8.1 Magnets and Electromagnets

You probably became familiar with magnets by playing with them when you were a child. You learned that magnets are attracted to some materials but not to others. In this section, you will learn about magnetic materials and how some of these materials deep inside Earth produce Earth's magnetic field. You will also learn how a magnetic field surrounds all magnets and how moving electric charges produce a magnetic field.

Auroras

Imagine going camping in northern Canada, and on your first night you look up and see bright greenish-white ribbons of light stretching across the night sky. The glowing lights, shown in **Figure 1**, are in motion, rippling up and down. What causes these lights to appear? Why do they move and swirl?

Figure 1 The aurora borealis flashes green light over the northern skyline.

The swirls of lights that you see in the sky are the aurora borealis. The same phenomenon in the southern hemisphere is called the aurora australis. One reason these auroras appear is because Earth exhibits the properties of a large magnet. A magnetic field surrounds Earth as if Earth were a bar magnet. Recall from Grade 11 that magnetic fields are strongest at the poles and that magnetic field lines fan out from Earth's south pole and converge at Earth's north pole. A stream of charged particles called the solar wind escapes the Sun's gravity and flows past Earth. Charged particles entering Earth's magnetic field travel in spiral paths along the magnetic field lines toward the poles, where they spiral down the field lines toward Earth's surface. In the upper atmosphere, the charged particles collide with oxygen and nitrogen atoms. These collisions energize the gas atoms. The atoms then release their extra energy as light that we see as the auroras. When you see the lights of the aurora borealis, you are really watching the interplay of electricity and magnetism. WEB LINK

Permanent Magnets

magnetic field line one of a set of lines drawn to indicate the strength and direction of a magnetic field

The first observations of magnetic fields involved materials that can easily be magnetized, called permanent magnets. Permanent magnets are used in numerous devices, such as compass needles, refrigerator magnets, speakers, and some motors. **Figure 2(a)** shows a permanent magnet made in the shape of a bar, with small iron filings sprinkled around the bar magnet. The magnetic field of the bar magnet, indicated by $\vec{B}$ in the figure, is not visible, but the iron filings follow imaginary lines, called **magnetic field lines**, corresponding to the magnetic field's strength and direction. **Figures 2(b)** and **(c)** show how the magnetic fields of two magnets interact when the magnets are close together. The poles of a magnet are analogous to positive and negative electric charges.

Just as opposite electric charges attract, opposite magnetic poles attract. The north pole (N) of one magnet attracts the south pole (S) of another magnet. The effect is different, however, when like poles approach each other. Two north poles repel each other, and two south poles repel each other. This is analogous to the way two positive electric charges or two negative electric charges repel each other, except that the magnetic poles are electrically neutral.

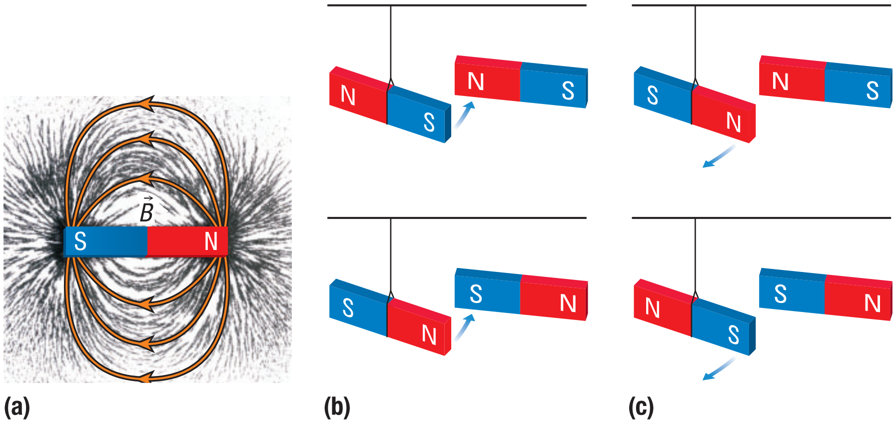

Figure 2 (a) The iron filings around the bar magnet show that the magnetic field $\vec{B}$ extends from the north pole of a magnet to the south pole. (b) The interaction of the magnetic fields of two magnets causes unlike poles to attract each other. (c) The interaction of the magnetic fields causes like poles to repel each other.

