36 MAGNETISM

Objectives

- Explain how magnetic poles affect each other. (36.1)
- Describe the magnetic field in the space around a magnet. (36.2)
- Describe how magnetic fields are produced. (36.3)
- Describe how to make a permanent magnet. (36.4)
- Describe the magnetic field produced by a current-carrying wire. (36.5)
- Describe how a magnetic field exerts a force on a charged particle in the field. (36.6)
- Describe how current is affected by a magnetic field. (36.7)
- Describe how a galvanometer and a motor work. (36.8)
- Suggest a possible cause for Earth's magnetic field. (36.9)

discover!

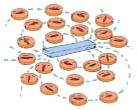
MATERIALS bar magnets, iron filings, sheet of glass or plastic

EXPECTED OUTCOME Students will observe different magnetic field patterns.

ANALYZE AND CONCLUDE

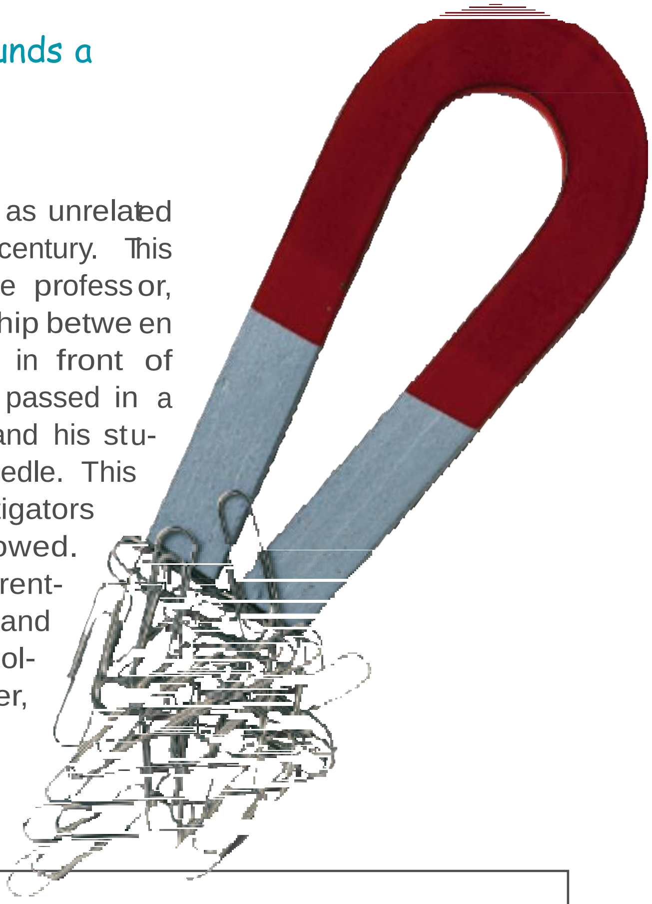
1. Sketches should show the closed loops formed by the lines of filings. Density of the lines is greatest near the magnet.
2. A horseshoe magnet is a bent bar magnet; in their predictions, students may note similarities to the field patterns observed in Steps 2 and 3.
3. Common characteristics: lines appear continuous and form closed loops; density of lines is greatest near the magnet; lines do not cross.

36 MAGNETISM



THE BIG IDEA

A magnetic field surrounds a moving electric charge.



Electricity and magnetism were regarded as unrelated phenomena into the early nineteenth century. This changed in 1820 when a Danish science professor, Hans Christian Oersted, discovered a relationship between the two while demonstrating electric currents in front of a class of students. When electric current was passed in a wire near a magnetic compass, both Oersted and his students noticed the deflection of the compass needle. This was the connecting link that had eluded investigators for decades.[36.0] Other discoveries soon followed. Magnets were found to exert forces on current-carrying wires, which led to electric meters and motors. The stage was set for a whole new technology, which would eventually bring electric power, radio, and television.

discover!

What Does a Magnetic Field Look Like?

1. Place a bar magnet on a level surface. Cover the magnet with a thin sheet of glass, clear plastic, or cardboard.
2. Sprinkle iron filings onto the sheet in the area above the magnet. Gently tap the sheet and observe the pattern formed by the filings.
3. Repeat Steps 1 and 2 using two bar magnets. Arrange the magnets in a straight line with opposite poles facing each other. Leave a gap of 4–6 cm between the poles.
4. Rotate one of the magnets 180 degrees and observe any change in the pattern formed by the filings.

Analyze and Conclude

1. **Observing** Make sketches of the patterns produced by the single magnet and by the pair of magnets in both orientations.
2. **Predicting** What pattern do you think would be formed if you used a horseshoe magnet in Step 1?
3. **Making Generalizations** Describe some characteristics common to the patterns you observed. What do you think these patterns represent?

FIGURE 36.1
Which interaction has the greater strength—the gravitational attraction between the scrap iron and Earth, or the magnetic attraction between the magnet and the scrap iron?

36.1 Magnetic Poles

Magnets exert forces on one another. They are similar to electric charges, for they can both attract and repel without touching, depending on which end is held near the other. Also, like electric charges, the strength of their interaction depends on the distance of separation of the two magnets. Whereas electric charges produce electrical forces, regions called **magnetic poles** produce magnetic forces.

If you suspend a bar magnet from its center by a piece of string, it will act as a compass. The end that points northward is called the *north-seeking pole*, and the end that points southward is called the *south-seeking pole*. More simply, these are called the *north* and *south poles*. All magnets have both a north and a south pole. For a simple bar magnet the poles are located at the two ends. The common horseshoe magnet is a bar magnet that has been bent, so its poles are also at its two ends.

If the north pole of one magnet is brought near the north pole of another magnet, they repel. The same is true of a south pole near a south pole. If opposite poles are brought together, however, attraction occurs.[36.1] ✓ **Like poles repel; opposite poles attract.**

FIGURE 36.2
Common magnets come in a variety of shapes.

Beware of junk scientists who sell magnets to cure physical ailments. Claims for cures are bogus. We need a knowledge filter to tell the difference between what is true and what seems to be true. The best knowledge filter ever invented is science.

think!

Does every magnet necessarily have a north and a south pole?
Answer: 36.1

This chapter, like so many others, links the subject matter to the environment. The material in this chapter is a prerequisite for the next chapter. Be sure to pass out some magnets to your students.

