



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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LAUNCH Lab



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.



■ **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)**.

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.

a



b





■ **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 **aluminum**, **nickel**, and **cobalt**. 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.




■ **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.

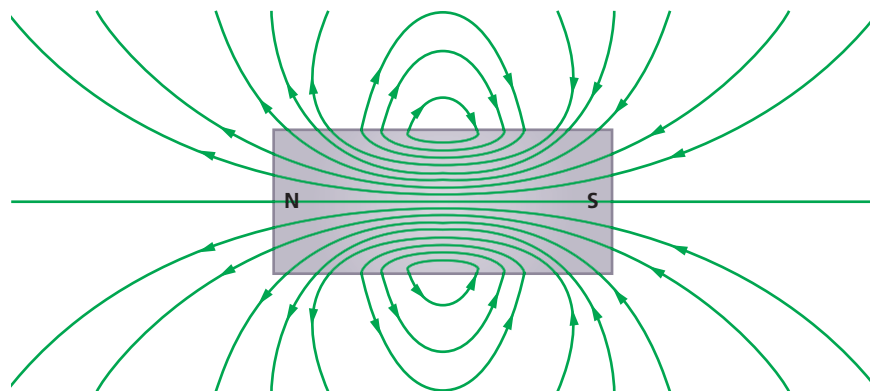
The direction of a magnetic field line is defined as the direction in which the north pole of a compass points when it is placed in the magnetic field. Outside the magnet, the field lines emerge from the magnet at its north pole and enter the magnet at its south pole, as illustrated in **Figure 24-5**. 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.

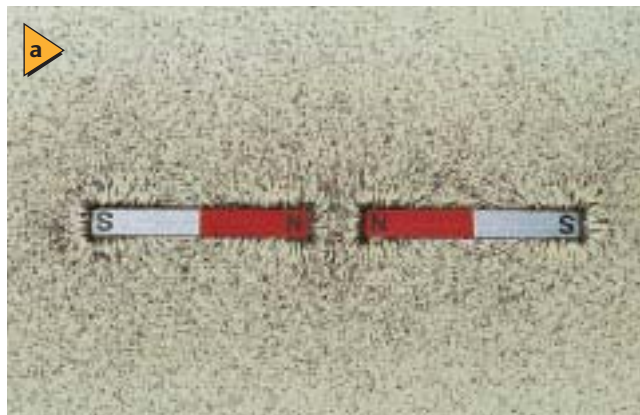
**Color Convention**

- 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.





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.

■ **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.



Interactive Figure To see an animation on magnetism, visit physicspp.com.



▶ PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

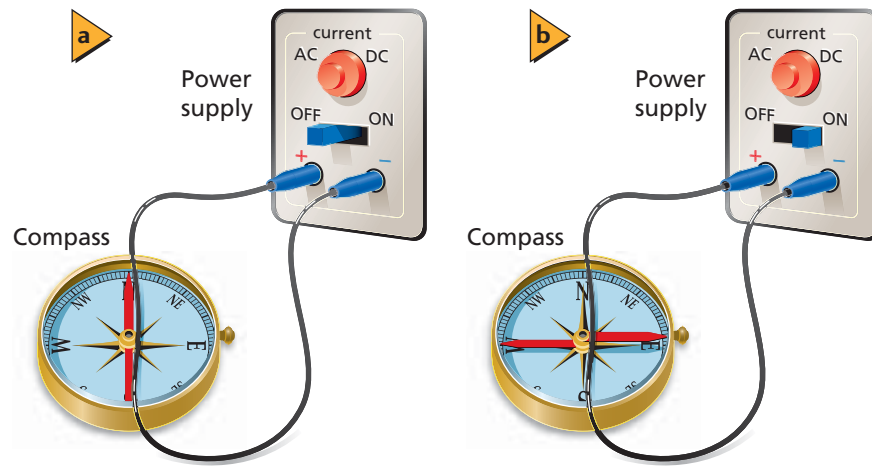
- If you hold a bar magnet in each hand and bring your hands close together, will the force be attractive or repulsive if the magnets are held in the following ways?
 - the two north poles are brought close together
 - a north pole and a south pole are brought together
- Figure 24-7** shows five disk 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?
- 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?
- 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)**.