You can see in Figure 2(a) that the iron filings are crowded together near each pole. This crowding indicates that the magnetic field is strongest at the poles. Magnetic field lines move outward from the north pole of a magnet and inward toward the south pole. Opposite poles attract each other because the magnetic fields are oriented in opposite directions. Like poles repel each other because the magnetic fields are oriented in the same direction.

The attraction and repulsion of magnetic poles explain the alignment of the iron filings with the magnetic field lines of the bar magnet in Figure 2(a). Iron is a magnetic material; it produces a magnetic field in response to an applied magnetic field. Each magnetized iron filing has its own north and south poles. The north pole of each iron filing is attracted to the south pole of the large bar magnet and is repelled from the north pole. At the same time, the south pole of an iron filing is attracted to the north pole of the large bar magnet and is repelled from the south pole. These magnetic forces cause the iron filing to align parallel to the magnetic field lines and hence parallel to $\vec{B}$. This is similar to the situation with electric dipoles and electric fields (**Figure 3**), with an important difference. An electric field can result from a single charge. For example, the electric field of a single positive charge radiates outward from the charge. A magnetic field, however, will always result from a magnetic dipole. There will always be a north pole and a south pole producing the magnetic field. You can never have only a south pole or only a north pole.

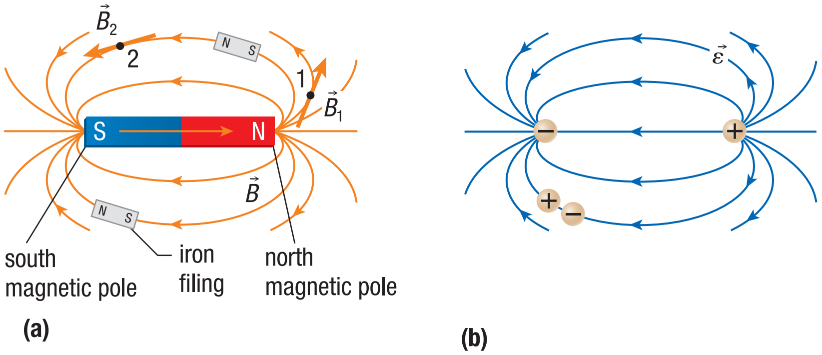

Figure 3 The magnetic field lines of a bar magnet are similar to the electric field lines of an electric dipole. (a) The iron filings align with $\vec{B}$. (b) The electric dipoles align with $\vec{\varepsilon}$.

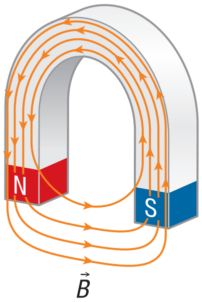

Figure 4 The magnetic field lines of a horseshoe magnet form closed loops pointing from the north pole to the south pole, just as they do with a bar magnet.

The magnetic field lines of a bar magnet extend from the north pole to the south pole outside the magnet and from south to north inside the magnet, forming a closed loop. Magnetic field lines always form closed loops. You can make a horseshoe magnet by simply bending a bar magnet (**Figure 4**). One end of the horseshoe magnet has a north pole, and the other end has a south pole. The field lines form closed loops as they circulate through the horseshoe. The field lines extend across the gap between the ends of the magnet so the direction of the field is from the north pole toward the south pole, just as it is with a bar magnet. The magnetic field strength is greatest in the gap between the poles. Magnets with horseshoe shapes have many applications, including in motors and generators.

Permanent magnets come in many shapes and sizes. Regardless of the shape of a magnet, the magnetic field lines form closed loops, the field lines point from the north pole toward the south pole, and the field is strongest at the poles.

