CHAPTER

12

Key Concepts

In this chapter, you will learn about:
- magnetic fields
- moving charges in magnetic and electric fields
- electromagnetic induction

Learning Outcomes

When you have completed this chapter, you will be able to:

Knowledge
- define electric current as the amount of charge passing a reference point per unit of time
- describe magnetic interactions in terms of forces and fields
- compare gravitational, electric, and magnetic fields
- describe how the work of Oersted and Faraday led to the theory relating electricity to magnetism
- describe a moving charge as the source of a magnetic field and predict the field's orientation
- explain how uniform magnetic and electric fields affect a moving charge
- describe and explain the interaction between a magnetic field and a moving charge and a conductor
- explain, quantitatively, the effect of an external magnetic field on a current-carrying conductor
- describe the effects of moving a conductor in an external magnetic field in terms of moving charges

Science, Technology, and Society
- explain that concepts, models, and theories are often used in interpreting, explaining, and predicting observations
- explain that technology provides solutions to practical problems
- explain that scientific knowledge may lead to the development of new technologies and vice versa

Properties of electric and magnetic fields apply in nature and technology.

▲ **Figure 12.1** Aurora borealis or northern lights

The spectacular aurora borealis paints the night sky with shimmering colours in northern latitudes (Figure 12.1). Frequently seen above 60° north, its scientific name translates from Latin into "dawn of the north." In southern latitudes, where it is seen mainly above 60° south, it is called the aurora australis — "dawn of the south."

Many ancient civilizations created stories to explain these dancing lights in the sky. Some Inuit peoples of northern Canada believed that the sky was a hard dome that arched over Earth. Spirits could pass through a hole in the dome to the heavens, where they would light torches to guide new arrivals. Other Aboriginal traditions spoke of the creator of Earth travelling to the north when he finished his task of creation. There he remained, building large fires to remind his people that he still thought of them. The northern lights were reflections of these fires.

What are the auroras and what causes them? Why can they be observed only in the far northern or southern latitudes? Is there a relationship between the auroras and surface activity on the Sun, called solar flares? Are they related to other physical phenomena observed on Earth? Finally, how can an understanding of the science of the auroras aid in the development of new technologies? Your studies in this chapter will help answer these questions.

12-1 QuickLab

Magnetic Fields in a Bottle

Problem

What is the shape of a magnetic field?

Materials

50 mL of iron filings
450 mL of light cooking oil
1 clear plastic 591-mL pop bottle
string
1 cylindrical cow magnet (must be able to fit in the bottle)
tape

Procedure

1. Pour 50 mL of iron filings into the bottle.
2. Pour cooking oil into the bottle until it is about three-quarters full.
3. Replace the cap on the bottle securely and shake the bottle several times so that the iron filings disperse throughout the oil. Remove the cap.
4. Attach the string to one end of the cow magnet and insert the magnet in the bottle. Make sure the magnet is suspended vertically in the middle of the bottle. Tape the other end of the string to the top of the bottle.
5. Replace the cap on the bottle and place the bottle on a table to allow the mixture to settle. Observe the pattern produced by the iron filings.

Questions

1. In your notebook, draw a diagram of the pattern created by the iron filings.
2. Is the pattern created by the iron filings one-, two-, or three-dimensional? Explain your answer.
3. Identify where the density of the iron filings is the greatest and the least. Explain why the filings are distributed this way.
4. From the pattern of the iron filings, is it possible to determine the strength and the direction of the magnetic influence around the magnet? Explain your answer.

Think About It

1. Describe a probable cause of the pattern of the iron filings in 12-1 QuickLab.
2. What types of substances produce this influence?
3. What types of objects are affected by this influence?

Discuss and compare your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes to your ideas.

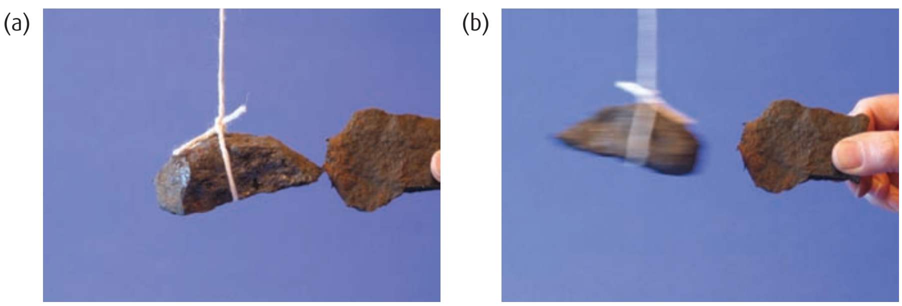
12.1 Magnetic Forces and Fields

▲ **Figure 12.2** The magnetic effects of certain materials were observed by ancient Greeks as early as 800 BCE

An ancient Greek legend from about 800 BCE describes how the shepherd Magnes, while tending his flock, noticed that pieces of a certain type of rock were attracted to the nails on his shoes and to his metal staff (Figure 12.2). This phenomenon was called magnetism and, as time passed, further studies of the behaviour of this rock revealed several curious effects.

For example, a piece of this rock could either attract or repel another similar piece (Figure 12.3). This effect seemed to result from two different magnetic effects, so investigators thought that there must be two different types of "magnetic ends," or poles, on the rock. This observation led to the **law of magnetism**, which states:

Like magnetic poles repel and unlike poles attract each other.



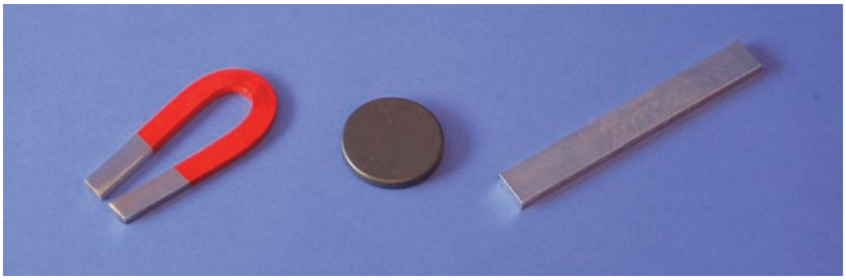
▲ **Figure 12.3** A piece of magnetic rock, held near one end of a similar piece of magnetic rock, would attract at one end (a) and repel at the other end (b).

info **BIT**

Magnetic poles always exist in pairs. In the 1930s, Paul Dirac (1902–1984) suggested the existence of a particle called a magnetic monopole. To date, all experiments to discover this one-poled particle have failed, but these particles are still under experimental investigation.

In 1269, Pierre de Maricourt was mapping the position of a magnetized needle placed at various positions on the surface of a spherical piece of this rock. He observed that the directions of the needle formed a pattern that encircled the rock, like meridian lines, and converged at two points on opposite ends of the rock. When this rock was then suspended by a string, the two converging points tended to align along Earth's north–south axis. This property of the rock earned it the name "lodestone" or "leading stone." Maricourt called the end pointing northward the north-seeking or north pole and the end pointing southward the south-seeking or south pole. All magnets have both poles. Lodestone, which contains the mineral magnetite (Fe_3O_4), was later used in the development of compass technology.

Concept Check



▲ **Figure 12.4** A U-magnet, a circular magnet, and a bar magnet

Copy the picture of each magnet in Figure 12.4 into your notebook. Since each magnet must have two poles, label the possible positions of the north and south poles of each magnet.

The next big advance in knowledge about magnetism came from the work of William Gilbert. In his book *De Magnete*, published in 1600, he not only reviewed and criticized past explanations of magnetism but he also presented many important new hypotheses.

He compared the orientation of magnetized needles on the surface of a spherical piece of lodestone with the north–south orientation of a compass needle at various locations on Earth's surface. From this study, he proposed that Earth itself is a lodestone with north and south magnetic poles.

Concept Check

The north pole of a magnetic compass needle points toward Earth's magnetic north. What can you conclude about this point on Earth?

Gilbert was also intrigued by the forces that magnets could exert on other magnetic objects. If you suspend a magnet on a string and bring another magnet close to one of its poles, the suspended magnet will rotate, even though there is no visible contact between the two magnets. Magnets appeared to have the ability to exert forces that seemed to originate from the magnetic poles, and they could affect another magnetic object even without contact. The ancient Greeks called this effect "action at a distance." Recall from chapter 11 that they used the same terminology to describe the effects of electric charges.

In attempting to explain the action at a distance caused by a magnet, Gilbert suggested that an invisible "orb of virtue" surrounds a magnet and extends in all directions around it. Other magnetic substances react to a force created by this orb of virtue and move or rotate in response. His orbs of virtue were the beginnings of the idea of "fields" that would revolutionize physics.

magnetic field: a three-dimensional region of influence surrounding a magnet, in which other magnets are affected by magnetic forces

Michael Faraday (1791–1867) further developed this concept. He defined a **magnetic field** as a three-dimensional region of magnetic influence surrounding a magnet, in which other magnets are affected by magnetic forces. The direction of the magnetic field at a given location is defined as the direction in which the north pole of the compass needle points at that location. Some materials, such as iron, act like magnets while in a magnetic field.

12-2 QuickLab

Observing Magnetic Fields

Problem

How can the magnitude and direction of magnetic fields be observed and analyzed?

Materials

1 bar magnet
1 sheet of paper (216 mm × 279 mm)
25 mL of iron filings
1 compass

Procedure

1. Lay the bar magnet on a table and place the paper over the magnet. Trace the shape of the magnet on the paper and label the poles.
2. Carefully sprinkle the iron filings onto the surface of the paper.
3. Tap the paper lightly to reinforce the alignment of the iron filings on the sheet. Draw the pattern of the iron filings around the magnet.
4. Clean the iron filings from the paper and replace the paper over the magnet.
5. Place the compass at several positions around the magnet and trace the direction of the compass needle.

Questions

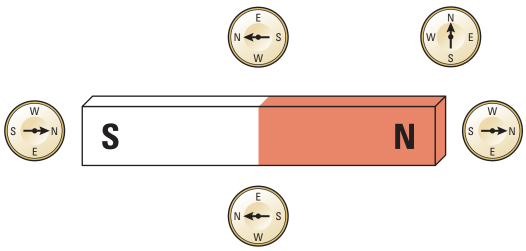
1. Describe the cause of the pattern produced by the iron filings.
2. Is the pattern created by the iron filings one-, two-, or three-dimensional? Explain.
3. Identify where the density of the iron filings is the greatest and the least. Explain why the filings are distributed this way.
4. Is it possible to determine the strength and direction of the magnetic field surrounding the magnet from the pattern of the iron filings alone? Explain your answer.
5. From your investigation of the effect of a magnetic field on a compass, what appears to be the direction of the magnetic field around a magnet?

Magnetic Fields

The magnetic field surrounding a magnet is represented by the symbol $\vec{B}$ and is measured in teslas (T). A typical bar magnet in the classroom can have a magnetic field of approximately 1×10^{-2} T, whereas Earth's magnetic field is about 5×10^{-5} T. The magnetic field is a vector quantity, so it is represented by a vector arrow. In diagrams, the length of the vector arrow represents the magnitude of the field, and the direction of the arrow represents the direction of the field at a point. You can also use compasses to show the direction of the magnetic field at any position surrounding a magnet, as illustrated in Figure 12.5. Figure 12.5 shows that, in general, this direction is from the north to the south pole of the magnet.

info **BIT**

Magnetic field lines run parallel to Earth's surface only at the equator. As they reach the magnetic poles, they gradually dip toward the surface. At the poles, the magnetic field lines point perpendicular to Earth's surface. Navigators in the far north or south must be aware that the magnetic compasses may be of limited use in those areas.



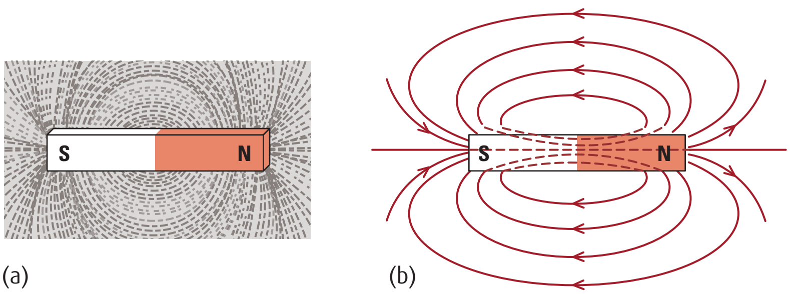
▲ **Figure 12.5** The direction of a magnetic field is the direction of the force on the north pole of a compass placed in the field.

To represent the entire magnetic field surrounding a magnet, it would be necessary to draw arrows at an infinite number of points around the magnet. This is impractical. Instead, you can draw a few magnetic field lines with a single arrow head indicating the direction of the magnetic field. To find the field direction at a given point, move the arrow head along the field line through that point so that it keeps pointing in the direction of the tangent to the field line. The field lines in Figure 12.6 are a map of the magnetic field with the following features:

- Outside a magnet, the magnetic field lines point away from the north pole of a magnet and toward the south pole.
- The closeness of the lines represents the magnitude of the magnetic field.

e **LAB**

For a probeware activity where you use a magnetic field sensor to determine the relationship between the distance from a magnet and the intensity of the field, go to www.pearsoned.ca/school/physicssource.



▲ **Figure 12.6** (a) The pattern of iron filings surrounding a bar magnet outlines the magnetic field. (b) Magnetic field lines, representing the direction and magnitude of the magnetic field, can replace the iron filings. The number of magnetic field lines that exit a magnetic material is equal to the number of magnetic field lines that enter the magnetic material, forming closed loops.

Table 12.1 shows some examples of magnetic field strengths.

PHYSICS INSIGHT

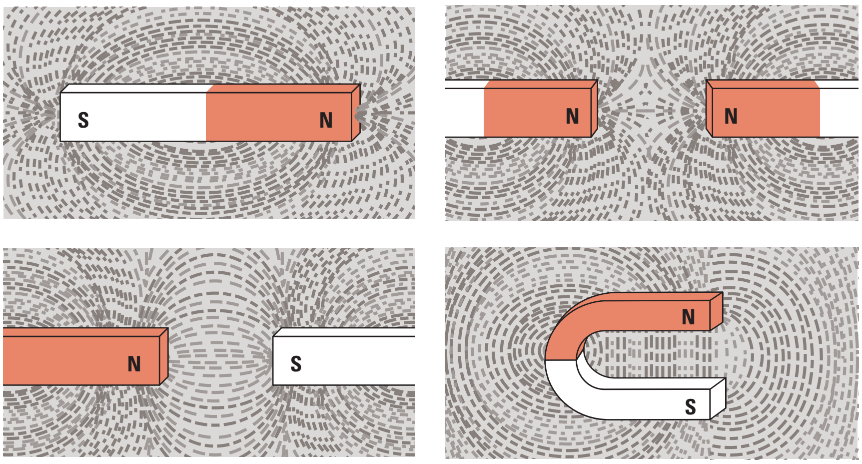
Before the adoption of SI units, magnetic fields were sometimes measured in a CGS unit called the gauss (G). You might see this unit in some older books. $1\ T = 10^4\ G$.

▼ **Table 12.1** Magnetic Field Strengths

Physical system	Magnetic field (T)
Earth	5×10^{-5}
Bar magnet	1×10^{-2}
Sunspots	1×10^{-1}
High field magnetic resonance imaging device (MRI)	15
Strongest humanmade magnetic field	40
Magnetar (magnetic neutron star)	1×10^{11}

Concept Check

Figure 12.7 shows the patterns produced by iron filings that are influenced by the magnetic fields of one or two magnets. Sketch the magnetic field lines in each case.



▲ **Figure 12.7**

Concept Check

List at least two similarities and two differences between gravitational, electric, and magnetic fields.

Cause of Magnetism

The force of magnetic repulsion between like poles of magnets is the same force that causes the almost frictionless ride of the Maglev (**mag**netically **lev**itated) train (Figure 12.8). What is the source of this "magnetic levitation" on the train?

(a)

(b)

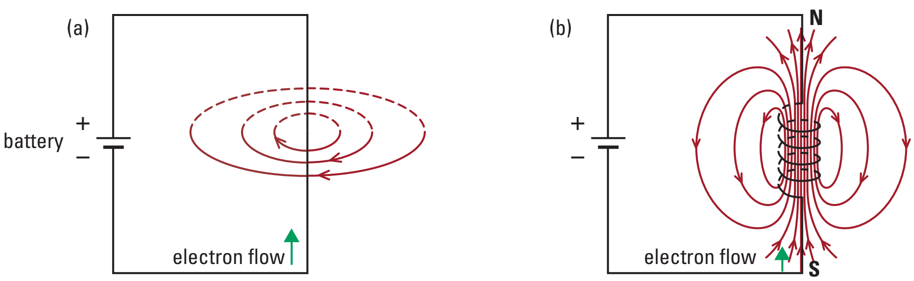
▲ **Figure 12.8** (a) The force of magnetic repulsion between like poles can cause one magnet to levitate over another. (b) The Maglev train, developed in Japan, floats several centimetres above the guideway, providing a smooth and almost frictionless ride.

Experiments by early investigators revealed many facts about the magnetic fields surrounding magnets and their effects on magnetic objects. However, the actual cause of magnetism eluded scientists until 1820. While demonstrating to students that the current passing through a wire produces heat, Danish professor Hans Christian Oersted (1777–1851) noticed that the needle of a nearby compass deflected each time the circuit was switched on.