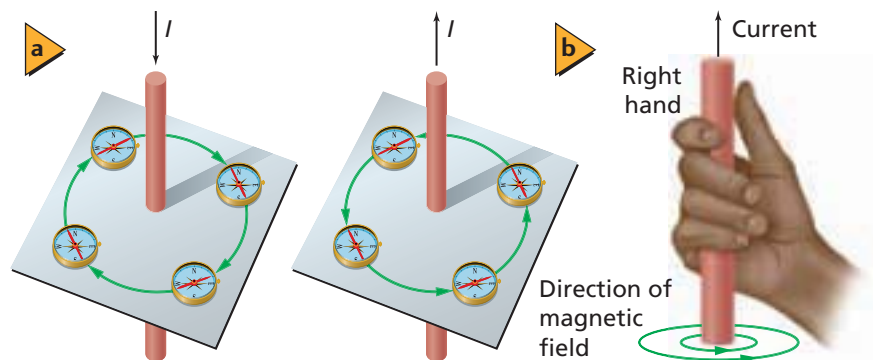


Electromagnetism

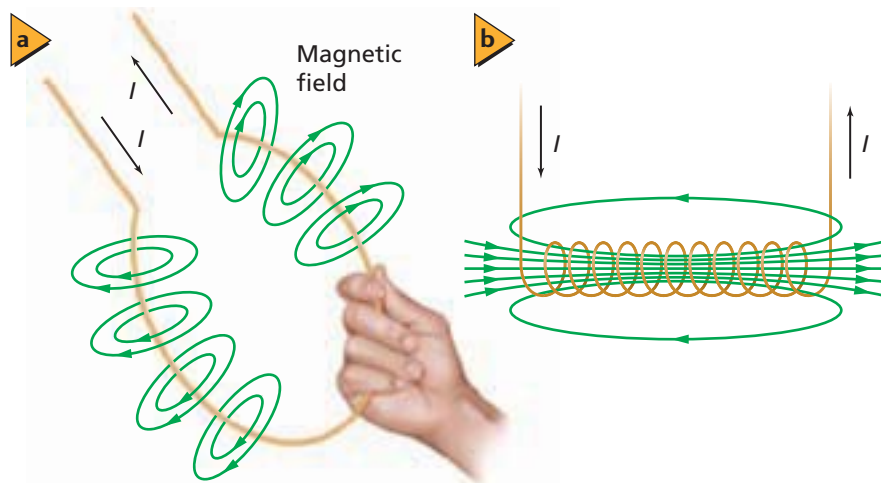
In 1820, Danish physicist Hans Christian Oersted was experimenting with electric currents in wires. Oersted laid a wire across the top of a small compass and connected the ends of the wire to complete an electrical circuit, as shown in **Figure 24-8a**. He had expected the needle to point toward the 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.

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)**.

Concepts in Motion

Interactive Figure To see an animation on the first and second right-hand rules, visit physicspp.com.



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.

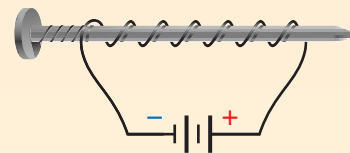




PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

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?
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.



■ Figure 24-13

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

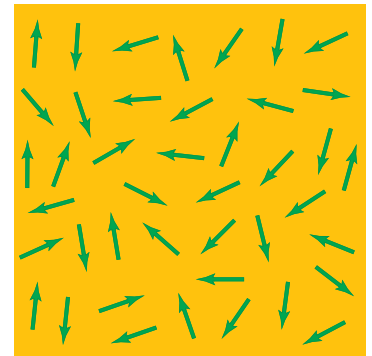
3. **Explain** what evidence you have that the nail became magnetized.
4. Make a 3-D drawing that shows the magnetic field around the magnet.



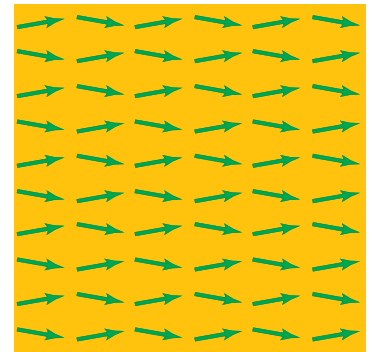
Recording media Electromagnets make up the recording heads of audio-cassette and videotape recorders. Recorders create electrical signals that represent the sounds or pictures being recorded. The electric signals produce currents in the recording head that create magnetic fields. When magnetic recording 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.

a



b



■ **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?





