positive wire from the power supply to one of the primary connections. Turn the power supply to nearly its maximum output setting. Holding the free end of the wire attached to the negative connection, gently tap its end to the other primary coil connection. Observe the area where you touch the wire to the connection. Record your observations in the data table.



Horizons Companies

Data Table	
Number of primary coils	
Number of secondary coils	
Step 3 observation	
Step 4 observation	
Step 5 observation	
Step 6 observation	
Step 7 coil volts (V)	
Step 8 observation	
Step 9 iron core	

4. Observe the lightbulb while you are gently tapping the connection. What happens as the wire makes contact and then breaks the electric contact? Record your observation in the data table.
5. Hold the negative wire to the primary coil connection for 5 s and observe the lightbulb. Record your observation in the data table.
6. Disconnect the DC power supply and put it away while leaving the small lightbulb attached to the secondary coil. Attach the AC power supply to the two primary coil connections. Plug in the AC power supply and observe the lightbulb. Record your observations in the data table.
7. Select the AC scale for your voltmeter. Insert the probes into the voltmeter and carefully touch them to the primary coil and measure the applied voltage. Move the probe from the primary coil and measure the secondary coil voltage. Record both readings in the data table.
8. Repeat step 7, but slowly remove the iron core from the secondary coil. What happens to the lightbulb? Measure both primary and secondary coil voltages while the core is being removed. Record your observations in the data table.
9. Carefully feel the iron core. What is your observation? Record it in the data table.

Analyze

1. Calculate the ratio of N_s/N_p from your data.
2. Calculate the ratio of V_s/V_p from your data.
3. **Interpret Data** How do the ratios N_s/N_p and V_s/V_p compare?
4. **Recognize Cause and Effect** Based on the data for step 7, is this transformer a step-up or a step-down transformer? What evidence do you have to support this conclusion?

Conclude and Apply

1. **Infer** How can you explain your observation of the lightbulb in step 4?
2. **Infer** How can you explain the phenomena you observed at the negative connection of the primary coil in step 3?
3. **Infer** How can you explain your observations of the primary and the secondary coil voltages as you removed the iron core in step 8?
4. **Explain** Explain the temperature of the iron core you observed in step 9.

Going Further

Why does the transformer work only with alternating and not direct current?

Real-World Physics

Discuss the use of transformers to assist in the delivery of electricity from the power plant to your home.

Physics Online

To find out more about induction and transformers, visit the Web site: physicspp.com

How it Works
How a Credit-Card Reader Works

Credit cards have revolutionized the world's economies by enabling money to be transferred quickly and easily. The credit-card reader, which captures data from a magnetic strip on the back of a card, is one of the most important links in the electronic transfer of money.