36.1 Electric Fields

Key Term
magnetic pole

Common Misconception
Magnetic poles are to magnets what electric charges are to electricity.

FACT Unlike electric charges, magnetic poles cannot be separated.

Note that the text avoids the confusion of the geographic north pole of Earth being a south magnetic pole (to attract the opposite north poles of magnets), and the geographic south pole being a north magnetic pole. It is annoying when this exercise in reverse language is featured on exams. Please stick to physics!

Teaching Tip Begin by holding a magnet above some nails or paper clips on your lecture table. State that the nails or clips are flat on the table because every particle of matter in the whole world is gravitationally pulling them to the table. Then show that your magnet will "outpull" the whole world and lift the nails or clips off the table.

CONCEPT CHECK Like poles repel; opposite poles attract.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *36-2*

36.2 Magnetic Fields

Key Term
magnetic field

Demonstration

Introduce the concept of a magnetic field by showing field patterns about bar magnets using an overhead projector and iron filings. Simply place a magnet on the glass surface of the projector and cover it with a sheet of plastic. Then sprinkle iron filings on the plastic. (See Figures 36.4 and 36.5.)

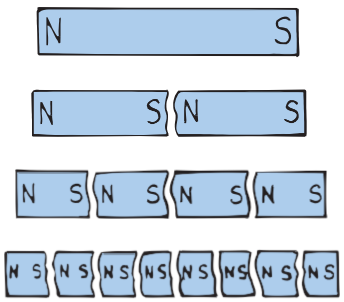


FIGURE 36.3
Magnetic poles always exist in pairs. Keep breaking a magnet in half and you will never isolate a single pole.

Magnetic poles behave similarly to electric charges in some ways, but there is a very important difference. Electric charges can be isolated, but magnetic poles cannot. Negatively charged electrons and positively charged protons are entities by themselves. A cluster of electrons need not be accompanied by a cluster of protons, and vice versa. But a north magnetic pole never exists without the presence of a south pole, and vice versa. The north and south poles of a magnet are like the head and tail of the same coin.

If you break a bar magnet in half, as shown in Figure 36.3, each half still behaves as a complete magnet. Break the pieces in half again, and you have four complete magnets. You can continue breaking the pieces in half and never isolate a single pole. Even when your piece is one atom thick, there are two poles. This suggests that atoms themselves are magnets.

CONCEPT CHECK How do magnetic poles affect each other?

36.2 Magnetic Fields

Place a sheet of paper over a bar magnet and sprinkle iron filings on the paper. The filings will tend to trace out an orderly pattern of lines that surround the magnet. The space around a magnet, in which a magnetic force is exerted, is filled with a **magnetic field.** The shape of the field is revealed by *magnetic field lines.* Magnetic field lines spread out from one pole, curve around the magnet, and return to the other pole, as shown in Figure 36.4.

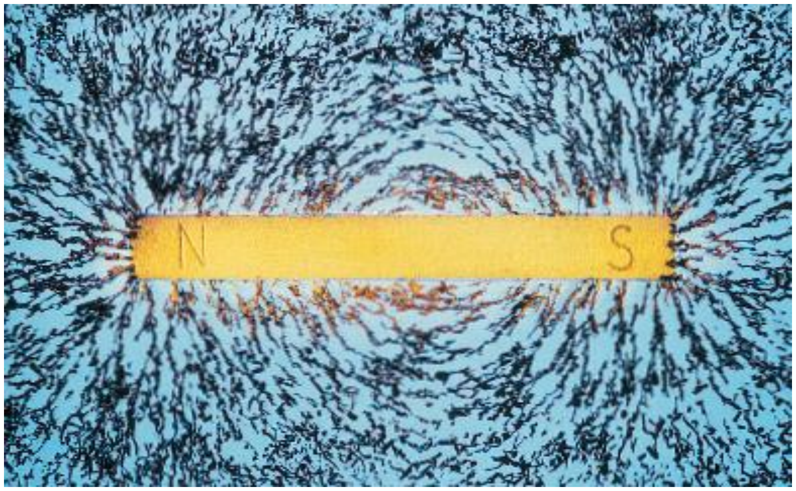


FIGURE 36.4
Iron filings trace out a pattern of magnetic field lines in the space surrounding the magnet.

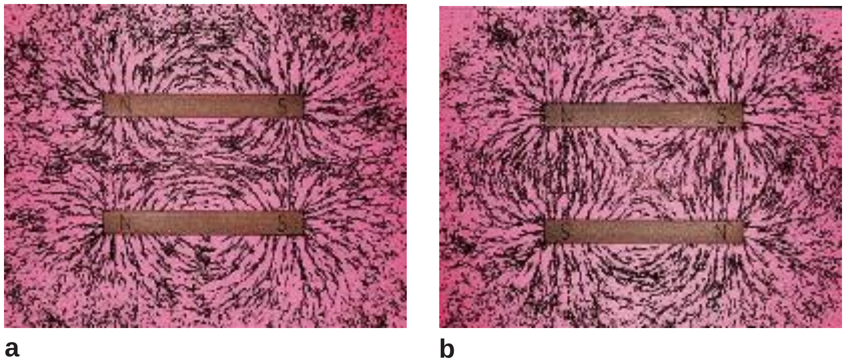


FIGURE 36.5
You observe different magnetic field patterns for a pair of magnets when **a.** like poles are near each other, and **b.** opposite poles are near each other.

The direction of the magnetic field outside a magnet is from the north to the south pole. Where the lines are closer together, the field strength is greater. We see that the magnetic field strength is greater at the poles. If we place another magnet or a small compass anywhere in the field, its poles will tend to line up with the magnetic field, as shown in Figure 36.6.

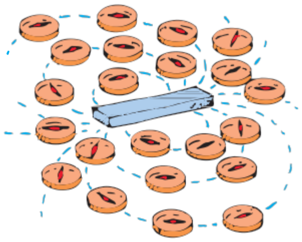


FIGURE 36.6
Like the iron filings, the compasses line up with the magnetic field lines.

CONCEPT CHECK What is the direction of the magnetic field outside a magnet?

