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CHAPTER 21

Magnetism

PHYSICS IN ACTION

Some satellites contain loops of wire called *torque coils* that can be activated by a computer or a satellite operator on Earth.

When activated, a torque coil has a current in it. As you will learn in this chapter, the current-carrying coil behaves like a magnet. Because Earth also has magnetic properties, a magnetic torque is exerted on the satellite, just as two magnets brought close together exert a force on one another. In this way, the satellite can be oriented so that its instruments point in the desired direction.

- *How does a current in the coil give the coil magnetic properties?*
- *How does the direction of the current in the wire affect the direction of the torque on the satellite?*

CONCEPT REVIEW

Force (Section 4-1)

Force that maintains circular motion (Section 7-3)

Torque (Section 8-1)

Electric fields (Section 17-3)

Electric current (Section 19-1)

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21-1
Magnets and magnetic fields

21-1 SECTION OBJECTIVES

- For given situations, predict whether magnets will repel or attract each other.
- Describe the magnetic field around a permanent magnet.
- Describe the orientation of Earth's magnetic field.

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MAGNETS

Most people have had experience with different kinds of magnets, such as those shown in **Figure 21-1.** You are probably familiar with the horseshoe magnet, which can pick up iron-containing objects such as paper clips and nails, and flat magnets, such as those used to attach items to a refrigerator. In the following discussion, we will assume that the magnet has the shape of a bar. Iron objects are most strongly attracted to the ends of such a magnet. These ends are called *poles;* one is called the *north pole,* and the other is called the *south pole.* The names derive from the behavior of a magnet on Earth. If a bar magnet is suspended from its midpoint so that it can swing freely in a horizontal plane, it will rotate until its north pole points north and its south pole points south. In fact, a compass is just a magnetic needle that swings freely on a pivot.

The list of important technological applications of magnetism is very long. For instance, large electromagnets are used to pick up heavy loads. Magnets are also used in meters, motors, and loudspeakers. Magnetic tapes are routinely used in sound- and video-recording equipment, and magnetic recording material is used on computer discs. Superconducting magnets are currently being used to contain the plasmas used in controlled-nuclear-fusion research (heated to temperatures on the order of 10^8 K), and they are used to levitate modern trains. These so-called *maglev* trains are faster and provide a smoother ride than the ordinary track system because of the absence of friction between the train and the track.

Figure 21-1
Regardless of their shape, all magnets have both a north pole and a south pole.

Like poles repel each other, and unlike poles attract each other

The magnetic force between two magnets can be likened to the electric force between charged objects in that unlike poles of two magnets attract one another and like poles repel one another. Thus, the north pole of a magnet is attracted to the south pole of another magnet, and two north poles (or two south poles) brought close together repel each other. Electric charges differ from magnetic poles in that they can be isolated, while magnetic poles cannot. In fact, no matter how many times a permanent magnet is cut, each piece always has a north pole and a south pole. Thus, magnetic poles always occur in pairs.

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Some materials can be made into permanent magnets

Just as two materials, such as rubber and wool, can become charged after they are rubbed together, an unmagnetized piece of iron can become a permanent magnet by being stroked with a permanent magnet. Magnetism can be induced by other means as well. For example, if a piece of unmagnetized iron is placed near a strong permanent magnet, the piece of iron will eventually become magnetized. The process can be reversed either by heating and cooling the iron or by hammering.

A magnetic piece of material is classified as magnetically *hard* or *soft,* depending on the extent to which it retains its magnetism. Soft magnetic materials, such as iron, are easily magnetized but also tend to lose their magnetism easily. In contrast, hard magnetic materials, such as cobalt and nickel, are difficult to magnetize, but once they are magnetized, they tend to retain their magnetism.

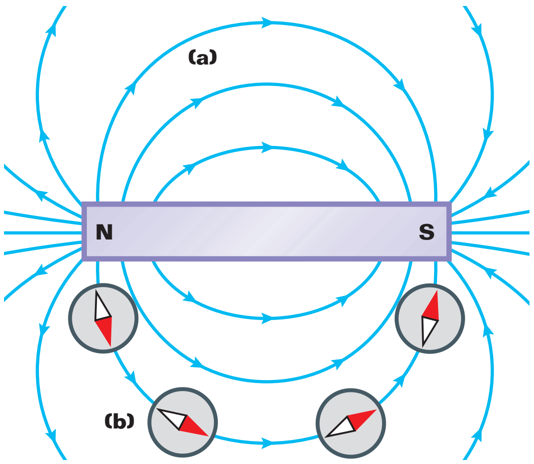

Figure 21-2
The magnetic field **(a)** of a bar magnet can be traced with a compass **(b).** Note that the north poles of the compasses point in the direction of the field lines from the magnet's north pole to its south pole.

MAGNETIC FIELDS

You know that the interaction between charged objects can be described using the concept of an electric field. A similar approach can be used to describe the **magnetic field** surrounding any magnetized material.

magnetic field

a region in which a magnetic force can be detected

The direction of the magnetic field, **B,** at any location is defined as the direction in which the north pole of a compass needle points at that location. **Figure 21-2** shows how the magnetic field of a bar magnet can be traced with the aid of a compass. Note that the direction of the magnetic field is the same as the direction of the needles, and its magnitude is greatest close to the poles.

To indicate the direction of **B** when it points into or out of the page, use the conventions shown in **Table 21-1.** If **B** is directed into the page, we will use a series of blue *crosses,* representing the tails of arrows. If **B** is directed out of the page, we will use a series of blue *dots,* representing the tips of arrows.

When describing a small bar magnet as having north and south poles, it is more proper to say that it has a "north-seeking" pole and a "south-seeking" pole. This means that if such a magnet is used as a compass, the north pole of the magnet will seek, or point to, the geographic North Pole of Earth. Because unlike poles attract, we can deduce that the geographic North Pole of Earth corresponds to the magnetic south pole, and the geographic South Pole of Earth corresponds to the magnetic north pole.

The difference between true north, defined as the geographic North Pole, and north indicated by a compass varies from point to point on Earth, and the difference is referred to as *magnetic declination.* For example, along a line through South Carolina and the Great Lakes, a compass will point to true north (0° declination), whereas in Washington state it will point 25° east of true north (25° E declination).

Table 21-1 Conventions for representing the direction of a magnetic field

In the plane of the page	↑ (blue arrow)
Into the page	× (blue cross)
Out of the page	• (blue dot)

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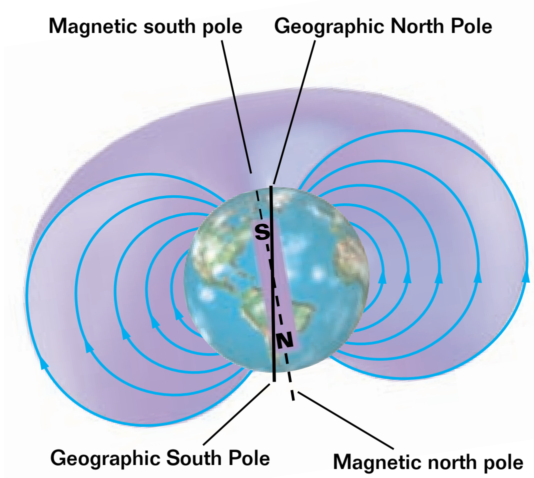

Figure 21-3
Earth's magnetic field has a configuration similar to a bar magnet's. Note that the magnetic south pole is near the geographic North Pole and that the magnetic north pole is near the geographic South Pole.

Note that the configuration of Earth's magnetic field, pictured in **Figure 21-3,** resembles the field that would be produced if a bar magnet were buried within Earth.

If a compass needle is allowed to rotate in the vertical plane as well as in the horizontal plane, the needle will be horizontal with respect to Earth's surface only near the equator. As the compass is moved northward, the needle will rotate so that it points more toward the surface of Earth. Finally, at a point just north of Hudson Bay, in Canada, the north pole of the needle will point directly downward. This site is considered to be the location of the magnetic south pole of Earth. It is approximately 1500 km from Earth's geographic North Pole. Similarly, the magnetic north pole of Earth is roughly the same distance from the geographic South Pole. Thus, it is only an approximation to say that a compass needle points toward the geographic North Pole.

Although Earth has large deposits of iron ore deep beneath its surface, the high temperatures in Earth's liquid core prevent the iron from retaining any permanent magnetization. It is considered more likely that the source of Earth's magnetic field is the movement of charges in convection currents in Earth's core. Charged ions or electrons circling in the liquid interior could produce a magnetic field. There is also evidence that the strength of a planet's magnetic field is related to the planet's rate of rotation. For example, Jupiter rotates at a faster rate than Earth, and recent space probes indicate that Jupiter's magnetic field is stronger than Earth's. Conversely, Venus rotates more slowly than Earth, and its magnetic field has been found to be weaker. Investigation into the cause of Earth's magnetism continues.