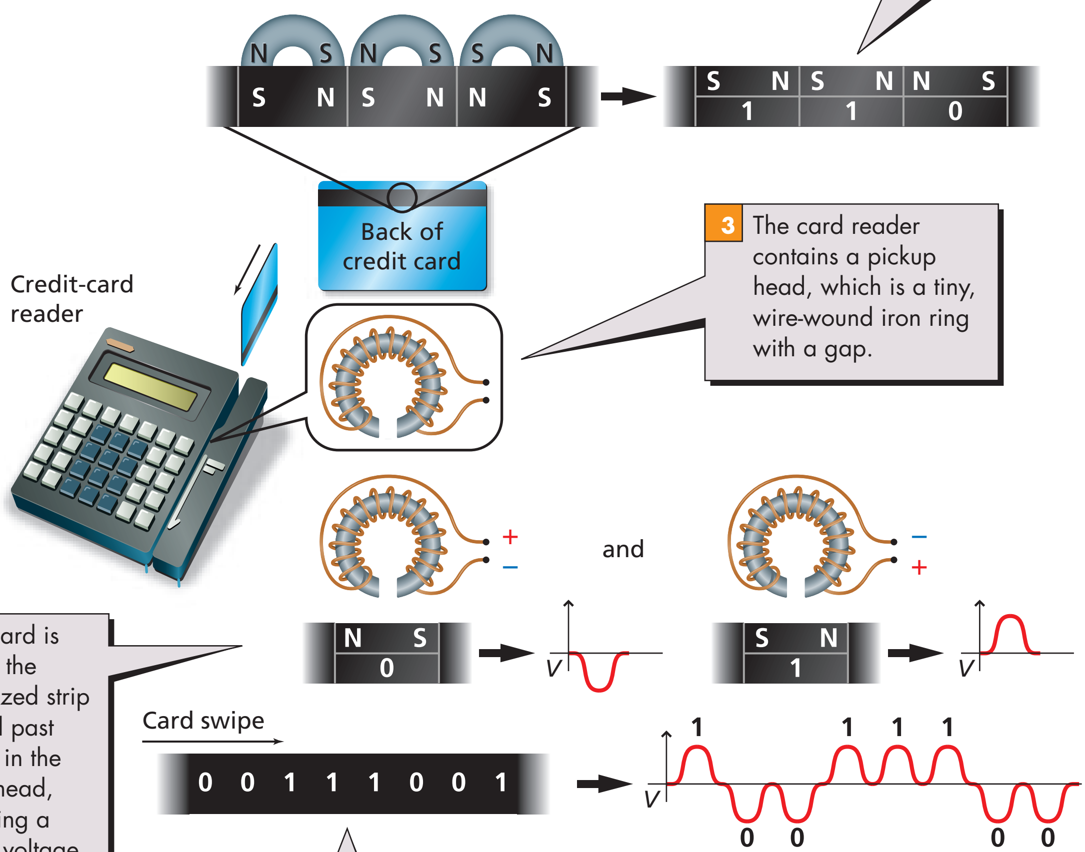
1 A permanent magnet that is touched to a strip of plastic coated with iron oxide leaves a magnetized region.

2 The magnet can be turned around to produce regions of opposite polarity. These regions are assigned the binary digits 1 and 0 and code information, such as the card holder's name and card number.

3 The card reader contains a pickup head, which is a tiny, wire-wound iron ring with a gap.

4 As the card is swiped, the magnetized strip is pulled past the gap in the pickup head, generating a varying voltage across the coil.

5 The binary code on the strip is translated into a voltage waveform. The resulting waveform is stored in a computer's memory and then transmitted to the bank's verification office.



Thinking Critically

1. **Observe** Why is the order of the binary numbers in step 5 reversed from the magnetic strip to the voltage waveform?
2. **Analyze** What would happen if the tiny iron ring did not have a gap in it?

Chapter 25

Study Guide

25.1 Electric Current from Changing Magnetic Fields

Vocabulary

- electromagnetic induction (p. 672)
- fourth right-hand rule (p. 672)
- electromotive force (p. 673)
- electric generator (p. 675)
- average power (p. 677)

Key Concepts

- Michael Faraday discovered that if a wire moves through a magnetic field, an electric current can flow.
- The current produced depends upon the angle between the velocity of the wire and the magnetic field. Maximum current occurs when the wire is moving at right angles to the field.
- Electromotive force, *EMF*, is the potential difference created across the moving wire. *EMF* is measured in volts.
- The *EMF* in a straight length of wire moving through a uniform magnetic field is the product of the magnetic field, B, the length of the wire, L, and the component of the velocity of the moving wire through the field that is perpendicular to the field, $v(\sin\theta)$.

$$EMF = BLv \sin\theta$$

- Effective current and voltage can be used to describe alternating current and voltage.

$$I_{eff} = 0.707\, I_{max}$$

$$V_{eff} = 0.707\, V_{max}$$

- A generator and a motor are similar devices. A generator converts mechanical energy to electric energy, whereas a motor converts electric energy to mechanical energy.

