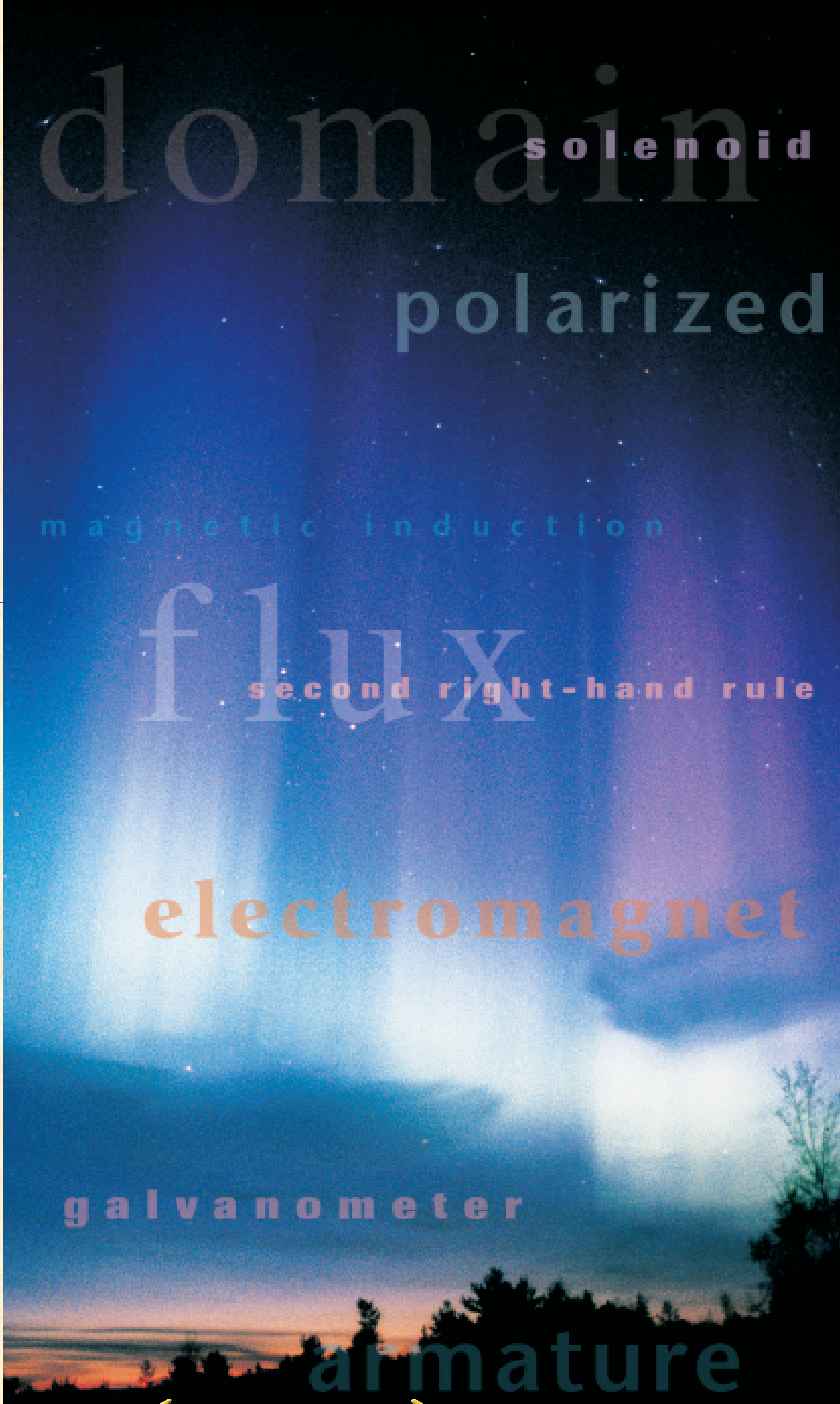
Northern Light Show

The displays of the northern lights, also known as the aurora borealis, have fascinated and mystified people for centuries. Storytellers and poets have found inspiration in the luminous streaks and patches of color in the night sky of the northern hemisphere. What causes these unusual light shows of the northern sky?

Look at the text on page 573 for the answer.



CHAPTER

24 Magnetic Fields

Arcs of ethereal color streak across a night sky. Luminous curtains shimmer in tones of red, green, or purple. Lights in the sky resemble transparent drapery rippling in a soft breeze. All of these are forms of aurora: magnificent light displays most visible near Earth's north and south poles. According to ancient myths, the aurora borealis, or the northern lights, were thought to be caused by ghostly spirits moving between this world and the next.

Today's scientific knowledge tells us that the aurora borealis results from the interaction between the solar wind and Earth's magnetic field. To fully understand how the aurora borealis occurs, you will need to know more about these two phenomena.

Solar winds are streams of electrically charged particles sprayed from the sun. Earth's magnetic field deflects these particles into circular regions around the poles of Earth, called the Van Allen radiation belts. The electrically charged particles collide with atoms in the Earth's atmosphere and make them release energy in the form of flashes of light.

The existence of magnets and magnetic fields has been known for more than 2000 years. Chinese sailors employed magnets as navigational compasses before the first European explorers reached China in the 1500s. Early scientists throughout the world studied magnetic rocks, called lodestones. Today magnets play an increasing role in our everyday lives. Electric generators, simple electric motors, television sets, computer screens, and tape recorders depend on the magnetic effects of electric currents.

The topic of this chapter will play an important part of your investigation of electricity, your knowledge of common electric devices, and your understanding of one of nature's most dramatic phenomena.

WHAT YOU'LL LEARN

- You will relate magnetism to electric charge and electricity.
- You will describe how electromagnetism is harnessed to produce mechanical work.

WHY IT'S IMPORTANT

- Using electromagnetism in electric motors, you can convert electrical energy to mechanical energy.
- Every day, you apply mechanical energy produced from electrical energy.

PHYSICS Online

To find out more about magnetic fields, visit the Glencoe Science Web site at **science.glencoe.com**

CLICK HERE

24.1 Magnets: Permanent and Temporary

OBJECTIVES

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

If you have ever used a compass to tell direction or picked up tacks or paper clips with a magnet, you have observed some effects of magnetism. You might even 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.

General Properties of Magnets

To enhance your study of magnetism, you can experiment with two bar or ceramic magnets such as those shown in **Figure 24–1.**

Magnetic poles Suspend a magnet from a thread, as in **Figure 24–2a.** If it is a bar magnet, you may have to tie a yoke to keep it horizontal. Note that when the magnet comes to rest, it has lined up in a north-south direction. Put a mark on the magnet end that points north. If you rotate it away from that direction, it will return. From this simple experiment, you can conclude that a magnet is **polarized,** that is, it has two ends, one of which is the north-seeking end, or north pole; the other is the south-seeking end, or south pole. A compass is nothing more than a small magnet mounted so that it is free to turn.

Suspend another magnet and mark the end that points north. While one magnet is suspended, observe the interaction of two magnets by bringing the second magnet near, as in **Figure 24–2b.** Note that the two ends that pointed north, the north poles, repel each other, as do the two south poles. The north pole of one magnet, however, will attract the south pole of the other magnet. That is, 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, but each still has two poles. Scientists have tried breaking magnets into separate north and south poles, or "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 probably 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.