36.3 The Nature of a Magnetic Field

Magnetism is very much related to electricity. Just as an electric charge is surrounded by an electric field, a moving electric charge is also surrounded by a magnetic field. This is due to the “distortions” in the electric field caused by motion, and was explained by Albert Einstein in 1905 in his theory of special relativity. This text will not go into the details, except to acknowledge that a magnetic field is a relativistic by-product of the electric field. Charges in motion have associated with them both an electric and a magnetic field. **A magnetic field is produced by the motion of electric charge.**[36.3.1]

Electrons in Motion Where is the motion of electric charges in a common bar magnet? Although the magnet as a whole may be stationary, it is composed of atoms whose electrons are in constant motion about atomic nuclei. This moving charge constitutes a tiny current and produces a magnetic field. More important, electrons can be thought of as spinning about their own axes like tops. A spinning electron constitutes a charge in motion and thus creates another magnetic field. In most materials, the field due to spinning predominates over the field due to orbital motion.

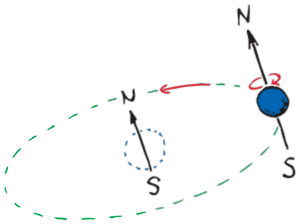


FIGURE 36.7
Both the orbital motion and the spinning motion of every electron in an atom produce magnetic fields.

Ask **How do the field lines of magnetic, electric, and gravitational fields differ?** *Magnetic field lines form closed loops, and conventionally circle from north to south poles outside a magnet, and from south to north poles inside the magnet. Electric field lines emanate from positive charges, and connect to negative charges. Gravitational field lines emanate only from mass.*

CONCEPT CHECK The direction of the magnetic field outside a magnet is from the north to the south pole.

Teaching Resources

- **Reading and Study Workbook**
- **Laboratory Manual** *97*
- **Transparency** *85*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *36-1*

36.3 The Nature of a Magnetic Field

CONCEPT CHECK A magnetic field is produced by the motion of electric charge.

Teaching Resources

- **Reading and Study Workbook**
- **Problem-Solving Exercises in Physics** *18-1*
- **Presentation*EXPRESS***
- **Interactive Textbook**

36.4 Magnetic Domains

Key Term
magnetic domain

Teaching Tip Compare Figures 32.12 and 32.13 (page 656)—where bits of paper were attracted to a charged object and charged balloons stuck to walls by electrostatic induction—with the similar case of the magnet and nails in Figure 36.9.

Spin Magnetism Every spinning electron is a tiny magnet. A pair of electrons spinning in the same direction makes up a stronger magnet. Electrons spinning in opposite directions, however, work against one another. Their magnetic fields cancel. This is why most substances are not magnets. In most atoms, the various fields cancel one another because the electrons spin in opposite directions. In materials such as iron, nickel, and cobalt, however, the fields do not cancel one another entirely. Each iron atom has four electrons whose spin magnetism is uncanceled. Each iron atom, then, is a tiny magnet. The same is true to a lesser degree for the atoms of nickel and cobalt.[36.3.2]

CONCEPT CHECK How is a magnetic field produced?

36.4 Magnetic Domains

The magnetic fields of individual iron atoms are so strong that interactions among adjacent iron atoms cause large clusters of them to line up with one another. These clusters of aligned atoms are called **magnetic domains.** Each domain is perfectly magnetized, and is made up of billions of aligned atoms. The domains are microscopic, and there are many of them in a crystal of iron.

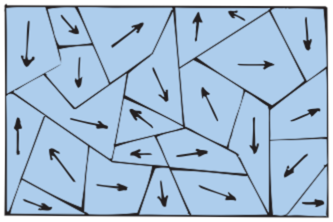


FIGURE 36.8
A crystal of iron contains microscopic clusters of aligned atoms called magnetic domains. Each domain consists of billions of aligned iron atoms.

The difference between a piece of ordinary iron and an iron magnet is the alignment of domains. In a common iron nail, the domains are randomly oriented. When a strong magnet is brought nearby, as shown in Figure 36.9, two effects take place. One is a growth in size of domains that are oriented in the direction of the magnetic field. This growth is at the expense of domains that are not aligned. The other effect is a rotation of domains as they are brought into alignment. The domains become aligned much as electric dipoles are aligned in the presence of a charged rod. When you remove the nail from the magnet, ordinary thermal motion causes most or all of the domains in the nail to return to a random arrangement.

think!

The iron filings sprinkled on the paper that covers the magnet in Figure 36.4 were not initially magnetized. Why, then, do they line up with the magnetic field of the magnet?
Answer: 36.4

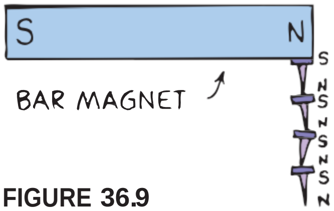


FIGURE 36.9
The iron nails become induced magnets.

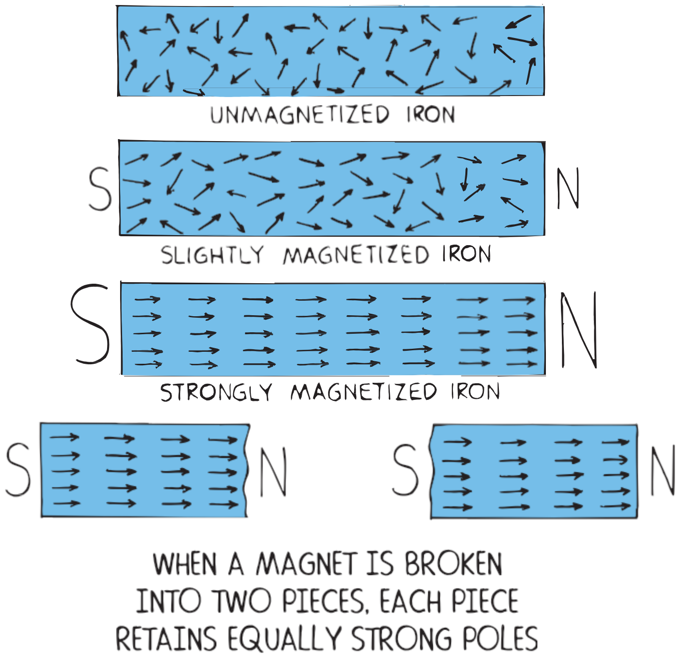


FIGURE 36.10
The illustrations show a piece of iron in successive stages of magne- tism. The arrows represent domains, where the head is a north pole and the tail a south pole. Poles of neighboring domains neutralize one another's effects, except at the ends.

