

# 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!

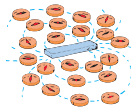
**MATERIALS** bar magnets, iron filings, sheet of glass or plastic

**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.

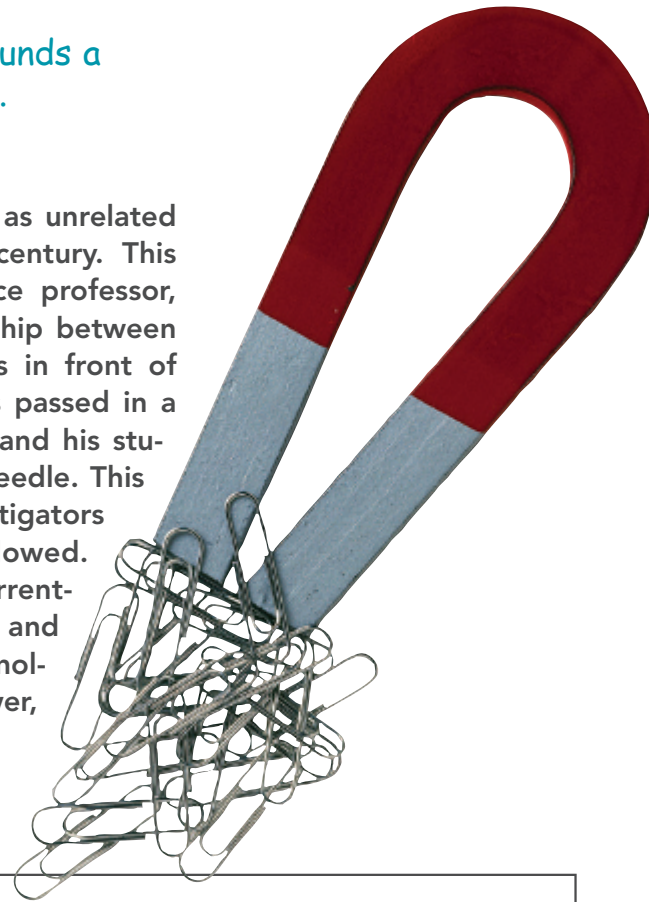
# 36 MAGNETISM



## 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.<sup>36.0</sup> 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?

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.

PAUL

## 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!

PAUL

► **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.

## 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.<sup>36.1</sup> ✓ **Like poles repel; opposite poles attract.**

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*



◀ **FIGURE 36.2**

Common magnets come in a variety of shapes.

**CONCEPT** : Like poles repel;  
**CHECK** : opposite poles attract.

### Teaching Resources

- Reading and Study Workbook
- PresentationEXPRESS
- Interactive Textbook
- Next-Time Question 36-2

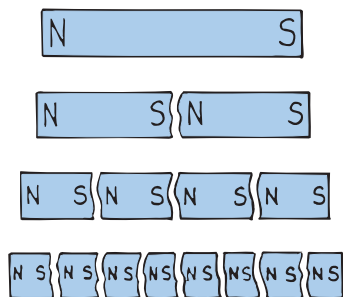
## 36.2 Magnetic Fields

### 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.

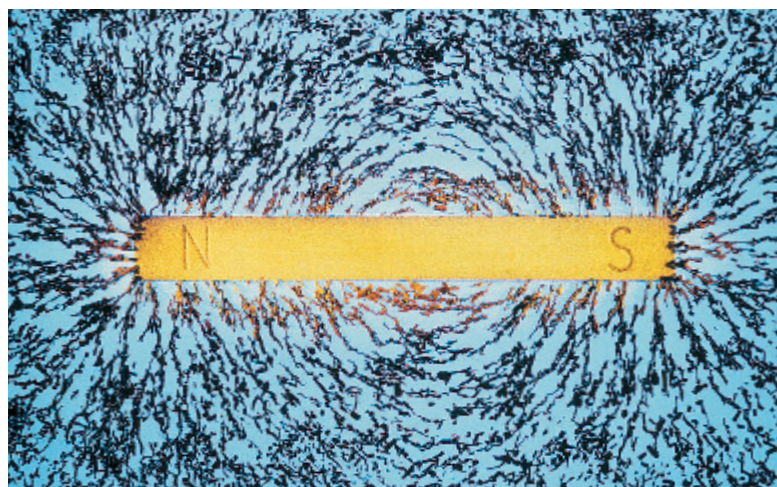
Magnetic poles behave similarly to electric charges in some ways, but there is a very important difference. Electric charges can be isolated, but magnetic poles cannot. Negatively charged electrons and positively charged protons are entities by themselves. A cluster of electrons need not be accompanied 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** : How do magnetic poles affect each other?  
**CHECK** :