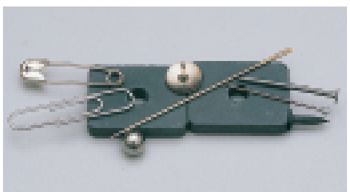
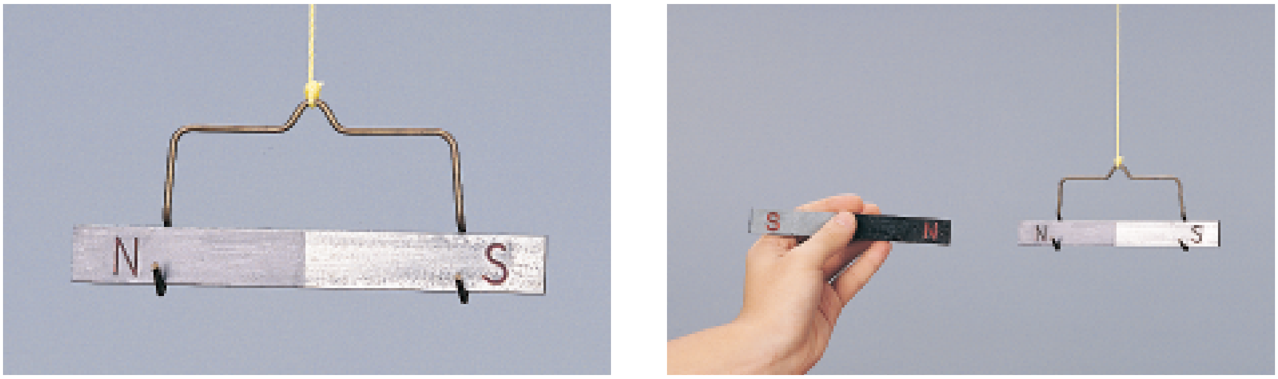


FIGURE 24–1 Ceramic magnets are commonly available in most hardware stores.

How do magnets affect other materials? As you probably discovered as a child, magnets attract things besides other magnets—things like nails, tacks, paper clips, and many other metal objects. Unlike the



a b

FIGURE 24–2 If you suspend a magnet by a thread, it will align itself with Earth's magnetic field **(a).** Its 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).**

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. The nail is only temporarily magnetized; if you pull away the magnet, the nail's magnetism disappears. The polarization induced in the nail is similar to the polarization induced in a conductor by a nearby charged object, which you learned about in Chapter 20.

Permanent magnets The magnetism of permanent magnets is produced in the same way that you created the magnetism of the nail. But because of the microscopic structure of the magnet material, the induced magnetism becomes permanent. Many permanent magnets are made of ALNICO V, an iron alloy containing 8% **Al**uminum, 14% **Ni**ckel, and 3% **Co**balt. A variety of rare earth elements, such as neodymium and gadolinium, produce permanent magnets that are extremely strong for their size.

Pocket Lab

Monopoles?

Place a disk magnet flat on the center of your paper. Place another disk magnet flat at the top of your paper and slowly slide it toward the center magnet.

Observing and Inferring
Does the first magnet attract or repel the second magnet? Rotate one of the magnets and note the effect on the other. Does each magnet have only one pole?

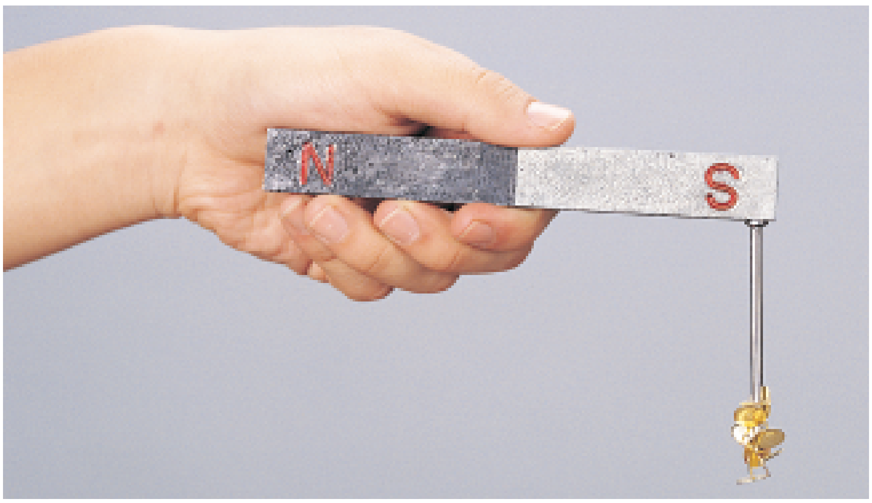


FIGURE 24–3 If you touch an iron nail with a magnet, the nail will become magnetized and will in turn attract other iron objects. However, as soon as the magnet is removed, the nail will lose its magnetism.

Color Conventions

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

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 **magnetic fields** around magnets.

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 at that point. **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. These lines of filings can help you to visualize magnetic field lines.

Magnetic field lines Note that magnetic field lines, like electric field lines, are imaginary. Not only do field lines help us visualize the field, but they also provide a measure of its strength. 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, and this is where the magnetic field strength is the greatest.

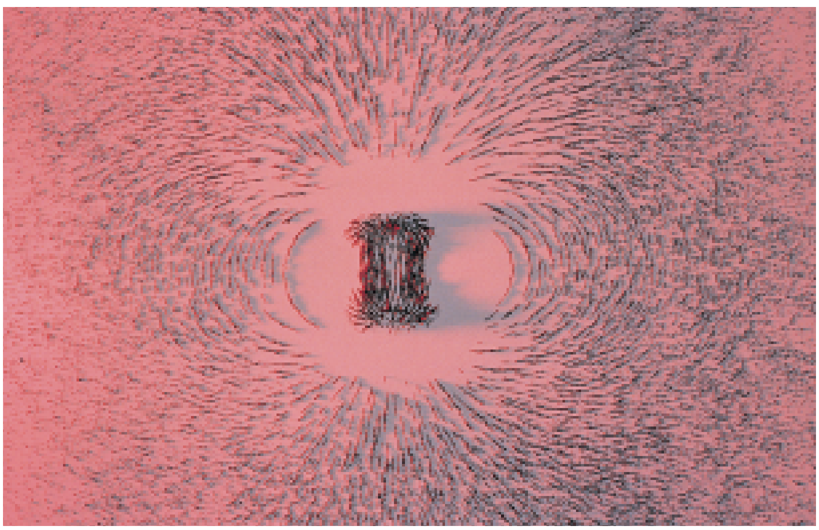
The direction of a magnetic field line is defined as the direction in which the N-pole of a compass points when it is placed in the magnetic field. Outside the magnet, the field lines come out of the magnet at its N-pole and enter the magnet at its S-pole, as illustrated in **Figure 24–5.** What happens 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.

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 beneath a sheet of paper covered with iron filings to see the pattern of magnetic fields in two dimensions **(b).**

Picture not available on CD

a

b



CONTENTS

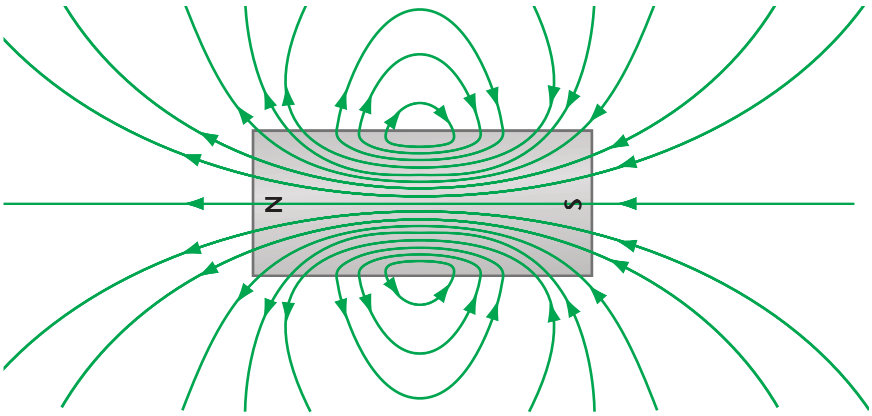


FIGURE 24–5 Magnetic field lines can be visualized as closed loops that leave the north pole of a magnet and enter the south pole.