This experiment led Oersted to the important conclusion that there is a relationship between electricity and magnetism, at a time when electricity and magnetism were considered separate phenomena. He proved that electric current was a cause of magnetism. Following his initial observations, it was later shown that if electric current was in a straight line, the magnetic field formed a circular pattern (Figure 12.9(a)), and if the electric current was circular, the magnetic field was straight within the coil (Figure 12.9(b)).

info **BIT**

Oersted was among the first to recognize the talent of the writer Hans Christian Andersen and encouraged him when he began writing his now famous fairy tales.



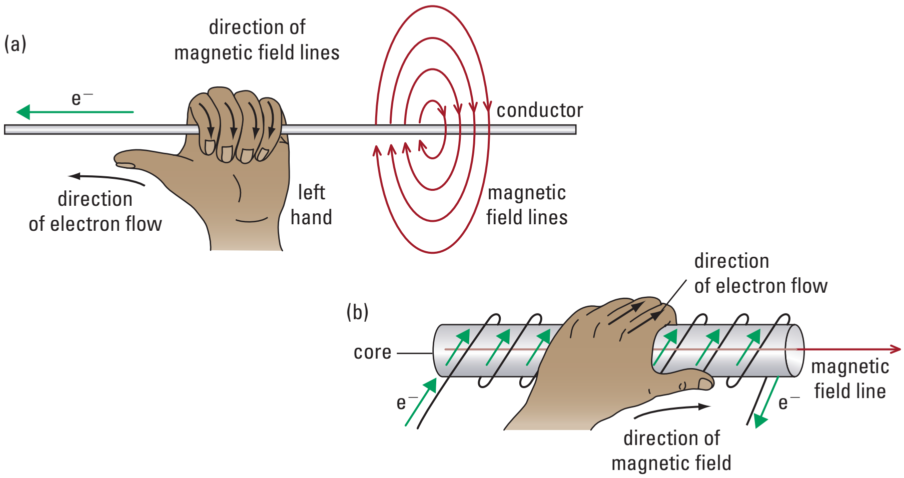
▲ **Figure 12.9** (a) A current passing through a straight conducting wire produces a magnetic field, represented by concentric red circular lines around the wire. (b) A current passing through a coil produces a magnetic field, represented by red circular lines, with poles similar to those of a bar magnet.

PHYSICS INSIGHT

The observation of a magnetic field produced by a moving charge depends on the frame of reference of the observer. If you are stationary and the charge moves past you, you observe a magnetic field. However, if you are moving along with the charge, the charge is stationary relative to you, so you do not observe a magnetic field.

Left-hand Rules for Magnetic Fields

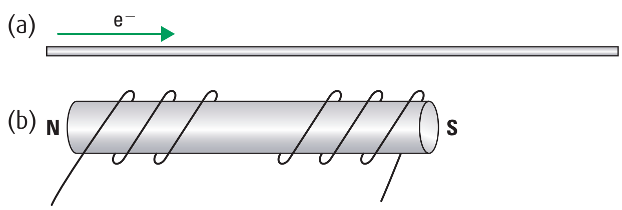
A useful left-hand rule to determine the direction of the magnetic field is the wire-grasp rule described in Figure 12.10. To determine the direction of the magnetic field produced by a moving charge, *use the left-hand wire-grasp rule if the moving charge is negative*. (If the moving charge is positive, then use the right-hand wire-grasp rule.)



▲ **Figure 12.10** Left-hand rule for direction of a magnetic field due to moving charges: (a) If the conducting wire is straight, then the thumb indicates the direction of the straight current and the cupped fingers indicate the direction of the circular magnetic field. (b) If the current is in a coil of conducting wire, the cupped fingers indicate the circular current and the straight thumb indicates the direction of the straight magnetic field within the coil.

SKILLS PRACTICE Using the Wire-grasp Rule

1. Sketch the following diagrams into your notebook. Indicate the direction of the magnetic field lines and the direction of current in the wire, as required.



Electromagnets

electromagnet: a magnet having its magnetic field produced by electric current flowing through a coil of wire

As shown in Figure 12.9(b), current in a circular loop or coil of wire produces a magnetic field like that of a bar magnet. An **electromagnet** uses a current-carrying coil of wire to generate a magnetic field that is easy to switch on and off. The strength of an electromagnet can be influenced by:

- increasing the current through the wire
- increasing the number of loops in the coil
- increasing the size of the loops in the coil
- changing the core of the coil

Powerful electromagnets have many industrial uses, such as lifting steel parts, machinery, or scrap iron. Electromagnets are widely used to remotely operate switches or valves. Often, a valve is activated by a metal rod that is drawn into the core of the electromagnet when current flows through the coil. Such mechanisms, called **solenoids**, are common in washing machines, dishwashers, furnaces, and industrial machinery. Figure 12.11 shows two applications of electromagnets.

solenoid: an electromagnet that operates a mechanical device

(a) (b)

▲ **Figure 12.11** (a) A lifting magnet (b) An appliance solenoid

info **BIT**

Geophysicists theorize that circulating currents of ions in the molten core of Earth produce its magnetic field.

Domain Theory and Magnetization

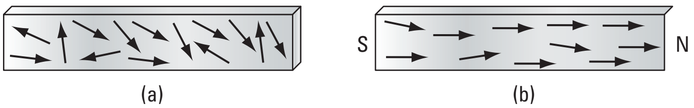
In some atoms, the configuration of the electrons is such that their movement generates a tiny magnetic field. In **ferromagnetic** materials, such as iron, nickel, and cobalt, the magnetic fields of adjacent atoms can align to reinforce each other, forming small regions, or **domains**, with intense magnetic fields. Domains generally range from 0.001 mm to 1 mm across, and may contain billions of atoms.

ferromagnetic: having magnetic properties like those of iron

domain: a region of a material in which the magnetic fields of most of the atoms are aligned

The orientations of the magnetic fields of the various domains are normally random, so their magnetic fields largely balance each other, leaving the material with little or no overall magnetization. However, the size of a domain and the direction of its magnetic field are relatively easy to change. An external magnetic field can cause the domains to align, thus magnetizing the material (Figure 12.12).

The small black arrows in Figure 12.12 indicate the orientation of the magnetic field of an individual domain.



▲ **Figure 12.12** (a) When the magnetic fields of atoms in a region line up, they create a magnetic domain in the substance. (b) Aligning the domains produces a magnet. A typical ferromagnetic object has vastly more domains than the diagrams can show.

If you hang an iron nail by a string and bring a magnet close to the nail, the nail will rotate toward the magnet, even before they touch. The nail is not a magnet with distinct poles, yet a magnetic attraction exists between it and the magnet. When the magnet is close to the nail, the domains in the nail that are oriented for attraction to the magnet increase in size while the other domains shrink. When the magnet is moved away again, the domains in the nail tend to return to random

e **WEB**

All magnetic substances can be classified as one of the following:

- ferromagnetic
- antiferromagnetic
- ferrimagnetic
- paramagnetic
- diamagnetic

Find out what distinguishes one type of magnetic substance from another. Begin your search at www.pearsoned.ca/school/physicssource.

orientations and the nail loses most of its magnetization. This example illustrates induced magnetization.

The nail will be much more strongly magnetized if it is stroked with a pole of the magnet. The magnetic fields of many of the domains in the nail will align along the direction of motion of the magnet. This magnetization is strong enough that the nail will remain somewhat magnetized when the magnet is removed.

Concept Check

A filing cabinet has been in one position for a long time. It is made of ferromagnetic material, so it can become a permanent magnet. If you hold a compass near the top of the filing cabinet, the compass needle points toward the filing cabinet. If you hold the compass near the bottom of the filing cabinet, the opposite end of the compass points toward the cabinet. Has the cabinet been magnetized by Earth's magnetic field? Or has the cabinet become magnetized by the magnetic compass? Explain your answer.

Magnetism in Nature

The effects of magnetism have been known since early civilizations, but the causes of magnetic behaviour are only now being revealed. A modern understanding of magnetic phenomena began with the development of field theory to replace "action at a distance." The symmetry of nature enabled scientists to use the same field theory to describe the gravitational field surrounding any mass, the electric field surrounding any charge, and the magnetic field surrounding any magnet.

Oersted's investigations, which revealed a relationship between electricity and magnetism, ultimately led to the domain theory to explain a cause of magnetism. As scientists probed deeper into the mysteries of magnetism, many more answers were found. However, the tremendous significance of magnetism has only recently been understood in explaining phenomena and producing technological applications. In the field of biology, for example, researchers have found that certain organisms have ferromagnetic crystals consisting of magnetite in their bodies. Some bacteria use these magnetite crystals to help orient themselves within Earth's magnetic field. Bees and pigeons have magnetite crystals within their brains to help with navigation. The human brain also has these magnetite crystals, but their function is not clear. It is known that an external magnetic field can disrupt the neural activity in the parietal lobe on one side of the human brain.

Understanding magnetism has also led to important technological advancements. These advancements range from simple applications, such as refrigerator magnets, magnetic stripes on cards, and magnetic audiocassette or VCR tapes, to more complicated applications involving magnetic levitation, such as the Maglev train and magnetic resonance imaging (MRI) machines used as a diagnostic tool in health care. Although much has been achieved, there are still many secrets of magnetism to uncover.

THEN, NOW, AND FUTURE — Earth's Magnetic Field

William Gilbert's "Terrella" experiment in the 1500s compared the magnetic field of Earth to that of a bar magnet. From that time, Earth has been considered to be a huge magnet, with similar magnetic properties to a much smaller, ordinary magnet.

This observation was successful in explaining many phenomena. However, care must be taken in comparing the causes of magnetic behaviour in Earth and in a bar magnet. If the cause of magnetism in substances is the motion of charges, scientists are not quite convinced that the motion of charges within Earth's molten core is responsible for Earth's magnetism. They know that Earth's molten core is simply too hot for atoms to remain aligned and exhibit any magnetic properties.

Other probable causes of Earth's magnetic field could be convection currents rising to the cooler surface of Earth, or the motion of charges in the upper ionosphere. The most acceptable and probable cause, though, is the motion of charges in the molten part of Earth, just beneath the crust (Figure 12.13).

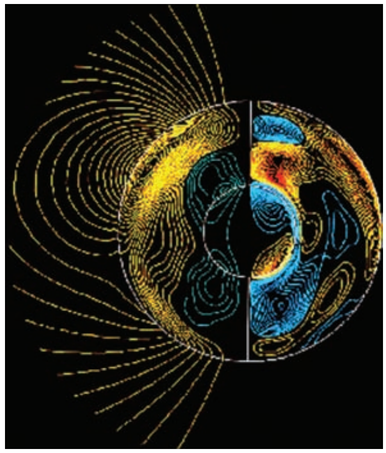
Whatever the cause of Earth's magnetic behaviour, it is known that the magnetic field of Earth is not stable. Molten rock within the interior of Earth has no magnetic properties.

However, when molten rock rises to the surface, it cools and solidifies, and its domains orient themselves in line with Earth's magnetic field at the time.

When samples of rock from different strata formed throughout geological times are tested, evidence shows that there are times when not only the magnitude of Earth's magnetic field changed, but also its direction. In the past five million years, more than 20 reversals have occurred, the last one about 780 000 years ago. Coincidentally, modern humans emerged during this time period.

One possible effect of a zero magnetic field, during a reversal, would be an increase in the cosmic ray intensity at Earth's surface. Normally, the magnetic field shields Earth from harmful radiation from space. Fossil evidence indicates that periods of no protective magnetic field have been effective in changing life forms. Evidence that these types of changes could have occurred also comes from heredity studies of fruit flies when exposed to X rays.

We cannot know precisely when the next reversal will occur. However, evidence from recent measurements indicates a decrease in the magnitude of Earth's magnetic field of about 5% in the last 100 years. Based on this evidence, another reversal of Earth's magnetic field may occur within the next 2000 years.



▲ **Figure 12.13** This computer model of Earth shows the molten outer core surrounding the inner core (the small circle). The right side shows the molten currents. The left side shows the magnetic field lines that extend outward through the rest of Earth's interior.

Questions

1. Can the motion of charges in Earth's core create domains? Explain your answer.
2. What is the most probable cause of Earth's magnetic behaviour?
3. What evidence is there on Earth that its magnetic field is not stable?

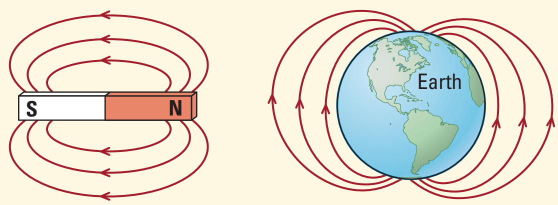
12.1 Check and Reflect

Knowledge

1. What is the law of magnetism?
2. Explain your answers to the following:
   (a) Does every magnet have a north and a south pole?
   (b) Does every charged object have positive and negative charges?
3. How did William Gilbert determine that Earth was a magnet?
4. What is the most probable cause of magnetism in
   (a) a bar magnet?
   (b) Earth?
5. What accidental discovery did Oersted make?
6. What is the shape of the magnetic field
   (a) around a straight current-carrying conductor?
   (b) within a coil of conducting wire carrying a current?

Applications

7. What would happen to a magnet if you broke it into two pieces?
8. A negatively charged sphere is approaching you. Describe the magnetic field surrounding the sphere and its direction. What would happen if the sphere were positively charged?
9. A spinning top is charged negatively and is spinning clockwise, as observed from above. Describe the magnetic field created by the spinning top and its direction.
10. List at least two differences and two similarities between
    (a) gravitational and electric fields
    (b) gravitational and magnetic fields
    (c) electric and magnetic fields
11. Using the domain theory, explain the following observations:
    (a) A magnet attracts an unmagnetized ferromagnetic material.
    (b) Stroking a nail with a magnet magnetizes the nail.
    (c) A metal table leg affects a compass.
12. Why does dropping or heating a bar magnet decrease its magnetic properties?
13. Consider a bar magnet and Earth, as shown below. Describe the similarities and the differences of their magnetic fields.



Extensions

14. Why is it difficult to get an accurate bearing with a magnetic compass near the poles?
15. Do magnetic field lines always run parallel to the surface of Earth? Explain your answer.
16. If a current-carrying wire is bent into a loop, why is the magnetic field stronger inside the loop than outside?

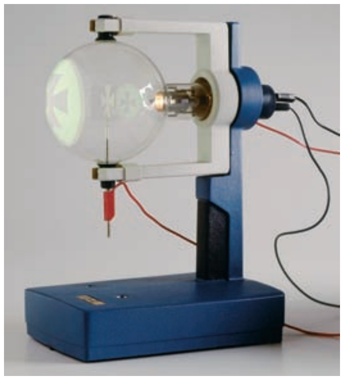
eTEST

To check your understanding of magnetic forces and fields, follow the eTest links at www.pearsoned.ca/school/physicssource.

12.2 Moving Charges and Magnetic Fields

Near the end of the 1800s, researchers were fascinated by a new technology called the cathode-ray tube (CRT), shown in Figure 12.14. It consisted of a glass tube from which air had been evacuated, and it had a positive plate (anode) at one end and a negative plate (cathode) at the other end. These new tubes used electric fields to accelerate a beam called a cathode ray through a large potential difference. The beam would "light up" the fluorescent screen at the end of the tube. Scientists were unsure whether this beam was a type of electromagnetic radiation (similar to light), a neutral particle, or a charged particle. They initially called it a cathode ray because it appeared to originate from the cathode plate.

This technology not only enabled the discovery of the electron in 1897 (see section 15.1), but also led to the later development of many other technologies, including television. Until recently, the image in most TVs was produced by an electron beam striking a fluorescent screen in a CRT.

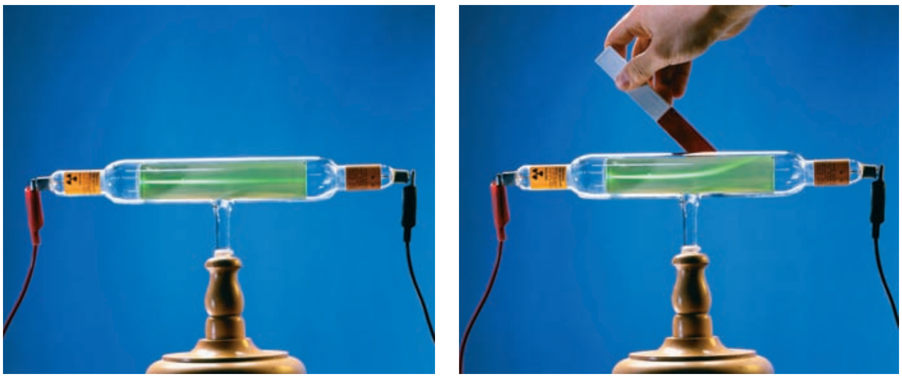


▲ **Figure 12.14** The image on the fluorescent screen at the left end of this cathode-ray tube shows that the rays originate from the negative terminal at the right end.