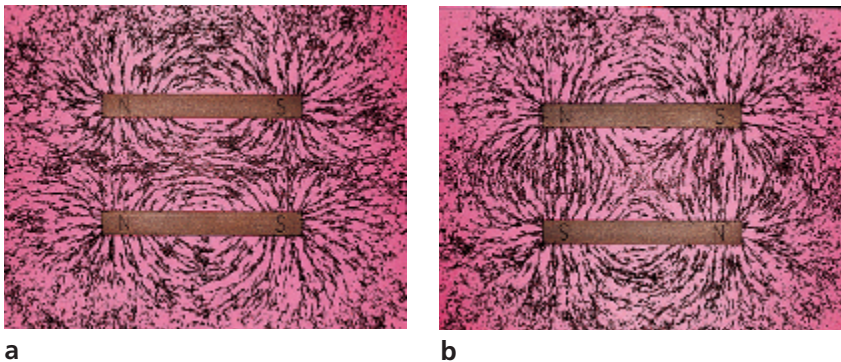
## 36.2 Magnetic Fields

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.

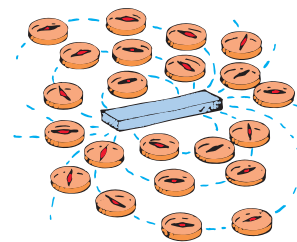
✓ **The direction of the magnetic field outside a magnet is from the north to the south pole.** Where the lines are closer together, the field strength is greater. We see that the magnetic field strength is greater at the poles. If we place another magnet or a small compass anywhere in the field, its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

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

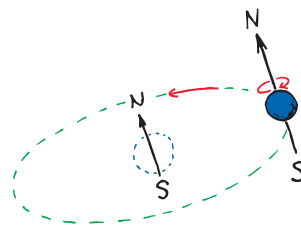
### 36.3 The Nature of a Magnetic Field

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.**<sup>36.3.1</sup>

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



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

#### Teaching Resources

- Reading and Study Workbook
- Laboratory Manual 97
- Transparency 85
- PresentationEXPRESS
- 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

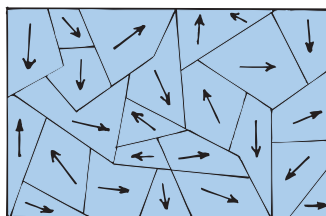
- Reading and Study Workbook
- Problem-Solving Exercises in Physics 18-1
- Presentation *EXPRESS*
- Interactive Textbook

## 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.



**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.

### 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

**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.<sup>36.3.2</sup>

**CONCEPT CHECK:** How is a magnetic field produced?

## 36.4 Magnetic Domains

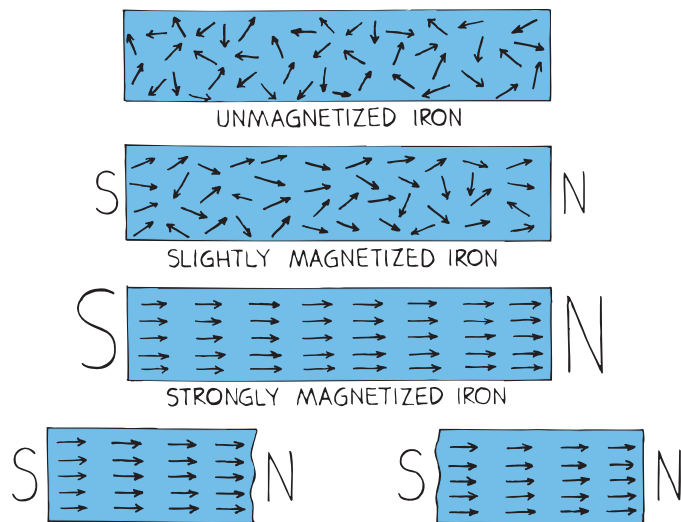
The magnetic fields of individual iron atoms are so strong that interactions among adjacent iron atoms cause large clusters of them to line up with one another. These clusters of aligned atoms are called **magnetic domains**. Each domain is perfectly magnetized, and is made up of billions of aligned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

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.