25.2 Changing Magnetic Fields Induce *EMF*

Vocabulary

- Lenz's law (p. 679)
- eddy current (p. 681)
- self-inductance (p. 681)
- transformer (p. 682)
- primary coil (p. 682)
- secondary coil (p. 682)
- mutual inductance (p. 682)
- step-up transformer (p. 682)
- step-down transformer (p. 682)

Key Concepts

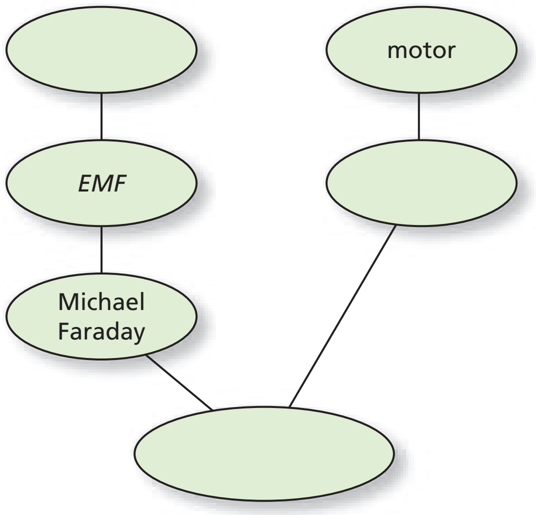
- Lenz's law states that an induced current is always produced in a direction such that the magnetic field resulting from the induced current opposes the change in the magnetic field that is causing the induced current.
- Back-*EMF* is created by a current-carrying wire moving in a magnetic field. Back-*EMF* opposes the current.
- Self-inductance is a property of a wire carrying a changing current. The faster the current is changing, the greater the induced *EMF* that opposes that change.
- A transformer has two coils wound about the same core. An AC current through the primary coil induces an alternating *EMF* in the secondary coil. The voltages in alternating-current circuits may be increased or decreased by transformers.

$$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Chapter 25 Assessment

Concept Mapping

24. Complete the following concept map using the following terms: *generator, back-EMF, Lenz's law.*



Mastering Concepts

25. What is the armature of an electric generator? (25.1)

26. Why is iron used in an armature? (25.1)

For problems 27–29, refer to ***Figure 25-16.***

27. A single conductor moves through a magnetic field and generates a voltage. In what direction should the wire be moved, relative to the magnetic field to generate the minimum voltage? (25.1)

28. What is the polarity of the voltage induced in the wire when it passes the south pole of the magnetic field? (25.1)

29. What is the effect of increasing the net conductor length in an electric generator? (25.1)

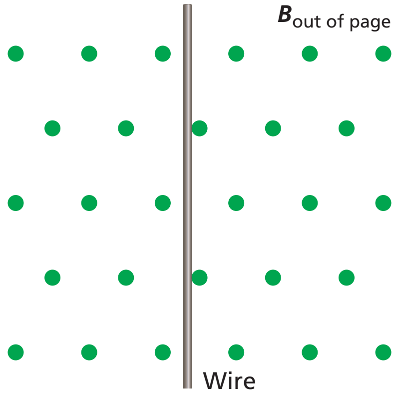


Figure 25-16

30. How were Oersted's and Faraday's results similar? How were they different? (25.1)

31. You have a coil of wire and a bar magnet. Describe how you could use them to generate an electric current. (25.1)

32. What does *EMF* stand for? Why is the name inaccurate? (25.1)

33. What is the difference between a generator and a motor? (25.1)

34. List the major parts of an AC generator. (25.1)

35. Why is the effective value of an AC current less than its maximum value? (25.1)

36. **Hydroelectricity** Water trapped behind a dam turns turbines that rotate generators. List all the forms of energy that take part in the cycle that includes the stored water and the electricity produced. (25.1)

37. State Lenz's law. (25.2)

38. What causes back-*EMF* in an electric motor? (25.2)

39. Why is there no spark when you close a switch and put current through an inductor, but there is a spark when you open the switch? (25.2)

40. Why is the self-inductance of a coil a major factor when the coil is in an AC circuit but a minor factor when the coil is in a DC circuit? (25.2)

41. Explain why the word *change* appears so often in this chapter. (25.2)

42. Upon what does the ratio of the *EMF* in the primary circuit of a transformer to the *EMF* in the secondary circuit of the transformer depend? (25.2)

Applying Concepts

43. Use unit substitution to show that the units of BLv are volts.

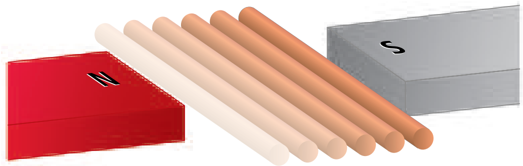
44. When a wire is moved through a magnetic field, does the resistance of the closed circuit affect current only, *EMF* only, both, or neither?