What kinds of magnetic fields are produced by pairs of bar magnets? You can visualize the fields by placing a sheet of paper over the poles of two magnets. Then sprinkle the paper with iron filings. **Figure 24–6a** shows the field lines between two like poles. By contrast, two unlike poles (N and S) 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 N-pole of one magnet pushes the N-pole of a second magnet away in the direction of the field line. The force exerted by the same field on the S-pole of the second magnet is attractive, in a direction opposite the field lines. The second magnet attempts to line up with the field, 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 N-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 N-pole becomes the sample's S-pole, and the sample is attracted to the magnet.

Pocket Lab

Funny Balls

Place a disk magnet flat on your paper. Roll a 3-mm steel ball at the magnet. Place a second steel ball on the paper, touching the magnet and the first steel ball.

Hypothesizing What happens? Why? Make a sketch to help explain your hypothesis. Devise a procedure to test your hypothesis.

a b

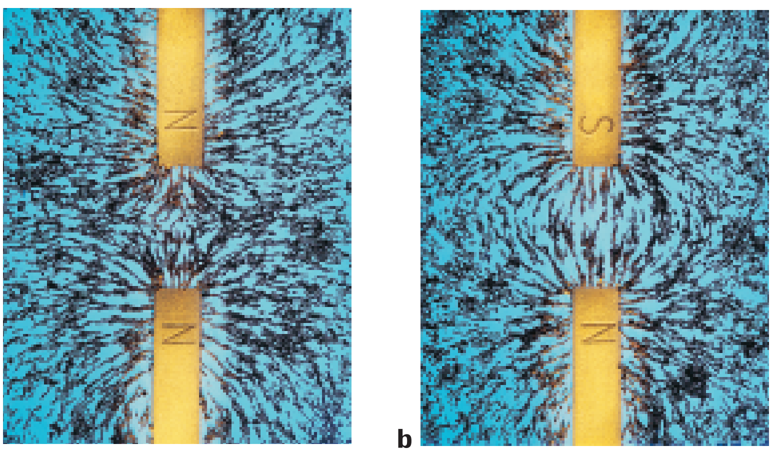


FIGURE 24–6 The magnetic field lines indicated by iron filings on paper over two magnets clearly show that like poles repel **(a)** and unlike poles attract **(b).** The iron filings do not form continuous lines between like poles. Between a north and a south pole, however, the iron filings show that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

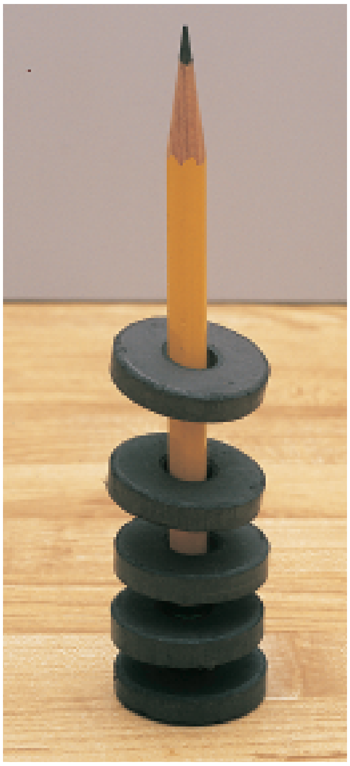


FIGURE 24–7

Practice Problems

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 so that
   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 the other magnets?
3. A magnet attracts a nail, which, in turn, attracts many small tacks, as shown in **Figure 24–3.** If the N-pole of the permanent magnet is the top face, which end of the nail is the N-pole?

Electromagnetism

How does electric charge affect a magnet? When you bring a magnet near a charged strip of transparent tape, there is no effect on the magnet or the tape. However, there is a marked effect on the magnet when the charge moves as an electrical current.

Magnetic field near a current-carrying wire In 1820, Danish physicist Hans Christian Oersted (1777–1851) 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 24–8.** 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. 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.

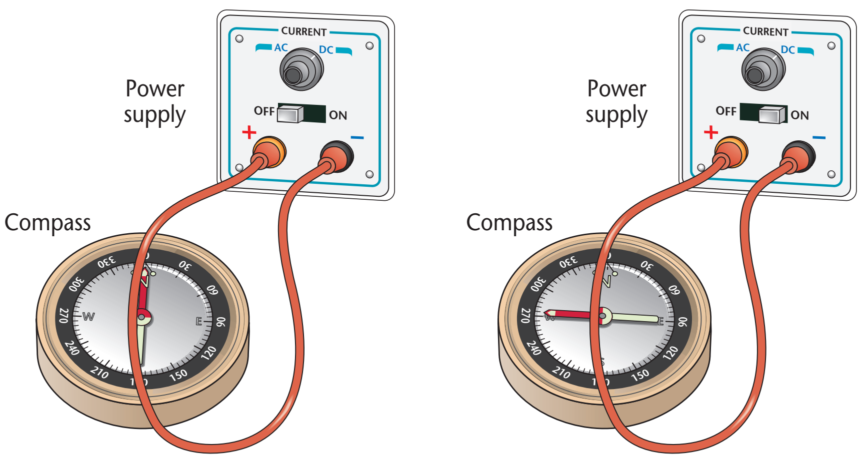


FIGURE 24–8 Using an apparatus similar to the one shown here, Oersted was able to demonstrate a connection between magnetism and electricity.

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 can easily 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 a current, tap the cardboard. 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 current, the compass needle also reverses its direction, as shown in **Figure 24–10a.** You can find the direction of the field around a wire using the **first right-hand rule.** 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.**

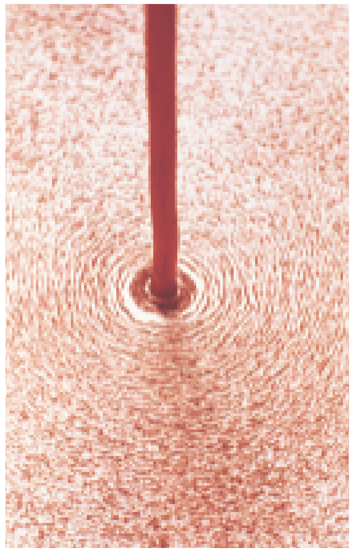


FIGURE 24–9 The magnetic field produced by current in a straight wire through a cardboard disc shows up as concentric circles of iron filings around the wire.

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 always 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.

When there is an electric current in a coil of wire, the coil has a field like that of a permanent magnet. When this current-carrying coil is brought close to a suspended bar magnet, one end of the coil repels the

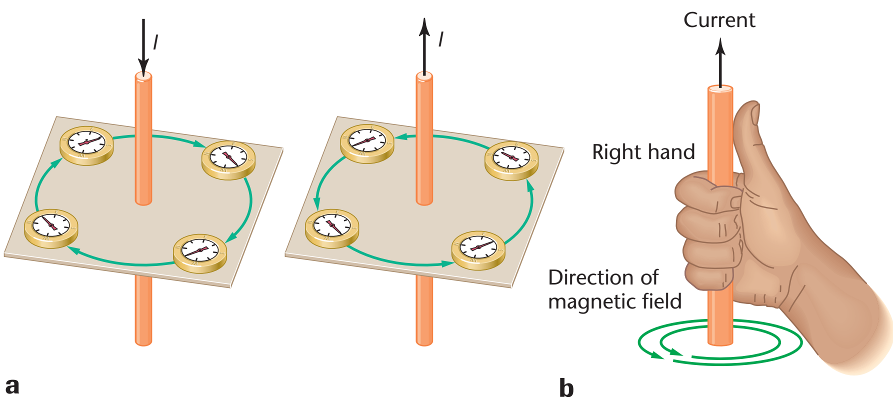


FIGURE 24–10 The magnetic field produced by current in a straight wire conductor reverses if the current in the wire is reversed **(a).** The right-hand rule for a straight, current-carrying wire shows the direction of the magnetic field **(b).**

Coils and Currents

Problem

You have seen that an electric current affects a magnetic compass needle. What happens to pieces of iron located inside a coil that carries a current? What is the effect of changing the magnitude of the current? Does an alternating current produce a different effect from that of a direct current?