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

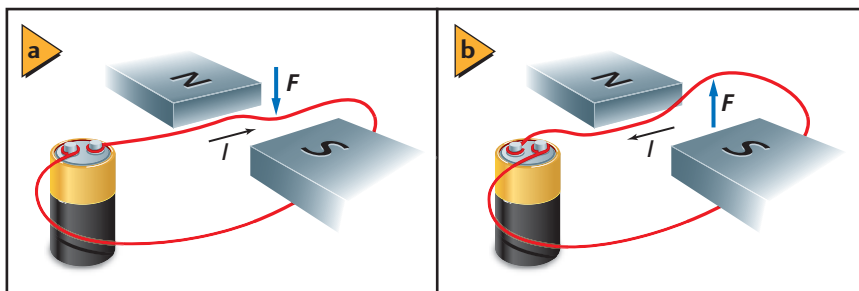
The force on a wire in a magnetic field can be demonstrated using the arrangement shown in **Figure 24-15**. A battery produces current in a wire directly between two bar magnets. Recall that the direction of the magnetic field between two magnets is from the north pole of one magnet to the south pole 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.

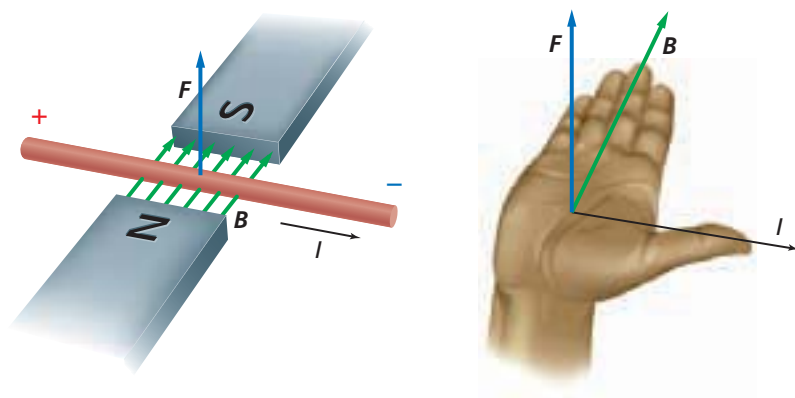
Determining the force's direction Faraday's description of the force on a current-carrying wire does not completely describe the direction because the force can be upward or downward. The direction of the force on a current-carrying wire in a magnetic field can be found by using **the third right-hand rule**. This technique is illustrated in **Figure 24-16**. The magnetic field is represented by the symbol \mathbf{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.



Interactive Figure To see an animation on the third right-hand rule, visit physicspp.com.



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 $F = ILB$

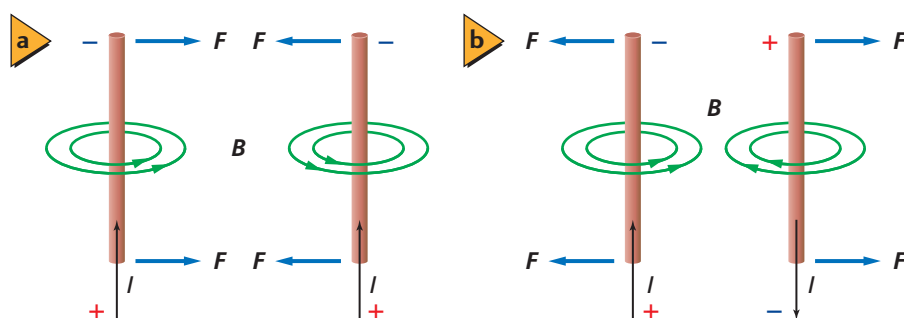
The force on a current-carrying wire in a magnetic field is equal to the product of the current, the length of the wire, and the magnetic field strength.

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 $\theta = 90^\circ$, 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.