**FIGURE 36.9** ▲ The iron nails become induced magnets.





WHEN A MAGNET IS BROKEN  
INTO TWO PIECES, EACH PIECE  
RETAINS EQUALLY STRONG POLES

◀ **FIGURE 36.10**

The illustrations show a piece of iron in successive stages of magnetism. 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.

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

✔ **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?

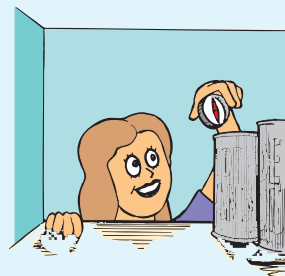
A magstripe on a credit card contains millions of tiny magnetic domains held together by a resin binder. Data are encoded in binary, with zeros and ones distinguished by the frequency of domain reversals.



## 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?



### Teaching Resources

- Reading and Study Workbook
- PresentationEXPRESS
- 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.

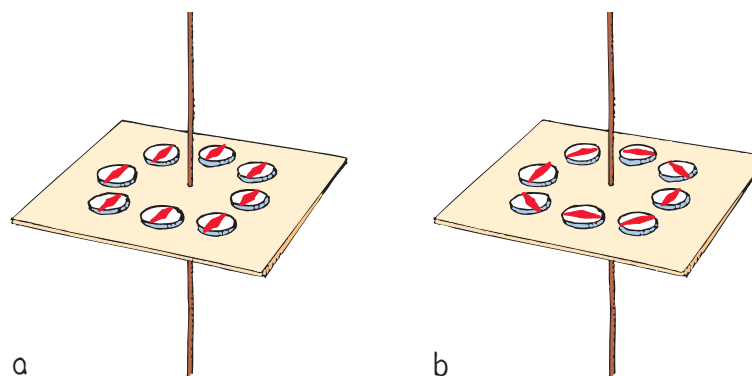
► **Teaching Tip** An interesting point to note is when the magnetic field around a current-carrying conductor is undesirable, double wires are used, with the return wire right next to the outgoing wire. The net current for the double wire is then zero and no magnetic field surrounds it. Wires are often 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 ►

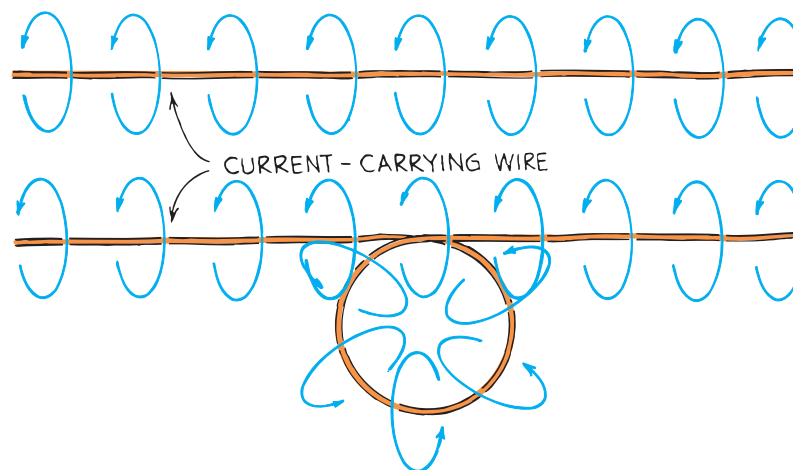
**a.** When there is no current in the wire, the compasses align with Earth’s magnetic field. **b.** When there is a current in the wire, the compasses align with the stronger magnetic field near the wire.