Naturally occurring magnetic materials, such as magnetite, achieve their magnetism because they have been subjected to Earth's magnetic field over very long periods of time. In fact, studies have shown that a type of anaerobic bacterium that lives in swamps has a magnetized chain of magnetite as part of its internal structure. (The term *anaerobic* means that these bacteria live and grow

Quick Lab

Magnetic Field of a File Cabinet

MATERIALS LIST

- ✔ compass
- ✔ metal file cabinet

Stand in front of the file cabinet, and hold the compass face up and parallel to the ground. Now move the compass from the top of the file cabinet to the bottom. Making sure that the compass is parallel to the ground, check to see if the direction of the compass needle changes as it moves from the top of the cabinet to the bottom. If the compass needle changes direction, the file cabinet is magnetized. Can you explain what might have caused the file cabinet to become magnetized? Remember that Earth's magnetic field has a vertical component as well as a horizontal component.

Try tracing the field around some large metal objects around your house. Can you find an object that has been magnetized by the horizontal component of Earth's magnetic field?

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without oxygen; in fact, oxygen is toxic to some of them.) The magnetized chain acts as a compass needle, enabling the bacteria to align with Earth's magnetic field. When they find themselves out of the mud at the bottom of the swamp, they return to their oxygen-free environment by following the magnetic-field lines of Earth. Further evidence of their magnetic-sensing ability is the discovery that the bacteria in the Northern Hemisphere have internal magnetite chains that are opposite in polarity to that of similar bacteria in the Southern Hemisphere. This is consistent with the fact that in the Northern Hemisphere Earth's magnetic field has a downward component, whereas in the Southern Hemisphere it has an upward component.

Section Review

1. For each of the cases in **Figure 21-4,** identify whether the magnets will attract or repel one another.

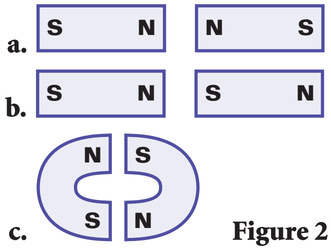

Figure 21-4

2. When you break a magnet in half, how many poles does each piece have?

3. Which of the compass-needle orientations in **Figure 21-5** might correctly describe the magnet's field at that point?

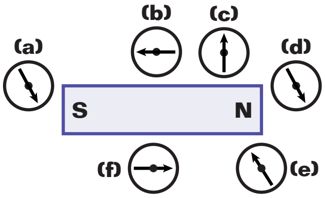

Figure 21-5

4. **Physics in Action** Satellite ground operators use the feedback from a device called a magnetometer, which senses the direction of Earth's magnetic field, to decide which torque coil to activate. What direction will the magnetometer read for Earth's magnetic field when the satellite passes over Earth's equator?

5. **Physics in Action** In order to protect other equipment, the body of a satellite must remain unmagnetized, even when the torque coils have been activated. Would hard or soft magnetic materials be best for building the rest of the satellite?

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21-2
Electromagnetism and magnetic domains

21-2 SECTION OBJECTIVES

- **Describe the magnetic field produced by the current in a straight conductor and in a solenoid.**
- **Explain magnetism in terms of the domain theory of magnetism.**

PHYSICS INTERACTIVE TUTOR

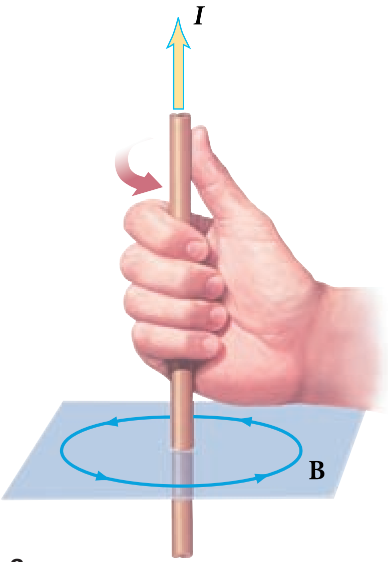
Module 18
"Magnetic Field of a Wire" provides an interactive lesson with guided problem-solving practice to teach you about magnetic fields produced by current-carrying wires.

MAGNETIC FIELD OF A CURRENT-CARRYING WIRE

The experiment shown in **Figure 21-6(a)** uses iron filings to show that a current-carrying conductor produces a magnetic field. In a similar experiment, several compass needles are placed in a horizontal plane near a long vertical wire. When there is no current in the wire, all needles point in the same direction (that of Earth's magnetic field). However, when the wire carries a strong, steady current, all the needles deflect in directions tangent to concentric circles around the wire, pointing in the direction of **B,** the magnetic field due to the current. When the current is reversed, the needles reverse direction. These observations show that the direction of **B** is consistent with this rule for conventional current, known as the right-hand rule: If the wire is grasped in the right hand with the thumb in the direction of the current, as shown in **Figure 21-6(b),** the fingers will curl in the direction of **B.**

As shown in **Figure 21-6(a),** the lines of **B** form concentric circles about the wire. By symmetry, the magnitude of **B** is the same everywhere on a circular path centered on the wire and lying in a plane perpendicular to the wire. Experiments show that **B** is proportional to the current in the wire and inversely proportional to the distance from the wire.

(a)



(b)

Figure 21-6
(a) When the wire carries a strong current, the iron filings show that the magnetic field due to the current forms concentric circles around the wire. **(b)** Use the right-hand rule to find the direction of this magnetic field.

MAGNETIC FIELD OF A CURRENT LOOP

The right-hand rule can also be applied to find the direction of the magnetic field of a current-carrying loop, such as the loop represented in **Figure 21-7(a).** Regardless of where on the loop you apply the right-hand rule, the field within the loop points in the same direction—upward. Note that the field lines of the current-carrying loop resemble those of a bar magnet, as shown in **Figure 21-7(b).** If a long, straight wire is bent into a coil of several closely spaced loops, as shown in **Figure 21-8,** the resulting device is called a **solenoid.**

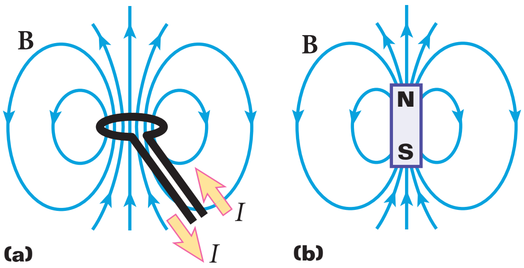


Figure 21-7
(a) The magnetic field of a current loop is similar to **(b)** that of a bar magnet.

Solenoids produce a strong magnetic field by combining several loops

A solenoid is important in many applications because it acts as a magnet when it carries a current. The magnetic field inside a solenoid increases with the current and is proportional to the number of coils per unit length. The magnetic field of a solenoid can be increased by inserting an iron rod through the center of the coil; this device is often called an *electromagnet.* The magnetic field that is induced in the rod adds to the magnetic field of the solenoid, often creating a powerful magnet.

Figure 21-8 shows the magnetic field lines of a solenoid. Note that the field lines inside the solenoid point in the same direction, are nearly parallel, are uniformly spaced, and are close together. This indicates that the field inside the solenoid is strong and nearly uniform. The field outside the solenoid is nonuniform and much weaker than the interior field.

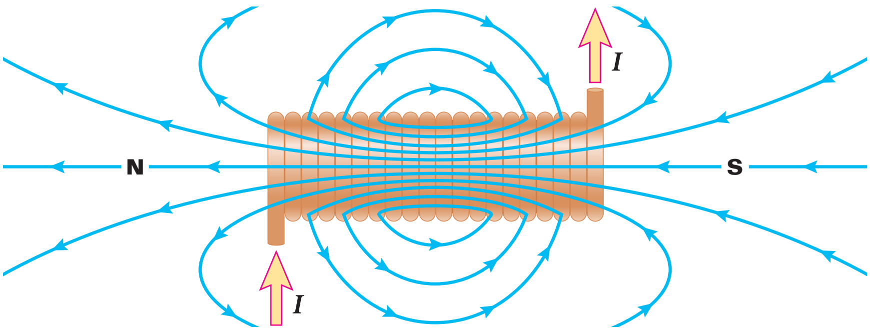


Figure 21-8
The magnetic field inside a solenoid is strong and nearly uniform. Note that the field lines resemble those of a bar magnet, so a solenoid effectively has north and south poles.

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solenoid

a long, helically wound coil of insulated wire

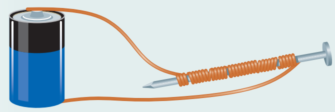
Quick Lab

Electromagnetism

MATERIALS LIST

- ✔ D-cell battery
- ✔ 1 m length of insulated wire
- ✔ large nail
- ✔ compass

Wind the wire around the nail as shown below. Remove the insulation from the ends of the wire, and hold these ends against the metal



terminals of the battery. Use the compass to determine whether the nail is magnetized. Next, flip the battery so that the direction of the current is reversed. Again bring the compass toward the same part of the nail. Can you explain why the compass needle now points in a different direction?