Earth's Magnetic Field

The largest magnet on Earth is Earth itself. A compass needle is a small bar magnet mounted so that it can swivel freely about its centre (**Figure 5(a)**). Earth's magnetic field exerts a torque (twisting force) on this magnet. From experiments done with compass needles, William Gilbert, a sixteenth-century English scientist, reasoned that Earth acts as a very large, permanent magnet oriented as shown in **Figure 5(b)**.

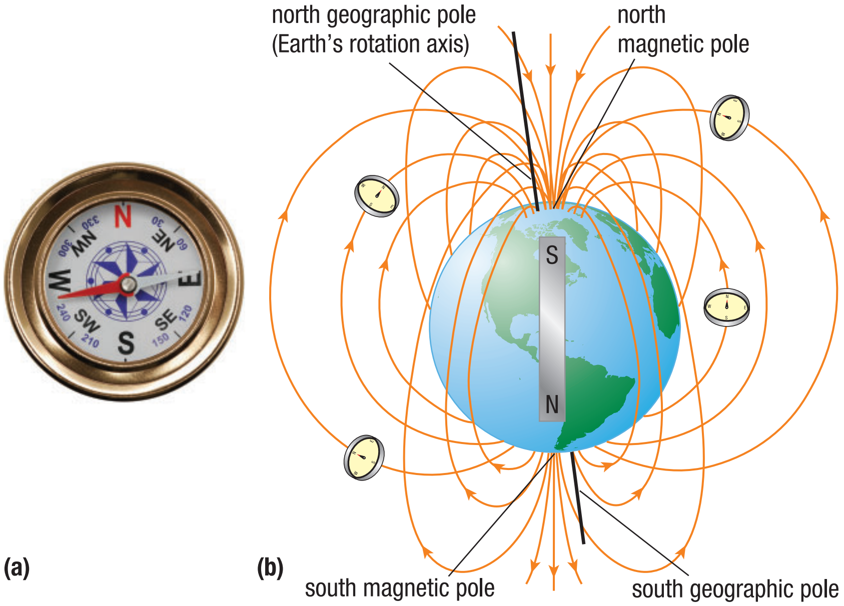

Figure 5 (a) A compass. (b) If we were to place compasses at different spots in Earth's magnetic field, each compass needle would be aligned parallel to the field.

Earth has two geographic poles, the north pole and the south pole, where Earth's axis of rotation meets Earth's surface. Every magnet, including Earth, has two magnetic poles, a north and a south pole. A compass needle aligns itself to point to Earth's magnetic poles. Earth's geographic poles are not exactly in the same location as its magnetic poles, but they are close enough that we can say that the north magnetic pole of a compass needle points approximately toward Earth's north geographic pole. This behaviour is why the poles of a bar magnet were given the names "north" and "south." Note: the north magnetic pole of one magnet (the compass needle) points to the south magnetic pole of a second magnet, so Earth's north geographic pole is actually a south magnetic pole. However, it is convention to refer to the north magnetic pole as Earth's north magnetic pole, even though it is a south pole of a magnet.

Our knowledge of what causes Earth's magnetic field is incomplete, but several clues point to an explanation. First, we know that Earth's magnetic poles do not quite coincide with its geographic poles. In fact, Earth's magnetic poles move slowly from day to day and year to year. For centuries Earth's magnetic north pole was in northern Canada (**Figure 6**). In 2011, the north magnetic pole was located at 84.7° N, 129.1° W, well within the Arctic Ocean, and was moving toward Russia at approximately 60 km per year. Second, geological studies show that Earth's magnetic field has completely reversed direction many times during the planet's history. The last reversal occurred about 780 000 years ago. In the years just before that time, the north pole of a compass needle would have pointed toward Earth's south magnetic pole.

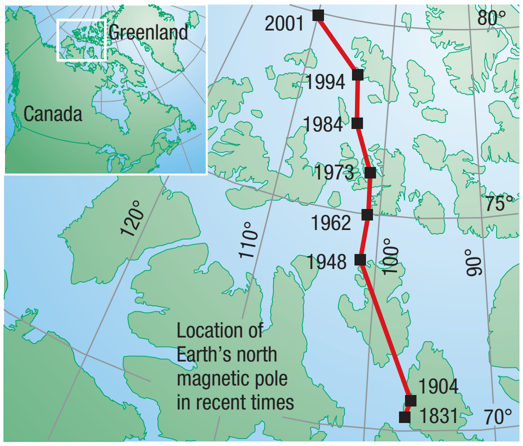

Figure 6 Earth's magnetic poles move from year to year. The north magnetic pole was near latitude 70° in northern Canada less than 200 years ago.