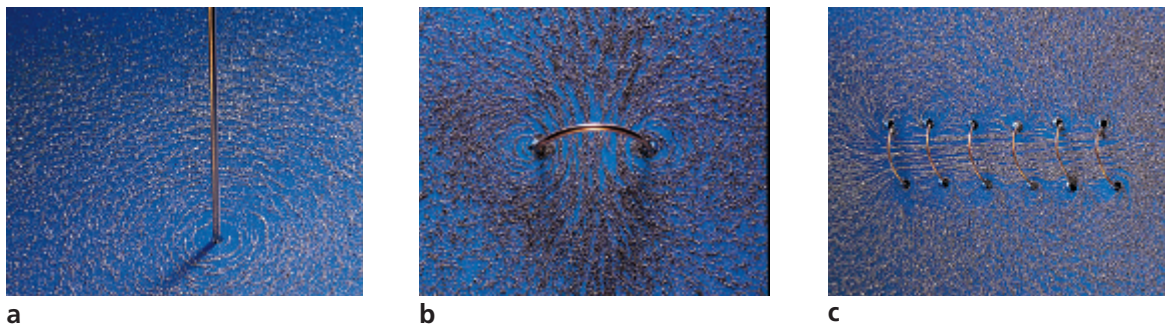


If the wire is bent into a loop, the magnetic field lines become bunched up inside the loop, as shown in Figure 36.12. If the wire is bent into another loop, overlapping the first, the concentration of magnetic field lines inside the double loop is twice as much as in the single loop. It follows that 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:** Why does a current-carrying wire deflect a **CHECK:** 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:** An electric current **CHECK:** 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.

In your next physics course you'll learn the "simple" right-hand rule!



## 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.<sup>36.6</sup> 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.**

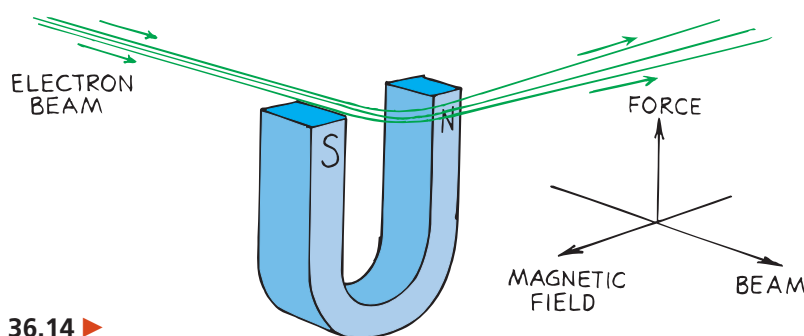


FIGURE 36.14 ►

A beam of electrons is deflected by a magnetic field.

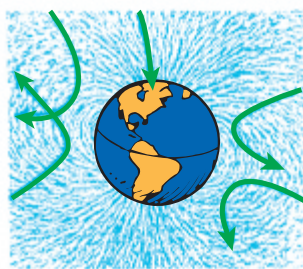


FIGURE 36.15 ▲

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

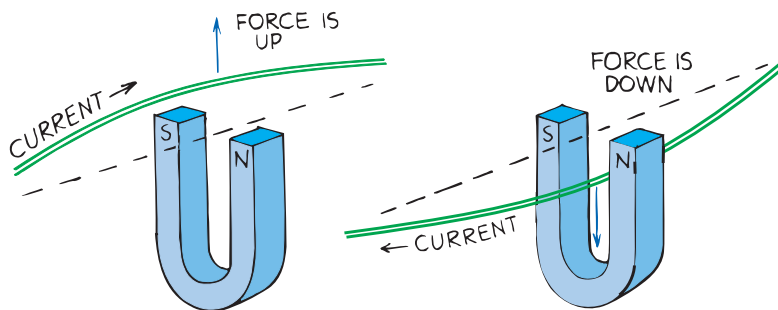
This sideways deflecting force is very different from the forces that occur in other interactions, such as the force of gravitation between masses, the electrostatic force between charges, and the force between magnetic poles. The force that acts on a moving charged particle does not act in a direction 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.

**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.

PAUL

### 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.

### 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:** 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
- PresentationEXPRESS
- 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.

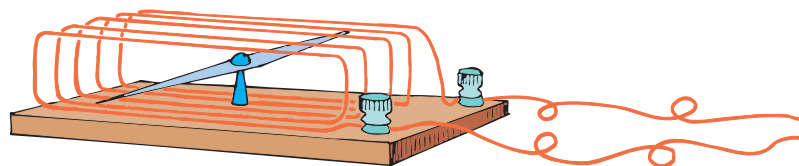
With your largest meter (galvanometer, ammeter, or voltmeter in which the coil that rotates in the magnetic field is visible), point out to your class the coil of wire that is suspended in the magnetic field of the permanent magnet (Figure 36.18).