45. **Biking** As Logan slows his bike, what happens to the *EMF* produced by his bike's generator? Use the term *armature* in your explanation.

46. The direction of AC voltage changes 120 times each second. Does this mean that a device connected to an AC voltage alternately delivers and accepts energy?

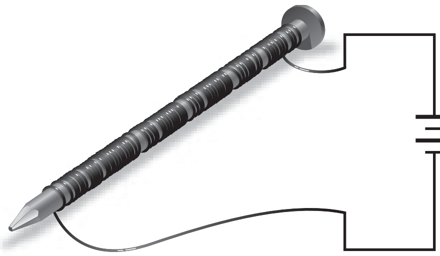
For more problems, go to Additional Problems, Appendix B.

47. A wire is moved horizontally between the poles of a magnet, as shown in **Figure 25-17.** What is the direction of the induced current?



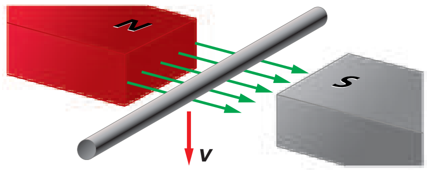
■ Figure 25-17

48. You make an electromagnet by winding wire around a large nail, as shown in **Figure 25-18.** If you connect the magnet to a battery, is the current larger just after you make the connection or several tenths of a second after the connection is made? Or, is it always the same? Explain.



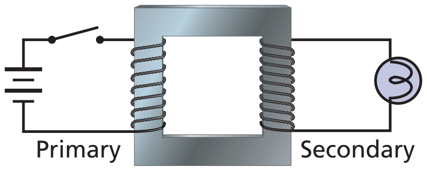
■ Figure 25-18

49. A segment of a wire loop is moving downward through the poles of a magnet, as shown in **Figure 25-19.** What is the direction of the induced current?



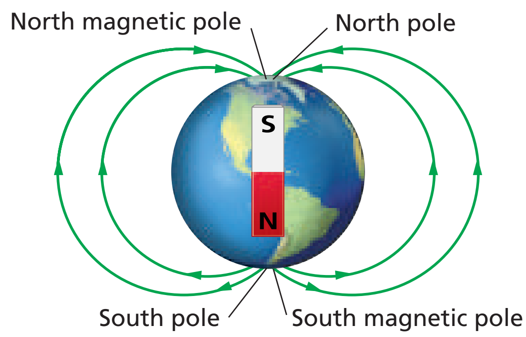
■ Figure 25-19

50. A transformer is connected to a battery through a switch. The secondary circuit contains a lightbulb, as shown in **Figure 25-20.** Will the lamp be lighted as long as the switch is closed, only at the moment the switch is closed, or only at the moment the switch is opened? Explain.



■ Figure 25-20

51. Earth's Magnetic Field The direction of Earth's magnetic field in the northern hemisphere is downward and to the north as shown in **Figure 25-21.** If an east-west wire moves from north to south, in which direction is the current?



■ Figure 25-21

52. You move a length of copper wire down through a magnetic field, *B*, as shown in Figure 25-19.

a. Will the induced current move to the right or left in the wire segment in the diagram?

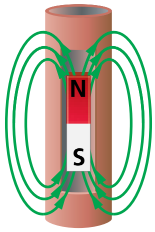
b. As soon as the wire is moved in the field, a current appears in it. Thus, the wire segment is a current-carrying wire located in a magnetic field. A force must act on the wire. What will be the direction of the force acting on the wire as a result of the induced current?