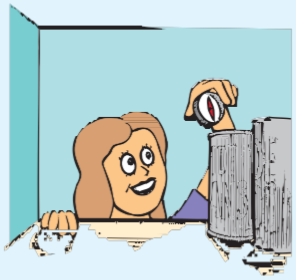
Permanent magnets are made by simply placing pieces of iron or certain iron alloys in strong magnetic fields. Alloys of iron differ; soft iron is easier to magnetize than steel. It helps to tap the iron to nudge any stubborn domains into alignment. Another way of making a permanent magnet is to stroke a piece of iron with a magnet. The stroking motion aligns the domains in the iron. If a permanent magnet is dropped or heated, some of the domains are jostled out of alignment and the magnet becomes weaker.

CONCEPT CHECK How can you make a permanent magnet?

A magstripe on a credit card contains millions of tiny magnetic domains held together by a resin binder. Data are encoded in binary, with zeros and ones distinguished by the frequency of domain reversals.

discover!

Uncanny Magnetism?



1. Hold a magnetic compass vertically, just above the tops of some iron or steel objects in your classroom or home.
2. See if the north pole of the compass points to the tops of the objects, and the south pole points to the bottoms. If so, the objects have become magnetized by Earth's magnetic field.
3. Place the compass alongside a can of stored food in your pantry. See if the can is magnetized.
4. Turn the can over and see how many days it takes for it to lose its magnetism and then reverse its polarity.
5. **Think** Why does the can gradually lose its magnetism after you turn it over?

CONCEPT CHECK Permanent magnets are made by simply placing pieces of iron or certain iron alloys in strong magnetic fields.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

discover!

MATERIALS magnetic compass, iron or steel objects, food cans

EXPECTED OUTCOME Over time, iron and steel objects become magnetized by Earth's magnetic field. Magnetized objects will cause a magnetic compass needle to point toward the tops of the objects.

36.5 Electric Currents and Magnetic Fields

Key Term
electromagnet

Teaching Tip Discuss the source of magnetism—the motion of charges. Magnetism starts with a moving electric charge—in the spin of the electron about its own axis, its revolution about the nuclear axis, and its drift as part of an electric current.

It should be enough to simply acknowledge that the magnetic field is a relativistic "side effect" or "distortion" in the electric field of a moving charge. Unless you've already done special relativity in great detail, the relativistic explanation may be too involved to be effective.

PAUL

Demonstration

Do as Oersted did and hold a wire above a compass while you touch the ends of the wire to a battery (or equivalent), so the class can see the compass deflect when current flows.

Teaching Tip An interesting point to note is when the magnetic field around a current-carrying conductor is undesirable, double wires are used, with the return wire right next to the outgoing wire. The net current for the double wire is then zero and no magnetic field surrounds it. Wires are often braided to combat slight magnetic fields where the cancellation nearby is not perfect.

36.5 Electric Currents and Magnetic Fields

A moving charge produces a magnetic field. You also observe a magnetic field when many charges are in motion—that is, when a current flows through a conductor. **An electric current produces a magnetic field.** The magnetic field that surrounds a current-carrying conductor can be demonstrated by arranging an assortment of magnetic compasses around a wire and passing a current through it, as shown in Figure 36.11. The compasses line up with the magnetic field produced by the current and show it to be a pattern of concentric circles about the wire. When the current reverses direction, the compasses turn completely around, showing that the direction of the magnetic field changes also. This is the effect that Oersted first demonstrated.

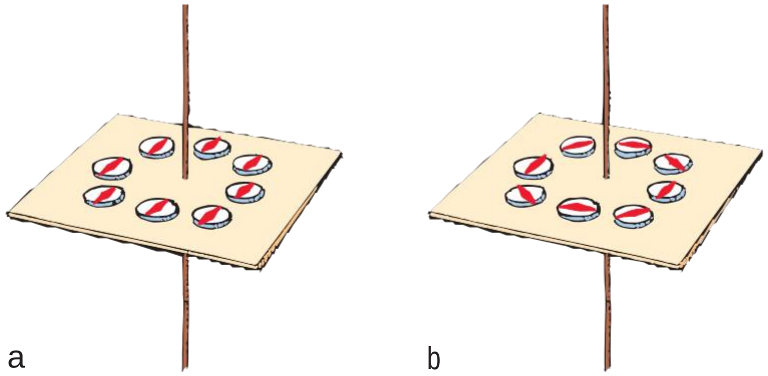


FIGURE 36.11
a. When there is no current in the wire, the compasses align with Earth's magnetic field. **b.** When there is a current in the wire, the compasses align with the stronger magnetic field near the wire.

If the wire is bent into a loop, the magnetic field lines become bunched up inside the loop, as shown in Figure 36.12. If the wire is bent into another loop, overlapping the first, the concentration of magnetic field lines inside the double loop is twice as much as in the single loop. It follows that the magnetic field intensity in this region is increased as the number of loops is increased. A current-carrying coil of wire with many loops is an **electromagnet.**

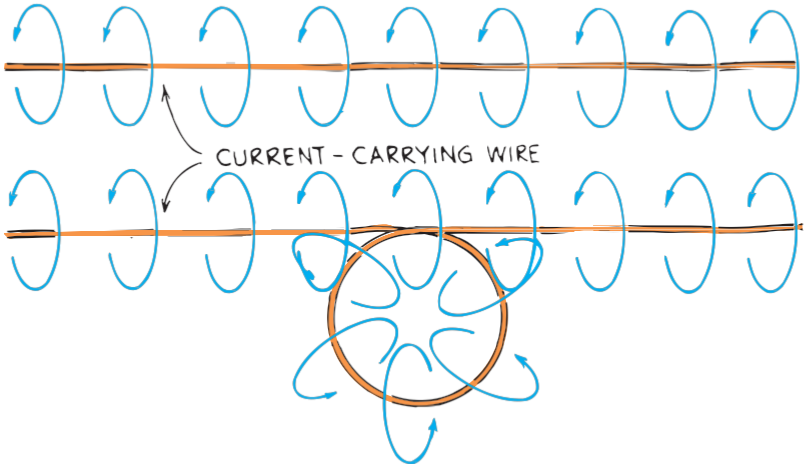


FIGURE 36.12
Magnetic field lines about a current-carrying wire crowd up when the wire is bent into a loop.