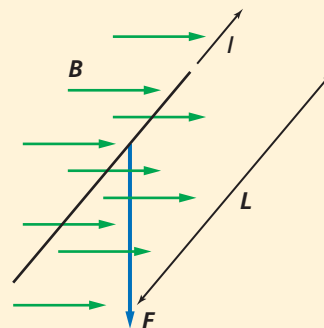
Known: **Unknown:**

$$I = 5.0 \text{ A}$$

$$B = ?$$

$$L = 0.10 \text{ m}$$

$$F = 0.20 \text{ N}$$



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

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

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

Math Handbook

Operations with
Significant Digits
pages 835–836

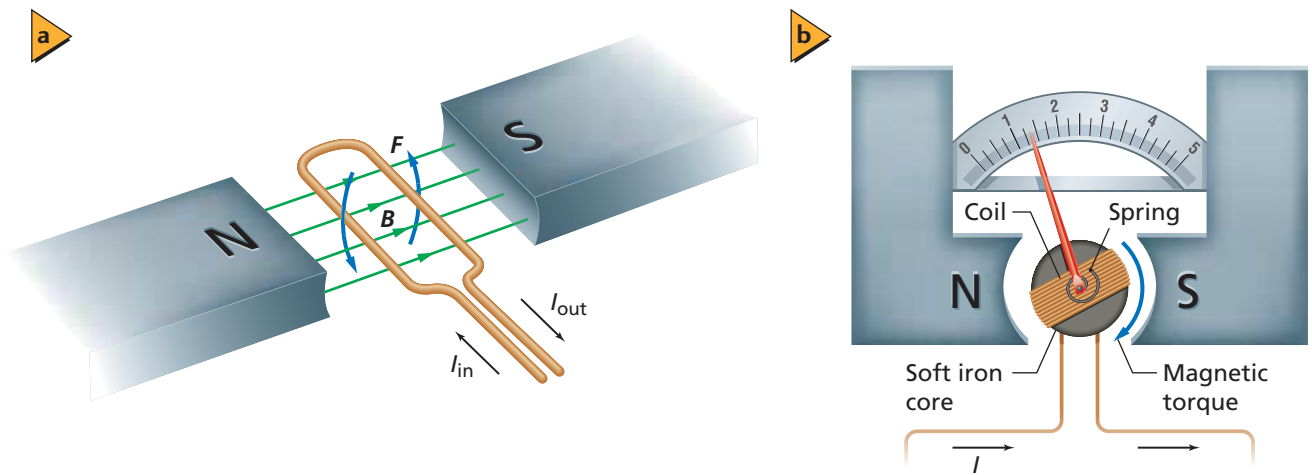
3 Evaluate the Answer

- **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
• Solutions to Selected Problems, Appendix C

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?



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.

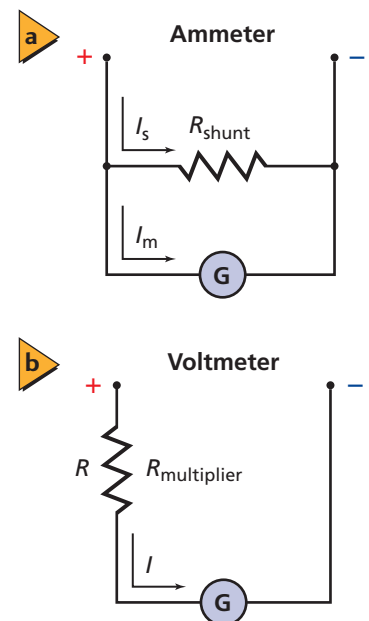
A small spring in the galvanometer exerts a torque that opposes the torque that results from the flow of current through the wire loop; thus, the amount of rotation is proportional to the current. The meter is calibrated by finding out how much the coil turns when a known current is sent through it,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

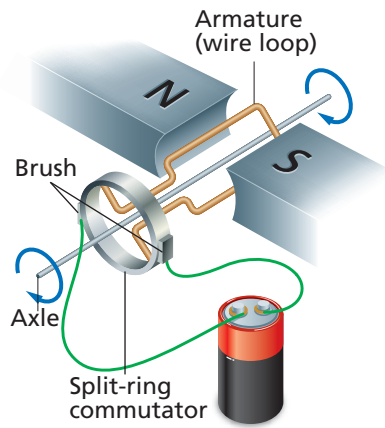
Many galvanometers produce full-scale deflections with as little as $50\ \mu\text{A}$ ($50 \times 10^{-6}\ \text{A}$) of current. The resistance of the coil of wire in a sensitive galvanometer is about $1000\ \Omega$. To measure larger currents, a galvanometer can be converted into an ammeter by placing 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 $10\ \text{V}$ is placed across it. The resistor is chosen so that at $10\ \text{V}$, the meter is deflected full-scale by the current through the meter and the resistor.

■ **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)**.

■ **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° .



Interactive Figure To see an animation on electric motors, visit physicspp.com.



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.

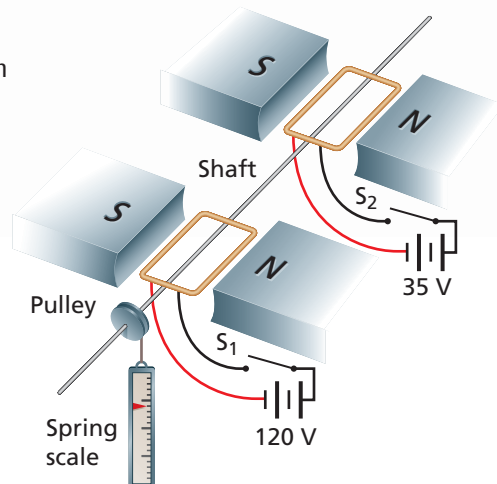
How can you allow the loop to continue to rotate? The current through the loop must reverse direction just as the loop reaches its vertical position. This reversal allows the loop to continue rotating, as illustrated in **Figure 24-20**. To reverse current direction, an electric connection is made between 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.