Electric currents in Earth's core probably cause this behaviour of the magnetic field. Earth's core is made of liquid metal. This liquid conducts electricity, and the spin of Earth about its axis causes the liquid to circulate much like the current in a conducting loop. The circulating current causes a magnetic field. Scientists believe that circulation within Earth's core has a complicated flow pattern that varies with time. These variations cause changes in the magnetic field, resulting in the movement of Earth's magnetic poles. Scientists still do not have a complete understanding of these phenomena, however. As is the case with any phenomenon that is not fully understood, more studies will take place and scientists' working theories will continue to be modified.

We usually think of the regions far above Earth's atmosphere between Earth, the Moon, and the Sun as empty. These regions actually contain many charged particles, including electrons and protons, that come from the Sun or from outside our solar system. Such particles are called cosmic rays. Earth's magnetic field affects their motion because they have electric charge. **Figure 7** shows two positively charged cosmic ray particles that approach Earth's equator.

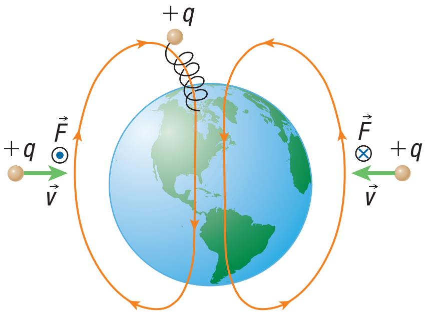

Figure 7 Earth's magnetic field affects the motion of cosmic rays. Cosmic ray particles at the poles spiral in along the field lines, while cosmic rays at the equator are deflected away from Earth. The circled x on the right of the figure indicates that the force is directed into the page for that particle. The circled dot on the left indicates the force is directed out of the page for that particle.

A magnetic field exerts a force on a charged particle that is perpendicular to both the field and the particle's velocity. Consider the particle on the right in Figure 7 on the previous page. At this location, the magnetic field runs parallel to Earth's surface in a geographic south-to-north direction. The magnetic force on the charged particle points perpendicular to the plane of the drawing and parallel to Earth's surface in a west-to-east direction. Earth's magnetic field deflects charged cosmic rays near the equator so that they tend to move away from the surface. At the poles, the magnetic field is perpendicular to the surface and much stronger. Cosmic rays spiral along magnetic field lines, and at the poles they spiral downward. The interaction of these cosmic rays with atmospheric gases causes the aurora borealis that you read about at the start of this chapter. You will learn more about the circular motion of charged particles in magnetic fields in Section 8.4.

Electromagnetism

In 1820, Danish physicist Hans Christian Oersted was demonstrating how a wire becomes warmer when electric charge flows through it. In the course of his demonstration, he noticed that the needle in a nearby compass moved each time he switched on the electricity. This strange event led Oersted to conclude that a magnetic field surrounds moving electric charges. This idea is now known as the **principle of electromagnetism**.

Principle of Electromagnetism

Moving electric charges produce a magnetic field.

LEARNING **TIP**

Current Direction

The direction of conventional current is defined as the direction of flow of positive charge. The direction in which electrons flow (negative charge) in a wire is opposite to the direction of conventional current. When you apply the right-hand rule, consider the direction of conventional current.

Magnetic Field of a Straight Conductor

Moving charges, like those in an electric current, produce a magnetic field. Current in a straight wire or other long, straight conductor creates a magnetic field whose lines look like circles centred on the wire (**Figure 8(a)**).

You can determine the direction of the magnetic field lines around a straight wire by using the **right-hand rule for a straight conductor** (**Figure 8(b)**). If you reverse the direction of the conventional current, the magnetic field lines also reverse.