53. A physics instructor drops a magnet through a copper pipe, as illustrated in **Figure 25-22.** The magnet falls very slowly, and the students in the class conclude that there must be some force opposing gravity.

a. What is the direction of the current induced in the pipe by the falling magnet if the south pole is toward the bottom?

b. The induced current produces a magnetic field. What is the direction of the field?

c. How does this field reduce the acceleration of the falling magnet?



■ Figure 25-22

54. Generators Why is a generator more difficult to rotate when it is connected to a circuit and supplying current than it is when it is standing alone?

55. Explain why the initial start-up current is so high in an electric motor. Also explain how Lenz's law applies at the instant $t > 0$.

56. Using Figure 25-10 in conjunction with Lenz's law, explain why all practical transformer cores incorporate a laminated core.

57. A practical transformer is constructed with a laminated core that is not a superconductor. Because the eddy currents cannot be completely eliminated, there is always a small core loss. This results, in part, in a net loss of power within the transformer. What fundamental law makes it impossible to bring this loss to zero?

58. Explain the process of mutual induction within a transformer.

59. Shawn drops a magnet, north pole down, through a vertical copper pipe.

a. What is the direction of the induced current in the copper pipe as the bottom of the magnet passes?

b. The induced current produces a magnetic field. What is the direction of the induced magnetic field?

Mastering Problems

25.1 Electric Current from Changing Magnetic Fields

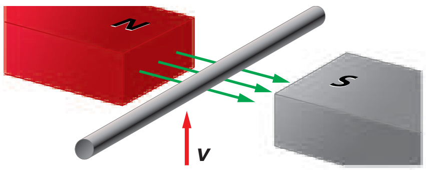
60. A wire, 20.0-m long, moves at 4.0 m/s perpendicularly through a magnetic field. An *EMF* of 40 V is induced in the wire. What is the strength of the magnetic field?

61. **Airplanes** An airplane traveling at 9.50×10^{2} km/h passes over a region where Earth's magnetic field is 4.5×10^{-5} T and is nearly vertical. What voltage is induced between the plane's wing tips, which are 75 m apart?

62. A straight wire, 0.75-m long, moves upward through a horizontal 0.30-T magnetic field, as shown in **Figure 25-23,** at a speed of 16 m/s.

a. What *EMF* is induced in the wire?

b. The wire is part of a circuit with a total resistance of 11 Ω. What is the current?



■ Figure 25-23

63. At what speed would a 0.20-m length of wire have to move across a 2.5-T magnetic field to induce an *EMF* of 10 V?

64. An AC generator develops a maximum *EMF* of 565 V. What effective *EMF* does the generator deliver to an external circuit?

65. An AC generator develops a maximum voltage of 150 V. It delivers a maximum current of 30.0 A to an external circuit.

a. What is the effective voltage of the generator?

b. What effective current does the generator deliver to the external circuit?

c. What is the effective power dissipated in the circuit?

66. **Electric Stove** An electric stove is connected to an AC source with an effective voltage of 240 V.

a. Find the maximum voltage across one of the stove's elements when it is operating.

b. The resistance of the operating element is 11 Ω. What is the effective current?

67. You wish to generate an *EMF* of 4.5 V by moving a wire at 4.0 m/s through a 0.050-T magnetic field. How long must the wire be, and what should be the angle between the field and direction of motion to use the shortest wire?

68. A 40.0-cm wire is moved perpendicularly through a magnetic field of 0.32 T with a velocity of 1.3 m/s. If this wire is connected into a circuit of 10-Ω resistance, what is the current?

69. You connect both ends of a copper wire with a total resistance of 0.10 Ω to the terminals of a galvanometer. The galvanometer has a resistance of 875 Ω. You then move a 10.0-cm segment of the wire upward at 1.0 m/s through a 2.0×10^{-2}-T magnetic field. What current will the galvanometer indicate?

70. The direction of a 0.045-T magnetic field is 60° above the horizontal. A wire, 2.5-m long, moves horizontally at 2.4 m/s.

a. What is the vertical component of the magnetic field?

b. What *EMF* is induced in the wire?