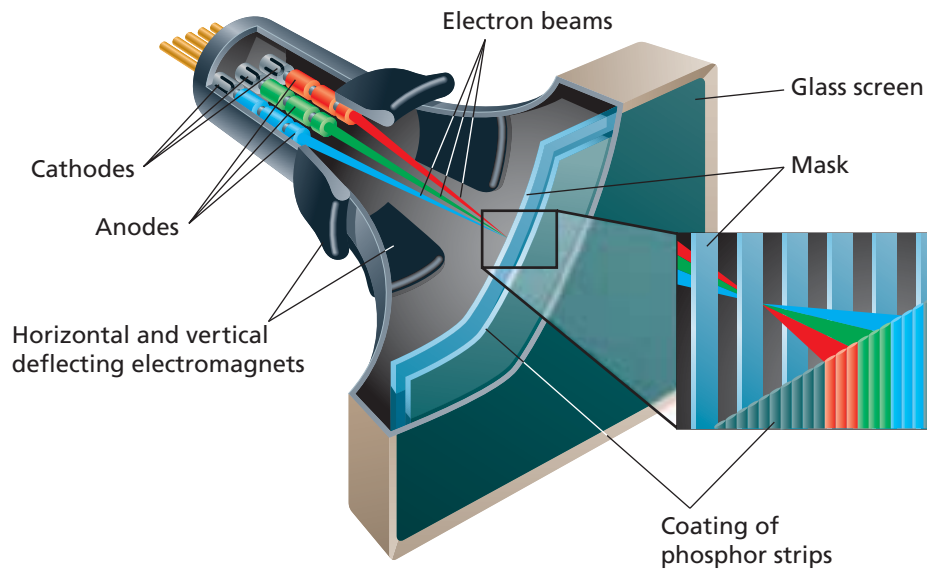
Although only one loop is indicated in Figure 24-20, in an electric motor, the wire coil, called the **armature**, is made of many loops mounted on a shaft or axle. The total force acting on the armature is proportional to $nILB$, where n is the total number of turns on the armature, B is the strength 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 $12\ \Omega$. 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?





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 charge of the particle, its velocity, and the field strength.

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.

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

► 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:

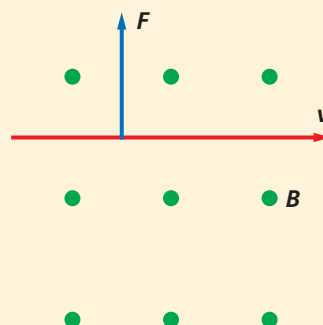
$$v = 3.0 \times 10^6 \text{ m/s}$$

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

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

Unknown:

$$F = ?$$



2 Solve for the Unknown

$$F = qvB$$

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

$$= -1.9 \times 10^{-14} \text{ N}$$

Substitute $q = -1.60 \times 10^{-19} \text{ C}$, $v = 3.0 \times 10^6 \text{ m/s}$,
 $B = 4.0 \times 10^{-2} \text{ T}$

3 Evaluate the Answer

- Are the units correct?** $T = \text{N}/(\text{A} \cdot \text{m})$, and $A = \text{C/s}$; so $T = \text{N} \cdot \text{s}/(\text{C} \cdot \text{m})$. Thus, $(\text{T} \cdot \text{C} \cdot \text{m})/\text{s} = \text{N}$, 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.

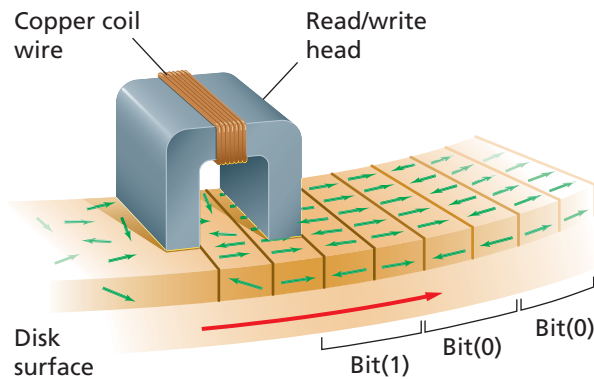
Physics online

Personal Tutor For an online tutorial on force on a charged particle, visit physicspp.com.