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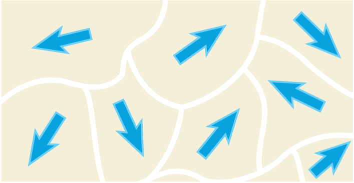

Figure 21-9
When a substance is unmagnetized, its domains are randomly oriented.

domain

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

MAGNETIC DOMAINS

The magnetic properties of many materials are explained in terms of a model in which an electron is said to spin on its axis much like a top does. (This classical description should not be taken literally. The property of electron spin can be understood only with the methods of quantum mechanics.) The spinning electron represents a charge in motion that produces a magnetic field. In atoms containing many electrons, the electrons usually pair up with their spins opposite each other, and their fields cancel each other. That is why most substances, such as wood and plastic, are not magnets. However, in materials such as iron, cobalt, and nickel, the magnetic fields produced by the electron spins do not cancel completely. Such materials are said to be *ferromagnetic*. In ferromagnetic materials, strong coupling occurs between neighboring atoms to form large groups of atoms whose net spins are aligned; these groups are called **domains.** Domains typically range in size from about 10^{-4} cm to 0.1 cm. In an unmagnetized substance, the domains are randomly oriented, as shown in **Figure 21-9.** When an external field is applied, the orientation of the magnetic fields of each domain may change slightly to more closely align with the external magnetic field, or the domains that are already aligned with the external field may grow at the expense of the other domains.

In hard magnetic materials, domain alignment persists after the external magnetic field is removed; the result is a permanent magnet. In soft magnetic materials, such as iron, once the external field is removed, the random motion of the particles in the material changes the orientation of the domains and the material returns to an unmagnetized state.

As mentioned earlier, the strength of a solenoid can be increased dramatically by the insertion of an iron rod into the coil's center. The magnetic field produced by the current in the loops causes alignment of the domains in the iron, producing a large net external field.

Section Review

1. What is the shape of the magnetic field produced by a straight current-carrying wire?
2. Why is the magnetic field inside a solenoid stronger than the magnetic field outside?
3. If electrons behave like magnets, then why aren't all atoms magnets?
4. **Physics in Action** In some satellites, torque coils are replaced by devices called torque rods. In torque rods, a ferromagnetic material is inserted inside the coil. Why does a torque rod have a stronger magnetic field than a torque coil?

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21-3
Magnetic force

21-3 SECTION OBJECTIVES

- **Given the force on a charge in a magnetic field, determine the strength of the magnetic field.**
- **Use the right-hand rule to find the direction of the force on a charge moving through a magnetic field.**
- **Determine the magnitude and direction of the force on a wire carrying current in a magnetic field.**

CHARGED PARTICLES IN A MAGNETIC FIELD

Although experiments show that a stationary charged particle does not interact with a constant magnetic field, charges moving through a magnetic field do experience a magnetic force. This force has its maximum value when the charge moves perpendicular to the magnetic field, decreases in value at other angles, and becomes zero when the particle moves along the field lines. For the purposes of this book, we will limit our discussion to situations in which charges move parallel or perpendicular to the magnetic-field lines.

A charge moving through a magnetic field experiences a force

In our discussion of electric forces, the electric field at a point in space was defined as the electric force per unit charge acting on some test charge placed at that point. In a similar manner, we can describe the properties of the magnetic field, **B,** in terms of the magnetic force exerted on a test charge at a given point. Our test object is assumed to be a positive charge, q, moving with velocity **v.** It has been found experimentally that the strength of the magnetic force on the particle moving perpendicular to the field is equal to the product of the magnitude of the charge, q, the magnitude of the velocity, v, and the strength of the external magnetic field, B, as shown by the following relationship.

$$F_{magnetic} = qvB$$

This expression can be rearranged as follows:

MAGNITUDE OF A MAGNETIC FIELD

$$B = \frac{F_{magnetic}}{qv}$$

$$\text{magnetic field} = \frac{\text{magnetic force on a charged particle}}{(\text{magnitude of charge})(\text{speed of charge})}$$

If the force is in newtons, the charge is in coulombs, and the speed is in meters per second, the unit of magnetic field strength is the tesla (T). Thus, if a 1 C charge moving at 1 m/s perpendicular to a magnetic field experiences a magnetic force of 1 N, the magnitude of the magnetic field is equal to 1 T. Note that 1 C is a very large amount of charge, so most magnetic fields are much smaller than 1 T. We can express the units of the magnetic field as follows:

$$T = N/(C\bullet m/s) = N/(A\bullet m) = (V\bullet s)/m^2$$

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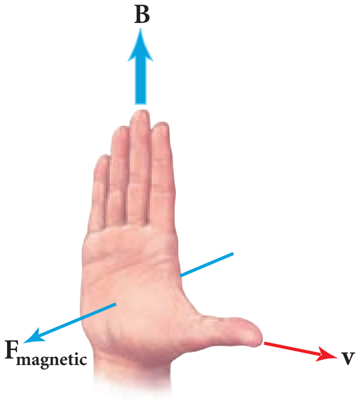

Figure 21-10
Use the right-hand rule to find the direction of the magnetic force on a positive charge.

Conventional laboratory magnets can produce magnetic fields up to about 1.5 T. Superconducting magnets that can generate magnetic fields as great as 30 T have been constructed. These values can be compared with Earth's magnetic field near its surface, which is about 50 μT (5×10^{-5} T).

Use the right-hand rule to find the direction of the magnetic force

Experiments show that the direction of the magnetic force is always perpendicular to both **v** and **B.** To determine the direction of the force, use the right-hand rule. As before, place your fingers in the direction of **B** with your thumb pointing in the direction of **v,** as illustrated in **Figure 21-10.** The magnetic force, $\mathbf{F}_{\mathbf{magnetic}}$, on a positive charge is directed *out* of the palm of your hand.

If the charge is negative rather than positive, the force is directed *opposite* that shown in **Figure 21-10.** That is, if q is negative, simply use the right-hand rule to find the direction of $\mathbf{F}_{\mathbf{magnetic}}$ for positive q, and then reverse this direction for the negative charge.

The force on a moving charge due to a magnetic field is used to create pictures on a television screen. The main component of a television is the *cathode ray tube,* which is essentially a vacuum tube in which electric fields are used to form a beam of electrons. Phosphor on the television screen glows when it is struck by the electrons in the beam. Without magnetism, however, only the center of the screen would be illuminated by the beam. The direction of the beam is changed by two electromagnets, one deflecting the beam horizontally, the other deflecting the beam vertically. The direction of the beam can be changed by changing the direction of the current in each electromagnet. In this way, the beam illuminates the entire screen.

In a color television, three different colors of phosphor—red, green, and blue—make up the screen. Three electron beams, one for each color, scan over the screen to produce a color picture.

SAMPLE PROBLEM 21A

Particle in a magnetic field

PROBLEM

A proton moving east experiences a force of 8.8×10^{-19} N upward due to the Earth's magnetic field. At this location, the field has a magnitude of 5.5×10^{-5} T to the north. Find the speed of the particle.

SOLUTION

Given: $q = 1.60 \times 10^{-19}$ C $\quad B = 5.5 \times 10^{-5}$ T

$F_{magnetic} = 8.8 \times 10^{-19}$ N

Unknown: $v = ?$

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Use the equation from page 773. Rearrange to solve for v.

$$B = \frac{F_{magnetic}}{qv}$$

$$v = \frac{F_{magnetic}}{qB}$$

$$v = \frac{8.8 \times 10^{-19}\ \text{N}}{(1.60 \times 10^{-19}\ \text{C})(5.5 \times 10^{-5}\ \text{T})} = 1.0 \times 10^{5}\ \text{m/s}$$

The directions given can be used to verify the right-hand rule. Imagine standing at this location and facing north. Turn the palm of your right hand upward (the direction of the force) with your thumb pointing east (the direction of the velocity). If your palm and thumb point in these directions, your fingers point directly north in the direction of the magnetic field, as they should.

PRACTICE 21A

Particle in a magnetic field

1. A proton moves perpendicularly to a magnetic field that has a magnitude of 4.20×10^{-2} T. What is the speed of the particle if the magnitude of the magnetic force on it is 2.40×10^{-14} N?

2. A proton traveling to the right along the x-axis enters a region where there is a magnetic field of magnitude 2.5 T directed upward along the y-axis. If the proton experiences a force of 3.2×10^{-12} N, find the speed of the proton.

3. If an electron in an electron beam experiences a downward force of 2.0×10^{-14} N while traveling in a magnetic field of 8.3×10^{-2} T west, what is the direction and magnitude of the velocity?

4. A uniform 1.5 T magnetic field points north. If an electron moves vertically downward (toward the ground) with a speed of 2.5×10^{7} m/s through this field, what force (magnitude and direction) will act on it?

5. A proton moves straight upward (away from the ground) through a uniform magnetic field that points from east to west and has a magnitude of 2.5 T. If the proton moves with a speed of 1.5×10^{7} m/s through this field, what force (magnitude and direction) will act on it?

6. An alpha particle (the nucleus of a helium atom, carrying a charge of 3.2×10^{-19} C) moves at 5.5×10^{7} m/s at a right angle to a magnetic field. If the particle experiences a force of 1.5×10^{-14} N due to the magnetic field, then what is the magnitude of the magnetic field?