The Motor Effect

Deflecting charged particles involves an interaction of two magnetic fields. A charged particle in uniform motion produces a circular magnetic field around it (the wire-grasp rule). Now suppose this charged particle enters an external magnetic field, produced between the faces of two opposite magnetic poles. The interaction of the circular magnetic field of the charge and the external magnetic field produces a magnetic *force* that acts on the particle to deflect it, as shown in Figure 12.15. This magnetic force is also called the **motor effect force** ($\vec{F}_m$) because it causes the rotation of a loop of current-carrying wire. This rotation is fundamental in the operation of an electric motor.

motor effect force: the deflecting force acting on a charged particle moving in a magnetic field



(a) (b)

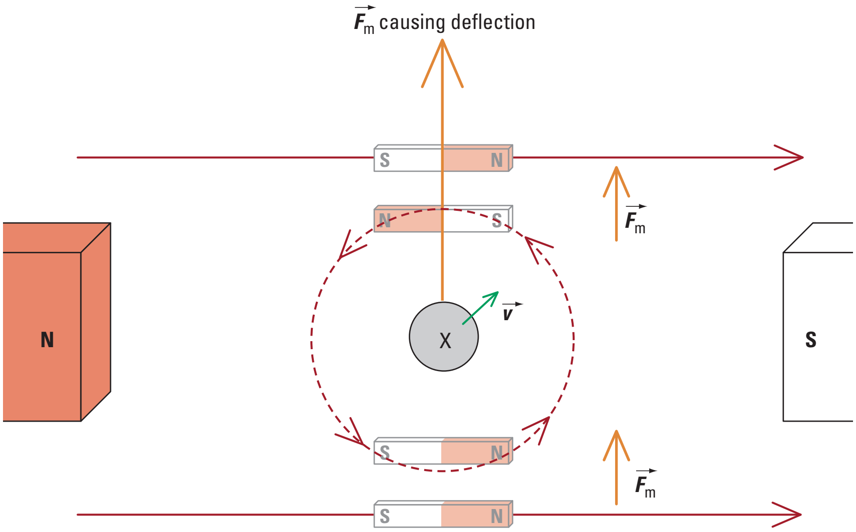
◀ **Figure 12.15** (a) The cathode ray accelerates in a straight line when it is only influenced by the electric field produced between the cathode and anode plates in a vacuum tube connected to a high-voltage source. (b) A cathode ray will deflect as shown when it is also under the influence of an external magnetic field.

In Figure 12.16, the straight, horizontal lines represent the external magnetic field of the magnetic poles, and the dashed lines represent the magnetic field surrounding the moving charge (using the left-hand rule). In the "replacement magnet" method of illustration, tiny magnets are drawn along the field lines to reinforce the idea of the direction and the effects of the interaction of the two magnetic fields. The × represents

PHYSICS INSIGHT

× represents a direction into the page, like the fletching of an arrow receding from you.
• represents a direction out of the page, like the point of an arrow approaching you. In Figure 12.16 × represents negative charge movement into the page.

negative charge moving into the page. In Figure 12.16, below the moving charge, the external magnetic field and the magnetic field surrounding the charge are in the same direction. Above the moving charge, the two magnetic fields are in opposite directions.



▲ **Figure 12.16** The combined magnetic forces due to the two magnetic fields cause the moving charge to deflect ($\vec{F}_m$) in a direction perpendicular to its direction of motion and perpendicular to the direction of the external magnetic field.

Since the external magnetic field is fixed, the combined effect of the two magnetic fields produces a net magnetic force ($\vec{F}_m$) on the moving charge. As a result, the moving charge deflects upward (toward the top of the page). The deflecting force is always perpendicular to the direction of both the external magnetic field and the motion of the moving charge, as shown in Figure 12.16.

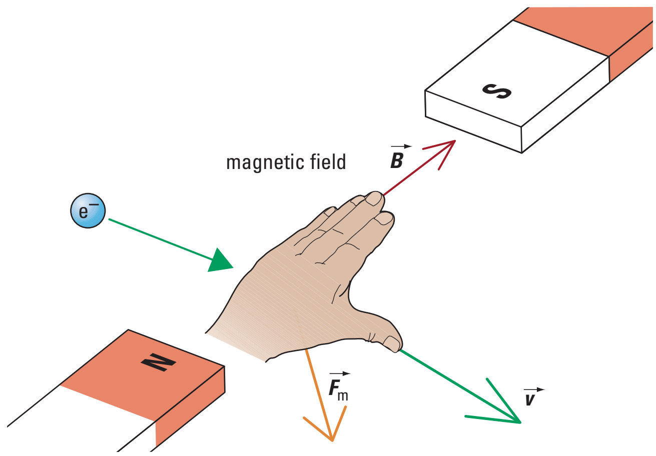
This property distinguishes a magnetic field from electric or gravitational fields. Since the direction of the electric force or gravitational force can be parallel to their respective fields, these fields can be used to change the speed of a charged particle. The magnetic force, on the other hand, is always perpendicular to the velocity of the charged particle. A magnetic force can never do any work on a charged particle, nor can it change the speed or kinetic energy of a charged particle. Since force is not in the direction of the displacement, then there can be no work done on the object. Only the direction of the charged particle's path may be changed.

Left-hand Rule for Deflection

Consider a negatively charged particle travelling perpendicular to an external magnetic field. When it enters the region of a uniform magnetic field, it is deflected in a direction perpendicular to both the original direction of charge movement and the direction of the external magnetic field. A useful hand rule to determine the direction of deflection is the left-hand rule shown in Figure 12.17:

- The thumb indicates the direction of the initial charge movement.
- The extended fingers indicate the direction of the external magnetic field, from north to south.
- The palm faces in the direction of the magnetic force.

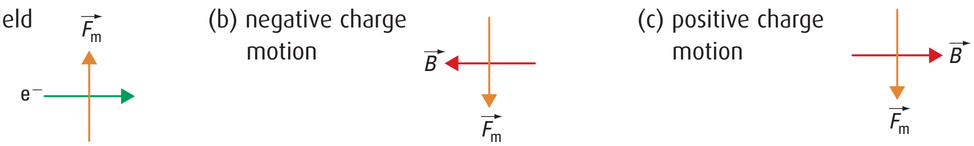
If the moving charge is positive, use the right-hand rule, with the thumb, fingers, and palm indicating the directions of the same quantities as in the left-hand rule.



▲ **Figure 12.17** How to use the left-hand rule to determine the deflection of a charged particle

SKILLS PRACTICE Using the Left-hand Rule for Deflection

1. In your notebook, sketch the direction of the unknown variable in each situation.
(a) external magnetic field
(b) negative charge motion
(c) positive charge motion



12-3 Inquiry Lab

Using Hand Rules with a Cathode-ray Tube — Demonstration

Required Skills

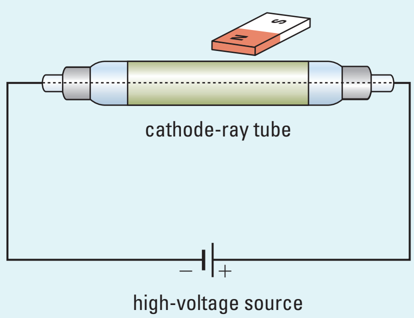
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Question

Do the hand rules predict the deflection of a cathode beam in an external magnetic field?

Materials and Equipment

1 cathode-ray tube
1 high-voltage source
1 strong bar magnet



▲ **Figure 12.18**

CAUTION! High voltage. Be very careful around electrical equipment to avoid shocks.

Procedure

1. Connect the cathode-ray tube to the high-voltage source, as shown in Figure 12.18. Identify the cathode and anode of the CRT.
2. Turn on the current supply. Observe the path of the cathode rays that are produced.
3. Carefully hold the north pole of a bar magnet near one side of the centre of the cathode tube, in the horizontal plane. Note the direction in which the cathode rays are deflected.
4. Repeat the procedure in step 3 with the south pole of the bar magnet.
5. Repeat steps 3 and 4 by holding the magnet on the other side of the cathode tube, in the horizontal plane and then in the vertical plane. Observe the direction of the deflection of the beam in each case.

Analysis

1. What types of particles would be attracted from the cathode to the anode of the CRT? Does the hand rule applicable for these particles predict all of the deflections that you observed?
2. What types of particles would be attracted from the anode to the cathode of the CRT? Does the hand rule for these particles predict any of the deflections that you observed?
3. Explain how the observed deflections show that cathode rays consist of charged particles.
4. Can you use the hand rules to determine the type of charge carried by cathode rays? Explain why or why not.

Concept Check

Compare the magnetic force of an external magnetic field on a moving charged particle with:

- the gravitational force of Earth on the mass of the charged particle
- the electric force due to another nearby charged particle

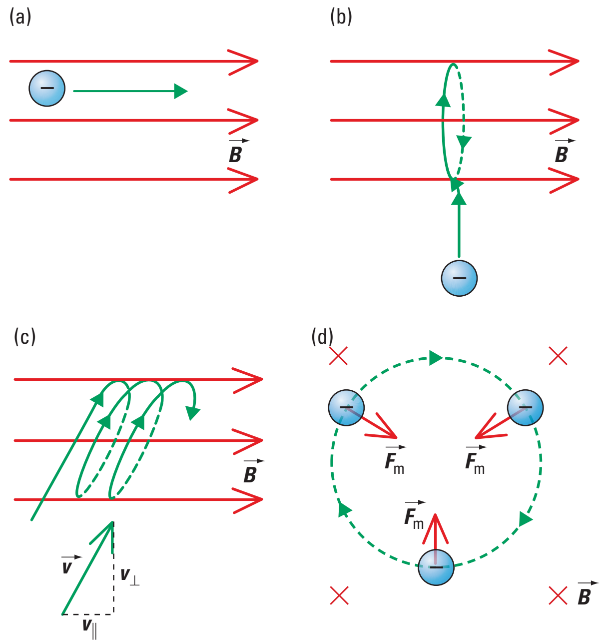
eSIM

Explore the motion of a charged particle in a uniform magnetic field. Follow the eSim links at www.pearsoned.ca/school/physicssource.

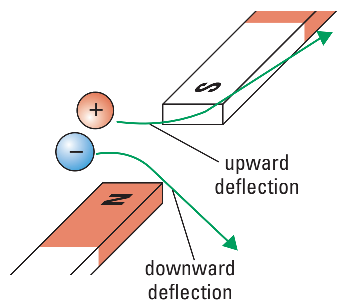
Charged Particle Motion in a Magnetic Field

The direction of the initial motion of a charged particle in an external magnetic field determines how the charged particle will deflect. Figure 12.19 shows what can happen to a charged particle as it enters an external magnetic field:

(a) If the initial motion of the charged particle is parallel to the external magnetic field, then there is no effect.
(b) If the initial motion of the charged particle is perpendicular to the external magnetic field, the charge is deflected in a circular arc.
(c) If the initial motion of the charged particle is at an angle to an external magnetic field, the charge deflects in a circular motion that will form a helical path.



◀ **Figure 12.19** (a) When the charged particle's velocity is parallel to the external magnetic field ($\vec{B}$), the charged particle's path is a straight line. (b) The charged particle's motion is perpendicular to the magnetic field, so the particle is deflected in a circular arc. (c) The charged particle's motion is at an angle to the magnetic field, so the particle follows a helical path. (d) This side view from the left shows the magnetic force acting as the centripetal force that causes the charge to follow a circular path.



▲ **Figure 12.20** A magnetic field deflects moving oppositely charged particles in opposite directions, as shown.

Oppositely charged particles deflect in opposite directions in a magnetic field (Figure 12.20). If the magnitude of the external magnetic field is large enough, the field can cause circular motion that remains contained in the magnetic field. In this circular motion, the centripetal force is the magnetic force.

Magnetic deflection of charged particles is the underlying principle for useful powerful analytical and research tools such as mass spectrometers and particle accelerators. Unit VIII presents these devices and their applications in science, medicine, and industry.

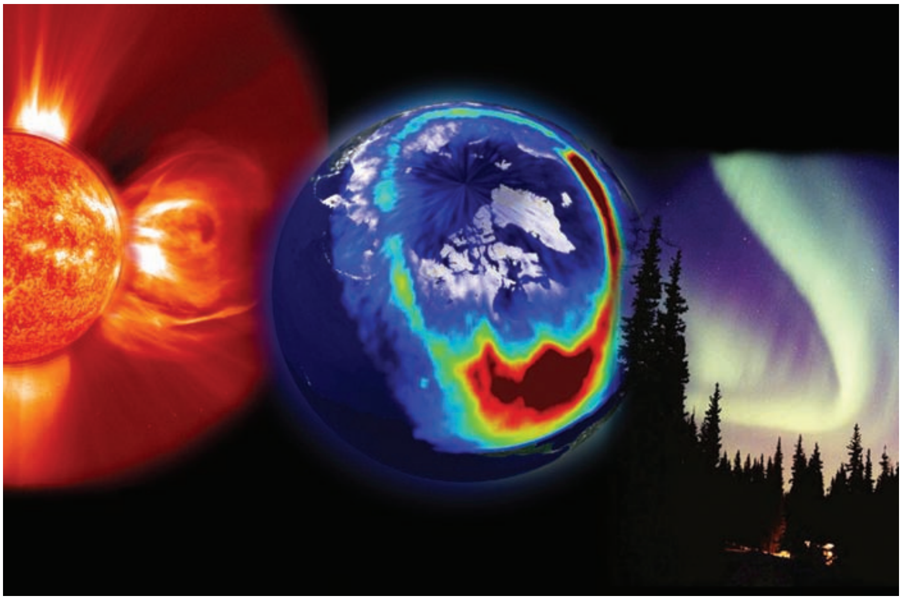
Auroras

Tremendous expulsions of magnetic energy from the solar atmosphere, called solar flares, expel streams of charged particles at speeds around 10% of the speed of light (Figure 12.21). When some of these particles strike Earth's magnetic field, they are deflected by the magnetic force and spiral in a helical path along Earth's magnetic field lines. These particles enter the atmosphere as they approach Earth's magnetic poles, and collide with air molecules.

These collisions excite the atoms of the air molecules, in a process that will be described in Chapter 15, causing them to emit visible light that we see as the aurora. The process repeats because Earth's non-uniform magnetic field produces a magnetic force component that causes the charged particles to reverse their direction of motion, travelling to Earth's opposite pole. The same auroral effect is produced at this pole, and the process continues to repeat as the charged particles oscillate back and forth between the poles, trapped in a type of "magnetic bottle" called the Van Allen belt.

e WEB

Research the formation of the Van Allen belts. Consider the shape of the Van Allen belt on the side of Earth facing the Sun and on the side of Earth away from the Sun. What is the cause of this difference in shape? Begin your search at www.pearsoned.ca/school/physicssource.



▲ **Figure 12.21** This composite image shows the cause of the aurora borealis. Streams of high-energy charged particles erupt from the Sun (far left). They are deflected by Earth's magnetic field toward the poles, creating the bright ring shown in the satellite image of Earth (centre). There they interact with air molecules in the atmosphere to produce the aurora (far right).

Calculating the Magnetic Force

By studying the different types of deflections, scientists can also explain the complex deflection of charged particles entering a magnetic field at an angle, such as the particles that cause the auroras.

The magnitude of the deflecting force ($|\vec{F}_{\mathrm{m}}|$) depends on all of the following:

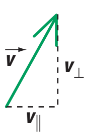
- the magnitude of the moving charge (q)
- the magnitude of the perpendicular velocity component ($v_{\perp}$)
- the magnitude of the external magnetic field ($|\vec{B}|$)

The magnitude of the deflecting force can be calculated using this equation:

$$|\vec{F}_{\mathrm{m}}| = qv_{\perp}|\vec{B}|$$

where q is the magnitude of moving charge in coulombs (C); $v_{\perp}$ is the component of the speed perpendicular to the magnetic field in metres per second (m/s); and B is the magnitude of the external magnetic field in teslas (T). Example 12.1 describes how to calculate the magnetic force on a charge moving perpendicular to an external magnetic field.

When the velocity of the charge is not perpendicular to the magnetic field, you can use trigonometry to find the perpendicular component:

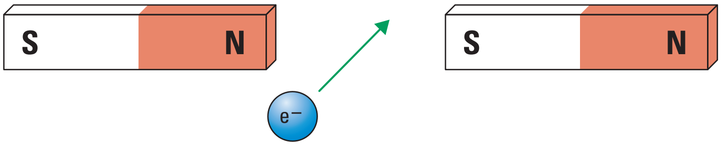


$$v_{\perp} = v \sin \theta$$

where θ is the angle between the charge's velocity, $\vec{v}$, and the magnetic field, $\vec{B}$.

Example 12.1

An electron is travelling at 3.20×10^5 m/s perpendicular to an external magnetic field of magnitude 2.20×10^{-1} T (Figure 12.22). Determine the magnetic force acting on the electron.



▲ **Figure 12.22**

Given

q = charge on 1 electron = -1.60×10^{-19} C

$|\vec{B}| = 2.20 \times 10^{-1}$ T

$v_{\perp} = 3.20 \times 10^5$ m/s

Required

magnetic force ($\vec{F}_{\text{m}}$)

Analysis and Solution

Determine the magnitude of the magnetic deflecting force:

$$|\vec{F}_{\text{m}}| = qv_{\perp}|\vec{B}|$$
$$= (1.60 \times 10^{-19}\ \text{C})(3.20 \times 10^5\ \tfrac{\text{m}}{\text{s}})(2.20 \times 10^{-1}\ \text{T})$$
$$= 1.13 \times 10^{-14}\ \text{N}$$

Since the charge is negative, use the left-hand rule for deflection to determine the direction of the magnetic force.