► PRACTICE Problems

- Additional Problems, Appendix B
- Solutions to Selected Problems, Appendix C

- 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?
- 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?
- 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?
- 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?
- 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 $180\ \mu\text{A}$ 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.*

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.**



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.
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?

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?

Real-World Physics

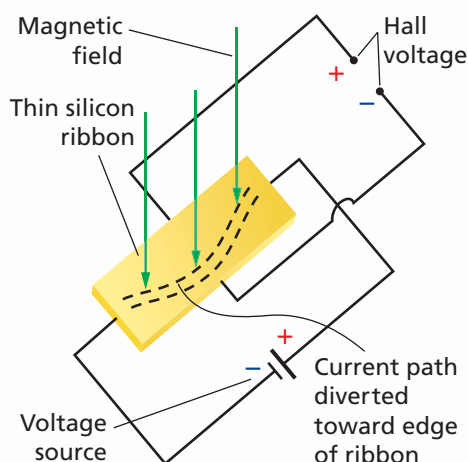
1. If you needed to create a stronger electromagnet for use in a small space, such as inside a laptop computer, what method would you use to increase the electromagnetic strength, given the size constraints?
2. Some buildings have electromagnets to hold fire doors open when the building is occupied. 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?



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

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.

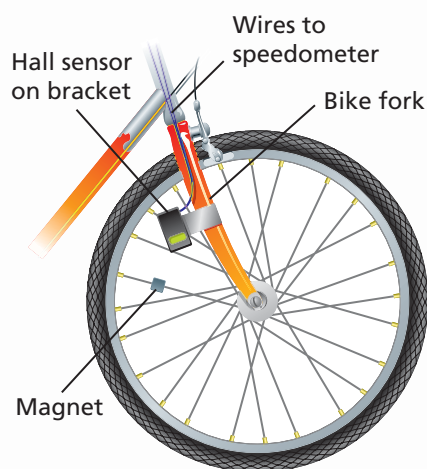
The magnetic lines of force are perpendicular to the ribbon's broad surface. This makes the flowing electrons crowd into one side of the ribbon. Because there are more electrons on one edge of the ribbon than on the other, a voltage, called the *Hall voltage*, is generated across the width of the ribbon.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

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 current flow, the length of the wire, and the field strength.

$$F = ILB$$

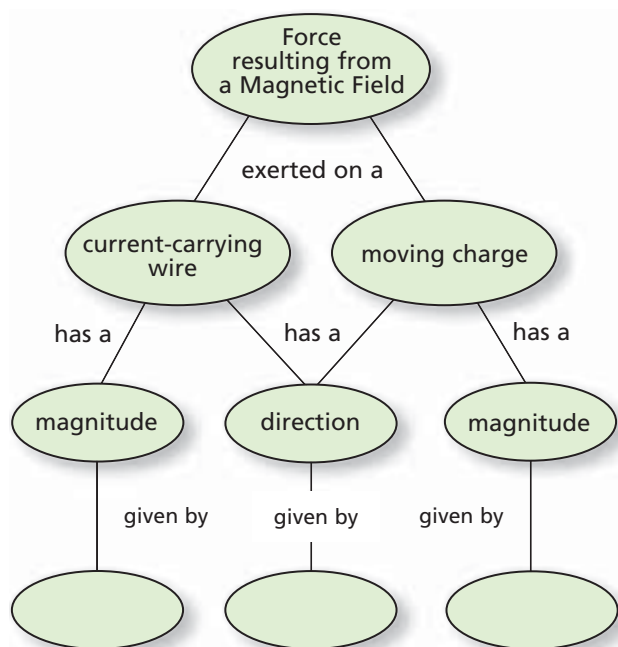
- A galvanometer consists of a loop of wire in a magnetic field, and is used to measure small currents. When current is passed through the loop, a force on the wire loop results in a deflection of the loop.
- A galvanometer can be used as an ammeter by adding a shunt resistor in parallel with the galvanometer.
- 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 charge of the particle, the velocity 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.

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)
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?

Applying Concepts

54. Two wires carry equal currents and run parallel to each other.
- 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?
 - Where will the magnetic field from both be exactly twice as large as from one wire?
 - 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.