71. **Dams** A generator at a dam can supply 375 MW (375×10^{6} W) of electrical power. Assume that the turbine and generator are 85 percent efficient.

a. Find the rate at which falling water must supply energy to the turbine.

b. The energy of the water comes from a change in potential energy, $PE = mgh$. What is the change in *PE* needed each second?

c. If the water falls 22 m, what is the mass of the water that must pass through the turbine each second to supply this power?

For more problems, go to Additional Problems, Appendix B.

72. A conductor rotating in a magnetic field has a length of 20 cm. If the magnetic-flux density is 4.0 T, determine the induced voltage when the conductor is moving perpendicular to the line of force. Assume that the conductor travels at a constant velocity of 1 m/s.

73. Refer to Example Problem 1 and **Figure 25-24** to determine the following.
- **a.** induced voltage in the conductor
- **b.** current flow (I)
- **c.** direction of flux rotation around the conductor
- **d.** polarity of point A relative to point B

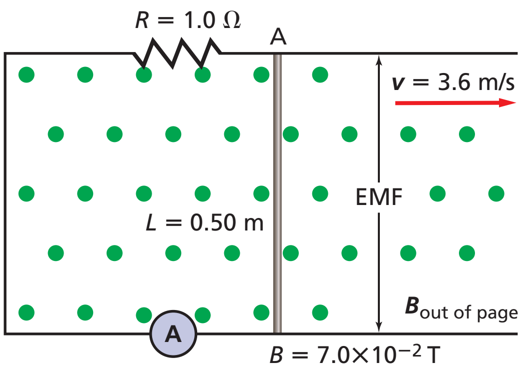


Figure 25-24

25.2 Changing Magnetic Fields Induce *EMF*

74. The primary coil of a transformer has 150 turns. It is connected to a 120-V source. Calculate the number of turns on the secondary coil needed to supply the following voltages.
- **a.** 625 V
- **b.** 35 V
- **c.** 6.0 V

75. A step-up transformer has 80 turns on its primary coil and 1200 turns on its secondary coil. The primary circuit is supplied with an alternating current at 120 V.
- **a.** What voltage is being applied across the secondary circuit?
- **b.** The current in the secondary circuit is 2.0 A. What current is in the primary circuit?
- **c.** What are the power input and output of the transformer?

76. **Laptop Computers** The power supply in a laptop computer requires an effective voltage of 9.0 V from a 120-V line.
- **a.** If the primary coil has 475 turns, how many does the secondary coil have?
- **b.** A 125-mA current is in the computer. What current is in the primary circuit?

77. **Hair Dryers** A hair dryer manufactured for use in the United States uses 10 A at 120 V. It is used with a transformer in England, where the line voltage is 240 V.
- **a.** What should be the ratio of the turns of the transformer?
- **b.** What current will the hair dryer now draw?

78. A 150-W transformer has an input voltage of 9.0 V and an output current of 5.0 A.
- **a.** Is this a step-up or step-down transformer?
- **b.** What is the ratio of V_{output} to V_{input}?

79. Scott connects a transformer to a 24-V source and measures 8.0 V at the secondary circuit. If the primary and secondary circuits were reversed, what would the new output voltage be?

Mixed Review

80. A step-up transformer's primary coil has 500 turns. Its secondary coil has 15,000 turns. The primary circuit is connected to an AC generator having an *EMF* of 120 V.
- **a.** Calculate the *EMF* of the secondary circuit.
- **b.** Find the current in the primary circuit if the current in the secondary circuit is 3.0 A.
- **c.** What power is drawn by the primary circuit? What power is supplied by the secondary circuit?

81. With what speed must a 0.20-m-long wire cut across a magnetic field for which B is 2.5 T if it is to have an *EMF* of 10 V induced in it?

82. At what speed must a wire conductor 50-cm long be moved at right angles to a magnetic field of induction 0.20 T to induce an *EMF* of 1.0 V in it?

83. A house lighting circuit is rated at 120-V effective voltage. What is the peak voltage that can be expected in this circuit?

84. **Toaster** A toaster draws 2.5 A of alternating current. What is the peak current through this toaster?