Hypothesis

Write a testable hypothesis that addresses the questions posed in the problem.

Possible Materials

a ring stand with crossbar and clamp
two 20-cm lengths of thick, insulated iron wire
75 cm of thread
magnetic compass
miniature lamp with socket
500-turn, air-core solenoid
a variable power supply that can produce AC and DC voltages and currents
electrical leads and alligator clips

Plan the Experiment

1. Develop a plan and design a circuit you can use to test your hypothesis.
2. **Check the Plan** Show your teacher your plan before you start to build the circuit. **CAUTION:** *Be sure the power supply is off as you build the circuit.*
3. **CAUTION:** *Your teacher must inspect your setup before you turn the power on and begin your investigation.*
4. When you have completed the lab, dispose of or recycle appropriate materials. Put away materials that can be reused.

Analyze and Conclude

1. **Making Observations** Describe your observations as you increased the direct current produced by the power supply.
2. **Drawing Conclusions** What conclusion can you make regarding the strength of the magnetic field as you increased the current?
3. **Interpreting Results** What can you conclude from the results of your experimentation comparing the effects of direct and alternating currents?
4. **Making Predictions** Predict what would happen to the magnetic field if the number of turns on the coil was doubled. How would you test your prediction?

Apply

1. Large and powerful electromagnets are often used at scrap metal facilities. Would you expect that these magnets use AC current or DC current? Explain why.
2. In some apartment and office buildings, a tenant can “buzz” visitors into the building using a switch inside his or her unit. Explain how coils and currents work together to make this possible.

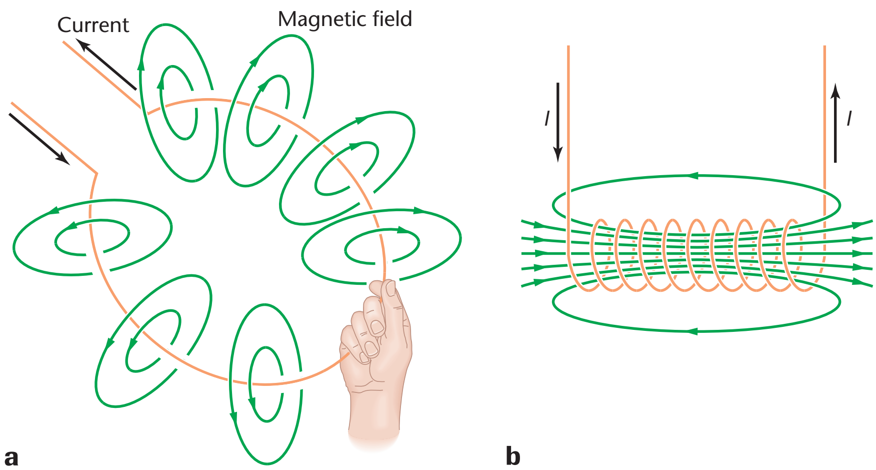


FIGURE 24–11 The magnetic field around a circular loop of current-carrying wire can be modeled with the aid of the right-hand rule **(a).** A current in a solenoid creates a magnetic field with the field from each coil adding to all the others **(b).**

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 is called an **electromagnet.** The strength of the field of an electromagnet is proportional to the current in the coil. The magnetic field produced by each loop of a coil is the same as that produced by any other loop. Because these fields are in the same direction, increasing the number of loops in an electromagnet increases the strength of the magnetic field.

The strength of an electromagnet can also be increased by placing an iron rod or core inside the coil, because the field inside the coil magnetizes the core. The magnetic strength of the core adds to that of the coil to produce a much stronger magnet.

The direction of the field produced by an electromagnet can be found by using the **second right-hand rule.** Imagine holding an insulated coil with your right hand. Curl your fingers around the loops in the direction of the conventional (positive) current, as in **Figure 24–12.** Your thumb points toward the N-pole of the electromagnet.

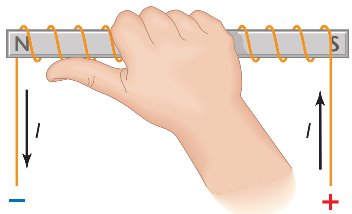


FIGURE 24–12 The second right-hand rule can be used to determine the polarity of an electromagnet.

Practice Problems

4. A long, straight, current-carrying wire runs from north to south.
  a. A compass needle placed above the wire points with its N-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?

5. How does the strength of the magnetic field 1 cm from a current-carrying wire compare with
  a. the strength of the field 2 cm from the wire?
  b. the strength of the field 3 cm from the wire?

6. 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?

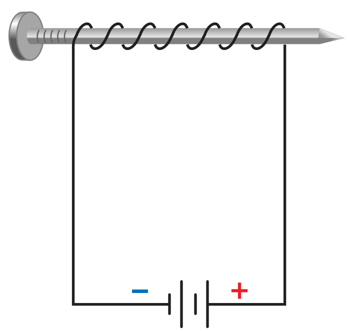


FIGURE 24–13

Pocket Lab

3-D Magnetic Fields

Most illustrations are able to show the shape of the magnetic field around a magnet only two-dimensionally. Try this activity to see the shape of a magnetic field in 3-D. 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. This will magnetize the nail. Turn off the power to the coil and remove the nail. Now hold the string to suspend the nail and slowly move it close to a permanent magnet. Try this for magnets of various shapes.

Analyze What evidence do you have that the nail became magnetized? Using your results, make a 3-D drawing that shows the magnetic field around the nail.

A Microscopic Picture of Magnetic Materials

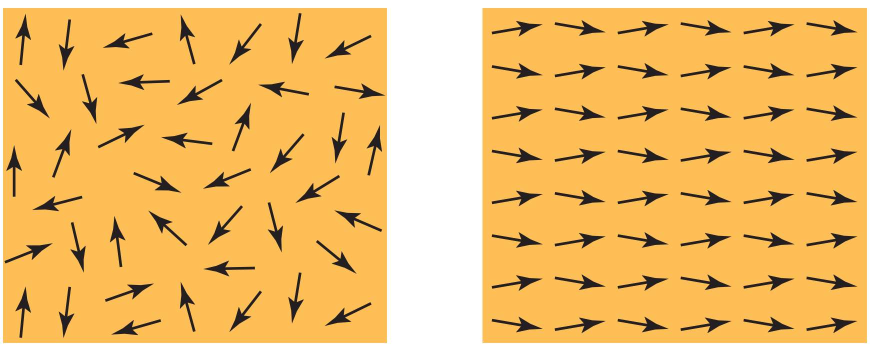
Recall that if you put a piece of iron, nickel, or cobalt next to a magnet, it too becomes magnetic. That is, you will have created north and south poles. The magnetism is, however, only temporary. The creation of this temporary polarity depends on the direction of the external field. When you take away the external field, the sample loses its magnetism. The three ferromagnetic elements—iron, nickel, and cobalt—behave in many ways like an electromagnet.

In the early 19th century, the 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. The magnetic fields of the electrons in a group of neighboring atoms can combine together. Such a 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. Their magnetic fields cancel one another. If, however, the 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 permanent magnets, the iron has been alloyed with other substances that keep the domains aligned after the external magnetic field is removed.