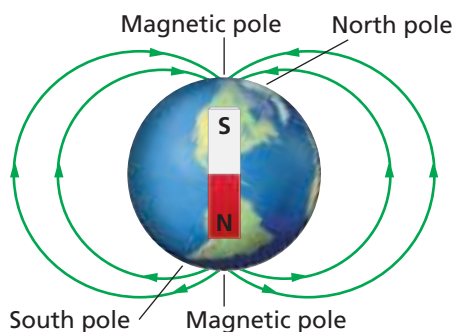


Figure 24-23

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?

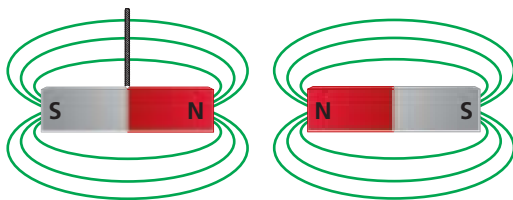


Figure 24-24

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

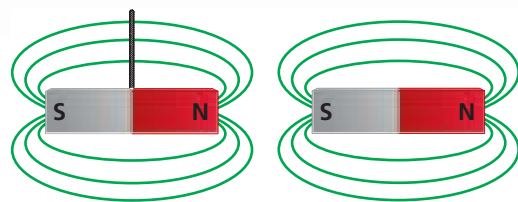


Figure 24-25

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

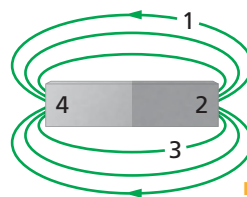


Figure 24-26

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?

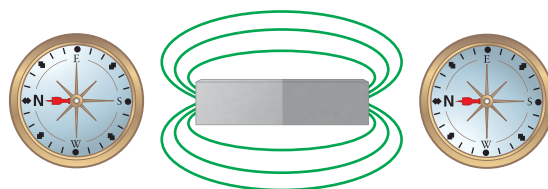


Figure 24-27

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.

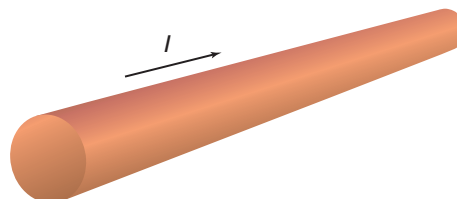


Figure 24-28

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.

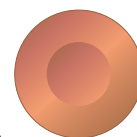
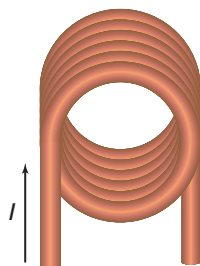


Figure 24-29

Chapter 24 Assessment

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



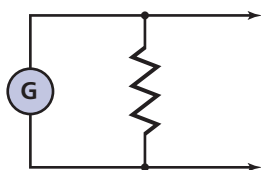
■ Figure 24-30

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

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

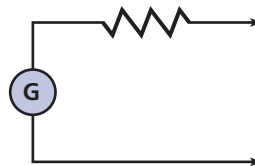
68. The arrangement shown in **Figure 24-31** is used to convert a galvanometer to what type of device?



■ Figure 24-31

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

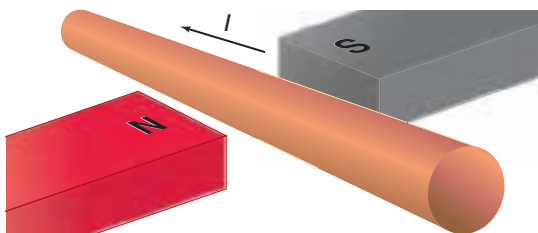
70. The arrangement shown in **Figure 24-32** is used to convert a galvanometer to what type of device?



■ 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 $5.0 \times 10^{-5} \text{ T}$ 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?

80. A power line carries a 225-A current from east to west, parallel to the surface of Earth.
- What is the magnitude of the force resulting from Earth's magnetic field acting on each meter of the wire? Use $B_{\text{Earth}} = 5.0 \times 10^{-5} \text{ T}$.
 - What is the direction of the force?
 - 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 $50.0\text{-}\mu\text{A}$ current.
- What must be the total resistance of the series resistor and the galvanometer to make a voltmeter with 10.0-V full-scale deflection?
 - If the galvanometer has a resistance of $1.0 \text{ k}\Omega$, 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.
- What is the potential difference across the galvanometer ($1.0 \text{ k}\Omega$ resistance) when a current of $50 \mu\text{A}$ passes through it?
 - What is the equivalent resistance of parallel resistors having the potential difference calculated in a circuit with a total current of 10 mA?
 - 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 $6.0 \times 10^{-2} \text{ T}$. The electrons have a velocity of $2.5 \times 10^6 \text{ m/s}$. 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 $4.21 \times 10^7 \text{ m/s}$ at right angles to a magnetic field. The muon experiences a force of $5.00 \times 10^{-12} \text{ N}$.
- How strong is the magnetic field?
 - What acceleration does the muon experience if its mass is $1.88 \times 10^{-28} \text{ kg}$?