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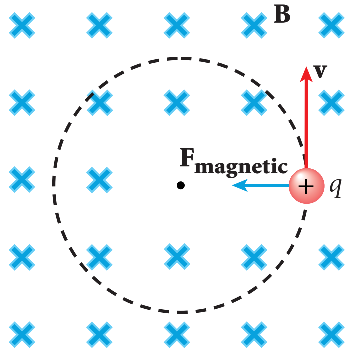

Figure 21-11
When the velocity, **v,** of a charged particle is perpendicular to a uniform magnetic field, the particle moves in a circle whose plane is perpendicular to **B.**

A charge moving through a magnetic field follows a circular path

Consider a positively charged particle moving in a uniform magnetic field so that the direction of the particle's velocity is perpendicular to the field, as in **Figure 21-11.** Application of the right-hand rule for the charge q shows that the direction of the magnetic force, $\mathbf{F}_{magnetic}$, at the charge's location is to the left. This causes the particle to alter its direction and to follow a curved path. Application of the right-hand rule at any point shows that the magnetic force is always directed toward the center of the circular path. Therefore, the magnetic force is, in effect, a force that maintains circular motion and changes only the direction of **v,** not its magnitude.

Now consider a charged particle traveling through a uniform magnetic field with a velocity that is neither parallel nor perpendicular to the direction of the magnetic field. In this case, the particle will follow a helical path along the direction of the magnetic field.

PHYSICS INTERACTIVE TUTOR

Module 19
"Magnetic Force on a Wire" provides an interactive lesson with guided problem-solving practice to teach you about the magnetic force on current-carrying wires that are not perpendicular to the magnetic field.

MAGNETIC FORCE ON A CURRENT-CARRYING CONDUCTOR

Recall that current is a collection of many charged particles in motion. If a force is exerted on a single charged particle when the particle moves through a magnetic field, it should be no surprise that a current-carrying wire also experiences a force when it is placed in a magnetic field. The resultant force on the wire is due to the sum of the individual forces on the charged particles. The force on the particles is transmitted to the bulk of the wire through collisions with the atoms making up the wire.

Consider a straight segment of wire of length ℓ carrying current, I, in a uniform external magnetic field, **B,** as in **Figure 21-12.** The magnitude of the total magnetic force on the wire is given by the following relationship.

FORCE ON A CURRENT-CARRYING CONDUCTOR PERPENDICULAR TO A MAGNETIC FIELD

$$F_{magnetic} = BI\ell$$

magnitude of magnetic force = (magnitude of magnetic field) (current)(length of conductor within B)

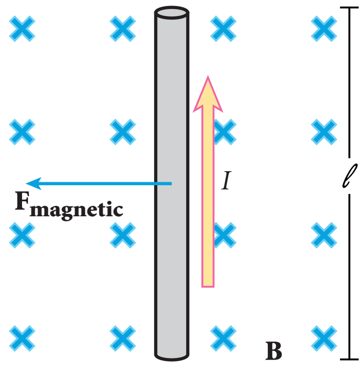

Figure 21-12
A current-carrying conductor in a magnetic field experiences a force that is perpendicular to the direction of the current.

This equation can be used only when the current and the magnetic field are at right angles to each other.

The direction of the magnetic force on a wire can be obtained by using the right-hand rule. However, in this case, you must place your thumb in the direction of the current rather than in the direction of the velocity, **v.** In **Figure 21-12,** the direction of the magnetic force on the wire is to the left. When the current is either in the direction of the field or opposite the direction of the field, the magnetic force on the wire is zero.

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Two parallel conducting wires exert a force on one another

Since a current in a conductor creates its own magnetic field, it is easy to understand that two current-carrying wires placed close together exert magnetic forces on each other. When the two conductors are parallel to each other, the direction of the magnetic field created by one is perpendicular to the direction of the current of the other, and vice versa. In this way, a force of $F_{magnetic} = BI\ell$ acts on each wire, where B is the magnitude of the magnetic field created by the other wire.

Consider the two long, straight, parallel wires shown in **Figure 21-13.** When the current in each is in the same direction, as shown in **Figure 21-13(a),** the two wires attract one another. You can confirm this by using the right-hand rule. Point your thumb in the direction of current in one wire, and point your fingers in the direction of the field produced by the other wire. By doing this, you find that the direction of the force (pointing out from the palm of your hand) is toward the other wire. When the currents in each wire are in opposite directions, as shown in **Figure 21-13(b),** the wires repel one another.

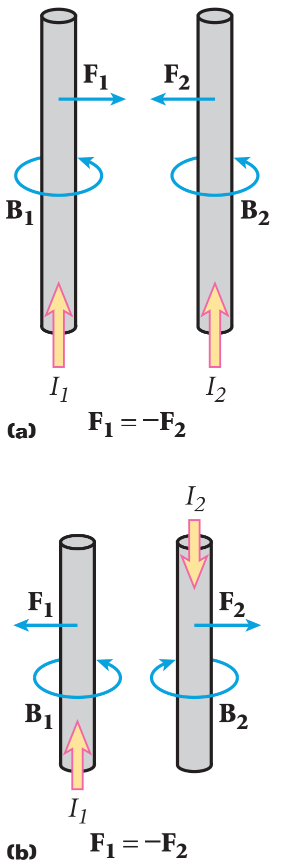

Figure 21-13
Two parallel wires, each carrying a steady current, exert forces on each other. The force is **(a)** attractive if the currents have the same direction and **(b)** repulsive if the two currents have opposite directions.

Loudspeakers use magnetic force to produce sound

The loudspeakers in most sound systems use a magnetic force acting on a current-carrying wire in a magnetic field to produce sound waves. One speaker design, shown in **Figure 21-14,** consists of a coil of wire, a flexible paper cone attached to the coil that acts as the speaker, and a permanent magnet. A sound signal is converted to a varying electric signal and is sent to the coil. The current causes a magnetic force to act on the coil. When the current reverses direction, the magnetic force on the coil reverses direction, and the cone accelerates in the opposite direction. This alternating force on the coil results in vibrations of the attached cone, which produce variations in the density of the air in front of it. In this way, an electric signal is converted to a sound wave that closely resembles the sound wave produced by the source.

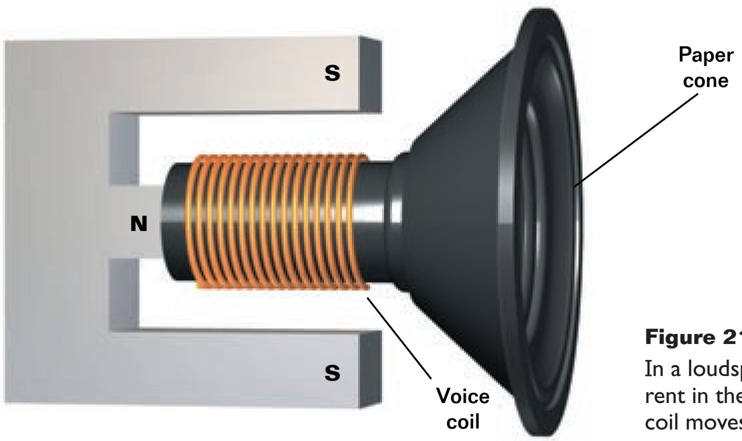

Figure 21-14
In a loudspeaker, when the direction and magnitude of the current in the coil of wire change, the paper cone attached to the coil moves, producing sound waves.

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SAMPLE PROBLEM 21B

Force on a current-carrying conductor

PROBLEM

A wire 36 m long carries a current of 22 A from east to west. If the maximum magnetic force on the wire at this point is downward (toward Earth) and has a magnitude of 4.0×10^{-2} N, find the magnitude and direction of the magnetic field at this location.

SOLUTION

Given: $\ell = 36$ m $\quad I = 22$ A $\quad F_{magnetic} = 4.0 \times 10^{-2}$ N

Unknown: $B = ?$

Use the equation for the force on a current-carrying conductor perpendicular to a magnetic field, shown on page 776.

$$F_{magnetic} = BI\ell$$

Rearrange to solve for B.

$$B = \frac{F_{magnetic}}{I\ell} = \frac{4.0 \times 10^{-2}\ \text{N}}{(22\ \text{A})(36\ \text{m})} = 5.0 \times 10^{-5}\ \text{T}$$

Using the right-hand rule to find the direction of B, face north with your thumb pointing to the west (in the direction of the current) and the palm of your hand down (in the direction of the force). Your fingers point north. Thus, Earth's magnetic field is from south to north.

PRACTICE 21B

Force on a current-carrying conductor

1. A 6.0 m wire carries a current of 7.0 A toward the $+x$ direction. A magnetic force of 7.0×10^{-6} N acts on the wire in the $-y$ direction. Find the magnitude and direction of the magnetic field producing the force.

2. A wire 1.0 m long experiences a magnetic force of 0.50 N due to a perpendicular uniform magnetic field. If the wire carries a current of 10.0 A, what is the magnitude of the magnetic field?

3. The magnetic force on a straight 0.15 m segment of wire carrying a current of 4.5 A is 1.0 N. What is the magnitude of the component of the magnetic field that is perpendicular to the wire?