Right-Hand Rule for a Straight Conductor

If your right thumb is pointing in the direction of conventional current, and you curl your fingers forward, your curled fingers point in the direction of the magnetic field lines.

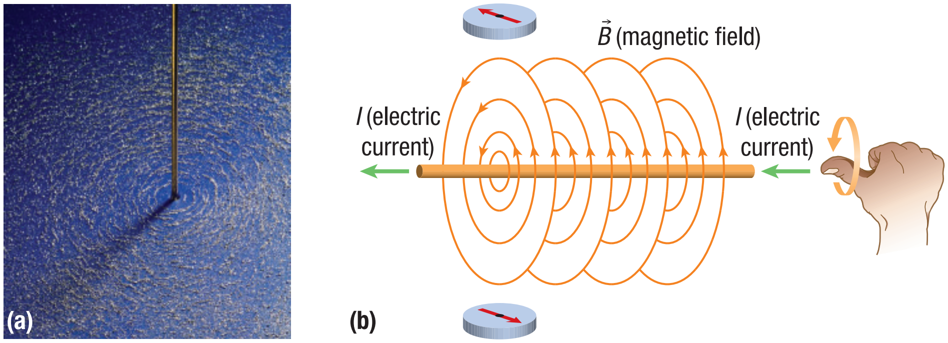

Figure 8 (a) Iron filings indicate the circular magnetic field around a conducting wire. (b) The right-hand rule for a straight conductor indicates the direction of the magnetic field.

Magnetic Field of a Current Loop

If you make a circular loop from a straight wire and run a current through the wire, the magnetic field will circle around each segment of the loop. The field lines inside the loop create a stronger magnetic field than those on the outside because they are closer together. You can still use the right-hand rule for a straight conductor to determine the direction of the magnetic field for a single loop (**Figure 9**).