85. A singly ionized particle experiences a force of $4.1 \times 10^{-13} \text{ N}$ 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 $5.78 \times 10^{-16} \text{ N}$ acts on an unknown particle traveling at a 90° angle through a magnetic field. If the velocity of the particle is $5.65 \times 10^4 \text{ m/s}$ and the field is $3.20 \times 10^{-2} \text{ T}$, 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.
- Determine the force on the wire (direction and magnitude) when the switch is open.
 - Determine the force on the wire (direction and magnitude) when the switch is closed.
 - Determine the force on the wire (direction and magnitude) when the switch is closed and the battery is reversed.
 - 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 5.5Ω .

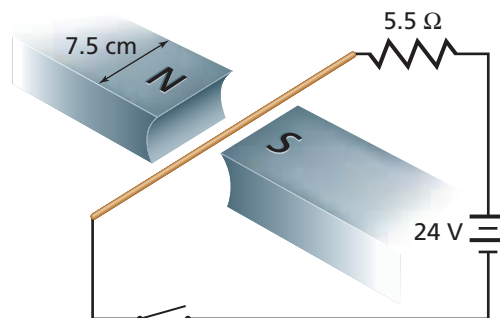


Figure 24-34

89. Two galvanometers are available. One has $50.0\text{-}\mu\text{A}$ full-scale sensitivity and the other has $500.0\text{-}\mu\text{A}$ full-scale sensitivity. Both have the same coil resistance of 855Ω . Your challenge is to convert them to measure a current of 100.0 mA, full-scale.
- Determine the shunt resistor for the $50.0\text{-}\mu\text{A}$ meter.
 - Determine the shunt resistor for the $500.0\text{-}\mu\text{A}$ meter.
 - 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 $2.5 \times 10^7 \text{ m/s}$. What size force acts on the particle?
91. The mass of an electron is $9.11 \times 10^{-31} \text{ kg}$. What is the magnitude of the acceleration of the beta particle described in problem 90?

Chapter 24 Assessment

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 $8.0 \, \Omega$. 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.
- State the direction of the electric field between the plates as either P_1 to P_2 or P_2 to P_1 .
 - In terms of the information given, calculate the electron's speed at plate P_2 .
 - 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?

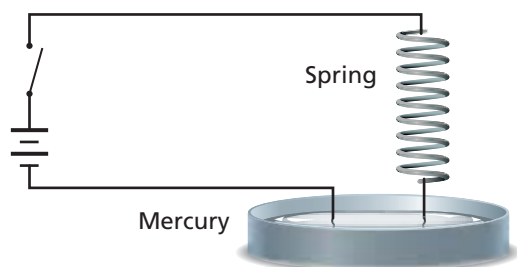


Figure 24-36

97. **Apply Concepts** The magnetic field produced by a long, current-carrying wire is represented by $B = (2 \times 10^{-7} \text{ T} \cdot \text{m/A})(I/d)$, 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.
- 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?
 - 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?
 - 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, $55\text{-}\Omega$ resistors connected in parallel and then series-connected to two $55\text{-}\Omega$ resistors connected in series. (Chapter 23)

Standardized Test Practice

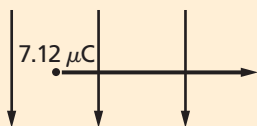
Multiple Choice

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	(C) 1.3×10^{-1} m
(B) 3.1×10^{-2} 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?

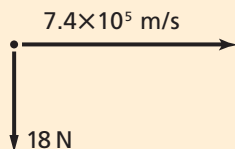
(A) 3.4×10^{-7} A	(C) 1.0×10^{-2} A
(B) 9.8×10^{-3} A	(D) 9.8 A
3. A $7.12\text{-}\mu\text{C}$ charge is moving at the speed of light in a magnetic field of 4.02 mT. What is the force on the charge?

(A) 8.59 N	(C) 8.59×10^{12} N
(B) 2.90×10^1 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	(C) 1.3×10^7 T
(B) 2.4×10^{-5} 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 $18\ \Omega$. 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.