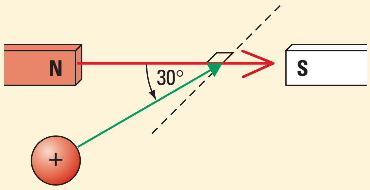
- Thumb points in the direction of the charged particle's movement, into the page.
- Extended fingers point in the direction of the external magnetic field, to the right of the page (north to south).
- Palm points in the direction of the magnetic deflecting force, toward the top of the page.

Paraphrase

The magnetic force is 1.13×10^{-14} N [upward] (toward the top of the page).

Practice Problems

1. A proton with a charge of 1.60×10^{-19} C is travelling with a speed of 3.50×10^4 m/s perpendicularly through an external magnetic field of magnitude 4.20×10^{-4} T. Determine the magnitude of the magnetic deflecting force on the proton.
2. An ion with a charge of $+3.20 \times 10^{-19}$ C and a speed of 2.30×10^5 m/s enters an external magnetic field of 2.20×10^{-1} T, at an angle of 30°, as shown in the figure below. Calculate the magnitude of the magnetic deflecting force on the ion.



3. A negatively charged sphere travels from west to east along Earth's surface at the equator. What is the direction of the magnetic deflecting force on the sphere?

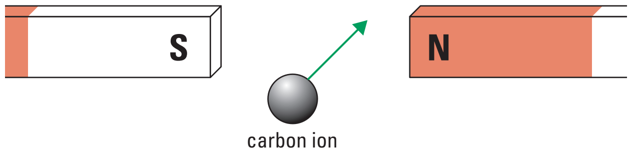
Answers

1. 2.35×10^{-18} N
2. 8.10×10^{-15} N
3. Downward toward Earth's surface

Often, a charged particle may be influenced by a combination of two fields, such as a magnetic field and a gravitational field, or a magnetic field and an electric field. "Crossed-field" devices are technologies that use both magnetic and electric fields. An example is the magnetron, which produces microwaves in microwave ovens.

Example 12.2

A carbon ion, with a mass of 2.01×10^{-26} kg and a positive charge of magnitude 1.60×10^{-19} C, enters the region of an external magnetic field of magnitude 6.32×10^{-5} T, as shown in Figure 12.23. Find the perpendicular speed at which the magnetic deflecting force will balance the gravitational force such that the carbon ion will travel in a straight line.



▲ **Figure 12.23**

Given

$m = 2.01 \times 10^{-26}$ kg

$|\vec{B}| = 6.32 \times 10^{-5}$ T

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

$g = 9.81$ N/kg

Required

speed (v) at which the magnitudes of the magnetic force, $|\vec{F}_m|$, and the gravitational force, $|\vec{F}_g|$, are equal

Analysis and Solution

The gravitational force on the carbon ion has a magnitude of $|\vec{F}_g| = mg$ and is directed downward (toward the bottom of the page).

The magnetic force on the carbon ion has a magnitude of $|\vec{F}_m| = qv_\perp|\vec{B}|$ and must be directed upward (toward the top of the page).

$$|\vec{F}_{net}| = |\vec{F}_m| - |\vec{F}_g|$$

But the magnetic deflecting force and the gravitational force balance (Figure 12.24), so $|\vec{F}_{net}| = 0$. Therefore,

$$\begin{aligned}
|\vec{F}_m| &= |\vec{F}_g| \\
qv_\perp|\vec{B}| &= mg \\
v_\perp &= \frac{mg}{|\vec{B}|q} \\
&= \frac{(2.01 \times 10^{-26}\ \cancel{\text{kg}})\left(9.81\ \frac{\text{N}}{\cancel{\text{kg}}}\right)}{(6.32 \times 10^{-5}\ \text{T})(1.60 \times 10^{-19}\ \text{C})} \\
&= 1.95 \times 10^{-2}\ \text{m/s}
\end{aligned}$$

▲ **Figure 12.24**

Paraphrase

The carbon atom will travel in a straight line if its speed is 1.95×10^{-2} m/s.

Practice Problems

1. An electron, with a charge of magnitude 1.60×10^{-19} C and a mass of 9.11×10^{-31} kg, is travelling west along the surface of Earth at the equator. If the magnitude of the magnetic field at this location is 5.00×10^{-5} T, what minimum speed must the electron maintain to remain at the same height above Earth's surface?
2. Ions, with a charge of 1.60×10^{-19} C and a mass of 8.12×10^{-26} kg, travel perpendicularly through a region with an external magnetic field of 0.150 T. If the perpendicular speed of the ions is 8.00×10^4 m/s, determine
   (a) the magnitude of the deflecting force on the ion
   (b) the radius of curvature of the motion of the deflected ion

Hint: The magnetic deflecting force is the centripetal force.

$$\begin{aligned}
|\vec{F}_m| &= |\vec{F}_c| \\
qv_\perp|\vec{B}| &= \frac{mv^2}{r}
\end{aligned}$$

Answers

1. 1.12×10^{-6} m/s
2. (a) 1.92×10^{-15} N
   (b) 0.271 m

In this section, you have studied the deflection of a moving charged particle in a magnetic field. Applying this science, you learned not only the importance of this phenomenon in technologies, such as a television and a magnetron, but also the significance of this phenomenon in protecting Earth from harmful cosmic radiations. The magnetic field of Earth, in deflecting dangerous charged particles from striking Earth's surface, also produces one of the most beautiful and spectacular natural light shows—the aurora.

12.2 Check and Reflect

Knowledge

1. Why is a cathode ray called a cathode ray?
2. What is the difference between a magnetic field vector arrow and a magnetic field line?
3. An electron and a proton, both with the same perpendicular velocity, enter a region with a uniform external magnetic field. What can you state about the deflections of both particles?
4. Describe the key differences in how magnetic and electric fields affect a moving charged particle.

Applications

5. A positively charged lithium ion is travelling horizontally along Earth's surface. Describe the deflection due to the magnetic force if the ion travels
   (a) south to north
   (b) east to west
   (c) upward into the atmosphere
6. A proton with a speed of 2.00×10^5 m/s enters an external magnetic field of magnitude 0.200 T. Calculate the magnitude of the deflecting force if the proton enters
   (a) perpendicular to the magnetic field
   (b) at an angle of 35.0° to the field
7. A 0.020-g metal ball with a charge of -3.0 μC is thrown horizontally along Earth's equator. How fast must the ball be thrown so that it maintains the same height, during its motion tangential to Earth's surface, if the magnitude of Earth's magnetic field is 5.0×10^{-5} T?
8. An alpha particle, with a charge of $2 \times 1.60 \times 10^{-19}$ C, is travelling perpendicularly through a magnetic field of magnitude 2.00×10^{-2} T at a speed of 1.02×10^{-5} m/s. What minimum gravitational force is required to suspend the alpha particle at the same position above Earth's surface?
9. Electrons in the picture tube of a television are accelerated to a speed of 1.30×10^6 m/s. As they travel through the tube, they experience a perpendicular magnetic field of magnitude 0.0700 T. What is the radius of deflection of the electrons in the tube?
10. A cosmic ray proton travelling through space at 4.38×10^6 m/s deflects in a circular arc with a radius of 5.50×10^6 m. What is the magnitude of the magnetic field at that point in space?

Extensions

11. Why are auroras seen only at higher latitudes?

eTEST

To check your understanding of moving charges and magnetic fields, follow the eTest links at www.pearsoned.ca/school/physicssource.

12.3 Current-carrying Conductors and Magnetic Fields

info **BIT**

The first sensitive meter to measure small currents was developed by Luigi Galvani in the 1700s. While dissecting a frog's leg, he noticed that an electric current caused the frog's leg to twitch. He realized that he had accidentally discovered a method of detecting small currents and used this discovery to design the galvanometer.

▲ **Figure 12.25** A galvanometer and an electric motor, like the one in this lawn mower, apply magnetic fields produced by a flow of charge.

Two of the most common applications of magnetic fields acting on moving charged particles are meters (such as ammeters, voltmeters, and galvanometers) and electric motors (Figure 12.25). Although these technologies appear to be different from the technology of the television, the basic operating principle of all these technologies is similar. Recall from earlier science studies that a galvanometer is a device for detecting and measuring small electric currents. How does a galvanometer operate? How is its operation similar to the technologies of the electric motor and television?

Electric Current

current: the quantity of charge that flows through a wire in a given unit of time

ampere: the flow of 1 C of charge past a point in a conductor in 1 s

Recall from earlier science courses that electric **current** is the movement of charged particles. It can be defined more precisely as the quantity of charge that flows through a wire in a given unit of time.

The unit for current, the **ampere** (A), is a measure of the rate of current. The ampere is an SI base unit. A current of 1 A is equivalent to the flow of 1 C of charge past a point in a conductor in 1 s. In other words, 1 A = 1 C/s. For example, the effective value of the current through a 100-W light bulb is about one ampere (1 A) of current. The ampere is named in honour of the French scientist André-Marie Ampère (1775–1836), who is renowned for his analysis of the relationship between current and magnetic force.

This equation shows the relationship between current and charge:

$$I = \frac{q}{t}$$

where I is the current in amperes, q is the magnitude of charge in coulombs, and t is the time elapsed in seconds.

Example 12.3

Calculate the current in a wire through which 20.0 C of charge passes in 4.00 s.

Given

$q = 20.0\ \text{C}$

$t = 4.00\ \text{s}$

Required

current (I)

Analysis and Solution

To calculate the current, use the equation

$$I = \frac{q}{t} = \frac{20.0\ \text{C}}{4.00\ \text{s}} = 5.00\ \frac{\text{C}}{\text{s}} = 5.00\ \text{A}$$

Paraphrase

The current in the conducting wire is 5.00 A.

Practice Problems

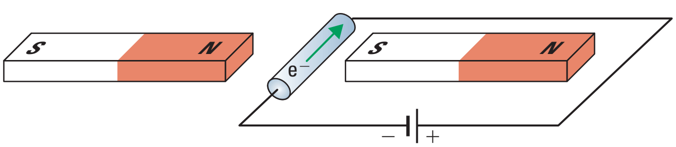
1. A lightning strike transfers 20.0 C of charge to the ground in 1.00 ms. Calculate the current during this lightning strike.
2. If the current in a household appliance is 5.00 A, calculate the amount of charge that passes through the appliance in 10.0 s.

Answers

1. 2.00×10^4 A
2. 50.0 C

Magnetic Force on a Current-carrying Conductor

In a CRT picture tube, powerful external magnetic fields are used to deflect moving electrons to produce an image on a screen. To analyze the operation of a galvanometer or electric motor, and to reveal the similarity of their operation to that of a television, consider the movement of electrons as a current in a wire conductor. When there is an electric current in a wire that is perpendicular to an external magnetic field, each electron experiences a magnetic force caused by the interactions of its own magnetic field and the external magnetic field (Figure 12.26). You can observe the effect of this force. The magnetic force causes the electrons to deflect upward. However, the electrons cannot escape the wire, so if the magnetic force on the electrons is great enough, the whole wire will rise upward, opposite to the force of gravity. The magnetic force on a conducting wire is the same as the magnetic deflecting force on a moving charge ($\vec{F}_m$) that you studied in section 12.2.



▲ **Figure 12.26** A current of electrons passes through a conducting wire lying perpendicular to an external magnetic field.

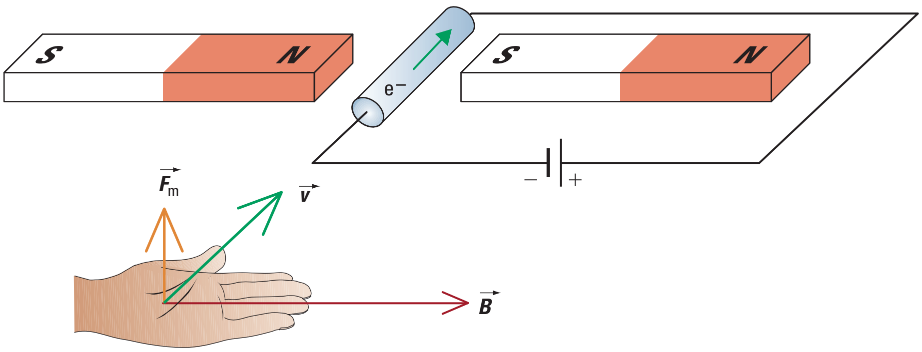
Left-hand Rule for Magnetic Force

PHYSICS INSIGHT

Remember: If the moving charges are negative, use your left hand; and if the moving charges are positive, use your right hand.

To determine the direction of the magnetic force, you can use the left-hand rule, as shown in Figure 12.27:

- Your thumb indicates the direction of electron flow in the conductor.
- Your extended fingers point in the direction of the external magnetic field.
- Your palm indicates the direction of the magnetic deflecting force on the wire.

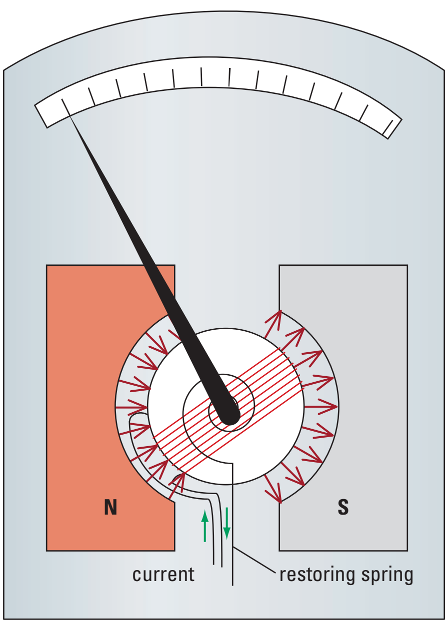


▲ **Figure 12.27** The left-hand rule for determining the direction of magnetic force

To calculate the magnitude of the magnetic force for a length of current-carrying conducting wire, use the equation

$$|\vec{F}_m| = Il_{\perp}|\vec{B}|$$

where I is the current measured in amperes; $l_{\perp}$ is the length of the wire perpendicular to the magnetic field in metres; B is the magnitude of the external magnetic field in teslas; and $|\vec{F}_m|$ is the magnitude of the magnetic force in newtons.



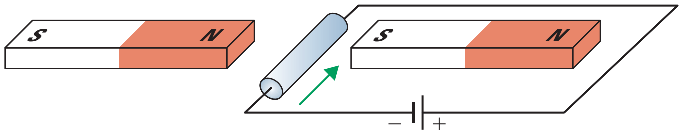
▲ **Figure 12.28** A schematic diagram of a galvanometer reveals all the essential components in its operation.

The Galvanometer

In the operation of the galvanometer, a coil of wire is mounted to allow for movement within the strong magnetic field of the permanent magnet (Figure 12.28). The coil turns against a spring with an attached needle pointing to a calibrated scale. When there is a current in the coil, the magnetic forces cause the coil to rotate. The greater the current, the greater the rotation, as registered on the scale by the needle. The galvanometer, which measures very small currents, can be made to measure larger currents (ammeter) by connecting a small resistance in parallel, and to measure larger potential differences (voltmeter) by connecting a large resistance in series. The magnetic force produced on a current-carrying wire can be demonstrated in the 12-4 QuickLab on page 606.

Example 12.4

An 8.50-cm length of conducting wire lies perpendicular to an external magnetic field of magnitude 4.20 mT, as shown in Figure 12.29. If there is a negative charge flow of 2.10 A in the conductor, calculate the magnitude and determine the direction of the magnetic force on the wire.



▲ **Figure 12.29**

Given

$l_{\perp} = 8.50 \text{ cm} = 8.50 \times 10^{-2} \text{ m}$

$|\vec{B}| = 4.20 \text{ mT} = 4.20 \times 10^{-3} \text{ T}$

$I = 2.10 \text{ A}$

Required

magnitude and direction of the magnetic force on the wire ($\vec{F}_{\mathrm{m}}$)

Analysis and Solution

Determine the magnitude of the magnetic force:

$$\begin{aligned} |\vec{F}_{\mathrm{m}}| &= Il_{\perp}|\vec{B}| \\ &= (2.10 \text{ A})(8.50 \times 10^{-2} \text{ m})(4.20 \times 10^{-3} \text{ T}) \\ &= 7.50 \times 10^{-4} \text{ N} \end{aligned}$$

Use the left-hand rule to determine the direction of the magnetic force, because the moving charges are negative:

- Thumb points in the direction of the charge movement or current, into the page.
- Extended fingers point in the direction of the external magnetic field, to the right of the page (north to south).
- Palm points in the direction of the magnetic force, to the top of the page.

Paraphrase

The magnetic force is 7.50×10^{-4} N [upward] (toward the top of the page).

Practice Problems

1. A 0.500-m length of conducting wire carrying a current of 10.0 A is perpendicular to an external magnetic field of magnitude 0.200 T. Determine the magnitude of the magnetic force on this wire.
2. A thin conducting wire 0.75 m long has a mass of 0.060 kg. What is the minimum current required in the wire to make it "float" in a magnetic field of magnitude 0.15 T?