4. The magnetic force acting on a wire that is perpendicular to a 1.5 T uniform magnetic field is 4.4 N. If the current in the wire is 5.0 A, what is the length of the wire that is inside the magnetic field?

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GALVANOMETERS

A *galvanometer* is a device used in the construction of both ammeters and voltmeters. Its operation is based on the idea that a torque acts on a current loop in the presence of a magnetic field. **Figure 21-15** shows a simplified arrangement of the main components of a galvanometer. It consists of a coil of wire wrapped around a soft iron core mounted so that it is free to pivot in the magnetic field provided by the permanent magnet. The torque experienced by the coil is proportional to the current in the coil. This means that the larger the current, the greater the torque and the more the coil will rotate before the spring tightens enough to stop the movement. Hence, the amount of deflection of the needle is proportional to the current in the coil. When there is no current in the coil, the spring returns the needle to zero. Once the instrument is properly calibrated, it can be used in conjunction with other circuit elements as an ammeter (to measure currents) or as a voltmeter (to measure potential differences).

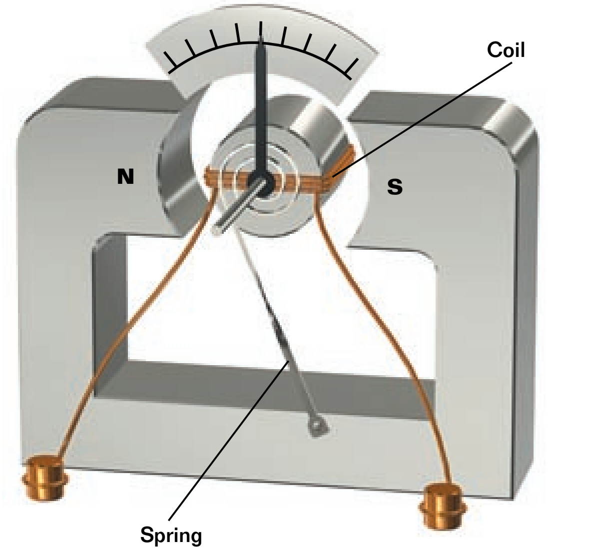

Figure 21-15
In a galvanometer, when current enters the coil, which is in a magnetic field, the magnetic force causes the coil to twist.

Section Review

1. A particle with a charge of 0.030 C experiences a magnetic force of 1.5 N while moving at right angles to a uniform magnetic field. If the speed of the charge is 620 m/s, what is the magnitude of the magnetic field the particle passes through?
2. An electron moving north encounters a uniform magnetic field. If the magnetic field points east, what is the direction of the magnetic force on the electron?
3. A straight segment of wire has a length of 25 cm and carries a current of 5.0 A. If the wire is perpendicular to a magnetic field of 0.60 T, then what is the magnitude of the magnetic force on this segment of the wire?
4. Two parallel wires have charges moving in the same direction. Is the force between them attractive or repulsive?
5. Find the direction of the magnetic force on the current-carrying wire in **Figure 21-16.**

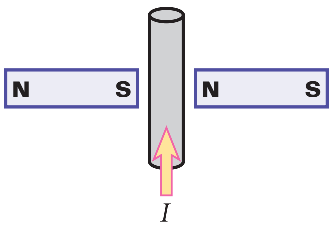

Figure 21-16

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CHAPTER 21
Summary

KEY TERMS

domain (p. 772)

magnetic field (p. 767)

solenoid (p. 771)

KEY IDEAS

Section 21-1 Magnets and magnetic fields
- Like magnetic poles repel, and unlike poles attract.
- The direction of any magnetic field is defined as the direction the north pole of a magnet would point if placed in the field. The magnetic field of a magnet points from the north pole of the magnet to the south pole.
- The magnetic north pole of Earth corresponds to the geographic South Pole, and the magnetic south pole corresponds to the geographic North Pole.

Section 21-2 Electromagnetism and magnetic domains
- A magnetic field exists around any current-carrying wire; the direction of the magnetic field follows a circular path around the wire.
- The magnetic field created by a solenoid or coil is similar to the magnetic field of a permanent magnet.
- A domain is a group of atoms whose magnetic fields are aligned.

Section 21-3 Magnetic force
- The direction of the force on a positive charge moving through a magnetic field can be found using the right-hand rule. The magnitude of a magnetic field is given by the relation $B = \frac{F_{magnetic}}{qv}$.
- A length of wire, ℓ, in an external magnetic field undergoes a magnetic force with a magnitude of $F_{magnetic} = BI\ell$. The direction of the magnetic force on the wire can be found using the right-hand rule.
- Two parallel current-carrying wires exert on one another forces that are equal in magnitude and opposite in direction. If the currents are in the same direction, the two wires attract one another. If the currents are in opposite directions, the wires repel one another.

Diagram symbols

Magnetic field vector	↑
Magnetic field pointing into the page	×
Magnetic field pointing out of the page	•

Variable symbols

Quantities		Units		Conversions
B	magnetic field	T	tesla	$= \frac{N}{C \bullet m/s} = \frac{N}{A \bullet m}$
$F_{magnetic}$	magnetic force	N	newtons	$= \frac{kg \bullet m}{s^2}$
ℓ	length of conductor in field	m	meters	

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CHAPTER 21
Review and Assess

MAGNETS AND MAGNETIC FIELDS

Review questions

1. What is the minimum number of poles for a magnet?
2. When you break a magnet in half, how many poles does each piece have?
3. The north pole of a magnet is attracted to the geographic North Pole of Earth, yet like poles repel. Can you explain this?
4. Which way would a compass needle point if you were at the magnetic north pole?

Conceptual questions

5. You are an astronaut stranded on a planet with no test equipment or minerals around. The planet does not even have a magnetic field. You have two iron bars in your possession; one is magnetized, one is not. How can you determine which one is magnetized?
6. In **Figure 21-17,** two permanent magnets with holes bored through their centers are placed one over the other. Because the poles of the upper magnet are the reverse of those of the lower, the upper magnet levitates above the lower magnet. If the upper magnet were displaced slightly, either up or down, would the resulting motion be periodic? Explain. What would happen if the upper magnet were inverted?

Figure 21-17

ELECTROMAGNETISM AND MAGNETIC DOMAINS

Review questions

7. What is a magnetic domain?
8. Why are iron atoms so strongly affected by magnetic fields?
9. When a magnetized steel needle is strongly heated in a Bunsen burner flame, it becomes demagnetized. Explain why.
10. What indicates that a piece of iron is magnetic, its attraction to or repulsion from another piece of iron?
11. Why does a very strong magnet attract both poles of a weak magnet?
12. A magnet attracts a piece of iron. The iron can then attract another piece of iron. Explain, on the basis of alignment of domains, what happens in each piece of iron.
13. When a small magnet is repeatedly dropped, it becomes demagnetized. Explain what happens to the magnet subatomically.
14. A conductor carrying a current is arranged so that electrons flow in one segment from east to west. If a compass is held over this segment of the wire, in what direction is the needle deflected?
15. What factors does the strength of the magnetic field of a solenoid depend on?

Conceptual questions

16. A solenoid with ends marked *A* and *B* is suspended by a thread so that the core can rotate in the horizontal plane. A current is maintained in the coil so that the electrons move clockwise when viewed from end *A* toward end *B*. How will the coil align itself in Earth's magnetic field?

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17. Is it possible to orient a current-carrying loop of wire in a uniform magnetic field so that the loop will not tend to rotate?

18. If a solenoid were suspended by a string so that it could rotate freely, could it be used as a compass when it carried a direct current? Could it also be used if the current were alternating in direction?

MAGNETIC FORCE

Review questions

19. Two charged particles are projected into a region where there is a magnetic field perpendicular to their velocities. If the particles are deflected in opposite directions, what can you say about them?

20. Suppose an electron is chasing a proton up this page when suddenly a magnetic field pointing into the page is applied. What would happen to the particles?

21. Why does the picture on a television screen become distorted when a magnet is brought near the screen?

22. A proton moving horizontally enters a region where there is a uniform magnetic field perpendicular to the proton's velocity, as shown in **Figure 21-18.** Describe the proton's subsequent motion. How would an electron behave under the same circumstances?

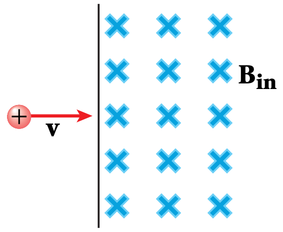

Figure 21-18

23. Explain why two parallel wires carrying currents in opposite directions repel each other.

24. Can a stationary magnetic field set a resting electron in motion? Explain.

25. At a given instant, a proton moves in the positive x direction in a region where there is a magnetic field in the negative z direction. What is the direction of the magnetic force? Does the proton continue to move along the x–axis? Explain.

26. Find the direction of the magnetic field for a positively charged particle moving in each situation in **Figure 21-19** if the direction of the magnetic force acting on it is as indicated.