85. The insulation of a capacitor will break down if the instantaneous voltage exceeds 575 V. What is the largest effective alternating voltage that may be applied to the capacitor?

86. **Circuit Breaker** A magnetic circuit breaker will open its circuit if the instantaneous current reaches 21.25 A. What is the largest effective current the circuit will carry?

87. The electricity received at an electrical substation has a potential difference of 240,000 V. What should the ratio of the turns of the step-down transformer be to have an output of 440 V?

88. An alternating-current electric generator supplies a 45-kW industrial electric heater. If the system voltage is 660 V_{rms}, what is the peak current supplied?

89. A certain step-down transformer has 100 turns on the primary coil and 10 turns on the secondary coil. If a 2.0-kW resistive load is connected to the transformer, what is the effective primary current that flows? Assume that the secondary voltage is 60.0 V_{pk}.

90. A transformer rated at 100 kVA has an efficiency of 98 percent.
a. If the connected load consumes 98 kW of power, what is the input power to the transformer?
b. What is the maximum primary current with the transformer consuming its rated reactive power? Assume that $V_P = 600$ V.

91. A wire, 0.40-m long, cuts perpendicularly across a magnetic field for which *B* is 2.0 T at a velocity of 8.0 m/s.
a. What *EMF* is induced in the wire?
b. If the wire is in a circuit with a resistance of 6.4 Ω, what is the size of the current in the wire?

92. A coil of wire, which has a total length of 7.50 m, is moved perpendicularly to Earth's magnetic field at 5.50 m/s. What is the size of the current in the wire if the total resistance of the wire is 5.0×10^{-2} mΩ? Assume Earth's magnetic field is 5×10^{-5} T.

93. The peak value of the alternating voltage applied to a 144-Ω resistor is 1.00×10^{2} V. What power must the resistor be able to handle?

94. Television The CRT in a television uses a step-up transformer to change 120 V to 48,000 V. The secondary side of the transformer has 20,000 turns and an output of 1.0 mA.
a. How many turns does the primary side have?
b. What is the input current?

Thinking Critically

95. Apply Concepts Suppose that an "anti-Lenz's law" existed that meant a force was exerted to increase the change in a magnetic field. Thus, when more energy was demanded, the force needed to turn the generator would be reduced. What conservation law would be violated by this new "law"? Explain.

96. Analyze Real transformers are not 100 percent efficient. Write an expression for transformer efficiency in percent using power. A step-down transformer that has an efficiency of 92.5 percent is used to obtain 28.0 V from a 125-V household voltage. The current in the secondary circuit is 25.0 A. What is the current in the primary circuit?

97. Analyze and Conclude A transformer that supplies eight homes has an efficiency of 95 percent. All eight homes have operating electric ovens that each draw 35 A from 240-V lines. How much power is supplied to the ovens in the eight homes? How much power is dissipated as heat in the transformer?

Writing in Physics

98. Common tools, such as an electric drill, are typically constructed using a universal motor. Using your local library, and other sources, explain how this type of motor may operate on either AC or DC current.

Cumulative Review

99. Light is emitted by a distant star at a frequency of 4.56×10^{14} Hz. If the star is moving toward Earth at a speed of 2750 km/s, what frequency light will be detected by observers on Earth? (Chapter 16)

100. A distant galaxy emits light at a frequency of 7.29×10^{14} Hz. Observers on Earth receive the light at a frequency of 6.14×10^{14} Hz. How fast is the galaxy moving, and in what direction? (Chapter 16)

101. How much charge is on a 22-μF capacitor with 48 V applied to it? (Chapter 21)

102. Find the voltage across a 22-Ω, 5.0-W resistor operating at half of its rating. (Chapter 22)

103. Determine the total resistance of three, 85-Ω resistors connected in parallel and then series-connected to two 85-Ω resistors connected in parallel, as shown in **Figure 25-25.** (Chapter 23)