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. When magnetic recording tape, which has many tiny bits of magnetic material bonded to thin plastic, passes over the



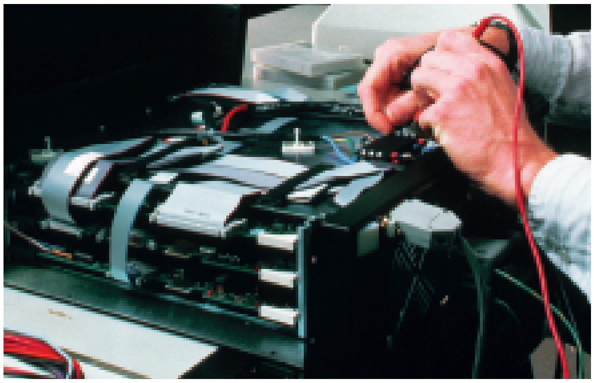
a b

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

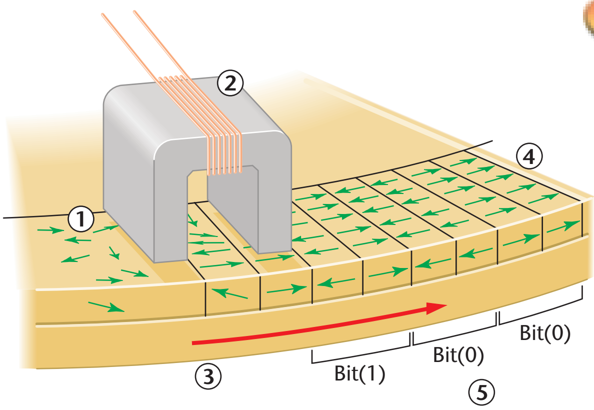
How It Works

Computer Storage Disks

Magnetic fields are essential to the operation of computer storage disks. 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?



1 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. Formatting organizes the disk's surface into sectors and tracks.



2 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.

3 As the read/write head passes over the spinning storage disk, the domains of atoms in the magnetic film line up in bands. The orientation of the domains depends on the direction of the current.

4 Two bands code for one bit. 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.

5 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 0s and 1s.

Thinking Critically

1. Why do manufacturers recommend keeping floppy disks away from objects such as electric motors, computer and television screens, and audio speakers?
2. After a data bit has been stored, the direction of current through the read/write head is automatically reversed to begin the next data bit. Explain why.

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 material on the tape is chosen so that the domains can keep their alignments permanently. On playback of the tape, a pair of signals produced by 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 disorients the magnetic particles on the tape.

EARTH SCIENCE CONNECTION

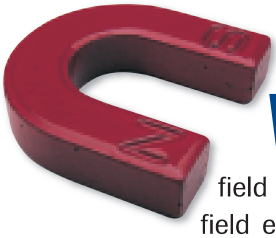
Rocks that contain iron have recorded the history of the direction of Earth's magnetic field. Rocks on the seafloor were produced when molten rock poured out of cracks in the bottom of the oceans. As they cooled, they were magnetized in the direction of Earth's field at that time. The seafloor spreads, so rocks farther from the crack are older than those near the crack. Scientists examining 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 periodically is even more of a mystery.

24.1 Section Review

1. Is a magnetic field real, or is it just a means of scientific modeling?
2. A 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 the first wire and parallel to it. There is an identical current in the second wire. If the two currents are in the same direction, how would the first magnetic field be affected? What if the two currents are in opposite directions?
3. Describe the right-hand rule used to determine the direction of a magnetic field around a straight, current-carrying wire.
4. Identify magnetic forces around you. How could you demonstrate the effects of those forces?
5. **Critical Thinking** Imagine a toy containing two parallel, horizontal metal rods.
   - **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 down no matter what its orientation is. What type of replacement rod must have been used?

Forces Caused by Magnetic Fields

24.2



While studying the behaviors of magnets, Ampère noted that an electric current produces a magnetic field like 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 that is placed in a magnetic field.

OBJECTIVES

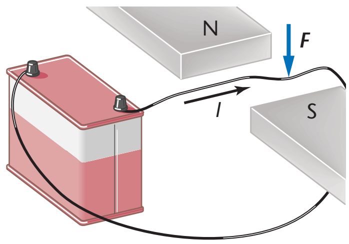
- **Relate** magnetic induction to the direction of the force on a current-carrying wire in a magnetic field.
- **Solve** problems involving magnetic field strength and the forces on current-carrying wires, and on moving, charged particles in magnetic fields.
- **Describe** the design and operation of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

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 the current in a wire that passes directly between two bar magnets. Recall that the direction of the magnetic field between two magnets is from the N-pole of one magnet to the S-pole of a second magnet. When there is a current in the wire, a force is exerted on the wire. As you can see, 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 (1791–1867) 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.

Faraday's description of the force on a current-carrying wire does not completely describe the direction. The force can be up or down. The direction of the force on a current-carrying wire in a magnetic field can be found by using the **third right-hand rule,** which is illustrated in **Figure 24–16.** The magnetic field can be indicated by the symbol ***B.*** Its direction is represented by a series of arrows, but when a field is directly into or out of the page, its direction is indicated by crosses or dots. The crosses suggest the feathers at the end of an archery arrow, and the dots suggest the point. To use the third right-hand rule, point the fingers of your right hand in the direction of the magnetic field. Point your thumb in the direction of the conventional (positive) current in the wire. The palm of your hand then faces in the direction of the force acting on the wire.

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 you recall 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. That is, when currents are in opposite directions, the forces push the wires apart.



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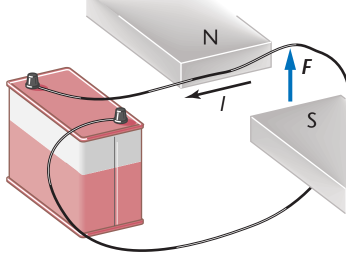
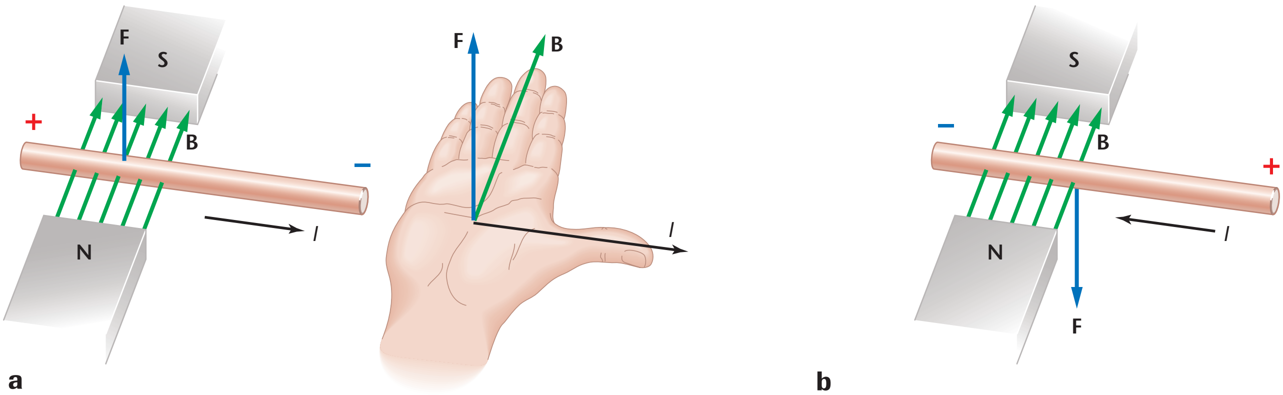


b

FIGURE 24–15 Current-carrying wires experience forces when they are placed in magnetic fields.



a b

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 **(a).** Use your own hand to demonstrate the direction of force for the setup in **(b).**

Force on a wire resulting from a magnetic field It is possible to determine the force of magnetism that is 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 three factors: the strength of the field, B, the current, I, in the wire, and the length, L, of the wire that lies in the magnetic field. The relationship of these four factors is as follows.