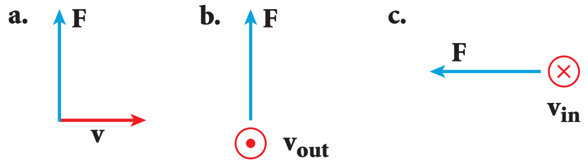

Figure 21-19

Conceptual questions

27. A stream of electrons is projected horizontally to the right. A straight conductor carrying a current is supported parallel to and above the electron stream.

  a. What is the effect on the electron stream if the current in the conductor is left to right?

  b. What is the effect if the current is reversed?

28. If the conductor in item 27 is replaced by a magnet with a downward magnetic field, what is the effect on the electron stream?

29. Two wires carrying equal but opposite currents are twisted together in the construction of a circuit. Why does this technique reduce stray magnetic fields?

Practice problems

30. A duck flying due east passes over Atlanta, where the magnetic field of the Earth is 5.0×10^{-5} T directed north. The duck has a positive charge of 4.0×10^{-8} C. If the magnetic force acting on the duck is 3.0×10^{-11} N upward, what is the duck's velocity?
(See Sample Problem 21A.)

31. A proton moves eastward in the plane of Earth's magnetic equator so that its distance from the ground remains constant. What is the speed of the proton if Earth's magnetic field points north and has a magnitude of 5.0×10^{-5} T?
(See Sample Problem 21A.)

32. A wire carries a 10.0 A current at an angle 90.0° from the direction of a magnetic field. If the magnitude of the magnetic force on a 5.00 m length of the wire is 15.0 N, what is the strength of the magnetic field?
(See Sample Problem 21B.)

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33. A thin 1.00 m long copper rod in a uniform magnetic field has a mass of 50.0 g. When the rod carries a current of 0.245 A, it floats in the magnetic field. What is the field strength of the magnetic field? (See Sample Problem 21B.)

MIXED REVIEW

34. A proton moves at 2.50×10^6 m/s horizontally at a right angle to a magnetic field.
- **a.** What is the strength of the magnetic field required to exactly balance the weight of the proton and keep it moving horizontally?
- **b.** Should the direction of the magnetic field be in a horizontal or a vertical plane?

35. Find the direction of the force on a proton moving through each magnetic field in **Figure 21-20.**

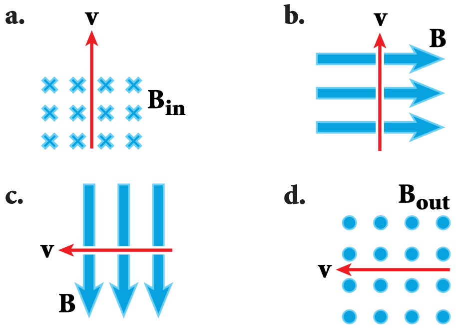

Figure 21-20

36. Find the direction of the force on an electron moving through each magnetic field in **Figure 21-20.**

37. In **Figure 21-20,** assume that in each case the velocity vector shown is replaced with a wire carrying a current in the direction of the velocity vector. Find the direction of the magnetic force acting on each wire.

38. A proton moves at a speed of 2.0×10^7 m/s at right angles to a magnetic field with a magnitude of 0.10 T. Find the magnitude of the acceleration of the proton.

39. A proton moves perpendicularly to a uniform magnetic field, **B,** with a speed of 1.0×10^7 m/s and experiences an acceleration of 2.0×10^{13} m/s^2 in the positive x direction when its velocity is in the positive z direction. Determine the magnitude and direction of the field.

40. A proton travels with a speed of 3.0×10^6 m/s at an angle of 37° west of north. A magnetic field of 0.30 T points to the north. Determine the following:
- **a.** the magnitude of the magnetic force on the proton
- **b.** the direction of the magnetic force on the proton
- **c.** the proton's acceleration as it moves through the magnetic field

(Hint: The magnetic force experienced by the proton in the magnetic field is proportional to the component of the proton's velocity that is perpendicular to the magnetic field.)

41. In **Figure 21-21,** a 15 cm length of conducting wire that is free to move is held in place between two thin conducting wires. All the wires are in a magnetic field. When a 5.0 A current is in the wire, as shown in the figure, the wire segment moves upward at a constant velocity. Assuming the wire slides without friction on the two vertical conductors and has a mass of 0.15 kg, find the magnitude and direction of the minimum magnetic field that is required to move the wire.

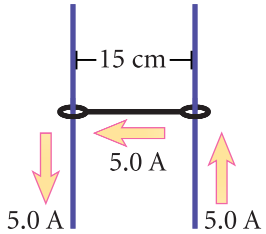

Figure 21-21

42. A current, I = 15 A, is directed along the positive x-axis and perpendicular to a uniform magnetic field. The conductor experiences a magnetic force per unit length of 0.12 N/m in the negative y direction. Calculate the magnitude and direction of the magnetic field in the region through which the current passes.

43. A proton moves in a circular path perpendicular to a constant magnetic field so that the proton takes 1.00×10^{-6} s to complete one revolution. Determine the strength of the constant magnetic field. (Hint: The magnetic force exerted on the proton is the force that maintains circular motion, and the number of radians per time interval is the angular speed.)

44. A singly charged positive ion that has a mass of 6.68×10^{-27} kg moves clockwise with a speed of 1.00×10^4 m/s. The positively-charged ion moves in a circular path that has a radius of 3.00 cm. Find the direction and strength of the uniform magnetic field. (Hint: The magnetic force exerted on the positive ion is the force that maintains circular motion, and the speed given for the positive ion is its tangential speed.)

Technology & Learning

Graphing calculators

Refer to Appendix B for instructions on downloading programs for your calculator. The program "Chap21" allows you to find the magnetic field of a solenoid given the amount of current in the solenoid.

The program "Chap21" stored on your graphing calculator makes use of line-fitting techniques to find the magnetic field of a solenoid when the amount of current in the solenoid in known. Before executing the program "Chap21," you will enter two sets of data for the magnetic field strength and current in a specific solenoid. Then, when you run the program "Chap21," your graphing calculator will use this data to draw a straight line using the following equation:

$$Y_1 = aX + b$$

Next, your calculator will ask you for the value of the current (X) in the solenoid. The calculator will then find the point along the line that corresponds to that current and report the *y* value. This *y* value is the magnetic field strength (Y_1) that corresponds to the current (X) that you input. Remember that this magnetic field strength corresponds to that current only for the solenoid described by this line; new data must be entered into the calculator when you want to analyze the current and magnetic field of a different solenoid.

a. Which letter in the above equation corresponds to the slope of the line?

Clear the data lists by pressing [STAT] [4] [2nd] [L1] [ENTER] and [STAT] [4] [2nd] [L2] [ENTER]. Press [STAT] [1], and enter the current data into the list [L1] and the magnetic field data into the list [L2]. (Remember to use [2nd] [EE] to enter exponents and the [(–)] key to enter negative numbers.) Press [2nd] [QUIT] to exit the stat list editor.

Execute "Chap21" on the [PRGM] menu, and press [ENTER] to begin the program. Enter the value for the current in amperes, and press [ENTER]. Once you have entered the value for the current in the solenoid, the calculator will fit that current to the line and display the magnetic field strength of the solenoid in units of teslas. Once you have finished using the graph for one situation, press [CLEAR] to end the program. Then enter the data for the next situation and run the program again.

Determine the magnetic field strength for the solenoid with the following current and magnetic field strength/current data points:

b. a current of 2.37 A in a solenoid that has a magnetic field strength of 2.54×10^{-2} T when the current is 3.35 A and 5.20×10^{-2} T when the current is 6.90 A

c. a current of 3.54 A in a solenoid that has a magnetic field strength of 5.50×10^{-3} T when the current is 1.25 A and 1.74×10^{-2} T when the current is 3.80 A

d. Solenoid A and B carry the same current. Solenoid A produces a magnetic field of 1.5×10^{-2} T, and solenoid B produces a magnetic field of 2.5×10^{-3} T. Based on this information, which solenoid has more turns per length?

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45. What speed would a proton need to achieve in order to circle Earth 1000.0 km above the magnetic equator? Assume that Earth's magnetic field is everywhere perpendicular to the path of the proton and that Earth's magnetic field has an intensity of 4.00×10^{-8} T. (Hint: The magnetic force exerted on the proton is equal to the force that maintains circular motion, and the speed needed by the proton is its tangential speed. Remember that the radius of the circular orbit should also include the radius of Earth.)

46. An electron moves in a circular path perpendicular to a magnetic field that has a magnitude of 1.00×10^{-3} T. If the angular momentum of the electron as it moves around the center of the circle is 4.00×10^{-25} J•s, determine the following quantities involved in the situation:

a. the radius of the circular path
b. the speed of the electron

Alternative Assessment

Performance assessment

1. During a field investigation with your class, you find a roundish chunk of metal that attracts iron objects. Design a procedure to determine whether the object is magnetic and, if so, to locate its poles. Describe the limitations of your method. What materials would you need? How would you draw your conclusions? List all the possible results you can anticipate and the conclusions you could draw from each result.