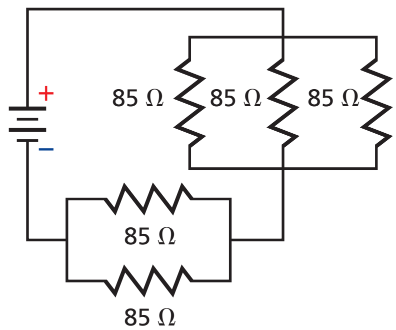


Figure 25-25

104. An electron with a velocity of 2.1×10^{6} m/s is at right angles to a 0.81-T magnetic field. What is the force on the electron produced by the magnetic field? What is the electron's acceleration? The mass of an electron is 9.11×10^{-31} kg. (Chapter 24)

Standardized Test Practice

Multiple Choice

1. Which dimensional analysis is correct for the calculation of *EMF*?

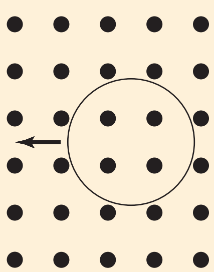
- (A) (N·A·m)(J)
- (B) (N·A/m)(m)(m/s)
- (C) J·C
- (D) (N·m·A/s)(1/m)(m/s)

2. 4.20 V of electromotive force are induced on a 427-mm-long piece of wire that is moving at a rate of 18.6 cm/s. What is the magnetic field that induced the *EMF*?

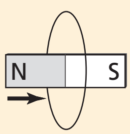
- (A) 5.29×10^{-4} T
- (B) 1.89×10^{-2} T
- (C) 0.334 T
- (D) 52.9 T

3. Which of the following will fail to induce an electric current in the wire?

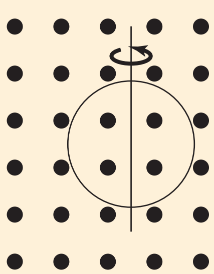
(A)



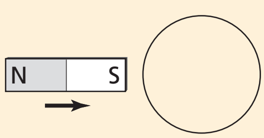
(B)



(C)



(D)



4. 15 cm of wire is moving at the rate of 0.12 m/s through a perpendicular magnetic field of strength 1.4 T. Calculate the *EMF* induced in the wire.

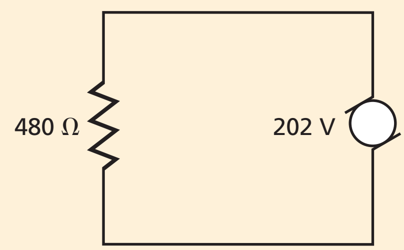
- (A) 0 V
- (B) 0.018 V
- (C) 0.025 V
- (D) 2.5 V

5. A transformer uses a 91-V supply to operate a 13-V device. If the transformer has 130 turns on the primary coil and the device uses 1.9 A of current from the transformer, what is the current supplied to the primary coil?

- (A) 0.27 A
- (B) 0.70 A
- (C) 4.8 A
- (D) 13.3 A

6. An AC generator that delivers a peak voltage of 202 V connects to an electric heater with a resistance of 480 Ω. What is the effective current in the heater?

- (A) 0.298 A
- (B) 1.68 A
- (C) 2.38 A
- (D) 3.37 A



Extended Answer

7. Compare the power lost in transmission for an 800-W line at 160 V to the same power on a line at 960 V. Assume the resistance of the line is 2 Ω. What conclusion can you draw?

✓ Test-Taking TIP

Investigate

Ask your instructor what kinds of questions to expect on the test. Also ask for practice tests so that you can become familiar with the test-taking materials.

Chapter 26

Electromagnetism

What You'll Learn

- You will learn how combined electric and magnetic fields can be used to determine the masses of electrons, atoms, and molecules.
- You will explain how electromagnetic waves are created, travel through space, and are detected.

Why It's Important

Many electromagnetic waves—from radio and television waves, to visible light, microwaves, and X rays—play vital roles in our lives.

Parabolic Receivers This parabolic dish antenna is designed to receive radio waves from satellites orbiting hundreds of kilometers above Earth's surface and objects well beyond the solar system.

Think About This ▶

A parabolic dish gets its name from the shape of its reflecting surface—a parabola. Why are parabolic dish antennas well suited for receiving weak television signals?

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