FIGURE 36.13
Iron filings sprinkled on paper reveal the magnetic field configurations about **a.** a current-carrying wire, **b.** a current-carrying loop, and **c.** a coil of loops.

Sometimes a piece of iron is placed inside the coil of an electromagnet. The magnetic domains in the iron are induced into alignment, increasing the magnetic field intensity. Beyond a certain limit, the magnetic field in iron "saturates," so iron is not used in the cores of the strongest electromagnets, which are made of superconducting material (see Section 34.4).

A superconducting electromagnet can generate a powerful magnetic field indefinitely without using any power. At Fermilab near Chicago, superconducting electromagnets guide high-energy particles around the four-mile-circumference accelerator. Since the substitution of superconducting electromagnets for conventional ones in 1983, monthly electric bills have been far less, even though the particles are accelerated to greater energies. Superconducting magnets can also be found in magnetic resonance imaging (MRI) devices in hospitals. They also hold much promise for high-speed transportation.

CONCEPT CHECK Why does a current-carrying wire deflect a magnetic compass?

Science, Technology, and Society

Maglev Transportation

An exciting application of superconducting electromagnets is magnetically levitated, or "maglev," transportation. Shown here is a maglev train that shuttles passengers to and from Shanghai International Airport at speeds up to 460 km/h. It covers some 30 kilometers in less than eight minutes. The train carries superconducting coils on its underside. Moving along the aluminum track, called a guideway, the coils generate currents in the aluminum that act as mirror-image magnets and repel the train. It floats about 10 millimeters above the guideway, and its speed is limited only by air friction and passenger comfort. Watch for the proliferation of this relatively new technology.

Critical Thinking What advantages do magnetically levitated trains have over conventional trains?

Teaching Tip Draw attention to the different ways the field lines about vertical wires are shown in Figures 36.11 and 36.13a.

Teaching Tip Explain the bunching up of magnetic field lines in a loop (Figure 36.12), and then multiple loops (Figure 36.13c). Now you have an electromagnet.

Demonstration

Make a simple electromagnet in front of your class by winding wire around a nail and picking up paper clips. Relate this to the junkyard magnet shown in Figure 36.1.

Teaching Tip Describe magnetic induction, and show how bringing an unmagnetized nail near a magnet induces it to become a magnet and be attracted. Then contrast this with a piece of aluminum. Discuss unpaired electron spins and magnetic domains.

CONCEPT CHECK An electric current produces a magnetic field.

Teaching Resources

- **Reading and Study Workbook**
- **Transparency** *86*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *36-3*

Science, Technology, and Society

CRITICAL THINKING Answers should include factors such as speed, comfort, and cost.

36.6 Magnetic Forces on Moving Charged Particles

Common Misconception
The magnetic force on charged particles, like the electric force on charged particles, is in the direction of the magnetic field.

FACT The magnetic force on charged particles is at right angles to both the field and the direction of motion of the charge.

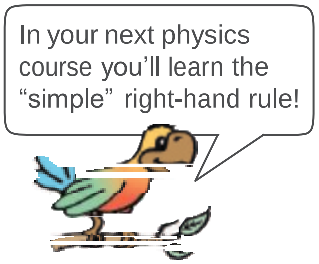
Demonstration

To show how a magnet deflects an electron beam, bring a magnet in front of a picture tube of an old black-and-white TV. (Don't do this with a color TV unless it is expendable, for you could magnetize the shields that prevent certain electrons from striking particular phosphors.) Stress the role of motion.

Teaching Tip Briefly discuss cyclotrons and bevatrons. Note that since the magnetic force on moving charges is always perpendicular to their direction of motion, there is never a component of force in the direction of motion. This means a magnetic field cannot do work on a moving charge. A magnetic field can only change the direction of the charge. So in cyclotrons and bevatrons, electric fields accelerate the charges and increase their kinetic energies; magnetic fields simply guide their paths.

CONCEPT CHECK A moving charge is deflected when it crosses magnetic field lines but not when it travels parallel to the field lines.

36.6 Magnetic Forces on Moving Charged Particles



A charged particle at rest will not interact with a static magnetic field. But if the charged particle *moves* in a magnetic field, the charged particle experiences a deflecting force.[36.6] This force is greatest when the particle moves in a direction perpendicular to the magnetic field lines. At other angles, the force is less; it becomes zero when the particle moves parallel to the field lines. In any case, the direction of the force is always perpendicular to both the magnetic field lines and the velocity of the charged particle, as shown in Figure 36.14. ✓ **A moving charge is deflected when it crosses magnetic field lines but not when it travels parallel to the field lines.**

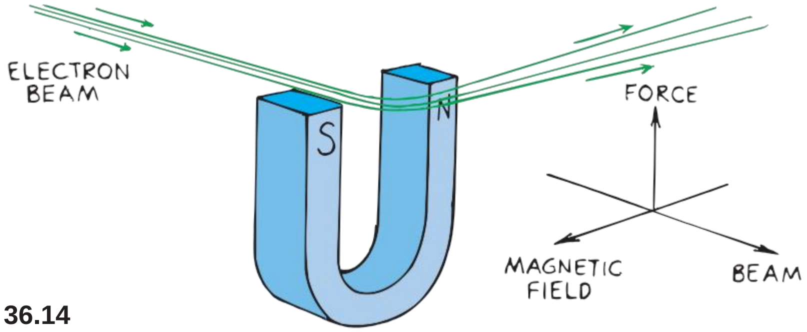


FIGURE 36.14
A beam of electrons is deflected by a magnetic field.

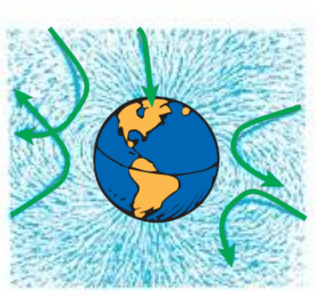


FIGURE 36.15
The magnetic field of Earth deflects many charged particles that make up cosmic radiation.