2. Imagine you have been hired by a manufacturer interested in making kitchen magnets. The manufacturer wants you to determine how to combine several magnets to get a very strong magnet. He also wants to know what protective material to use to cover the magnets. Develop a method for measuring the strength of different magnets by recording the maximum number of paper clips they can hold under various conditions. First open a paper clip to use as a hook. Test the strength of different magnets and combinations of magnets by holding up the magnet, placing the open clip on the magnet, and hooking the rest of the paper clips so that they hang below the magnet. Examine the effect of layering different materials between the magnet and the clips. Organize your data in tables and graphs to present your conclusions.

Portfolio projects

3. Research phenomena related to one of the following topics, and prepare a report or presentation with pictures and data.

a. How does Earth's magnetic field vary with latitude, with longitude, with the distance from Earth, and in time?
b. How do people who rely on compasses account for these differences in Earth's magnetic field?
c. What is the Van Allen Belt?
d. How do solar flares occur?
e. How do solar flares affect Earth?

4. Obtain old buzzers, bells, telephone receivers, speakers, motors from power or kitchen tools, and so on, to take apart. Identify the mechanical and electromagnetic components. Examine their connections. How do they produce magnetic fields? Work in a cooperative group to describe and organize your findings about several devices for a display entitled "Anatomy of Electromagnetic Devices."

5. Magnetic force was first described by the ancient Greeks, who mined a magnetic mineral called magnetite. Magnetite was used in early experiments on magnetic force. Research the historical development of the concept of magnetic force. Describe the work of Peregrinus, William Gilbert, Oersted, Faraday, and other scientists.

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CHAPTER 21
Laboratory Exercise

MAGNETIC FIELD OF A CONDUCTING WIRE

In this lab, you will study the magnetic field that occurs around a current-carrying wire. You will construct a circuit with a current-carrying wire and use a magnetic compass needle or a CBL and magnetic field sensor to investigate the relationship between the magnetic field and the current in the wire. You will be able to determine the magnitude and direction of the magnetic field surrounding the wire.

OBJECTIVES

- Use a compass or magnetic field sensor to explore the existence, magnitude, and direction of the magnetic field of a current-carrying wire.
- Analyze the relationship between the magnitude of the magnetic field of a conducting wire and the current in the wire.
- Analyze the relationship between the direction of the magnetic field of a conducting wire and the direction of the current in the wire.

MATERIALS LIST

- ✔ 1 Ω resistor
- ✔ galvanometer
- ✔ insulated connecting wires and bare copper wire
- ✔ masking tape
- ✔ power supply
- ✔ switch

PROCEDURE

CBL AND SENSORS

- ✔ alligator clips
- ✔ CBL
- ✔ CBL magnetic field sensor
- ✔ CBL voltage probe
- ✔ graphing calculator with link cable
- ✔ support stand and clamp

COMPASS

- ✔ compass
- ✔ multimeter or dc ammeter

SAFETY

- **Never close a circuit until it has been approved by your teacher. Never rewire or adjust any element of a closed circuit. Never work with electricity near water; be sure the floor and all work surfaces are dry.**
- **If the pointer on any kind of meter moves off scale, open the circuit immediately by opening the switch.**
- **Do not attempt this exercise with any batteries, electrical devices, or magnets other than those provided by your teacher for this purpose.**
- **Wire coils may heat up rapidly during this experiment. If heating occurs, open the switch immediately and handle the equipment with a hot mitt. Allow all equipment to cool before storing it.**

PREPARATION

1. Determine whether you will be using the CBL and sensors procedure or the compass procedure. Read the entire lab for the appropriate procedure, and plan what steps you will take.

2. Prepare a data table in your lab notebook.

- **CBL and sensors** Prepare a table with four columns and thirteen rows. In the first row, label the columns *Trial, Current Direction,* ΔV_R (*V*), and $B_{Measured}$ (*T*). Label the 2nd through 13th rows *1* through *12.*
- **Compass** Prepare a table with four columns and nine rows. In the first row, label the columns *Turns, Current (A), Current direction,* and *Compass reading.* In the first column, label the second through ninth rows *One, One, Two, Two, Three, Three, Four,* and *Four.*

Compass procedure begins on page 788.

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PROCEDURE

CBL AND SENSORS

Magnetic field strength

3. Set up the apparatus as shown in **Figure 21-22.** Use 1 m of copper wire to make a square loop around the coil support pins on the galvanometer apparatus. Attach alligator clips to the ends of the wire. Label one clip *A* and label the other *B*. Place the galvanometer apparatus so that you are facing the plane of the coil.

4. Use masking tape to mark a line on the stand of the galvanometer directly under the top of the coil. Make another tape line perpendicular to the first, as shown in **Figure 21-22.** The two tapes should cross in the middle of the apparatus. On the second tape, on the side away from you, mark the point 2 cm from the center. Using this point as the center point, draw a circle with a 1 cm radius.

5. Construct a circuit that contains the power supply and a 1 Ω resistor wired in series through the middle set of posts on the switch. Place the switch so that it moves from left to right. Connect the front right post of the switch to the end of the coil marked *A* and connect the rear right post of the switch to the end of the coil marked *B*. Now connect the front left post of the switch to the end of the coil marked *B* and the rear left post of the switch to the end of the coil marked *A*. ***Do not close the switch or turn on the power supply until your teacher has approved your circuit.***

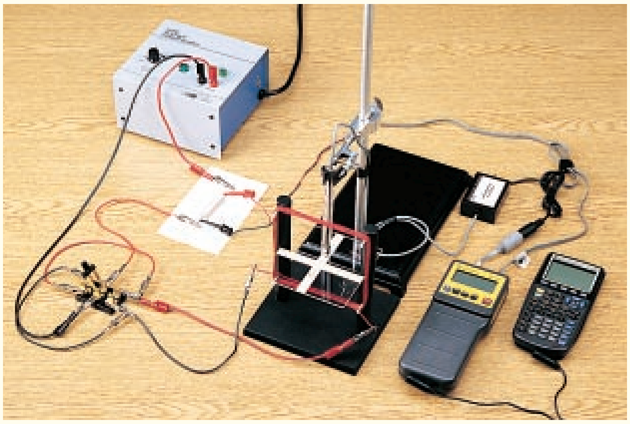

Figure 21-22

Step 3: Loop the copper wire around the support pins and attach alligator clips to the ends. Place the galvanometer with one support pin on the left and one on the right.

Step 4: Use two pieces of tape to mark perpendicular lines, and mark a circle to use as a reference for placing the sensor.

Step 5: Place the switch in front of you so that it moves from left to right. Check all connections carefully.

6. Connect the CBL to the calculator with the unit-to-unit link cable. Connect the CBL voltage probe to the CH1 port on the CBL and the magnetic field probe to the CH2 port. Connect the CBL voltage probe to measure the voltage across the resistor.

- Turn on the CBL and the graphing calculator. Start the program PHYSICS on the calculator. Select option *SET UP PROBES* from the MAIN MENU. Enter 2 for the number of probes. Select *MORE PROBES* from the SELECT PROBE menu. Select the *VOLTAGE* probe from the list. Enter 1 for the channel number.
- Select *MORE PROBES* from the SELECT PROBE menu. Select the *MAGNETIC FIELD* probe from the list. Enter 2 for the channel number. From the CALIBRATION menu, select *USE STORED.* For the MAGNETIC FIELD SETTING, select *HIGH (MTESLA).*

7. Select *OPTIONS* from the MAIN MENU. Select option *ZERO SENSOR* from the PHYSICS OPTIONS menu. Select *CHANNEL 2* to zero the magnetic field sensor.

8. Hold the magnetic field sensor vertically with the white dot facing north. The CBL will display the sensor readings in volts. When the CBL displays a constant value for the field strength, press TRIGGER on the CBL to zero the sensor.

9. Select the *COLLECT DATA* option from the MAIN MENU. Select the *MONITOR INPUT* option from the DATA COLLECTION menu. The graphing calculator will begin to display values.

10. Set up a support stand with a buret clamp to hold the magnetic field sensor vertically. Position the magnetic sensor securely so that the white dot is facing you and the sensor is directly above the 1 cm circle marked on the tape.

11. Make sure the dial on the power supply is turned completely counterclockwise. When your teacher has approved your circuit, turn the dial on the power supply about halfway to its full value. Close the switch briefly.

12. Read the potential difference across the resistor and the strength of the magnetic field. Open the switch as soon as you have made your observations. Record ΔV_R *(V)* and $B_{Measured}$ *(T)* for *Trial 1* in your data table. Determine and record the *Current Direction* (*A* to *B* or *B* to *A*).

13. Reverse the direction of the current by closing the switch in the opposite direction. Read and record the potential difference and the strength of the magnetic field for *Trial 2.* Open the switch as soon as you have made your observations. Determine and record the *Current Direction* (*A* to *B* or *B* to *A*).

14. Disconnect the alligator clips from A and B on the wire loop, and turn the wire loop 180°. Reconnect the alligator clips, making sure that clip A is on the same end of the wire it was for previous trials. Repeat steps 12 and 13 as *Trials 3* and *4.* Record all data in your data table. Always open the switch as soon as you have made your readings.