## 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*.<sup>36.8</sup>

FIGURE 36.17 ►

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

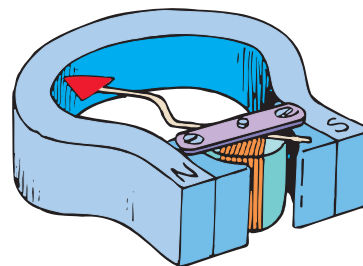


**Common Galvanometers** A more common design is shown in Figure 36.18a. It employs more loops of wire and is therefore more sensitive. The coil is mounted for movement and the magnet is held stationary. The coil turns against a spring, so the greater the current in its loops, the greater its deflection.

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.)

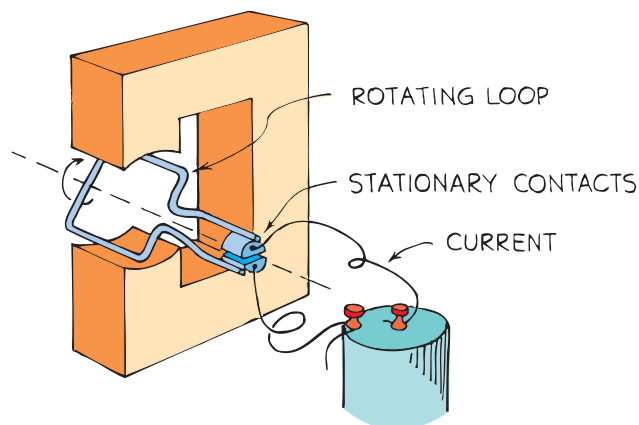


a



b

**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?



For: Links on electric motors

Visit: [www.SciLinks.org](http://www.SciLinks.org)

Web Code: csn - 3608

## 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 in/out 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.

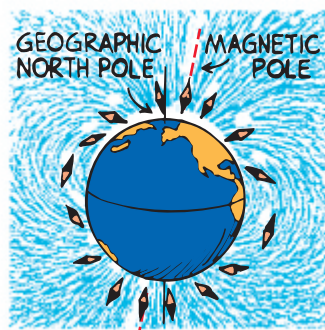
## Teaching Resources

- Reading and Study Workbook
- PresentationEXPRESS
- 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).



**FIGURE 36.20** ▲ Earth is a giant magnet.

### 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*.

**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.

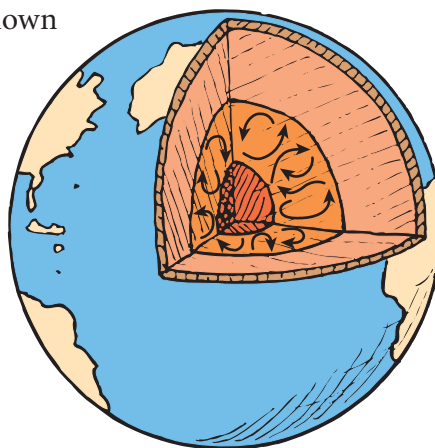
**Magnetic Field Reversals** Whatever the cause, the magnetic field of Earth is not stable; it has flip-flopped throughout geologic time. Evidence of this comes from analysis of the magnetic properties of rock strata. Iron atoms in a molten state tend to align themselves with Earth's magnetic field. 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?



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

Like tape from a tape recorder, the ocean bottom preserves its own record in a magnetic record.



► **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
- PresentationEXPRESS
- Interactive Textbook



## Teaching Resources

- TeacherEXPRESS
- Virtual Physics Lab 33

# 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 .....

**magnetic pole**  
(p. 721)

**magnetic field**  
(p. 722)

**magnetic domain**  
(p. 724)

**electromagnet**  
(p. 726)

## 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.

## Check Concepts .....

1. They both attract and repel one another.
2. Charges can be isolated, whereas poles cannot.
3. Altered space around a magnet; moving electric charges
4. Electrons spin in opposite directions, so their fields cancel.
5. Fields of iron's electrons do not entirely cancel.
6. Cluster of aligned iron atoms
7. Domains in some are aligned.
8. Align the domains with the magnetic field.
9. The domains are jostled out of alignment.
10. Concentric circles
11. The fields overlap inside the loop.
12. Moving across magnetic field lines.
13. Magnetic—force is perpendicular to the field; electric—force is parallel to the field.
14. It deflects incoming charged cosmic rays.
15. Same
16. Force acts on the current in the field and deflects the galvanometer coil.