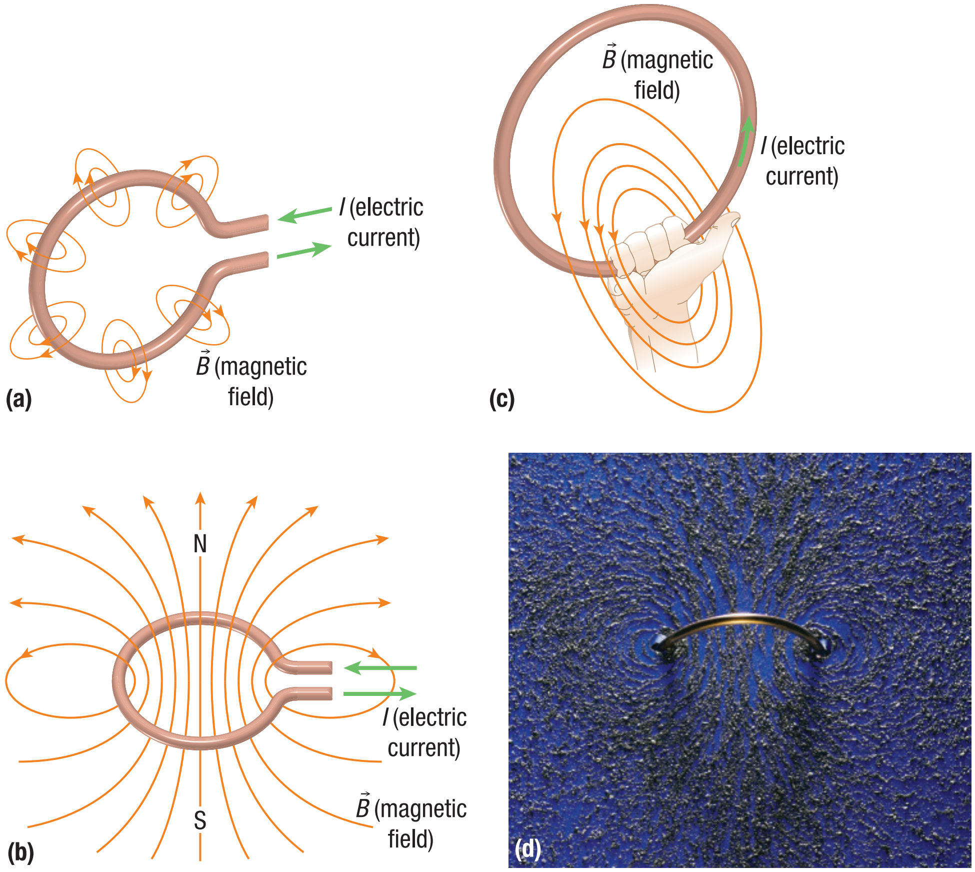

Figure 9 (a) Each segment of a current loop produces a magnetic field, $\vec{B}$, similar to that of a straight conductor. (b) The fields of each segment combine to produce a field similar to that of a bar magnet. (c) The right-hand rule for a straight conductor indicates the magnetic field direction for a single loop. (d) Iron filings show the magnetic field circling the loop.

Magnetic Field of a Coil or Solenoid

A solenoid is a conducting wire wound into a coil. The magnetic field of a solenoid is composed of the combined fields of all its loops. The field is strongest inside the coil because the field lines are closer together. The more tightly you wind the coil, the straighter and closer the field lines become. When the solenoid is loosely wound, field lines within the coil are curved.

To determine the direction of the magnetic field in coiled wire, you must use the **right-hand rule for a solenoid**.

Right-Hand Rule for a Solenoid

If you coil the fingers of your right hand around a solenoid in the direction of the conventional current, your thumb points in the direction of the magnetic field lines in the centre of the coil.

The magnetic field lines of a solenoid look like the field lines of a bar magnet (**Figure 10**). This occurs because the strengths of the fields can be added together, much like the net electric field is the vector sum of all the electric fields. Similarly, in a solenoid, the magnetic field around each segment of the loops corresponds to a straight conductor for that segment. A circular magnetic field forms around the wire at that point of the segment, as you can see from Figures 10(b) and (c). Adding all the magnetic fields together gives the resulting magnetic field of a solenoid. The magnetic field lines extend through the centre of the coil and then loop around the outside. The solenoid has the useful feature that we can switch the current in the wire on or off. Turning the current on and off enables us to control the magnetic field.

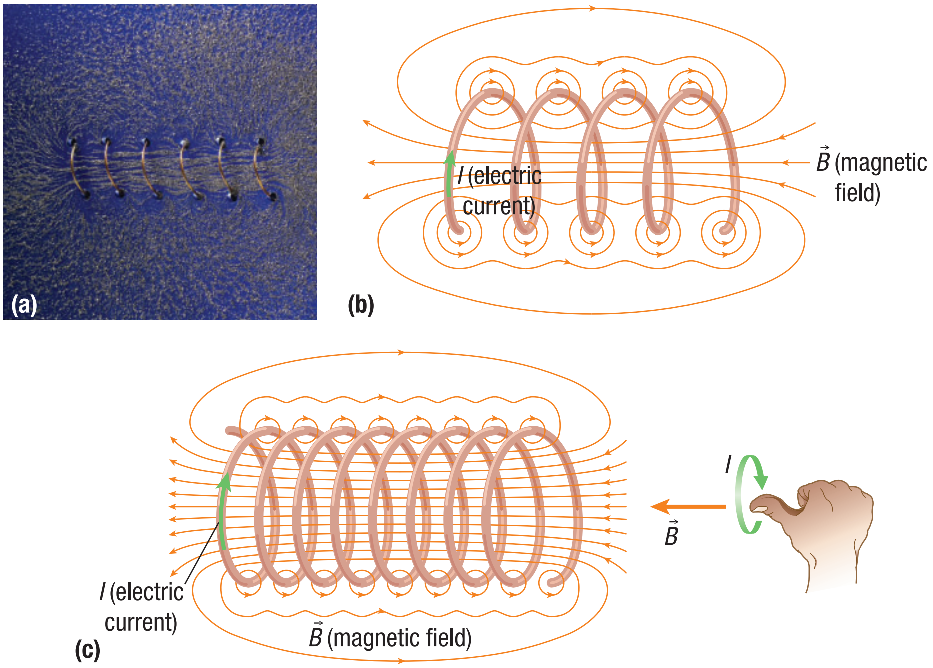

Figure 10 Magnetic field, $\vec{B}$, of a solenoid. (a) The iron filings indicate the direction of the solenoid's magnetic field. (b) The field lines are curved when the coil of the solenoid is loosely wound. (c) The field lines are straight for a tightly wound solenoid. The right-hand rule indicates the direction of the magnetic field through the solenoid.