15. Return the apparatus to the same position as it was in *Trial 1.* Increase the setting on the power supply to about two-thirds of the maximum setting on the dial. Repeat the procedure in steps 10 through 14. Record all data in your data table for *Trials 5* through *8.*

16. Repeat step 15 with the power supply set to one-third of the maximum setting. Record all data in your data table as *Trials 9* through *12.*

17. Clean up your work area. Put equipment away safely so that it is ready to be used again.

Analysis and interpretation begins on page 789.

PROCEDURE

COMPASS

Magnetic field of a current-carrying wire

3. Wrap the wire once around the galvanometer. Place the large compass on the stand of the galvanometer so that the compass needle is parallel to and directly below the wire, as shown in **Figure 21-23.** Turn the galvanometer until the turn of wire is in the north-to-south plane, as indicated by the compass needle.

4. Construct a circuit that contains the power supply, a current meter, a 1 Ω resistor, and a switch, all wired in series with the galvanometer. Connect the galvanometer so that the direction of the current will be from south to north through the segment of the loop above the compass needle. ***Do not close the switch until your teacher has approved your circuit.***

5. Set the power supply to its lowest output. When your teacher has approved your circuit, close the switch briefly. Using the power supply, adjust the current in the circuit to 1.5 A. Use the power supply to maintain this current throughout the lab. Record the current, the current direction, and the compass reading in your data table.

6. Reverse the direction of the current in the segments of the loop above the needle by reversing the wires connecting to the galvanometer.

7. Close the switch. Adjust the power supply to 1.5 A. Record your observations in your data table. Open the switch as soon as you have made your observations.

8. Remove the galvanometer from the circuit. Add a second turn of wire, and reconnect the galvanometer to the circuit so that the current direction will be south to north.

Back

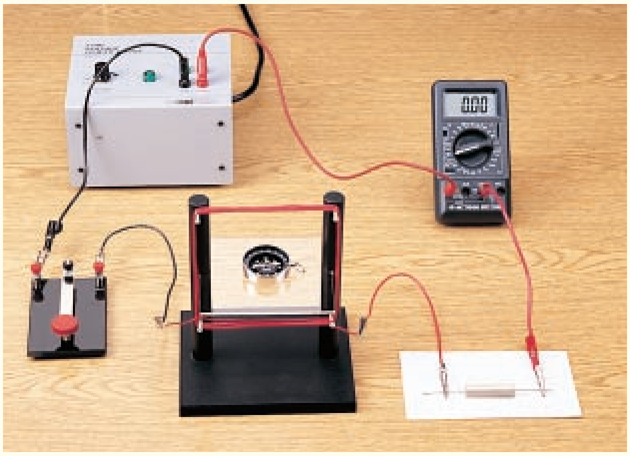

Figure 21-23
Step 3: Use the support pins on the galvanometer to wrap the wire into a loop. Adjust the apparatus so that the needle and wire are in the north-to-south plane.

9. Close the switch. Adjust the power supply to 1.5 A. Record your observations in your data table. Open the switch immediately.
10. Reverse the direction of the current through the segments of the loop above the needle by reversing the wires connecting to the galvanometer.
11. Close the switch. Adjust the power supply to 1.5 A.
12. Repeat the experiment for three turns and then four turns. For each, connect the circuit so that the direction of the current is from south to north and then north to south. Record all information.
13. Clean up your work area. Put equipment away safely so that it is ready to be used again.

ANALYSIS AND INTERPRETATION

Calculations and data analysis

1. **Analyzing data** Use the data for each trial.
   a. **CBL and sensors** Find the current using the equation $\Delta V = IR$.
   b. **Compass** Find the tangent of the angle of deflection for the compass needle.
2. **Graphing data** Use a computer, graphing calculator, or graph paper.
   a. **CBL and sensors** Use the data from *Trials 1, 5,* and *9* to plot a graph of B_{wire} in teslas against the current in the circuit. Also plot graphs for *Trials 2, 6,* and *10; Trials 3, 7,* and *11;* and *Trials 4, 8,* and *12.*
   b. **Compass** Plot a graph of the tangents found in item 1 against the number of turns in the wire.

Conclusions

3. **Analyzing graphs** Use your graphs to answer the following questions.
   a. **CBL and sensors** For each position, what is the relationship between the current in the wire loop and the magnetic field strength?
   b. **Compass** What is the relationship between the tangent of the angle and the number of turns? Explain.
4. **Applying conclusions** What is the relationship between the direction of current in the wire and the direction of the magnetic field? Explain.

Electromagnetic Fields: Can They Affect Your Health?

In the 1970s, many people became concerned about the electromagnetic radiation being produced by electric devices they used at work and at home. People already knew that microwaves could cook food and that exposure to ultraviolet light contributed to skin cancer. So if all these effects were possible, people reasoned, couldn't electromagnetic radiation given off by standard 60 Hz alternating current also cause harm?

Electromagnetic waves are produced when a charged particle undergoes acceleration. Accordingly, a 60 Hz alternating current in a wire produces 60 Hz electromagnetic radiation. This is fairly low on the electromagnetic spectrum, considering that AM radio waves have frequencies around 10^6 Hz, which is itself fairly low on the electromagnetic spectrum. The region of space through which electromagnetic radiation passes is an electromagnetic field. Electromagnetic waves produced by 60 Hz alternating current produce what is called an extremely low frequency electromagnetic field, or ELF.

Problems with power lines

In 1979, scientists reported that children who lived near high-voltage power-transmission lines were twice as likely to suffer from childhood leukemia as children who did not live near power lines. In 1986, another study seemed to confirm that occurrences of leukemia and other childhood cancers were linked to the presence of power lines. There were concerns that the 60 Hz electromagnetic fields from the power lines might be responsible.

Many scientists criticized these studies because the researchers did not measure the strengths of the fields the people were exposed to. Instead, they had estimated the amount of exposure from the way the power lines were arranged, the current running through the lines, and the distance of the lines from each house. Critics also pointed out that the research consisted only of epidemiological studies, which mathematically correlate the frequency of an illness to factors in the surroundings.

Partly as a result of this criticism, researchers were challenged to discover a mechanism (a specific biological change that would lead to the development of cancer) by which ELFs could affect biological systems. Soon, researchers began to report that ELFs could damage cell membranes, cause unusual expression of genes, increase the production of the hormone estrogen, and reduce the pineal gland's production of melatonin, a hormone that can limit the growth of cancerous cells.

From 1991 to 1995, scientists conducted another epidemiological study to relate the health problems of 130 000 electric utility workers to their on-the-job exposure to ELFs. The researchers made a few measurements of field strength in order to estimate the amount of exposure for each type of job. To their surprise, they did not find an increased risk of leukemia, as they had expected. Instead, they found that brain cancer occurred more than twice as often among these workers as it did among other kinds of workers. However, two other studies conducted at nearly the same time found the opposite results or no correlation at all. In these last two studies, scientists measured the ELF exposure of every worker.

A need for conclusions

By 1995, several billion dollars had been spent on research that essentially provided no conclusive results, so government and other institutions were becoming wary of pouring more money into further study. The public was also becoming increasingly uneasy over the conflicting claims about ELFs. In addition, a whole industry had built up around people's fears of ELFs. Companies were selling everything from useful devices, such as gaussmeters, which measure magnetic field strength, to questionable gadgets that promised to absorb ELFs and reradiate them in a "coherent" form that was supposedly beneficial to health.

In 1995, the American Physical Society (APS) reviewed all of the research and declared that the studies had failed to show any connection between electromagnetic fields and cancer. They added that researchers had not found any mechanism by which ELFs might cause cancer. The National Academy of Sciences (NAS) came to a similar conclusion in 1996, although it conceded that a correlation did exist between childhood leukemia and the presence of power lines. The NAS suggested that scientists should continue to search for a reason for this correlation. In 1997, the U.S. Department of Energy announced that it would no longer fund ELF programs.

Some scientists believe funding should be continued, saying that more-refined research would reveal a firm correlation. Others have criticized the APS, saying that the organization dismissed epidemiological studies too easily and was too focused on the lack of a confirmed mechanism. Still others were pleased that NAS supported continued research into the connection between power lines and leukemia. Scientists who defend the actions of the APS and NAS point out that research money is no longer easy to get and that it should be used in more-promising kinds of cancer research.

Researching the Issue

1. Evidence indicates that the incidence of cancer is more frequent among children who live near power-transmission lines but that the cancers are not caused by electromagnetic fields. What other factors would you suggest that scientists examine? The factors do not have to involve electricity.

2. Interpret the following statement in light of the public's perception of the disagreements over ELFs: "You can prove something to be unsafe, but you can never prove something to be completely safe."

3. Find Internet sites that offer products that claim to help people avoid exposure to electromagnetic fields. List and describe products that you think would be useful and those that you think would be a waste of money. Defend your classification of each item.

4. Electromagnetic fields from household devices, especially those with electric motors, are usually stronger than fields from nearby power lines when the fields are measured in the home. How can you account for this phenomenon?