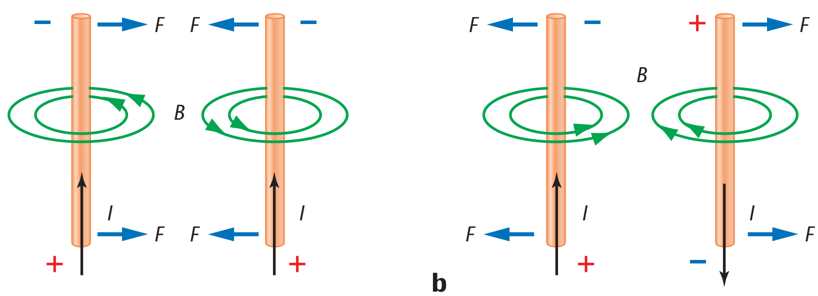
Force on a Current Carrying Wire in a Magnetic Field $F = BIL$

The strength of a magnetic field, B, is measured in teslas, T. The strengths of some typical magnetic fields are provided in **Table 24–1.** A magnetic field having a strength of one tesla causes a force of one newton to be exerted on a 1-m length of straight wire carrying one ampere of current. Based on $B = F/IL$, the following is obtained.

$$1\ \text{T} = 1\ \text{N/A·m}$$

TABLE 24–1
Typical Magnetic Field

Source and Location	Strength (T)
Surface of neutron star (predicted)	10^8
Strong laboratory electromagnet	10
Small bar magnet	0.01
Earth's magnetic field	5×10^{-5}



a b

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).**

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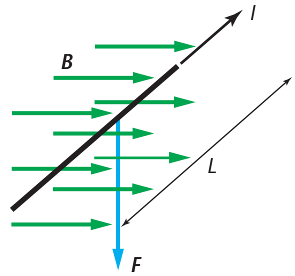
Example Problem

Calculating the Strength of a Magnetic Field

A straight wire that carries 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*?

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.



Calculate Your Answer

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

All are at right angles.

Strategy:

Use the equation $F = BIL$ because B is uniform and because B and I are perpendicular to each other. Calculate B.

Calculations:

$F = BIL$, so $B = F/IL$

$$B = \frac{0.20\ \text{N}}{(5.0\ \text{A})(0.10\ \text{m})} = 0.40\ \text{N/A·m} = 0.40\ \text{T}$$

Check Your Answer

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

Practice Problems

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

8. A wire 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?

9. A copper wire 40 cm long 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?

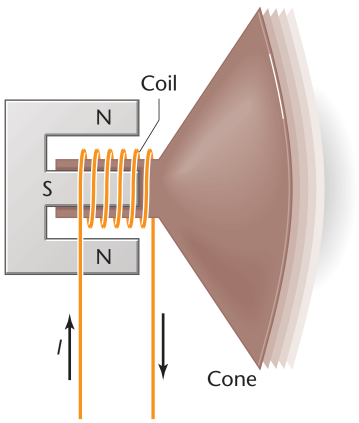


FIGURE 24–18 Sound waves can be created by exerting a force on a current-carrying wire in a magnetic field. This diagram of a loudspeaker shows how the coil can be pushed into and out of the magnetic field with changes in direction of the current.

Loudspeakers

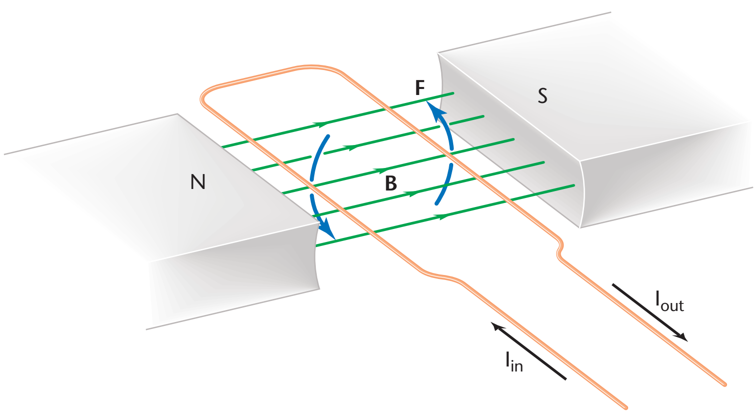
One use of the force on a current-carrying wire in a magnetic field is in a loudspeaker. A loudspeaker changes electrical energy to sound energy using a coil of fine wire mounted on a paper cone and placed in a magnetic field, as shown in **Figure 24–18.** The amplifier driving the loudspeaker sends 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, creating sound waves in the air.

Galvanometers

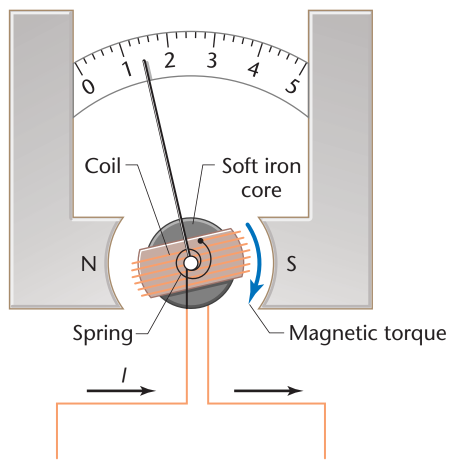
The forces exerted on a loop of wire in a magnetic field can be used to measure current. If a small loop of current-carrying wire is placed in the strong magnetic field of a permanent magnet, as in **Figure 24–19a,** it is possible to measure very small currents. The current passing through the loop 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. The magnitude of the torque acting on the loop is proportional to the magnitude of the current. This principle of measuring small currents is used in a galvanometer. A **galvanometer** is a device used to measure very small currents. For this reason, a galvanometer can be used as a voltmeter or an ammeter.

A small spring in the galvanometer exerts a torque that opposes the torque resulting from the current; 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 24–19b.** The galvanometer can then be used to measure unknown currents.

FIGURE 24–19 If a wire loop is placed in a magnetic field when there is a current, the loop will rotate because of the torque exerted by the field **(a).** An unknown current passing through a galvanometer can be metered, because the coil rotates in proportion to the magnitude of the current **(b).**



a



b

CONTENTS

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 ohms. In order to measure larger currents, such a galvanometer can be converted into an ammeter by placing a resistor with resistance smaller than that of the galvanometer in parallel with the meter, as shown in **Figure 24–20a.** 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 24–20b.** 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. Suppose you want a voltmeter that reads full-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 resistor.

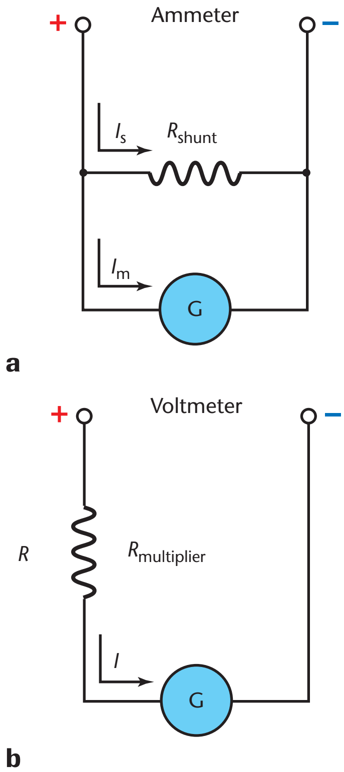


FIGURE 24–20 A galvanometer can be connected as either an ammeter **(a)** or a voltmeter **(b).**

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.