## Check Concepts .....

### Section 36.1

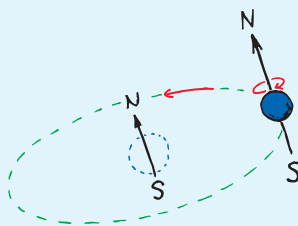
1. What do electric charges have in common with magnetic poles?
2. What is a major difference between electric charges and magnetic poles?

### Section 36.2

3. What is a magnetic field, and what is its source?

### Section 36.3

4. Every spinning electron is a tiny magnet. Since all atoms have spinning electrons, why are not all atoms tiny magnets?



5. What is so special about iron that makes each iron atom a tiny magnet?

### Section 36.4

6. What is a magnetic domain?
7. Why do some pieces of iron behave as magnets, while other pieces of iron do not?
8. How can a piece of iron be induced into becoming a magnet? For example, if you place a paper clip near a magnet, it will itself become a magnet. Why?

9. Why will heating or dropping a magnet on a hard surface weaken it?

### Section 36.5

10. What is the shape of the magnetic field that surrounds a current-carrying wire?
11. If a current-carrying wire is bent into a loop, why is the magnetic field stronger inside the loop than outside?

### Section 36.6

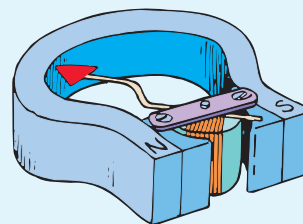
12. What must a charged particle be doing in order to experience a magnetic force?
13. With respect to an electric and a magnetic field, how does the direction of a magnetic force on a charged particle differ from the direction of the electric force?
14. What role does Earth's magnetic field play in cosmic ray bombardment?

### Section 36.7

15. How does the direction in which a current-carrying wire is forced when in a magnetic field compare with the direction that moving charges are forced?

### Section 36.8

16. How do the concepts of force, field, and current relate to a galvanometer?





17. So it will do more than rotate  $180^\circ$
18. Difference between geographic north and magnetic north
19. Currents in Earth's molten interior
20. N changes to S, S to N; magnetism found in rock strata.

### Think and Rank .....

21. B, C, A
22. a. B (attractive), C (repulsive), A (more repulsive)  
b. B, A = C = 0

# 36 ASSESS *(continued)*

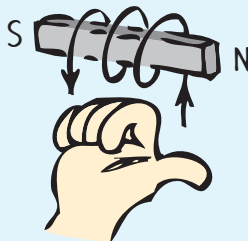
17. Why is it important that the current in the armature of a motor that uses a permanent magnet periodically change direction?

### Section 36.9

18. What is meant by magnetic declination?
19. According to most geophysicists, what is the probable cause of Earth's magnetic field?
20. What are magnetic pole reversals, and what evidence is there that Earth's magnetic field has undergone pole reversals throughout its history?

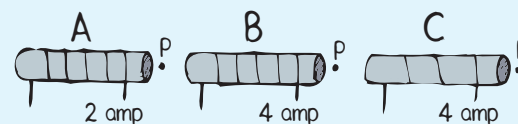
### Think and Rank .....

Suppose you wrap some wire into a coil around an iron bar. When the coil carries a current, you have an electromagnet. The polarity of the electromagnet can be found using your right hand: When you curl your right-hand fingers in the direction of the current, your thumb points to the north pole. (The opposite end of the electromagnet is the south pole.)

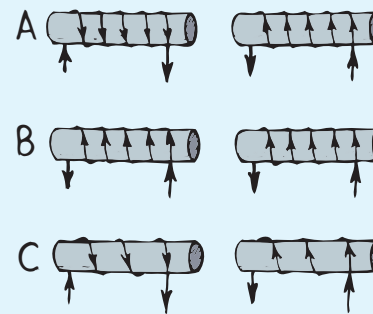


Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, separate them with an equal sign. (e.g., A = B)

21. The electromagnets A, B, and C are shown below. Note the number of turns of wire and the current in each. The iron cores are identical. Rank the electromagnets in magnetic field intensity at point P (just outside each electromagnet), from strongest to weakest.