This sideways deflecting force is very different from the forces that occur in other interactions, such as the force of gravitation between masses, the electrostatic force between charges, and the force between magnetic poles. The force that acts on a moving charged particle does not act in a direction between the sources of interaction, but instead acts perpendicular to both the magnetic field and the electron velocity.

It's nice that charged particles are deflected by magnetic fields, for this fact was employed in early TV tubes to steer electrons onto the inner surface of the screens and provide a picture. This effect of magnetic fields also works on a larger scale. As shown in Figure 36.15, charged particles from outer space are deflected by Earth's magnetic field, which reduces the intensity of cosmic radiation. A much greater reduction in intensity results from the absorption of cosmic rays in the atmosphere.

CONCEPT CHECK What happens when a charged particle moves in a magnetic field?

36.7 Magnetic Forces on Current-Carrying Wires

✓ **Since a charged particle moving through a magnetic field experiences a deflecting force, a current of charged particles moving through a magnetic field also experiences a deflecting force.** If the particles are trapped inside a wire when they respond to the deflecting force, the wire will also move as shown in Figure 36.16.

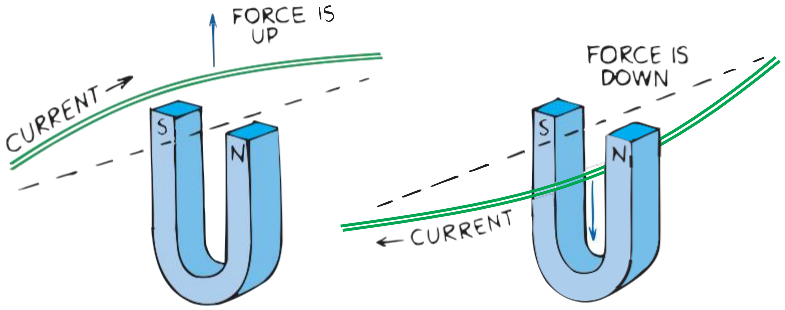


FIGURE 36.16
A current-carrying wire experiences a force in a magnetic field.

If the direction of current in the wire is reversed, the deflecting force acts in the opposite direction. The force is maximum when the current is perpendicular to the magnetic field lines. The direction of force is along neither the magnetic field lines nor the direction of current. The force is perpendicular to both field lines and current, and it is a sideways force.

There is a symmetry here—just as a current-carrying wire will deflect a magnetic compass, a magnet will deflect a current-carrying wire. Both cases show different effects of the same phenomenon. The discovery that a magnet exerts a force on a current-carrying wire created much excitement, for almost immediately people began harnessing this force for useful purposes—with great sensitivity in electric meters, and with great force in electric motors.

think!

What law of physics tells you that if a current-carrying wire produces a force on a magnet, a magnet must produce a force on a current-carrying wire?
Answer: 36.7

CONCEPT CHECK How is current affected by a magnetic field?

Link to TECHNOLOGY

Sound Reproduction The loudspeakers of sound-producing systems change electric signals into sound waves. Electric currents pass through a coil wound around the neck of a paper cone. This coil acts as an electromagnet, which is located near a permanent magnet. When current flows one way, magnetic force pushes the electromagnet toward the permanent magnet, pulling the cone inward. When current flows the other way, the cone is pushed outward. Vibrations in the electric signal then cause the cone to vibrate. Vibrations of the cone produce sound waves in the air.

36.7 Magnetic Forces on Current-Carrying Wire

It is a simple step from the deflection of charges to the deflection of wires that enclose these deflected charges.

Demonstration

Show how a wire jumps out of (or into) a magnet when current is passed through it (Figure 36.16). Reverse the current (or turn the wire around) to show both cases.

CONCEPT CHECK Since a charged particle moving through a magnetic field experiences a deflecting force, a current of charged particles moving through a magnetic field also experiences a deflecting force.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *36-1*
- **Laboratory Manual** *98*
- **Presentation*EXPRESS***
- **Interactive Textbook**

36.8 Meters to Motors

Demonstration

Put a compass near a current-carrying coil and show how the compass needle rotates as you vary the current.

With your largest meter (galvanometer, ammeter, or voltmeter in which the coil that rotates in the magnetic field is visible), point out to your class the coil of wire that is suspended in the magnetic field of the permanent magnet (Figure 36.18).

36.8 Meters to Motors

The simplest meter to detect electric current is shown in Figure 36.17. It consists of a magnetic needle on a pivot at the center of a number of loops of insulated wire. When an electric current passes through the coil, each loop produces its own effect on the needle so that a very small current can be detected. A sensitive current-indicating instrument is called a *galvanometer.*$^{36.8}$

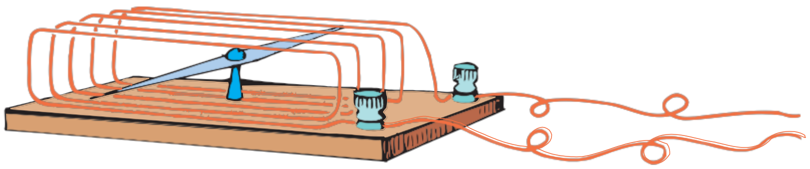


FIGURE 36.17
You can make a very simple galvanometer with a magnetic needle and insulated wire.

Common Galvanometers A more common design is shown in Figure 36.18a. It employs more loops of wire and is therefore more sensitive. The coil is mounted for movement and the magnet is held stationary. The coil turns against a spring, so the greater the current in its loops, the greater its deflection.