Answers

1. 1.00 N
2. 5.2 A

12-4 QuickLab

Demonstration of a Current-carrying Conductor in a Uniform Magnetic Field

Problem

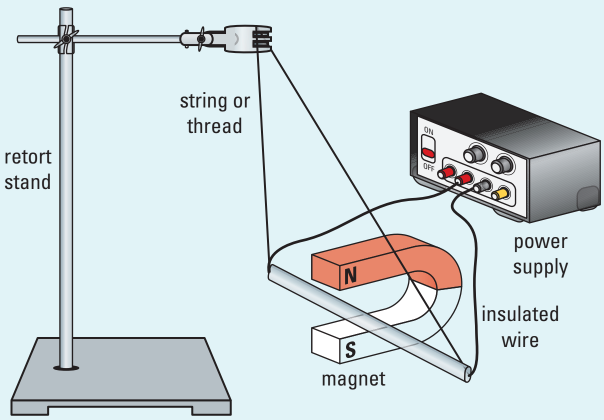
How does a uniform magnetic field affect a current-carrying conductor?

Materials

1 piece of stiff insulated conducting wire (6–8 cm long)
2 alligator clips
1 U-shaped magnet
thread or light string
retort stand and clamp
variable low-voltage DC power supply with ammeter

Procedure

1. Set up the apparatus as shown in Figure 12.30.



▲ **Figure 12.30**

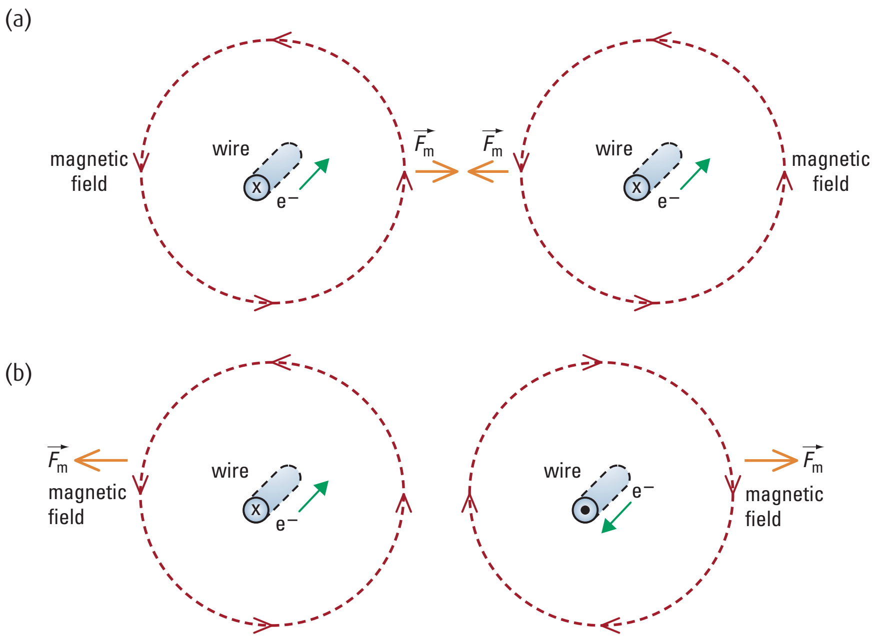
2. Carefully increase the current (amperage) from the power supply.
3. Observe any effects on the current-carrying conductor.

Questions

1. Describe any effects on the current-carrying conductor that occurred as the current through the conducting wire increased.
2. Does the hand rule verify the direction of the movement of the conducting wire? Explain which hand rule must be used.
3. What is the effect of an external magnetic field on a current-carrying conductor?
4. Based on what you have just observed, design a lab that would demonstrate the effects of a uniform magnetic field on a current-carrying conductor.

Magnetic Forces Between Two Current-carrying Conductors

After Oersted demonstrated that a current-carrying conductor creates a magnetic field around a conductor, the French scientist André-Marie Ampère performed extensive studies to determine the magnitude of the magnetic field at any point surrounding a current-carrying conductor. In addition to his mathematical analysis of magnetic fields, he is also noted for determining that two current-carrying conductors exert magnetic forces on each other. The charged particles in one wire are affected by magnetic forces when placed in the magnetic field of another current-carrying wire. Currents in the same direction attract each other (Figure 12.31(a)), and currents in opposite directions repel each other (Figure 12.31(b)).



▲ **Figure 12.31** From the left-hand rule for magnetic fields, the red dashed arrows indicate the orientation of the magnetic field around each wire. Use the left-hand rule for magnetic force to determine how the wires will move relative to each other. (a) When currents are in the same direction, the wires attract each other. (b) When currents are in opposite directions, the wires repel each other.

Through careful experimentation and measurement, Ampère was able to determine that the magnetic force between two current-carrying conductors depends on all of the following:

- the length of the conducting wire
- the distance between the two conducting wires
- the amount of current in each wire

The SI unit for current is named in honour of Ampère's work. This unit, the ampere, is now defined as the current required in each of two current-carrying wires, 1 m long and separated by 1 m in air, to produce a force of 2×10^{-7} N of magnetic attraction or repulsion. As you learned at the beginning of this section, an ampere is equivalent to the flow of 1 C of charge in 1 s. So, 1 A = 1 C/s, and 1 C = 1 A•s.

Concept Check

In intricate electrical circuits, two conducting wires carrying currents in opposite directions are usually crossed. What is the purpose of this crossing procedure?

12-5 Design a Lab

Using the Current Balance to Measure the Magnetic Force Between Two Current-carrying Conducting Wires

The Question

How can you use a current balance to investigate the factors that influence the magnetic force acting on two current-carrying conducting wires?

Design and Conduct Your Investigation

Study the operation of the current balance in your laboratory and design an experimental procedure to investigate the factors that determine the magnetic force acting on two current-carrying conducting wires. In your experimental design:

- Identify the factors that determine the magnetic force acting on two current-carrying conductors.
- Write an "if/then" hypothesis statement that predicts how changes in the variable affect the magnetic force.
- Clearly outline the procedure you will perform to investigate the relationship of each factor on the magnetic force.
- Describe what you will measure and how the data will be recorded and analyzed.
- Explain how the data will be used to answer the question.

As a group, identify and designate tasks. Prepare a report that describes your experimental design and present it to your teacher. After approval, conduct the investigation and answer the question. How well did your results agree with your hypothesis?

info BIT

Advancements in technology make it possible to construct extremely small electric motors. Today, 1000 of the smallest electric motors could fit in the period at the end of this sentence.

The Electric Motor

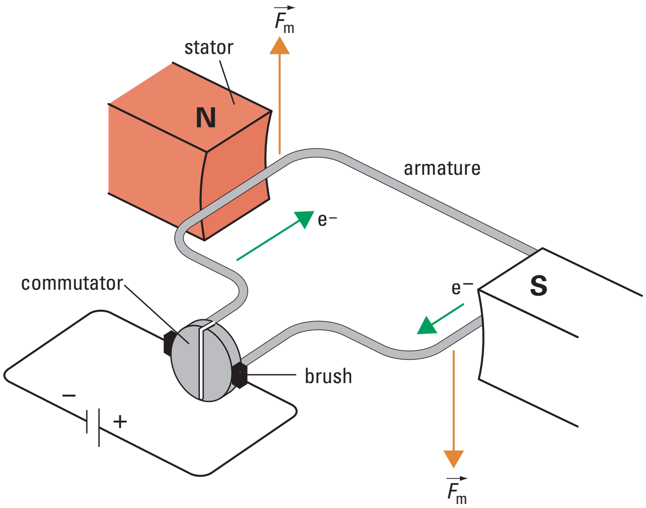
The most important application of the effect of an external magnetic field on current-carrying conductors is the electric motor. Figure 12.32 illustrates a simple electric motor that works with a current-carrying wire loop between two magnetic poles. The current is in one direction. Recall from earlier science studies that current in one direction is called a direct current (DC).

A simple DC electric motor consists of three fundamental components:

- a **stator**—a frame with a coil or permanent magnet to provide a magnetic field
- an **armature** or **rotor**—a rotating loop of conducting wire on a shaft
- a **commutator**—a split metal ring

commutator: a mechanism for maintaining a properly polarized connection to the moving coil in a motor or generator

As electrons in the current pass through the loop of wire in the armature in a clockwise direction (as seen from above in Figure 12.32), they experience a motor effect deflecting force. When you apply the left-hand rule for magnetic force, electrons on the left side of the loop experience a deflecting force upward, and electrons on the right side of the loop experience a deflecting force downward. The combined effect of both forces results in a rotation of the loop in a clockwise direction.



▲ **Figure 12.32** In a simple DC electric motor, the brushes provide a sliding contact between the wires from the battery and the armature. The magnetic field exerts an upward force on the left side of the wire loop and a downward force on the right side, causing the armature to rotate clockwise.

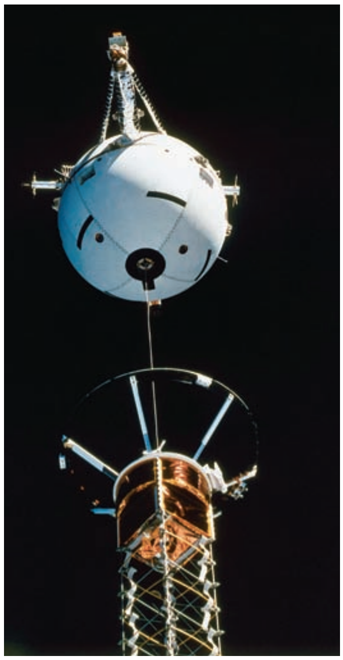
Concept Check

Describe the changes that must be made to the apparatus, shown in Figure 12.32, to cause the armature to rotate counterclockwise.

If the rotation of the loop is to continue, the direction of the motion of the electrons in the loop must change every half-rotation. To accomplish this, the armature is connected to a commutator. A commutator is a split metal ring that is fastened to both ends of the loop of wire in the armature. Each half of the metal ring acts as a contact to the terminals of a power supply. Every half-rotation, the leads of each side of the armature contact a different terminal, changing the direction of the electron movement. Once connected to a steady supply of moving electrons, the armature continues to rotate in one direction. This is the principle of a simple electric motor.

The Generator Effect (Electromagnetic Induction)

In 1996, NASA did an experiment that involved a satellite attached by a conducting tether wire to a NASA space shuttle orbiting in space around Earth (Figure 12.33). Researchers found that the combination generated a current of about 1 A through the wire. The experiment was of particular significance for space scientists because it showed that



▲ **Figure 12.33** A satellite tethered to a NASA space shuttle this procedure could provide a method of generating the electric energy necessary to power all the electrical components on a space vehicle.

This example is a useful and important application of a scientific phenomenon, but this phenomenon can also produce harmful effects in some situations. For example, engineers constructing the 1280-km north–south gas pipeline from Prudhoe Bay to Valdez in Alaska (Figure 12.34(a)) had to take precautions to eliminate the currents of electricity, called telluric currents, in the pipeline. These currents are caused by fluctuations in Earth's magnetic field. Special magnesium anodes were installed underground along the pipeline to ground it and eliminate the possibility of electrical sparks.

(a)

(b)

▲ **Figure 12.34** (a) A pipeline in Alaska; (b) An airplane in flight

Similarly, certain grounding conditions must be incorporated in the construction of an airplane to eliminate the current generated by the wings of an airplane in flight through Earth's magnetic field. These currents could affect the operation of all electrical components on the aircraft (Figure 12.34(b)). How are these examples related? What physical phenomenon is generating the current?

The examples described above all involve conductors moving through magnetic fields. The scientific explanation of how they generate electricity began with investigations over 200 years ago.

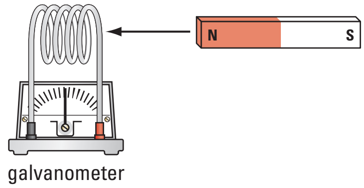
Faraday's and Henry's Discoveries

e **LAB**

For a probeware activity that demonstrates the principle of electromagnetic induction, go to www.pearsoned.ca/school/physicssource.

Most scientific discoveries are the result of many years of research and investigations. The process is often convoluted and results are often accidental. However, as you have learned, some scientific discoveries are a result of the symmetry of nature. This symmetry led Coulomb and Faraday to conclude that electrical and magnetic forces could be determined using inverse-square relationships similar to Newton's universal law of gravitation. Similarly, this symmetry in nature, and Oersted's discovery that electricity could produce magnetism, led scientists to predict that magnetism could produce electricity. Experiments conducted in 1831 by Michael Faraday in England and Joseph Henry (1797–1878) in the United States demonstrated this effect.

In a simplified version of their experiment, shown in Figure 12.35, a magnet is moved toward a coil of conducting wire connected to a sensitive galvanometer. When the magnet approaches the coil, the galvanometer's needle deflects in one direction, indicating that a current is being produced in the coil of wire. This current is called an induced current, which is produced by a generated voltage. When the magnet is pulled away from the coil, the galvanometer deflects in the opposite direction, indicating that the induced current in the coil is in the opposite direction. When the magnet is stationary, no current is induced. If the magnet were held stationary while the coil of wire was moved back and forth, similar induced currents would be produced. Evidently, it does not matter whether the magnet or the coil of wire moves, as long as there is relative motion between a coil of conducting wire and an external magnetic field.



▲ **Figure 12.35** When a magnet is moved toward a loop of wire connected to a galvanometer, the galvanometer needle deflects. This indicates that an induced current is being produced in the coil of wire.

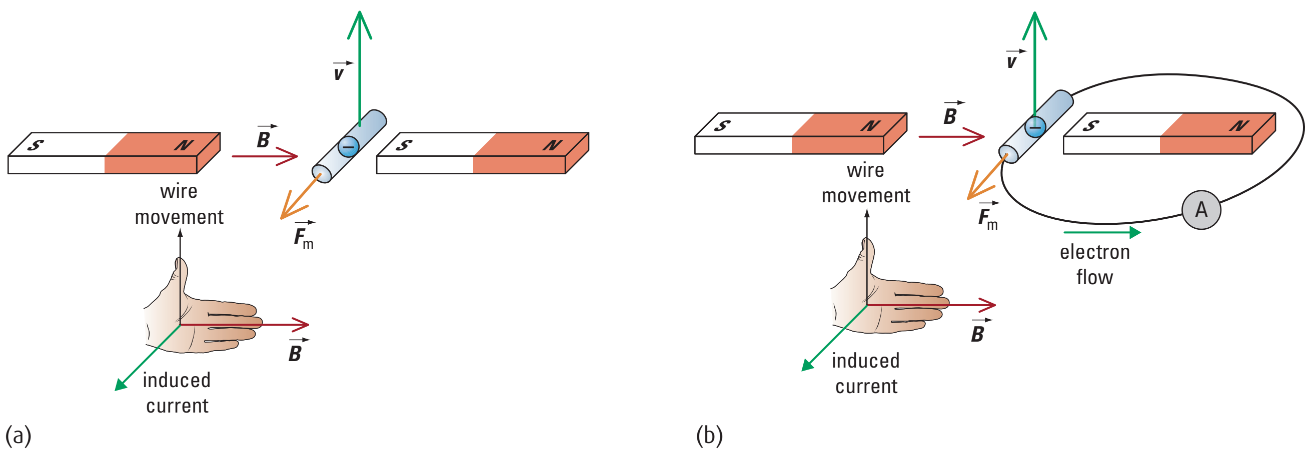
In their conclusions, Faraday and Henry stated that when a piece of conducting wire cuts through magnetic field lines, an induced current is produced. The production of electricity by magnetism is called the **generator effect** or **electromagnetic induction**. Figure 12.36(a) shows a piece of conducting wire being moved perpendicularly upward through an external magnetic field. As a result, electrons in the wire also move perpendicularly upward. Use the left-hand rule for magnetic force: If the wire is moving upward (thumb) through the external magnetic field (fingers), then each electron experiences a motor-effect force (palm). Electrons will gather at one end of the wire with stored electric energy from the work done on the system in moving the wire. Thus, one end of the wire has an accumulation of electrons with stored electric energy while the other end has a deficiency of electrons (Figure 12.36(a)).

generator effect or **electromagnetic induction:** production of electricity by magnetism

If this wire is part of an external circuit, as in Figure 12.36(b), the induced voltage causes a current to flow through the external wire. A difference in electric potential drives electrons through an external circuit, from a region of high electric potential to a region of lower electric potential.

Project **LINK**

How would you apply the principle of electromagnetic induction and the operation of commutators to construct a DC generator?



▲ **Figure 12.36** A current can be induced in a wire by moving the wire through a magnetic field.

12-6 Inquiry Lab

Magnetic Fields and Moving Conductors — Demonstration

Required Skills

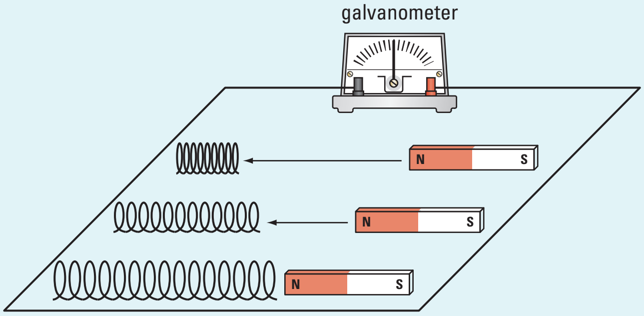
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Question

What factors influence the effect produced when there is relative motion between an external magnetic field and a conducting wire?