22. Three pairs of electromagnets made with identical iron cores are shown below. Note the number of turns of wire, each of which carries the same current.



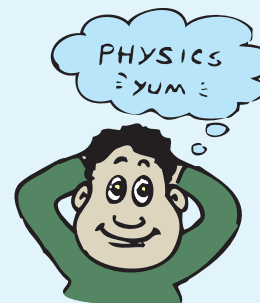
- a. Rank the electromagnet pairs A, B, and C in terms of the force between the electromagnets, from most attractive to most repulsive.
- b. Rank the electromagnet pairs A, B, and C in terms of the magnitude of the magnetic field at the exact midpoint between the electromagnets.

## Think and Explain . . . .

23. Only domains of aligned atoms make a magnet.
24. Electron must be moving to experience magnetic force.
25. An electric field; electric and magnetic fields
26. Iron, unlike wood, has magnetic domains that can be induced into alignment.
27. The attraction is due to inducing opposite polarity. North induces south; south induces north. (Similar to electric charge induction and charge polarization.)
28. Apply a small magnet to the door. If it sticks, your friend is wrong because aluminum is not magnetic. (If it doesn't stick, aluminum is only one of many possibilities.)
29. Magnetic domains in the filings are induced into alignment along the external magnetic field lines. This produces poles in the filings, which are then acted on by the external field, resulting in a torque on each filing. The torque produces a "couple" that aligns the filing with the field.
30. Yes; the compass aligns with Earth's magnetic field, which extends from pole to pole.
31. The forces in a force pair in any interaction are equal and opposite.
32. Yes; the forces are equal and opposite, in accord with Newton's third law.
33. The alignment of domains adds to the field strength.
34. No, no force on a stationary charge; yes
35. Perpendicular to the field lines; parallel to the field lines

## Think and Explain . . . .

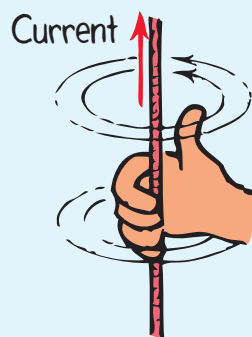
23. Since every iron atom is a tiny magnet, why aren't all iron materials themselves magnets?
24. "An electron always experiences a force in an electric field, but not always in a magnetic field." Defend this statement.
25. What kind of field surrounds a stationary electric charge? A moving electric charge?
26. Why can iron be made to behave as a magnet while wood cannot?
27. If you place a chunk of iron near the north pole of a magnet, attraction will occur. Why will attraction also occur if you place the iron near the south pole of the magnet?
28. A friend tells you that a refrigerator door, beneath a layer of white-painted plastic, is made of aluminum. How could you check to see if this is true (without any scraping)?
29. Since iron filings are not themselves magnets, by what mechanism do they align themselves with a magnetic field as shown in Figure 36.6?
30. We know a compass points northward because Earth is a giant magnet. Will the northward-pointing needle point northward when the compass is brought to the Southern Hemisphere?
31. A strong magnet and a weak magnet attract each other. Which magnet exerts the stronger force—the strong one or the weak one? (Could you have answered this using what you learned in Chapter 6?)
32. A strong magnet attracts a paper clip to itself with a certain force. Does the paper clip exert a force on the strong magnet? If not, why not? If so, does it exert as much force on the magnet as the magnet exerts on it? Defend your answers.
33. Why will the magnetic field strength be further increased inside a current-carrying coil if a piece of iron is placed in the coil?
34. Can an electron be set into motion with a magnetic field? With an electric field? Explain.
35. In what direction relative to a magnetic field does a charged particle travel in order to experience maximum magnetic force? Minimum magnetic force?
36. When a current-carrying wire is placed in a strong magnetic field, no force acts on the wire. What orientation of the wire is likely?
37. A magnetic field can deflect a beam of electrons, but it cannot do work on them to speed them up. Why? (*Hint:* Consider the direction of the force relative to the direction in which the electrons move.)