A galvanometer may be calibrated to measure current (amperes), in which case it is called an *ammeter*. Or it may be calibrated to measure electric potential (volts), in which case it is called a *voltmeter.*

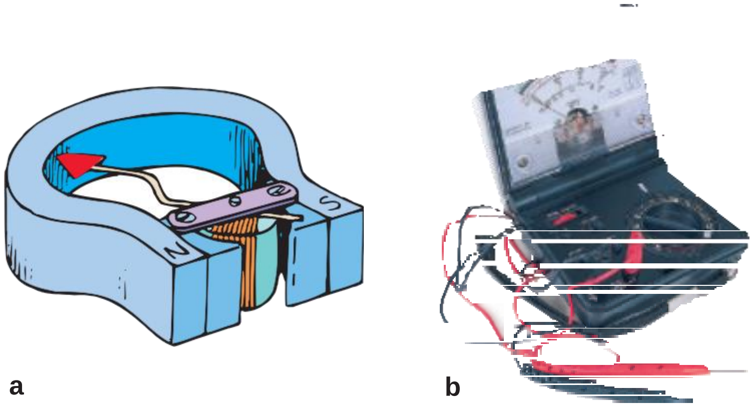


FIGURE 36.18
a. A common galvanometer consists of a stationary magnet and a movable coil of wire. **b.** A multimeter can function as both an ammeter and a voltmeter. (The resistance of the instrument is made to be very low for the ammeter, and very high for the voltmeter.)

Electric Motors If the design of the galvanometer is slightly modified, you have an electric motor. ✓ **The principal difference between a galvanometer and an electric motor is that in an electric motor, the current is made to change direction every time the coil makes a half revolution.** After it has been forced to rotate one half revolution, it overshoots just in time for the current to reverse, whereupon the coil is forced to continue another half revolution, and so on in cyclic fashion to produce continuous rotation.

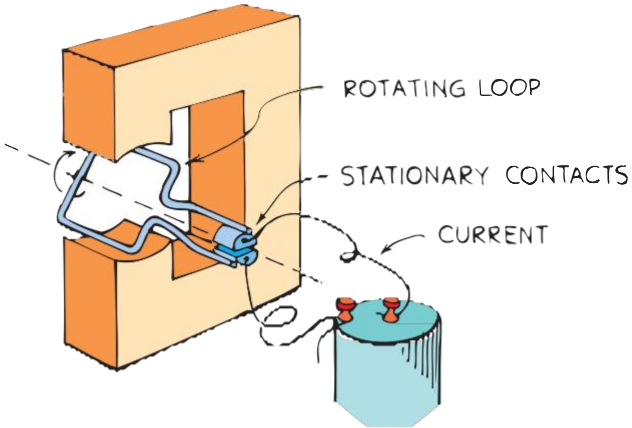


FIGURE 36.19
A simplified DC motor can be constructed from a magnet, a rotating loop of wire, and a voltage source.

A simple DC motor is shown in bare outline in Figure 36.19. A permanent magnet is used to produce a magnetic field in a region where a rectangular loop of wire is mounted so that it can turn about an axis as shown. When a current passes through the loop, it flows in opposite directions in the upper and lower sides of the loop. (It has to do this because if charge flows into one end of the loop, it must flow out the other end.) If the upper portion of the loop is forced to the left, then the lower portion is forced to the right, as if it were a galvanometer. But unlike a galvanometer, the current is reversed during each half revolution by means of stationary contacts on the shaft. The parts of the wire that brush against these contacts are called *brushes*. In this way, the current in the loop alternates so that the forces in the upper and lower regions do not change directions as the loop rotates. The rotation is continuous as long as current is supplied.

Larger motors, DC or AC, are usually made by replacing the permanent magnet with an electromagnet that is energized by the power source. Of course, more than a single loop is used. Many loops of wire are wound about an iron cylinder, called an *armature*, which then rotates when energized with electric current.

The advent of the motor made it possible to replace enormous human and animal toil by electric power in most parts of the world. Electric motors have greatly changed the way people live.

CONCEPT CHECK What is the main difference between a galvanometer and an electric motor?

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think!

How is a galvanometer similar to a simple electric motor? How do they fundamentally differ?
Answer: 36.8

A motor and a generator are the same device, with inout or output reversed. The electrical device in a hybrid car operates both ways.

Teaching Tip Tell students that the galvanometer is named after Luigi Galvani (1737–1798), who, while dissecting a frog's leg, discovered that electric charge caused the leg to twitch. This chance discovery led to the invention of the chemical cell and the battery. The next time you pick up a galvanized pail, think of Luigi Galvani in his anatomy laboratory.

Teaching Tip Extend the meter explanation to the electric motor. If possible, show the operation of a DC demonstration motor.

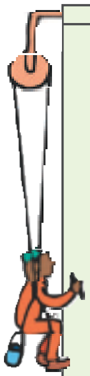
CONCEPT CHECK The principal difference between a galvanometer and an electric motor is that, in an electric motor, the current is made to change direction every time the coil makes a half revolution.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

36.9 Earth's Magnetic Field

Teaching Tip Tell students that Earth's magnetic field holds the Van Allen Radiation Belts around Earth. These rings are composed of charged particles trapped in Earth's magnetic field, 3000 to 15,000 km above Earth's surface. The belts consist of protons and electrons in the outer part, and principally electrons in the inner part. They used to consist of two donut-shaped rings, but have been combined by high-altitude nuclear explosions detonated in 1962. A third radiation belt was discovered in 1993 within the inner belt of protons. This new belt is a torus of anomalous cosmic ray particles that originate outside the solar system. At the magnetic poles, ions dip into the atmosphere and cause it to glow like a fluorescent lamp. This is the beautiful aurora borealis (northern lights).



Physics on the Job

Oceanographer

Earth scientists who study the oceans and seas are called oceanographers. Using submersibles that resemble spacecraft, oceanographers study the composition and characteristics of the ocean floor. Some oceanographers use sensitive instruments to identify and measure the magnetic fields found in deep ocean rocks. By studying these magnetic patterns, they have learned that the Atlantic Ocean gets a little bit wider each year. Job opportunities exist for oceanographers in academic, private, and government research laboratories.

36.9 Earth's Magnetic Field

A compass points northward because Earth itself is a huge magnet. The compass aligns with the magnetic field of Earth. The magnetic poles of Earth, however, do not coincide with the geographic poles—in fact, they aren't even close to the geographic poles. Figure 36.20 illustrates the discrepancy. The magnetic pole in the Northern Hemisphere, for example, is located some 800 kilometers from the geographic North Pole, northwest of Sverdrup Island in northern Canada. The other magnetic pole is located just off the coast of Antarctica. This means that compasses do not generally point to true north. The discrepancy between the orientation of a compass and true north is known as the *magnetic declination.*

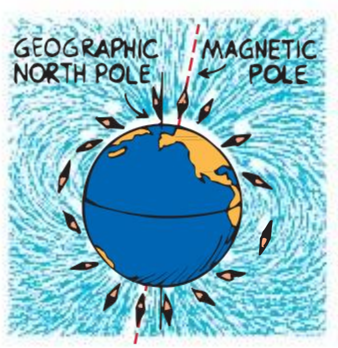


FIGURE 36.20
Earth is a giant magnet.