Materials and Equipment

2 bar magnets
3 different sizes of coils of conducting wire (the diameter of the coils should allow a bar magnet to be inserted)
galvanometer that can be projected onto a screen using an overhead projector



▲ **Figure 12.37**

Procedure

1. Set up the apparatus as shown in Figure 12.37.
2. Slowly push one bar magnet at a uniform speed into the largest coil. Then pull the bar magnet out in the opposite direction at the same speed. Observe the deflection of the galvanometer's needle in both cases.
3. Repeat step 2 with the other end of the magnet. Observe the deflection of the galvanometer's needle in both cases.
4. Repeat step 2, using two bar magnets. Observe the magnitude and direction of the galvanometer's deflection.
5. Repeat step 2, using two bar magnets at a faster speed through the largest coil. Observe the magnitude and direction of the galvanometer's deflection.
6. Repeat step 2, using two bar magnets at the same constant speed through the medium and the smaller coils of conducting wire. Observe the magnitude and direction of the galvanometer's deflection.

Analysis

1. How does the direction of the movement of the magnet affect the direction of the deflection of the galvanometer?
2. How does the polarity of the magnet affect the direction of the deflection?
3. Describe how each of the following factors influences the magnitude of the deflection of the galvanometer:
   (a) speed of the magnets through the conducting wire
   (b) strength of the external magnetic field
   (c) number of loops in the coil of conducting wire
4. What is the effect of relative motion between a conducting wire and a magnetic field?
5. Does it make any difference if the magnet or the conducting wire is moved?
6. What are the factors that determine the magnitude and direction of the induced current when there is relative motion between a conducting wire and an external magnetic field?
7. Based on your observations from this activity, design an experiment that demonstrates the effect of a uniform magnetic field on a moving conductor.

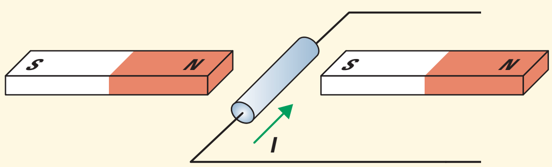
12.3 Check and Reflect

Knowledge

1. What are the factors that affect the magnetic force on a moving charge through an external magnetic field?
2. What are the factors that affect the magnetic force on a charge moving through a conducting wire in an external magnetic field?
3. What is the relationship between amperes and coulombs?
4. In the operation of a simple electric motor and simple electric generator, identify
   (a) a similarity
   (b) a difference
5. What symmetry in nature did Faraday and Henry apply in their discovery of electromagnetic induction?
6. What is the function of a split-ring commutator in the operation of a simple DC motor?
7. How do the electrons in a loop of wire in a generator gain energy?

Applications

8. A wire lying perpendicular to an external magnetic field carries a current in the direction shown in the diagram below. In what direction will the wire move due to the resulting magnetic force?



9. A battery supplies a current of 5.20 mA to a circuit. Determine the quantity of charge that flows through the circuit in 2.00 s.
10. Two conducting wires parallel to each other carry currents in opposite directions. Using the appropriate hand rule, determine whether the wires will attract or repel each other.
11. A wire 50 cm long and carrying a current of 0.56 A is perpendicular to an external magnetic field of 0.30 T. Determine the magnitude of the magnetic force on the wire.

Extension

12. Could a simple electric generator be converted to a simple electric motor? Suggest any alterations that must be made in the design.

e TEST

To check your understanding of current-carrying conductors and magnetic fields, follow the eTest links at www.pearsoned.ca/school/physicssource.

12.4 Magnetic Fields, Moving Charges, and New and Old Technologies

info BIT

Michael Faraday built the first electric motor in 1821. This motor had a stiff wire hanging from a stand. The lower end of the wire was immersed in a cup of mercury with a bar magnet upright in the middle. When current from a battery flowed through the wire, it rotated around the magnet.

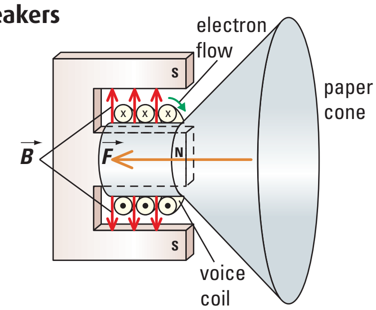
From the old technologies of the simple beginnings of electric motors, electric meters (such as galvanometers and ammeters), loudspeakers, and electromagnets to the new technologies of magnetohydrodynamic (MHD) propulsion systems and magnetic resonance imaging (MRI), the science of the production of magnetism by electricity plays a significant role in our everyday lives. Although examples of some of these technologies have been described in previous sections, following are other examples of old and new technological applications of this principle. Table 12.2 describes old and new technologies that use moving charges or current-carrying conductors to produce magnetic fields that can interact with external magnetic fields to produce powerful magnetic forces.

▼ **Table 12.2** Loudspeakers and MHD Propulsion

Old Technology	New Technology
Loudspeakers	**Magnetohydrodynamic (MHD) Propulsion**

Old Technology

Loudspeakers



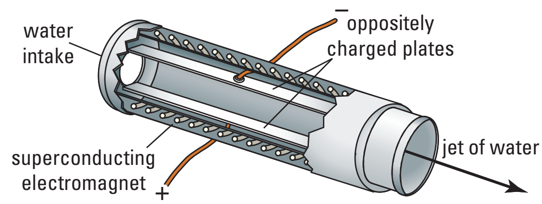
▲ **Figure 12.38** A simplified diagram of a loudspeaker

The operating principle of most loudspeakers is that current-carrying wires produce magnetic fields that can exert magnetic forces. In the design of the loudspeaker shown in Figure 12.38, a coil of wire, called a voice coil, surrounds the north pole of a very powerful external magnet at the back of the speaker. When your sound system sends an electric signal to the coil, a current is produced in the coil, which produces a magnetic field. As a result, the coil experiences a magnetic force due to the interaction of its magnetic field with the external magnetic field.

Depending on the direction of the current in the coil, the magnetic force of attraction or repulsion causes the coil to slide to the left or right. The direction of the current is determined by the electric signal produced by the sound system. As the voice coil slides back and forth, it causes the paper cone to vibrate in or out, creating sound waves as it pushes on the air in front of the cone. The electric signal from the sound system is thus converted to a mechanical sound wave in air.

New Technology

Magnetohydrodynamic (MHD) Propulsion



▲ **Figure 12.39** MHD uses magnetic fields as a propulsion system for seagoing vessels.

The MHD propulsion system is an experimental system for seagoing vessels to replace conventional propeller systems.

MHD uses magnetic fields to produce a jet of water for propulsion. Figure 12.39 is a simplified diagram of this type of system. A powerful superconducting magnet surrounds a thruster tube containing seawater. This magnet produces a magnetic field perpendicular to the tube's length. Inside the tube, electrodes produce a current of ions, perpendicular to the magnetic field, across the tube from the dissolved salts in seawater. As a result of the perpendicular movement of the ions through an external magnetic field, a magnetic force is exerted on the ions, causing them to deflect along the length of the tube. This movement of the water through the tube provides the necessary thrust to propel the vessel. An advantage of MHD propulsion systems is that they have no mechanical moving parts and thus require minimal maintenance.

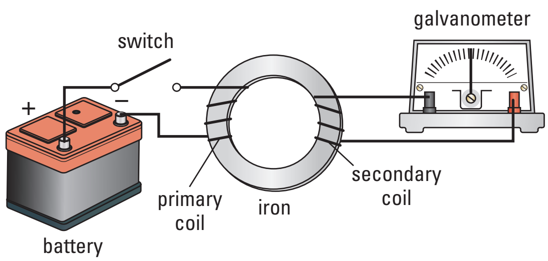
Generator Effect Applications

The discovery that moving a conducting wire through an external magnetic field generates an induced current in the conductor (generator effect) also led to many important technological applications. From the old technologies of the simple generators, induction coils, and transformers to the new technologies of infant breathing monitors and others, applications of the scientific principle of the production of electricity from magnetism are found everywhere in our lives. Table 12.3 describes two of these applications.

▼ **Table 12.3** Induction Coils, Transformers, and SIDS Monitors

<table>
<tr><th>Old Technology</th><th>New Technology</th></tr>
<tr>
<td>

Induction Coils



▲ **Figure 12.40** A simplified diagram of Faraday's induction coil

A change in the current in the primary coil produces a changing magnetic field in the iron core. This changing magnetic field produces an induced current in the secondary coil, causing the needle on the galvanometer to deflect. Such coils can induce current in a wire that has no direct connection to the power supply. Figure 12.40 shows a simplified version of Michael Faraday's original induction coil.

</td>
<td>

SIDS Monitors

▲ **Figure 12.41** Monitors are designed to detect changes in a baby's breathing.

In sudden infant death syndrome (SIDS), an infant stops breathing with no apparent cause. One type of SIDS monitor uses induced currents to measure an infant's breathing (Figure 12.41).

A coil of wire attached to one side of the infant's chest carries an alternating current, which produces a magnetic field. This alternating field cuts another coil taped to the other side of the chest and induces an alternating current in this other coil. As the chest moves up and down, the strength of the induced current varies. These variations are monitored.

</td>
</tr>
</table>

A Motor Is Really a Generator, Which Is Really a Motor

You have analyzed and studied the motor effect and the generator effect as separate phenomena in this chapter. However, the symmetry of nature suggests that related phenomena are really variations of the same effect. Since electricity can produce magnetism and magnetism can produce electricity, then perhaps the technologies that are derived from these phenomena are also similar. Is a motor really that different from a generator?

12-7 Inquiry Lab

The Curious Relationship Between Motors and Generators

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Question

What is the relationship between the motor effect and the generator effect?

Materials and Equipment

1 100-cm length of copper pipe (internal diameter approximately 1.4 cm)
1 cylindrical rare earth magnet (less than 1.4 cm in diameter)
1 metre-stick
1 stopwatch
1 scale

Procedure

1. Copy Table 12.4 into your notebook.

▼ Table 12.4 Data for *12-7 Inquiry Lab*

Mass of Magnet (m)(kg)	Length of Copper Pipe (Δd)(m)	Average Time Taken for the Magnet to Fall Through the Pipe (t)(s)

2. Measure the mass of the magnet on the scale, and record it in Table 12.4.
3. Measure the length of the copper pipe, and record it in Table 12.4.
4. Holding the pipe in a vertical position, drop the magnet from the exact top of the pipe. Measure the time for the magnet to reappear out the bottom. Record this time in the table.
5. Repeat the procedure in step 4 several times to obtain an average value for the time taken for the magnet to drop the length of the pipe.

Analysis

1. Copy Table 12.5 into your notebook. Use the data from Table 12.4 to complete the calculations in Table 12.5.

▼ Table 12.5 Calculations for *12-7 Inquiry Lab*

Magnitude of the Weight of the Magnet ($F_g = mg$) (N)	Magnitude of Acceleration of the Magnet Through the Copper Pipe $\left(a = \frac{2\Delta d}{t^2}\right)$ (m/s²)	Magnitude of Net Force Causing the Downward Acceleration of the Magnet ($F_a = ma$) (N)

2. What is the magnitude of the upward force on the falling magnet?
3. Identify and explain where the generator effect is occurring in this experiment.
4. Identify and explain where the motor effect is occurring in this experiment.
5. Do the generator effect and the motor effect complement each other as the magnet falls through the copper pipe? Explain your answer.

An Accidental Discovery

Simple DC electric motors and electric generators have three similar components:

- an external magnetic field
- a loop of conducting wire
- a commutator

At the 1873 Vienna Exhibition, the Belgian inventor Zénobe-Théophile Gramme (1826–1901) demonstrated a compact and efficient generator that he had designed. A steam engine provided the power to run the generator. A workman mistakenly connected the output of the generator to a second generator in the display. The shaft of the second generator began spinning even though it was not connected to the steam engine. Gramme immediately realized that the second generator was operating as a motor powered by the first generator.

Gramme and his colleagues then moved the generators several hundred metres apart and connected them with long wires. The American writer Henry Adams (1838–1918) described the importance of Gramme's demonstration: "Suddenly it became clear that ELECTRICITY could now do heavy work, transporting power through wires from place to place."

MINDS ON Perpetual Motion?

Suppose that a motor and generator are connected to the same shaft and wired such that the output of the generator powers the motor. If you spin the shaft, the generator supplies energy to the motor, which turns the shaft. The generator then produces more energy to run the motor. Explain why this process cannot continue indefinitely.

Lenz's Law

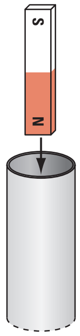
If you did the 12-7 Inquiry Lab, you discovered what happens when you drop a magnet down a metal tube. When a conductor cuts the magnetic field lines of a falling magnet, it generates an induced current in the conducting pipe (the generator effect). However, the induced current moves in a circular motion around the circular pipe, so it creates its own vertical magnetic field, inside the metal tube (the motor effect). The direction of the magnetic field can be directed either upward or downward. The direction of the magnetic field that is produced by the circular induced current in the pipe can have one of the following orientations:

- It will attract the magnet and cause it to fall faster, thus generating a greater induced current.
- It will repel and oppose the motion of the magnet, causing it to fall much slower.

The law of conservation of energy requires that you can never get more out of a system than you put into it. So, the direction of the new magnetic field will always oppose the motion of the magnetic field of the original magnet. This is the principle of **Lenz's law**, which states:

> The direction of a magnetically induced current is such as to oppose the cause of the current.

For example, if a magnet falls with its north pole directed downward, then the magnetic field produced by the induced current in the conducting pipe will have its north pole pointing upward to repel and oppose this motion.

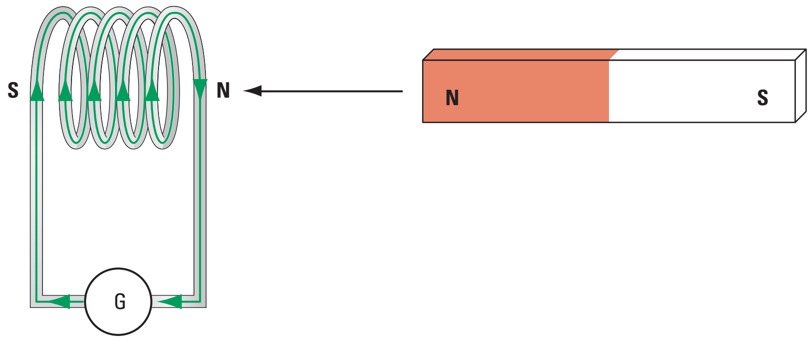


▲ **Figure 12.42** Dropping a magnet down a metal tube induces a current in the tube.

Concept Check

Copy Figure 12.42 into your notebook. Apply Lenz's law by sketching the direction of the induced current in the metal tube and the resulting orientation of the magnetic field in the tube. How would the induced current and magnetic field directions change if the falling magnet's south pole were directed downward?

Figure 12.43 shows a similar situation. As the north pole of a magnet approaches a coil of wire, the induced current generated in the coil produces a north pole to repel and oppose the approaching magnet.



▲ **Figure 12.43** Lenz's law helps us explain that the direction of current induced in the coil has a magnetic field that exerts a force on the bar magnet that opposes the magnet's motion.

MINDS ON Lenz's Law

Balance a dime on its edge on a smooth table. Carefully bring a magnet as close as 1 mm to the face of the dime. Quickly pull the magnet away.

What happens to the dime? How is this behaviour an application of Lenz's law?

The principle behind Lenz's law also hinders the operation of electric motors and generators. For an electric motor to operate, an electric current must first be supplied through a conducting loop of wire in a magnetic field, causing the motor effect, so the loop will rotate.

However, as the loop rotates, the conducting wire cuts the magnetic field lines, causing the generator effect. The generator effect induces a current in the loop of wire. The direction of the induced current must be in an opposing direction to the direction of the original current that was supplied. Similarly, to operate a generator, movement of a conducting wire in a magnetic field must be supplied, which will induce a current. However, as soon as the induced current moves through a conductor in a magnetic field, a force on the conducting wire will be produced that opposes the original force and hinders the movement of the conducting wire.

e WEB

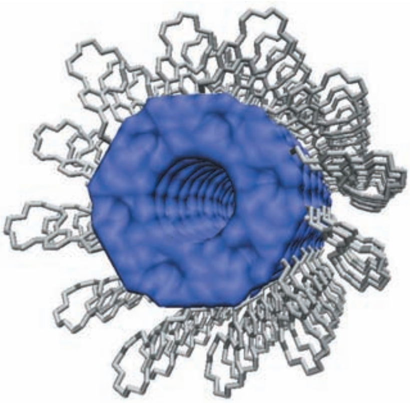
Research the relationship between Lenz's law and the operation of most vending machines. Write a short report analyzing the operation of vending machines, and describe whether they operate on the principles of Lenz's law and the generator effect or Lenz's law and the motor effect. In your description, include the term "eddy currents." Begin your search at www.pearsoned.ca/school/physicssource.

THEN, NOW, AND FUTURE Nanotechnology

Since the start of the Industrial Revolution and with advances in technology, machines have become increasingly smaller.

Scientists at University of California's Berkeley National Laboratory have developed the smallest synthetic electric motor ever made. Essentially, it is an electric rotor spinning on an axle 2000 times smaller than the width of a human hair. Imagine tiny electric motors so small that one motor could ride on the back of a virus, or thousands could fit in the period at the end of this sentence. This is the world of nanotechnology, which is an umbrella word that covers many areas of research and deals with objects that are measured in nanometres, or a billionth of a metre.