In an **electric motor,** an apparatus that converts electrical energy to kinetic energy, the loop must rotate a full 360° in the field; thus, the current running 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 24–21.** To reverse current direction, a split-ring commutator is used. Brushes, pieces of graphite that make contact with the commutator, allow current to flow into the loop. The split ring is arranged so that each half of the commutator changes brushes just as the loop reaches the vertical position. Changing brushes reverses 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 each half-turn, causing the loop to spin in the magnetic field.

Although only one loop is indicated in **Figure 24–21,** in an electric motor, the loop of wire, called the **armature,** is made of several loops mounted on a shaft or axle. The total force acting on the armature is proportional to $nBIL$, 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.

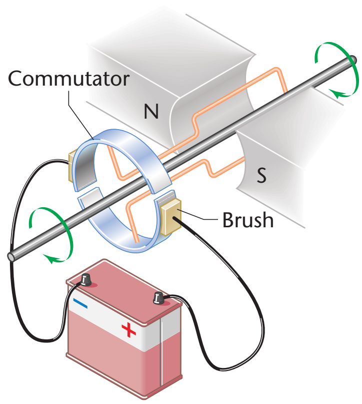


FIGURE 24–21 In an electric motor, split-ring commutators allow the wire loops in the motor to rotate 360°.

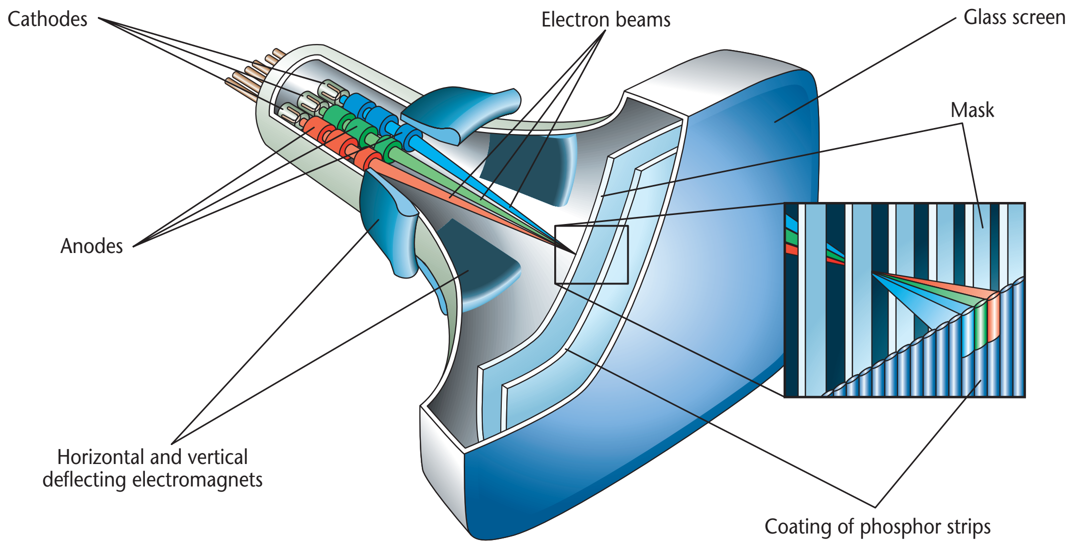


FIGURE 24–22 A computer monitor and a television use a cathode-ray tube to form pictures for viewing. Notice that the pairs of magnets deflect the electron beam vertically and horizontally.

The Force on a Single Charged Particle

Charged particles do not have to be confined to a wire, but can move across any region as long as the air has been removed to prevent collisions with air molecules. The picture tube, also called a cathode-ray tube, in computer monitors or television sets uses electrons deflected by magnetic fields to form the pictures on the screen, as illustrated in **Figure 24–22.** In a cathode-ray tube, 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 are used to control the motion of the beam back and forth and up and down across the screen of the tube. 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 length of the wire, 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

$$F = BIL = B\left(\frac{qv}{L}\right)L = Bqv$$

The particle's charge is measured in coulombs, its velocity in 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. Note, however, that the direction of the force is *opposite* that given by the third right-hand rule with the thumb pointed along the velocity of the positive particle. The direction of the force is opposite because the electron has a negative charge, and conventional current has a positive charge.

Electrons and positive ions trapped in the magnetic field of Earth form the Van Allen radiation belts. Solar storms send tremendous numbers of high-energy charged particles toward Earth. They disturb Earth's magnetic field, dumping electrons out of the Van Allen belts. These electrons excite atoms of nitrogen and oxygen in Earth's atmosphere and cause them to emit the red, green, and blue colors called the aurora borealis, or northern lights, that circle the north magnetic pole.

Northern Light Show

Answers question from page 554.

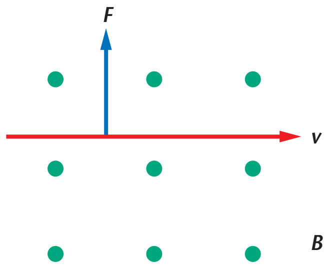
Example Problem

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 that acts on each electron?

Sketch the Problem

- Represent 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 that given by the third right-hand rule because of the electron's negative, elementary charge.



Calculate Your Answer

Known:

$v = 3.0 \times 10^{6}$ m/s

$B = 4.0 \times 10^{-2}$ T

$q = -1.60 \times 10^{-19}$ C

Unknown:

$F = ?$

Strategy:

Substitute the knowns, along with their respective units, into the equation $F = Bqv$. Calculate *F*.

Calculations:

$$F = (4.0 \times 10^{-2}\ \text{T})(-1.60 \times 10^{-19}\ \text{C})(3.0 \times 10^{6}\ \text{m/s})$$
$$= -1.9 \times 10^{-14}\ \text{T·C·m/s}$$
$$= -1.9 \times 10^{-14}\ \text{N}$$

Check Your 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 of the force 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 that given by the third right-hand rule.
- Is the magnitude realistic? Yes, forces on electrons and protons are always small fractions of a newton.

HELP WANTED

METEOROLOGIST

Do you have a sincere interest in the thorough study of data? Are you willing to make predictions, even when the data provide much less than a 100% probability? Join us and prepare for a highly respected profession. A bachelor's degree from an accredited meteorology program is required. Willingness to work your way up the ladder and take your turn with irregular shifts and possible relocation will help your career climb. For information contact:
American Meteorological Society, 45 Beacon Street, Boston, MA 02108

Practice Problems

10. 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?

11. 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?

12. 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?

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

24.2 Section Review

1. A horizontal, current-carrying wire runs north-south through Earth's magnetic field. If the current flows north, in which direction is the force on the wire?
2. 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?
3. Compare the diagram of a galvanometer in **Figure 24–19** with the electric motor in **Figure 24–21.** How is the galvanometer similar to an electric motor? How are they different?
4. 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 the coil doesn't rotate? Explain.
5. **Critical Thinking** How do you know that the forces on parallel current-carrying wires aren't a result of electrostatics? **Hint:** Consider what the charges would be like when the force is attractive. Then consider what the forces are if three wires carry currents in the same direction.

CHAPTER 24 REVIEW

Summary

24.1 Magnets: Permanent and Temporary

- 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 wire that carries current.
- A coil of wire that carries 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

- When a current-carrying wire is placed in a magnetic field, there exists a force on the wire that is perpendicular to both the field and the wire. Galvanometers are based on this principle.
- The strength of a magnetic field is measured in teslas (one newton per ampere per meter).
- 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.
- The force a magnetic field exerts on a charged particle depends on the velocity and 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.