Moving Changes Within Earth It is not known exactly why Earth itself is a magnet. The configuration of Earth's magnetic field is like that of a strong bar magnet placed near the center of Earth. But Earth is not a magnetized chunk of iron like a bar magnet. It is simply too hot for individual atoms to remain aligned.

Currents in the molten core of Earth provide a better explanation for Earth's magnetic field. Most geologists think that moving charges looping around within Earth create its magnetic field. Because of Earth's great size, the speed of moving charges would have to be less than one millimeter per second to account for the field.

The convection currents in Earth's molten interior, shown in Figure 36.21, are driven by rising heat from radioactive decay within Earth's core. Perhaps such convection currents combined with the rotational effects of Earth produce Earth's magnetic field. A firmer explanation awaits more study.

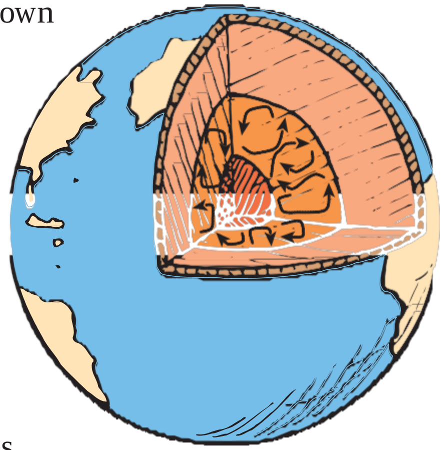


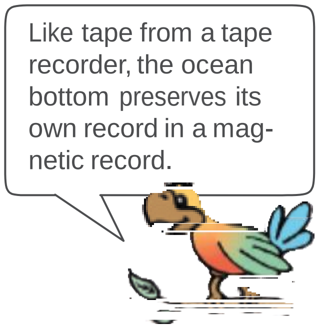
FIGURE 36.21 Convection currents in the molten parts of Earth's interior may produce Earth's magnetic field.

Magnetic Field Reversals Whatever the cause, the magnetic field of Earth is not stable; it has flip-flopped throughout geologic time. Evidence of this comes from analysis of the magnetic properties of rock strata. Iron atoms in a molten state tend to align themselves with Earth's magnetic field. When the iron solidifies, the direction of Earth's field is recorded by the orientation of the domains in the rock. The slight magnetism that results can be measured with sensitive instruments. The evidence from the rock shows that there have been times when the magnetic field of Earth has diminished to zero and then reversed itself.

This reversal of magnetic poles is clearly evident in the seafloor of the middle of the Atlantic Ocean. On the ocean floor at mid-ocean ridges, continuous eruption of lava produces new seafloor. This new rock is magnetized according to the existing magnetic field. Older seafloor is pushed away from the ridge as newer seafloor forms. Magnetic surveys of the ocean floor reveal a zebra-striped pattern centered along, and symmetrical to, the mid-ocean ridge. Because each stripe indicates magnetic direction, the alternating stripes show the change from periods of normal polarity to periods of reversed polarity.

More than twenty reversals have taken place in the past 5 million years. The most recent occurred 780,000 years ago. Prior reversals happened 870,000 and 950,000 years ago. Studies of deep-sea sediments indicate that the field was virtually switched off for 10,000 to 20,000 years just over 1 million years ago.

We cannot predict when the next reversal will occur because the reversal sequence is not regular. But there is a clue in recent measurements that show a decrease of over 5% of Earth's magnetic field strength in the last 100 years. If this change is maintained, we may well have another magnetic field reversal within 2000 years.



CONCEPT CHECK Why does a magnetic compass point northward?

Teaching Tip Explain that the magnetic field of Earth protects us from much cosmic radiation. Cosmic ray bombardment is maximum at the poles, because incoming particles do not cross Earth's field (they would be deflected), but follow the field lines and are not deflected. At sea level at the equator, incidence of cosmic rays averages from one to three particles per square centimeter each minute; this number increases rapidly with altitude. This is a primary reason for the relatively short working hours of flight personnel in high-flying aircraft. Two cross-country round trips expose them to a radiation dosage equivalent to a chest X-ray (more about this in Chapter 39).

Teaching Tidbit Until recently, cosmic rays were thought to come in all directions from outer space. Recent evidence is that most come from nearby galaxies. Exploration of the cosmos is an ongoing activity.

CONCEPT CHECK A compass points northward because Earth itself is a huge magnet.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

REVIEW

36 REVIEW

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Concept Summary

- Like poles repel; opposite poles attract.
- The direction of the magnetic field outside a magnet is from the north to the south pole.
- A magnetic field is produced by the motion of electric charge.
- Permanent magnets are made by simply placing pieces of iron or certain iron alloys in strong magnetic fields.
- An electric current produces a magnetic field.
- A moving charge is deflected when it crosses magnetic field lines but not when it travels parallel to the field lines.
- Since a charged particle moving through a magnetic field experiences a deflecting force, a current of charged particles moving through a magnetic field also experiences a deflecting force.
- The principal difference between a galvanometer and an electric motor is that in an electric motor, the current is made to change direction every time the coil makes a half revolution.
- A compass points northward because Earth itself is a huge magnet.

Key Terms

think! Answers

36.1 Yes, just as every coin has two sides, a “head” and a “tail.” (Some “trick” magnets have more than two poles.)

36.4 Domains align in the individual filings, causing them to act like tiny compasses. The poles of each “compass” are pulled in opposite directions, producing a torque that twists each filing into alignment with the external magnetic field.

36.7 Newton’s third law, which applies to all forces in nature.

36.8 A galvanometer and a motor are similar in that they both employ coils positioned in magnetic fields. When current passes through the coils, forces on the wires rotate the coils. The fundamental difference is that the maximum rotation of the coil in a galvanometer is one half turn, whereas in a motor the coil (armature) rotates through many complete turns. In the armature of a motor, the current is made to change direction with each half turn of the armature.