How do nanomachines work? As you have learned, conventional electric motors use electromagnets or strong external magnets to spin rotors made of loops of wire. The spinning of a rotor provides mechanical energy to do work. In the electric motor of nanotechnology, transistors act as switches to move negative and positive charges around a circle of electrodes. The charges jump around the stator electrodes, causing an electrically charged rotor to spin around and rotate a nanotube shaft. This spinning rotor provides mechanical energy, similar to a conventional electric motor.



▲ **Figure 12.44** A rosette nanotube

The nanomotor can perform only small functions, such as moving a second hand on a watch, but it has many advantages: It spins without gears or bearings; it is unaffected by gravity or inertia; and it can run for a long time with no breakdowns.

Another application of nanotechnology is the rosette nanotube, like the one shown in Figure 12.44. This type of tube was developed at the National Institute of Nanotechnology of the National Research Council, located at the University of Alberta. The nanotube is made of molecules that assemble themselves into this distinctive shape.

Possible future applications of these tubes include: nanowires in molecular electronics, drug delivery systems within the body, and environmentally friendly oil sands upgrading additives.

The potential of nanotechnology in electronics is now beginning to be realized and applied to many different fields. Imagine, for example, nanorobots that can be injected into the body to attack viruses and cancer cells.

In the future, it may even be possible to construct molecules of oil and gas, reducing our reliance on fossil fuels. The science of nanotechnology is the science of the future.

Questions

1. What are some advantages of nanotechnology?
2. Describe how a nanomotor works.
3. What could nanotubes be used for?

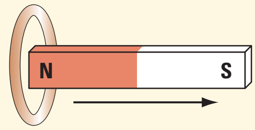
12.4 Check and Reflect

Knowledge

1. Identify two technological applications that employ
   (a) the motor effect
   (b) the generator effect
2. What are the three basic components of an electric motor and generator?
3. What is Lenz's law?

Applications

4. For an electric motor:
   (a) Describe what you must supply to start the operation of the device.
   (b) Describe what you get out of the operation of the device (motor effect).
   (c) Using Lenz's law, explain how the operation of the motor also produces the generator effect to hinder its own operation.
5. For an electric generator:
   (a) Describe what you must supply to start the operation of the device.
   (b) Describe what you get out of the operation of the device (generator effect).
   (c) Using Lenz's law, explain how the operation of the generator also produces the motor effect to hinder its own operation.
6. Explain why you will feel a force of repulsion if you attempt to move a magnet into a coil of wire.
7. The north pole of a magnet is pulled away from a copper ring, as shown in the diagram below. What is the direction of the induced current in the ring?



Extensions

8. An electric motor requires a current in a loop of wire. However, as the loop rotates, it generates a current which, according to Lenz's law, must be in an opposing direction. Why must the induced current be in an opposing direction?
9. A hair dryer operates on a very small current. If the electric motor in the hair dryer is suddenly prevented from rotating, the dryer overheats. Why?

e TEST

To check your understanding of magnetic fields, moving charges, and new and old technologies, follow the eTest links at www.pearsoned.ca/school/physicssource.

Key Terms and Concepts

law of magnetism
magnetic field
electromagnet
solenoid
ferromagnetic
domain
motor effect force
current
ampere
commutator
generator effect
electromagnetic induction
Lenz's law

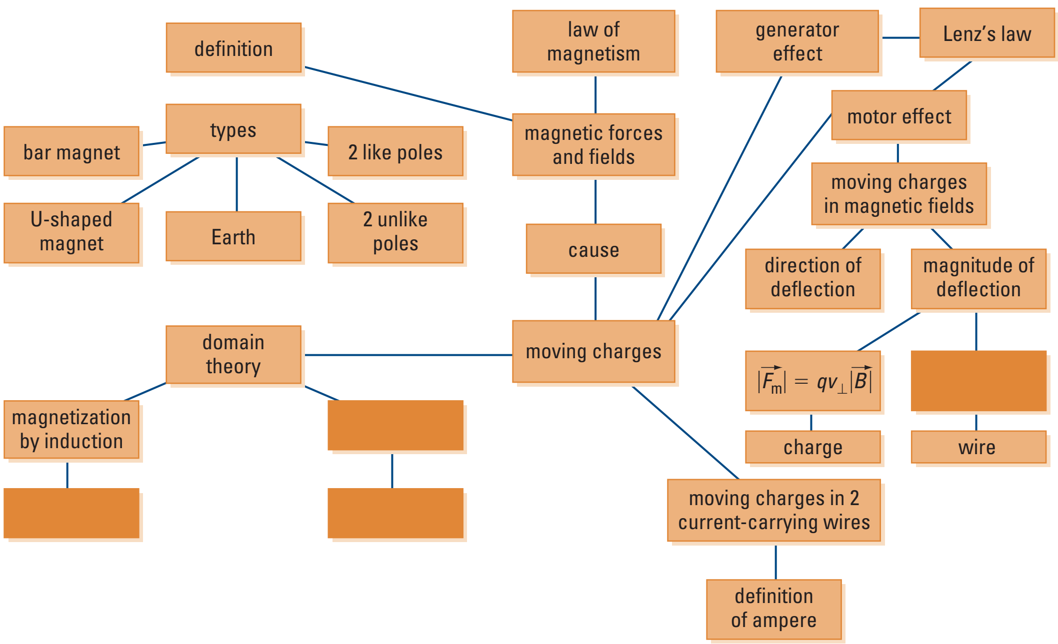
Key Equations

$|\vec{F}_m| = qv_{\perp}|\vec{B}|$

$|\vec{F}_m| = Il_{\perp}|\vec{B}|$

Conceptual Overview

The concept map below summarizes many of the concepts and equations in this chapter. Copy and complete the map to have a full summary of the chapter.



CHAPTER 12 REVIEW

Knowledge

1. (12.1) State the major contribution of each of the following scientists to the study of magnetism:
   (a) William Gilbert
   (b) Hans Christian Oersted
   (c) André Ampère
   (d) Michael Faraday
2. (12.1) State the definition of
   (a) a magnetic field
   (b) the direction of a magnetic field
3. (12.1) Compare a magnetic vector arrow at a point near a magnet and a magnetic field line around a magnet.
4. (12.1) How was it determined that there had to be two different types of magnetic poles?
5. (12.1) Sketch the magnetic field lines around each of the following objects and describe the differences in the magnetic fields of
   (a) a bar magnet and Earth
   (b) a current-carrying straight piece of conducting wire and a current-carrying coil of conducting wire
6. (12.2) Identify the sources of the two magnetic fields required to produce the motor effect force on a moving charge.
7. (12.2) Describe the deflection of a moving charge, through an external magnetic field, if the direction of the initial motion of the charge is
   (a) parallel to the external magnetic field lines
   (b) perpendicular to the external magnetic field lines
   (c) at an angle to the external magnetic field lines
8. (12.2) Where is a magnetic bottle formed?
9. (12.3) Describe a difference between a galvanometer and an ammeter.
10. (12.3) State two definitions for a current of one ampere.
11. (12.4) Identify two technologies that use the principles of
    (a) the motor effect
    (b) the generator effect
12. (12.4) What is the principle of Lenz's law?

Applications

13. Does every charged object necessarily have a positive and a negative charge? Does every magnetized object necessarily have a north and a south pole? Justify your answers.
14. If the direction of the magnetic field outside a magnet is from the north to the south pole, what is the direction of the magnetic field within the magnet?
15. Using domain theory, describe how an iron nail can become magnetic by
    (a) the process of magnetization by induction
    (b) the process of magnetization by contact
16. How will the magnetic force on a moving charged particle change if
    (a) only the charge is doubled?
    (b) the magnetic field is doubled and the speed is halved?
    (c) the mass of the charge is doubled?
17. Use domain theory to explain the difference between a permanent and a temporary magnet.
18. You are told that a straight piece of copper wire has a steady current in it. Given only a compass, describe how you can find the direction of the current in the wire.
19. A drinking straw with a green grape at one end is suspended by a string from a hanging support. When either end of a magnet is brought close to the grape, repulsion occurs. Describe a possible reason for this effect.
20. An electron in a TV tube is moving at 7.00×10^{6} m/s perpendicular to a magnetic field of magnitude 0.0880 T in the tube. What is the magnetic deflecting force on the electron?
21. A proton travelling at 35° to an external magnetic field of magnitude 0.0260 T experiences a force of magnitude 5.50×10^{-17} N.
    (a) Calculate the speed of the proton.
    (b) Calculate the kinetic energy of the proton in joules (J) and electron volts (eV).
22. What speed must an alpha particle maintain if it is to remain suspended, relative to Earth's surface, as it travels on a tangent to Earth's surface and perpendicularly through Earth's magnetic field of 50.0 μT?

23. An alpha particle travelling with a speed of 4.30×10^4 m/s enters a uniform magnetic field of 0.0300 T. Determine the magnetic force on the particle if it enters the field at an angle

(a) perpendicular to the magnetic field

(b) 30.0° to the magnetic field

(c) parallel to the magnetic field

24. A magnetic field is used to bend a beam of electrons. What uniform magnetic field is required to bend a beam of electrons moving at 1.2×10^6 m/s in a circular arc of 0.25 m?

25. Two parallel current-carrying wires are observed to attract each other. What is the source of the force of attraction? How could you demonstrate that the force of attraction is not electrostatic attraction?

26. The magnetic force between two magnets was measured as the distance between the magnets was varied. The following information was obtained:

Separation, r ($\times 10^{-2}$ m)	Magnitude of Force, F (N)
5.00	4.02
10.00	1.01
15.00	0.45
20.00	0.25
25.00	0.16

(a) Draw a graph of the magnetic force as a function of separation distance.

(b) From the shape of the graph, what is the relationship between force and separation?

27. An airplane is flying east over Earth's magnetic north pole. As a result of its motion, one wing was detected as having more electrons than the other. Explain why this phenomenon occurs. Identify which wing will have more electrons.

28. A power line carries a current of 500 A. Find the magnetic force on a 100-m length of wire lying perpendicular to Earth's magnetic field of 50.0 μT.

Extensions

29. A magnet is dropped through two similar vertical tubes of copper and glass. Which tube will allow the magnet to fall faster? Explain your answer.

30. A disk magnet on a table has two steel balls in contact with it on either side. The steel balls are slowly moved toward each other while still in contact with the disk magnet. As they move, they repel each other. Describe why the steel balls are attracted to the disk magnet, but repel each other.

Consolidate Your Understanding

Create your own summary of properties of magnetic and electric fields by answering the questions below. If you want to use a graphic organizer, refer to Student Reference 3: Using Graphic Organizers. Use the Key Terms and Concepts listed on page 621 and the Learning Outcomes on page 580.

1. Create a flowchart to identify technological devices that use electric fields, magnetic fields, or a combination of the two fields to control moving charges.

2. Write a paragraph comparing the effects of electric or magnetic fields on moving charges. Share your report with a classmate.

Think About It

Review your answers to the Think About It questions on page 581. How would you answer each question now?

e TEST

To check your understanding of the properties of electric and magnetic fields, follow the eTest links at www.pearsoned.ca/school/physicssource.

Building a Model of a Direct Current Generator

Scenario

The search for better electrical energy production began with the pioneering work of Faraday and Henry in the 1800s and continues today. Over half of the energy consumed in our world is electrical energy and the average consumption per person is increasing every year, so more efficient methods of electrical energy production are being sought all the time.

All DC electrical generators consist of three major parts: coils of wire wrapped around a core to make the armature, a commutator, and an external magnetic field. As you learned in this unit, the operating principle behind generators is the movement of a conducting wire through external magnetic field lines so that a voltage is generated in the wire. This in turn induces a current in an external line. All DC generators operate in this fashion.

The only difference among generators is the source of the mechanical energy required to turn the turbines that rotate the coil of wires in the magnetic field. In some places, this is the energy of falling water or tides, while in others it is the energy of moving steam from the combustion of fossil fuels or nuclear reactions. Recently, interest has grown in using wind energy to turn the turbines that operate a generator. A single wind generator can produce about 10 MW of electrical power, which is sufficient for a single small farm.

The purpose of this project is to research and investigate the operation of a wind-powered electrical generator and to build a model of a wind-powered DC generator capable of generating enough electricity to operate a mini-bulb.

Planning

Form a team of four or five members, and decide on and plan the required tasks to complete the project. These tasks may include researching the design of a simple generator, obtaining the necessary materials, constructing the model of the generator, preparing a written report, and presenting the project to the entire class.

Assessing Results

Assess the success of your project based on a rubric* designed in class that considers:

- research strategies
- thoroughness of the experimental design
- effectiveness of the experimental technique
- effectiveness of the team's public presentation

Materials

- insulated copper wire
- iron core
- split-ring commutator
- external magnets
- connecting wires
- mini-bulb with support base
- stiff paper to construct a turbine
- balsa wood for the axle
- household fan to produce wind

Procedure

1. Using the Internet, library, or other resources, research the operation of a simple DC electrical generator and create a design of the model that you will construct. Pay special attention to the commutator required for DC generation.
2. Construct a working model of the generator that can provide the electrical energy to light a mini-bulb. In your model, investigate the factors that determine the magnitude of the generated voltage.
3. Prepare a report explaining the design and the specific functions of all the components.

Thinking Further

1. What modifications did you make in the construction of your model of a generator that affected the magnitude of the generated voltage?
2. What other type of commutator could you have used in the design of your generator? What type of current would be induced by this commutator?
3. Identify at least three risks and three benefits of a wind-powered electrical generator.
4. Is wind-powered electrical generation a viable and desirable method of electrical energy generation for the future? Explain your answer.

*Note: Your instructor will assess the project using a similar assessment rubric.

UNIT VI SUMMARY

Unit Concepts and Skills: Quick Reference

Concepts	Summary	Resources and Skill Building
Chapter 10	**Physics laws can explain the behaviour of electric charges.**	
	10.1 Electrical Interactions	
Modern theory of electrostatics	Substances can be classified as conductors, insulators, semiconductors, and superconductors. Objects may be charged through the processes of friction, conduction, and induction.	10-1 QuickLab 10-2 Inquiry Lab
	10.2 Coulomb's Law	
Coulomb's law	Coulomb's law states that the electrical force acting on charged objects depends on the charges and the distance between the charges.	10-3 Inquiry Lab Examples 10.1, 10.2
Vector analysis	Electrostatic forces can be solved in one- and two-dimensional situations using vector analysis.	Examples 10.3–10.6
Chapter 11	**Electric field theory describes electrical phenomena.**	
	11.1 Forces and Fields	
Fields	Fields are used to explain action at a distance.	11-1 QuickLab, 11-2 Inquiry Lab
Electric field	An electric field is a three-dimensional region of influence surrounding every charge. Electrostatic force affects another charge placed in the field. The electric field is a vector quantity that has magnitude and direction.	Examples 11.1–11.4
	11.2 Electric Field Lines and Electric Potential	
Electric field lines	Electric field lines can depict the electric fields around different types of charged objects.	Minds On activities, eSIM
Electric potential energy	Electric potential energy is the amount of work done on a charged object to move it from infinity to a position in an electric field. Electric potential energy can be calculated.	Examples 11.5, 11.6
Electric potential	Electric potential is the amount of electric potential energy stored per unit charge and can be calculated.	Example 11.7
Electric potential difference	When a charge moves from a location where it has one electric potential to a location where it has another electric potential, the charge experiences an electric potential difference.	Example 11.8
	11.3 Electrical Interactions and the Law of Conservation of Energy	
Motion of a charge in an electric field	When a charge is placed in an electric field, it experiences a force that causes it to accelerate in the direction of the field. The acceleration of the charge is different in a non-uniform field surrounding a point charge than the acceleration of the charge in the uniform field between charged plates. Work done by the system on the charge increases the charge's potential energy, which can be converted to other forms of energy.	Examples 11.10–11.12
Chapter 12	**Properties of electric and magnetic fields apply in nature and technology.**	
	12.1 Magnetic Forces and Fields	
Magnetic fields	Magnetic fields are three-dimensional regions of magnetic influence surrounding every magnet in which other magnets or magnetic substances are affected by magnetic forces. Magnetic fields are vector fields and can be depicted by magnetic field lines.	12-1 QuickLab, 12-2 QuickLab
Cause of magnetism	The cause of magnetism is motion of charges and can be explained using the domain theory. If the motion of charges is straight, the magnetic field is circular. If the motion of charges is circular, the magnetic field is straight within the loop. The direction of the magnetic field lines can be described using hand rules.	Figure 12.10
Magnetizing objects	Objects can be magnetized through contact or induction.	Concept Check
	12.2 Moving Charges and Magnetic Fields	
Motor effect on a moving charge	A charge moving perpendicularly through an external magnetic field experiences a magnetic force due to two magnetic fields, which can be calculated. This motor effect force can explain the operation of electric motors and other technologies. The magnitude of the motor effect force can be calculated and its direction can be determined using hand rules.	12-3 Inquiry Lab Examples 12.1, 12.2
	12.3 Current-carrying Conductors and Magnetic Fields	
Motor effect on two current-carrying wires	A current-carrying conductor that is perpendicular to an external magnetic field experiences a magnetic force that can be calculated.	Example 12.4 12-4 QuickLab 12-5 Design a Lab
Generator effect	A conductor moving perpendicular to an external magnetic field can produce electricity.	12-6 Inquiry Lab
	12.4 Magnetic Fields, Moving Charges, and New and Old Technologies	
Applications of the generator effect and the motor effect	The generator effect and the motor effect are used in many technologies.	12-7 Inquiry Lab
Lenz's law	Lenz's law explains how a motor is really a generator and a generator is really a motor.	Minds On

UNIT VI REVIEW

Vocabulary

1. Use your own words to define the following terms, concepts, principles, or laws. Give examples where appropriate.

ampere
charge migration
charge shift
charging by induction
commutator
conduction
conductor
coulomb
Coulomb's law
current
domain
electric field line
electric potential (voltage)
electric potential difference
electric potential energy
electromagnet
electromagnetic induction
electron volt
electrostatics
ferromagnetic
field
generator effect
grounding
induction
insulator
law of conservation of charge
law of magnetism
Lenz's law
magnetic field
motor effect force
net charge
plasma
semiconductor
solenoid
source charge
superconductor
test charge

Knowledge

CHAPTER 10

2. Explain why silver is a better conductor of electricity than rubber.

3. State a technological advantage of developing materials that are superconductors.

4. A negatively charged rubber rod is brought near a small metal ball hanging from an insulated thread. The metal ball is momentarily grounded, and then the ground and the rubber rod are removed. Identify the procedure used to charge the metal ball, and determine the final charge on the metal ball.