Key Terms

24.1
- polarized
- magnetic field
- magnetic flux
- first right-hand rule
- solenoid
- electromagnet
- second right-hand rule
- domain

24.2
- third right-hand rule
- galvanometer
- electric motor
- armature

Key Equations

24.2

$F = BIL$ $\qquad$ $F = Bqv$

Reviewing Concepts

Section 24.1

1. State the rule for magnetic attraction and repulsion.
2. Describe how a temporary magnet differs from a permanent magnet.
3. Name the three most important common magnetic elements.
4. 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.
5. Draw the magnetic field between two like magnetic poles and then between two unlike magnetic poles. Show the directions of the fields.
6. If you broke a magnet in two, would you have isolated north and south poles? Explain.
7. Describe how to use the right-hand rule to determine the direction of a magnetic field around a straight current-carrying wire.
8. If a current-carrying wire is bent into a loop, why is the magnetic field inside the loop stronger than the magnetic field outside?
9. Describe how to use the right-hand rule to determine the polarity of an electromagnet.
10. Each electron in a piece of iron is like a tiny magnet. The iron, however, may not be a magnet. Explain.
11. Why will dropping or heating a magnet weaken it?

Section 24.2

12. Describe how to use the right-hand rule to determine the direction of

CONTENTS

force on a current-carrying wire placed in a magnetic field.

13. A strong current is suddenly 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.

14. What kind of meter is created when a shunt is added to a galvanometer?

Applying Concepts

15. A small bar magnet is hidden in a fixed position inside a tennis ball. Describe an experiment you could do to find the location of the N-pole and the S-pole of the magnet.

16. 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.

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

18. You are lost in the woods but have a compass with you. Unfortunately, the red paint marking the N-pole has worn off. You do have a flashlight with a battery and a length of wire. How could you identify the N-pole?

19. 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 that produce these similar phenomena.

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

21. In what 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?

22. 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 be exactly twice as large as that of either wire?

c. If the two currents are in the same direction, where will the magnetic field be exactly zero?

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

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

25. 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?

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

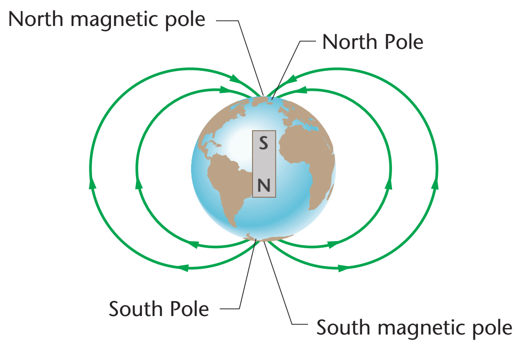


FIGURE 24–23

Problems

Section 24.1

27. A wire 1.50 m long 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?

28. A conventional current is in a wire as shown in **Figure 24–24.** Copy the wire segment and sketch the magnetic field that the current generates.

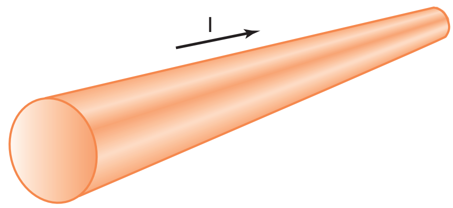


FIGURE 24–24

29. The current is coming straight out of the page in **Figure 24–25.** Copy the figure and sketch the magnetic field that the current generates.

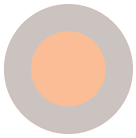


FIGURE 24–25

30. Figure 24–26 shows the end view of an electromagnet with the current as shown.
a. What is the direction of the magnetic field inside the loop?
b. What is the direction of the magnetic field outside the loop?

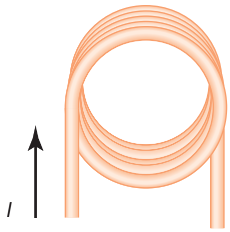


FIGURE 24–26

31. The repulsive force between two ceramic magnets was measured and found to depend on distance, as given in **Table 24–2.**

TABLE 24–2

Separation, *d* (mm)	Force, *F* (N)
10	3.93
12	0.40
14	0.13
16	0.057
18	0.030
20	0.018
22	0.011
24	0.0076
26	0.0053
28	0.0038
30	0.0028

a. Plot the force as a function of distance.
b. Does this force follow an inverse square law?

Section 24.2

32. A current-carrying wire is placed between the poles of a magnet, as shown in **Figure 24–27.** What is the direction of the force on the wire?

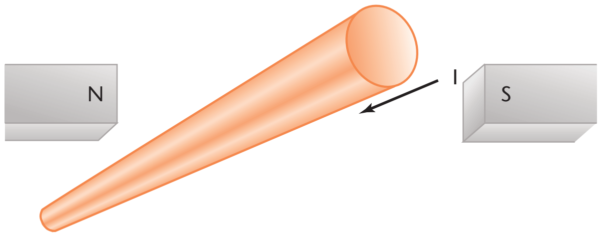


FIGURE 24–27

33. A wire 0.50 m long 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?

34. The current through a wire 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?

35. A wire 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?

36. A wire 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?

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

38. 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?

39. The force acting on a wire 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?

40. 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?
b. What is the direction of the force?
c. In your judgment, would this force be important in designing towers to hold these power lines?

41. 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?

42. The galvanometer in problem 41 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 that have the potential difference calculated in **a** for a circuit with a total current of 10 mA?
   c. What resistor should be placed in parallel with the galvanometer to make the resistance calculated in **b?**

43. 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?

44. 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?

45. The mass of an electron is 9.11×10^{-31} kg. What is the acceleration of the beta particle described in problem 44?

46. 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 direction of the force acting on the electron?

47. 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. How strong is the field?

48. The mass of a muon is 1.88×10^{-28} kg. What acceleration does the muon described in problem 47 experience?

49. 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?

50. A room contains a strong, uniform magnetic field. A loop of fine wire in the room has current flowing through it. Assuming 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?

51. 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.

52. 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 $F = BIL \sin \theta$. Find the force on the wire if it makes an angle with the magnetic field lines of
   a. 90°. **b.** 45°. **c.** 0°.

53. 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 24–28.** 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.

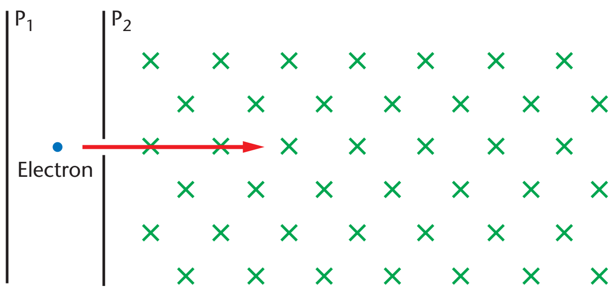


FIGURE 24–28

54. 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?

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

55. A current is sent through a vertical spring as shown in **Figure 24–29.** The end of the spring is in a cup filled with mercury. What will happen? Why?

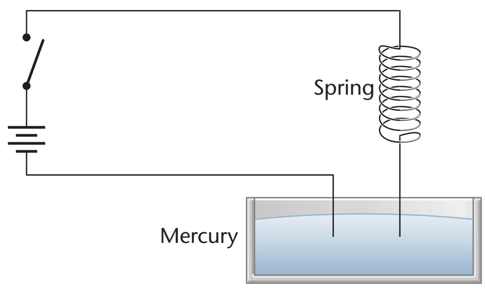


FIGURE 24–29

56. The magnetic field produced by a long, current-carrying wire is represented by $B = 2 \times 10^{-7}(\text{T}\cdot\text{m/A})I/d$, 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 field 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 that in your home?

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

Going Further

Adding Vectors In almost all cases described in problem 56, a second wire carries the same current in the opposite direction. Find the net magnetic field a distance 0.10 m from each wire that carries 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 the right-hand rule to draw vectors showing the direction of the fields. Finally, find the vector sum of the two fields. State its magnitude and direction.

Essay Research and describe the historical development of the concept of magnetic force. How are magnetic fields related to electrical fields? Evaluate the impact of research about magnetic field and electrical field interactions on society.

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