36. The wire is aligned with the magnetic field. In order to experience a force, the wire must be at a nonzero angle to the field. The maximum force occurs at an angle  $90^\circ$  to the field.
37. There is no component of magnetic force in the direction of motion.
38. The electric field increases the speed of an electric charge (force on the charge can be in the direction of motion). The magnetic force always acts perpendicular to the motion of the charge, so the force changes the direction of the charged particle's path.
39. Opposite hand for opposite direction of current
40. It likely allows them to sense the direction of Earth's magnetic field.
41. They are reversed. When mechanical energy is input, it's a generator. When electrical energy is input, and it spins and does mechanical work, it's a motor.
42. Agree; any coil spinning in a magnetic field cutting through magnetic field lines is a generator.
43. Charged particles moving downward at polar locations move more nearly parallel to Earth's magnetic field lines (less deflection) than particles moving downward in tropical locations.

# 36 ASSESS *(continued)*

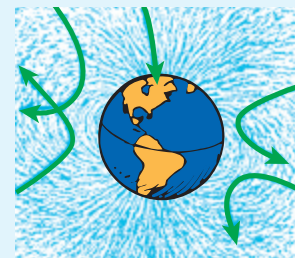
38. A cyclotron is a device for accelerating charged particles to high speeds in circular orbits of ever-increasing radius. The charged particles are subjected to both an electric field and a magnetic field. One of these fields increases the speed of the particles, and the other field holds them in a circular path. Which field performs which function?
39. By present-day custom, the direction of electric current is the direction in which positive charge flows. The direction of a magnetic field surrounding a current-carrying wire can be shown by what is called the "right-hand rule." Wrap your right-hand fingers around a current-carrying wire in such a way that your thumb points in the direction of the electric current; then your fingers point in the direction of the magnetic field. Suppose instead that the current direction were defined as the direction in which electrons move in the wire. Why then would a "left-hand rule" be used for identifying magnetic field direction?



40. Pigeons have multiple-domain magnetite magnets within their skulls that are connected through a large number of nerves to the pigeon's brain. How does this aid the pigeon in navigation? (Magnetic material also exists in the abdomens of bees.)



41. How do the input and output parts of a generator and a motor compare?
42. Your friend says that if you crank the shaft of a DC motor manually, the motor becomes a DC generator. Do you agree or disagree? Defend your position.
43. Residents of northern Canada are bombarded by more intense cosmic radiation than are residents of Mexico. Why is this so?



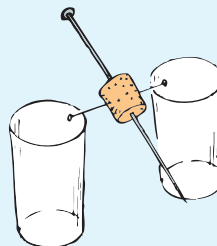
44. What changes in cosmic ray intensity at Earth's surface would you expect during periods in which Earth's magnetic field passed through a zero phase while undergoing pole reversals? (A speculation supported by fossil evidence is that the periods of no protective magnetic field may have been as effective in changing life forms as X-rays have been in the famous heredity studies of fruit flies.)
45. Earth's core is probably composed of iron and nickel, excellent metals for making permanent magnets. Why is it unlikely that Earth's core is a permanent magnet?



## Activities .....

46. An iron bar can be easily magnetized by aligning it with the magnetic field lines of Earth and striking it lightly a few times with a hammer. This works best if the bar is tilted down to match the dip of Earth's field. The hammering jostles the domains so they can better fall into alignment with Earth's field. The bar can be demagnetized by striking it when it is in an east–west direction.

47. Find the direction and dip of Earth's magnetic field lines in your locality. Magnetize a large steel needle or straight piece of steel wire by stroking it a few dozen times with a strong magnet. Run the needle or wire through a cork in such a way that when the cork floats, the thin magnet remains horizontal (parallel to the water surface). Float the cork in a plastic or wooden container of water. The needle will point toward the magnetic pole. Then press unmagnetized common pins into the sides of the cork perpendicular to the needle. Rest the pins on the rims of a pair of drinking glasses so that the needle or wire points toward the magnetic pole. It should dip in line with Earth's magnetic field.



44. Increased intensity of cosmic rays
45. It is too hot for iron and nickel to be magnetic.

## Activities .....

46. Domains are jostled when the bar is struck. Then they tend to settle in alignment with Earth's magnetic field. When the bar is struck when not oriented along the Earth's magnetic field, as when in an east–west direction, alignment of domains is not along the length of the bar. This tends to demagnetize a magnetized bar.
47. In all latitudes of the United States, the magnetic field not only points north, but also dips downward. The compass constructed in this activity will show the dip.

### Teaching Resources

- Computer Test Bank
- Chapter and Unit Tests