5. Describe a similarity and a difference between

(a) charging by friction and charging by conduction

(b) charge shift and charge migration

6. In each of the following examples, identify the charge on each object and state the method of charging the object.

(a) An ebonite rod is rubbed with fur and then is held near a neutral metal sphere.

(b) A glass rod is rubbed with silk and then is touched to a neutral metal sphere.

7. During the rubbing process of charging objects, one object gains a net negative charge. What can you conclude about the charge on the other object? Explain why.

8. How do the following factors affect the electrostatic force of attraction between two charged objects?

(a) amount of charge on each object

(b) distance between the centres of the two objects

(c) sign of the charge on each object

CHAPTER 11

9. State the superposition principle as it applies to vector fields.

10. Why must a test charge be small when it is used to determine the direction of an electric field around a larger primary charge?

11. Draw the electric field lines around
   (a) a negative point charge
   (b) a positive charge and a negative point charge in the same region
   (c) a negatively charged cone-shaped object
12. Why is there no net electric field inside a charged hollow sphere?
13. Explain the following statement: "It is impossible to shield against gravitational fields, but it is possible to shield against electric fields."
14. Draw a diagram showing two small, equally charged, positive spheres a small distance apart. On your diagram, identify a point A where the electric field is zero and a point B where the electric potential is zero.
15. Describe how electric potential energy changes for positive and negative charges as they move, relative to the reference point at infinity.
16. Two oppositely charged parallel plates are connected to a 120-V DC supply. What happens to the magnitude of the electric field between the plates if the distance between the plates decreases?
17. Describe the following for a point a small distance from a positively charged sphere:
   (a) the magnitude and direction of the electric field at this point
   (b) the electric potential energy of another small positive charge placed at this point
   (c) the electric potential at this point
18. Describe the relationship between the work done in moving a charge from one region in an electric field to another region, and the energy gained by the charge. What law governs this relationship?

CHAPTER 12

19. Draw a diagram of the magnetic field around a bar magnet and Earth.
   (a) List the similarities between the two fields.
   (b) List the differences between the two fields.
20. Explain why a single magnetic pole cannot exist by itself.
21. Describe two simple demonstration techniques used to outline the magnetic field around a magnet.
22. Justify the following statement: "A charge moving perpendicular to a uniform external magnetic field experiences a force but does not change its speed."
23. Show how a charge moving through an external magnetic field experiences a deflecting force because of the interaction of two magnetic fields.
24. A positively charged disk is spinning in a clockwise direction as seen from above. What is the direction of the magnetic field? Use a diagram to help you describe its shape.
25. Describe the shape and direction of the magnetic field around a negatively charged dart as it travels directly away from you toward a target on a wall.
26. What factors affect the magnetic force on a charge moving through an external magnetic field?
27. State a difference and a similarity between the motor effect and the generator effect.
28. Describe how Lenz's law affects the operation of
   (a) a motor
   (b) a generator

Applications

29. An insulator and a conductor are each contacted by a negatively charged rubber rod. Describe the distribution of charge on each object.
30. Describe how Earth's surface can become positively charged during a thunderstorm. In your description, include the terms "charging by friction" and "charging by conduction."
31. Assume you have only a negatively charged ebonite rod. Describe a procedure for charging a neutral electroscope
   (a) positively
   (b) negatively
32. Why does a negatively charged ebonite rod initially attract a piece of thread and then eventually push it away?
33. When you touch a Van de Graaff generator, your hair stands on end. Explain your answers to the following questions:
   (a) Are you being charged by friction, conduction, or induction?
   (b) Will the same effect occur if you are grounded?

34. A negatively charged ebonite rod is brought near a neutral pith ball hanging on an insulating thread. Describe what happens to the charges in the pith ball and the resulting effect

(a) before the rod and the pith ball touch

(b) after the rod and the pith ball touch

35. A straight length of conducting wire, lying horizontal to the surface of Earth, delivers a current in a direction from south to north. Describe the deflection of a compass needle held directly over the conducting wire.

36. A negatively charged foam plastic ball is hanging from an insulated thread. Another negatively charged ball is brought near, on the same horizontal plane, and the hanging ball swings away so that the supporting thread makes an angle of 30° to the vertical.

(a) Draw a free-body diagram depicting the tension force by the string, the force of gravitational attraction, and the electrical force of repulsion on the hanging ball.

(b) If the system is in equilibrium, identify the force that balances the gravitational force on the hanging ball and the force that balances the electrostatic force of repulsion on the hanging ball.

37. Explain how the properties of selenium are essential in the operation of a photocopier.

38. Explain the difference between charge shift and charge migration during the process of charging by induction.

39. The cell membrane of a neuron may be thought of as charged parallel plates. The electric potential difference between the outside and the inside of the membrane is about 0.70 V. If the thickness of the membrane is 5.0×10^{-9} m, calculate

(a) the magnitude of the electric field between the outside and the inside of the membrane

(b) the amount of work necessary to move a single sodium ion, Na^{+1}, with a charge of 1.6×10^{-19} C, across the membrane

40. In a chart, compare the similarities and differences between Newton's law of universal gravitation and Coulomb's law of electrostatics.

41. Determine the distance between two electrons if the mutual force of repulsion acting on them is 3.50×10^{-11} N.

42. A neutral small hollow metal sphere is touched to another metal sphere with a charge of -3.00×10^{-2} C. If the two charges are then placed 0.200 m apart, calculate the electrostatic force acting on the two spheres after they touch.

43. A football-shaped hollow conducting object is charged negatively.

(a) Draw the object and then draw the charge distribution on the surface of the object.

(b) Draw the electric field lines surrounding the object.

(c) Where will the intensity of the electric field appear to be the greatest?

(d) Explain how this effect can be used to describe the operation of a lightning rod.

44. A car with a vertical antenna is driven in an easterly direction along the equator of Earth.

(a) Describe how a current is induced in the antenna.

(b) Determine the direction of the induced current.

45. A small charge of $-2.0\ \mu$C experiences an electric force of 3.0×10^{-5} N to the left when it is placed in the electric field of another larger source charge. Determine the strength of the electric field at this point.

46. Calculate the kinetic energy gained by a proton that is allowed to move between two charged parallel plates with a potential difference of 2.0×10^4 V. What maximum speed could the proton acquire?

47. Two spheres with charges of $+4.00\ \mu$C and $+3.00\ \mu$C are placed 0.500 m apart. At what point between the two charges must a third charge of $-2.00\ \mu$C be placed so that the net electrostatic force acting on this charge is zero?

48. Two oppositely charged parallel plates have a voltage of 2.5×10^4 V between them. If 1.24 J of work is required to move a small charge from one plate to the other, calculate the magnitude of the charge.

49. A wire that is 0.30 m long, lying perpendicular to an external magnetic field of magnitude 0.50 T, experiences a magnetic force of 0.11 N. Determine the current in the wire.

50. A charge of $+3.0 \times 10^{-6}$ C is placed 0.50 m to the right of another charge of -1.5×10^{-5} C. Determine

(a) the net electric field at a point midway between the two charges

(b) the electrostatic force of attraction acting on the two charges

51. Touching a Van de Graaff generator can result in a painful shock. If a small length of conducting wire is bent into an L-shape and taped to the ball of the generator, so that a shaft of wire projects outward, you will not get a shock when you touch the ball.

(a) How does the ball of the generator initially acquire a negative charge?

(b) What process of charging objects is involved in the painful shock you receive initially?

(c) How does the shaft of wire that is taped to the ball prevent a shock?

(d) What is the function of the conducting strips projecting from the airplane wing tip shown in the photo below?

52. A small foam plastic ball with a mass of 0.015 kg and coated with a conducting material is suspended by a string 0.75 m long. If the ball is initially given a charge of magnitude 1.5×10^{-8} C, and another charged ball with a charge of magnitude 2.5×10^{-8} C is brought near, the hanging ball swings to a position 1.0 cm from its equilibrium position. Calculate the electrostatic force of repulsion acting on the two charges. Draw a free-body diagram.

53. The largest electric field that can exist between two oppositely charged plates with an air gap between them is 3.00×10^{6} N/C. If this electric field limit is exceeded, then a discharge of charge occurs between the plates, resulting in a spark. If the voltage between the plates is 500 V, what is the minimum distance between the plates before a spark occurs?

54. An electron with a mass of 9.11×10^{-31} kg and a charge of magnitude 1.60×10^{-19} C is 5.29×10^{-11} m from a proton with a mass of 1.67×10^{-27} kg and a charge of magnitude 1.60×10^{-19} C. Calculate

(a) the gravitational force of attraction between the two masses

(b) the electrical force of attraction between the two charges

(c) how many times greater the electrical force is than the gravitational force

55. An alpha particle, a proton, and an electron, travelling at the same speed, enter regions with external fields. Compare the motion of these particles as they travel perpendicularly through the same

(a) magnetic field

(b) electric field

(c) gravitational field

56. Given ebonite and glass rods and strips of fur and silk, describe the procedure to charge an electroscope negatively by

(a) conduction

(b) induction (include the grounding step)

57. A particle with a mass of 2.00×10^{-26} kg and a charge of magnitude 6.40×10^{-19} C is fired horizontally along the surface of Earth in an easterly direction. If the particle passes through a metal detector with a magnetic field of 2.00×10^{-4} T in a northerly direction, at what speed must the charged particle be travelling so that the magnetic force counteracts the gravitational force of Earth on the particle at this position? What is the charge of the particle?

58. A helium ion (He^{+2}) with a charge of 3.20×10^{-19} C and a mass of 6.65×10^{-27} kg is injected with a speed of 3.00×10^{6} m/s perpendicularly into a region with a uniform magnetic field of 3.30 T.

(a) Calculate the magnitude of the deflecting force on the helium ion.

(b) If this deflecting force causes the helium ion to travel in a circular arc, what is the radius of the arc?

59. Sphere A, with a charge of $+3.50\ \mu$C, is 4.35 cm to the left of sphere B, with a charge of $-2.44\ \mu$C. Calculate the net electrostatic force on a third sphere C, with a charge of $+1.00\ \mu$C, if this sphere is placed

(a) midway on a line joining charges A and B

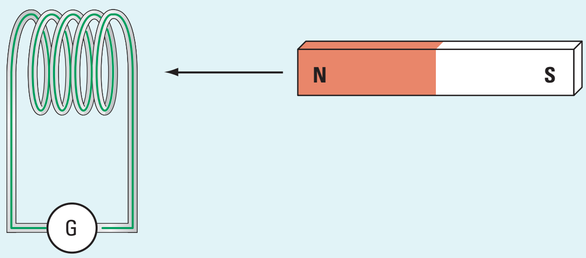
(b) at a point 2.50 cm to the right of charge B

(c) at a point 2.50 cm directly down from charge B

60. Calculate the potential difference required to accelerate a deuteron with a mass of 3.3×10^{-27} kg and a charge of magnitude 1.6×10^{-19} C from rest to a speed of 8.0×10^{5} m/s.

61. A uniform electric field of 7.81×10^6 N/C exists between two oppositely charged parallel plates, separated by a distance of 3.20 mm. An electron, initially at rest and with a mass of 9.11×10^{-31} kg, is injected into the electric field near the negative plate and accelerates toward the positive plate. The electron passes through a "hole" in the positive plate and then travels perpendicularly through an external magnetic field with a magnitude of 1.50 T.
   (a) What is the voltage between the oppositely charged plates?
   (b) Calculate the maximum speed acquired by the electron between the plates. Ignore relativistic effects.
   (c) Determine the magnetic force on the electron as it passes through the magnetic field.
   (d) Describe the motion of the electron through the electric field and then through the magnetic field.

62. A bar magnet is moved toward a coil of wire that is connected to a sensitive galvanometer, as shown in the figure below.



   (a) Explain what happens to the galvanometer readings as the north pole of the bar magnet approaches the coil of wire.
   (b) Describe how Lenz's law influences the movement of the magnet toward the coil of wire.
   (c) Explain what happens to the galvanometer readings as the north pole of the magnet is pulled out of the coil of wire.
   (d) Describe how Lenz's law influences the movement of the magnet away from the coil of wire.

Extensions

63. Explain why computer hard disks are encased in metal.

64. Explain why it is safe to remain inside a vehicle during a lightning storm.

65. Are gravitational, electrical, or magnetic forces responsible for the formation of a black hole in space? Explain your answer.

66. Why must technicians who work on very sensitive electronic equipment be grounded?

67. Describe why Earth's magnetic field creates a "magnetic bottle."

68. Charged particles in cosmic rays from the Sun are trapped in Earth's magnetic field in two major radiation belts, called Van Allen radiation belts. The first belt is about 25 500 km and the other is about 12 500 km above the surface of Earth. Explain why spacecraft must avoid these radiation belts.

69. Compare the motion of a negatively charged particle as it travels through a gravitational, electric, or magnetic field in a direction
   (a) perpendicular to the field
   (b) parallel to and in the same direction as the field

70. Why is lightning more likely to strike pointed objects than rounded objects on the ground?

71. Describe the process by which the steel beams in a high-rise building can become magnetized. Why does this effect not happen in homes built with wood beams?

72. High-voltage power lines operate with voltages as high as a million volts. Explain why a bird can perch on a power line with no effect, but must be careful not to touch two nearby power lines.

73. Explain the difference between the dip angle and the angle of declination of Earth's magnetic field. How do these two angles affect the operation of a directional compass in Alberta?

74. An electron is at rest. Can this electron be set in motion by a magnetic field? Explain your answer.

75. Given only a loop of wire connected to a sensitive galvanometer, describe a simple experiment that could be conducted to prove the existence of a changing magnetic field near a high-voltage power line.

76. The image of the magnetotactic bacterium, as seen under a microscope, reveals a row of magnetite crystals within its cellular structure. Make a hypothesis regarding the purpose of this row of magnetite crystals, and design and describe an experiment to test your hypothesis.

Skills Practice

77. Draw a Venn diagram to review the similarities and differences between electric and magnetic fields.

78. Design an experiment to determine the direction of gravitational, magnetic, and electric fields.

79. Construct a concept map for solving a two-dimensional electrostatic force problem involving three charges at the corners of a triangle.

80. Design an experiment to show that electrostatic forces vary with the inverse square law.

81. A current-carrying wire has a magnetic field surrounding it. The strength of this magnetic field can be found using the formula $|\vec{B}| = \frac{\mu I}{2\pi r}$, where $|\vec{B}|$ is the magnitude of the magnetic field surrounding the wire, in teslas, μ is the constant of permeability for space, in T•m/A, I is the current in the wire, in amperes, and r is the distance to the wire, in metres. An experiment is performed to establish the value of the constant, μ. The current was constant through the wire at 5.00 A, and the strength of the magnetic field was measured at various distances from the wire. The data recorded are given in the table below.

Distance from the wire, r (m)	Magnitude of the magnetic field, $\lvert\vec{B}\rvert$ (T)
0.100	6.28
0.200	3.14
0.300	2.09
0.400	1.57
0.500	1.26

(a) Plot a graph to determine the relationship between $|\vec{B}|$ and r.

(b) What is the relationship between $|\vec{B}|$ and r?

(c) What quantities need to be graphed in order to straighten the graph?

(d) Complete a new table of values to straighten the graph.

(e) Plot a new graph with the variables needed to straighten the graph.

(f) Use the graph-slope method and the data from the graph to determine the value of μ.

(g) Use the formula-data substitution method to determine the value of μ.

Self-assessment

82. Describe to a classmate which field concepts and laws you found most interesting when studying this unit. Give reasons for your choices.

83. Identify one topic pertaining to fields studied in this unit that you would like to investigate in greater detail.

84. What concept in this unit did you find most difficult? What steps could you take to improve your understanding?

85. Assess how well you are able to explain electric potential energy and electric potential. Explain to a classmate how you determine a reference point.

e **TEST**

To check your understanding of forces and fields, follow the eTest links at www.pearsoned.ca/school/physicssource.