Applying a current through a solenoid as described above causes the solenoid to become an electromagnet. Stronger electromagnets can be made using a solenoid with a magnetic material, such as iron, nickel, or cobalt, within the coil. The effect of this core material is to increase the strength of the magnetic field by aligning the electrons within the core material in such a way as to enhance the magnetic field.

Electromagnets have many applications:

- They are used in scrap-metal yards to pick up and drop large metal objects such as cars.
- They are used in washing machines and dishwashers to regulate the flow of water.
- They are used in doorbells to pull a lever against a bell and release it.
- Electromagnets also form the central piece of the MRI unit you read about at the start of this chapter.

UNIT TASK **BOOKMARK**

You can apply what you have learned about magnets and electromagnets to the Unit Task on page 422.

8.1 Review

Summary

- All magnets have magnetic poles. Opposite magnetic poles attract one another, and like magnetic poles repel one another.
- A magnetic field surrounds all magnets and goes from north to south outside the magnet and from south to north inside the magnet.
- Earth's magnetic field resembles that of a bar magnet. Earth's magnetic field changes orientation over time and is able to direct the motion of charged particles from space.
- The principle of electromagnetism states that moving electric charges produce a magnetic field.
- The right-hand rule for a straight conductor states that if your thumb points in the direction of conventional current, your curled fingers indicate the direction of the magnetic field lines around the straight conductor.
- The right-hand rule for a solenoid states that if the fingers of your right hand curl in the direction of the conventional current, your thumb points in the direction of the magnetic field lines in the centre of the coil.

Questions

1. What is a permanent magnet? K/U
2. Earth is surrounded by a magnetic field. K/U T/I A
   (a) Where are Earth's magnetic poles?
   (b) Explain how Earth's magnetic field contributes to the aurora borealis.
   (c) How can a hiker use Earth's magnetic field to identify directions?
3. Describe how you would use the right-hand rule to determine the direction of the magnetic field around
   (a) a long, straight conductor with a steady current
   (b) a loop of wire with a steady current
   (c) a long coil of wire with a steady current K/U
4. Look at the magnetic field lines of a tightly wound solenoid, as shown in Figure 10 on page 384. Describe the difference in the magnetic field lines inside and outside the coils. K/U
5. Examine the diagram of the interior of a doorbell shown in **Figure 11**. Use key terms from this section (which include *magnetic field line*, *principle of electromagnetism*, *right-hand rule for a straight conductor*, and *right-hand rule for a solenoid*) to explain how it works. K/U T/I C A

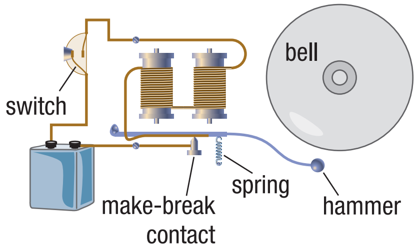

Figure 11

6. Design an experimental procedure to demonstrate the principle of electromagnetism. List the steps you would follow. T/I A
7. Scientists have discovered many living creatures that use Earth's magnetic field in different ways. Magnetotactic bacteria, honey bees, homing pigeons, and dolphins all rely on Earth's magnetic field in some way. **Figure 12** shows a micrograph of a magnetotactic spirilla cell. The dark, round dots inside the cell are magnetite crystals. Write a paragraph explaining how you think the bacterium might be using the crystals. Afterwards, research and prepare a presentation about the bacterium and other animals that use magnetism. 🌐 T/I C A

Figure 12

WEB LINK