# 16.1 Electricity and Magnetism

## SECTION OUTCOMES

- Define and describe magnetism.
- Describe the relationship between magnetic fields and electric current.
- Analyze and predict, by applying the right hand rule, the direction of current produced in a magnetic field.
- Interpret and illustrate, using experimental data, the magnetic field produced by a current flowing through a conductor.

## KEY TERMS

- north-seeking pole
- south-seeking pole
- North pole (N-pole)
- South pole (S-pole)
- magnetic dipole
- domain
- temporary magnets
- permanent magnets
- Curie point
- electromagnetism
- right-hand rules #1 and #2
- solenoid
- magnetic monopole

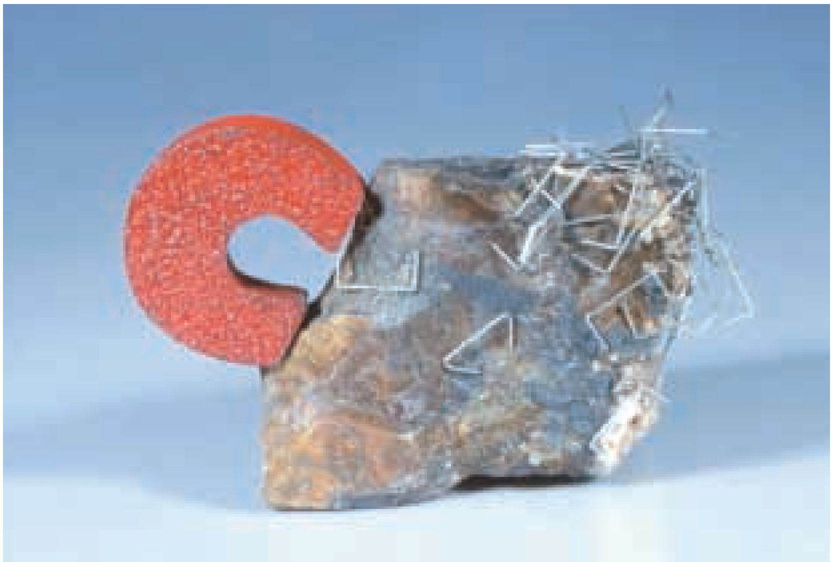


**Figure 16.1** This is a common enough sight that we usually take it for granted.

What is the mysterious force that enables some materials to attract others? The first descriptions of magnetism go back to over 500 years B.C.E. A Greek, named Thales, wrote about a rock that came from the town of Magnesia. Thales (624? – 547 B.C.E.) referred to it as the "magnetes lithos" (Greek for "Magnesian rock"). Eventually, rocks that displayed natural magnetism came to be known as lodestone. Chemical analysis has shown that lodestone gets its magnetic properties from the presence of an oxide of iron, $Fe_3O_4$, known today as magnetite or magnetic iron ore.

## Magnetic Poles

When you were doing the Multi Lab on the previous page, you probably realized that a compass needle is simply a small bar magnet which aligns itself on the north-south axis for the same reason as the suspended bar magnet. In the Northern Hemisphere, the presence of the North Star or Polaris, has always been a powerful symbol. Early observers assumed that the compass end was seeking the North Pole, hence the name **north-seeking pole** was given to the end of the magnet that seemed to always end up pointing in that direction. Similarly, the name **south-seeking pole** was given to the other end of the magnet. Gradually, these became known simply as the **North pole (N-pole)** and **South pole (S-pole)** of the magnet.

No matter how often you break a magnet into pieces, each piece is a complete magnet with a N-pole and a S-pole. Scientists assumed that you could do this until each piece had only one atom or molecule. This led scientists to believe that the individual atoms of a material must be magnets. Because magnets always seem to come with a N-pole paired with a S-pole, the bar magnet is often referred to as a **magnetic dipole**.

For early scientists, magnetism was a much easier field to study than static electricity. First, magnets did not discharge when touched and therefore were easier to manipulate. Second, magnetism had a very practical aspect in its direction-finding capabilities. For nations that were interested in exploration, the true nature of magnets was a very important topic.

The distance between magnets affects the strength of their interaction. This has been known since at least C.E. 1300. In 1785, Coulomb devised an experiment, for which he invented the torsion balance, to find the mathematical relationship between the separation and the force. He proved that the force of interaction between magnetic poles, attraction or repulsion, was inversely proportional to the square of the separation between them. Mathematically this is written as:

$$|\vec{F}| \propto \frac{1}{r^2}$$

$|\vec{F}|$ is the magnitude of the magnetic force between the poles and $r$ is the distance between the poles.

This explains why the N-pole of a bar magnet can exert a net force of attraction or repulsion on another bar magnet. When two magnets approach each other, it is almost certain that one pair of poles is going to be closer together. It is the interaction between the two poles nearest each other that will dominate the interaction of the two magnets. Thus, if the poles nearest to each other are unlike poles, then the force you observe will be one of attraction.

### RULES FOR MAGNETIC INTERACTIONS

1. Like poles repel each other.
2. Unlike poles attract each other.
3. The force of attraction varies inversely as the square of the distance between of the poles.

### TRY THIS...

What happens if you break a magnet in half? Do you get a separate N-pole and S-pole? Take a bar magnet and stroke the side of a hacksaw blade several times in the same direction with one pole of the bar magnet. When you have made about 20 strokes, confirm that the blade has become magnetized by bringing its ends near the poles of a compass. Does a force of attraction between the blade and the poles of the compass prove it is magnetized? Explain.

**Wrap the blade in a piece of cloth to protect your eyes and hands,** and break the blade in half. (They are relatively easy to break.) In turn, hold the ends of each half of the blade near the magnet. Do you have two magnets, each with an N-pole and a S-pole, or are there now separate N- and S-poles?

Wrap one section of the blade in the cloth, and break it in half again. Test each of the new parts of the blade for magnetism.

### History Link

A compass invented in China about C.E. 1000 consisted of a spoon made from lodestone that was placed on a bronze plate. The spoon represented the constellation Ursa Major (Big Dipper), with the handle end of the spoon representing Ursa Major pointing away from the North Star. Why did they make the base plate of bronze?

## Magnetic Domains

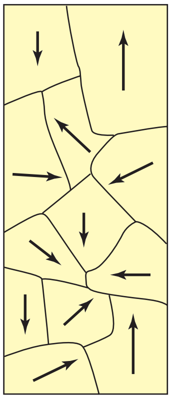


**Figure 16.2** Because the magnetic domains are randomly oriented, the material displays no net magnetic polarity. (The arrows represent the magnetic polarity of the domains.)

Imagine you have a box containing thousands of very tiny, very weak magnets. If you shake the box up, the magnets inside the box would tend to orient themselves randomly. A compass needle brought near the box might detect no appreciable net magnetic polarity for the box, even though you know it contains many magnets. Because the magnets inside the box are randomly oriented, more or less, the force of attraction from one magnet or group of magnets will be counteracted by the force of repulsion by other magnets or groups of magnets.

If you opened the box, what would you see? Probably there would be many regions, called **domains**, where a group of tiny magnets were lined up with each other, giving the domain a magnetic polarity (see Figure 16.2). Beside one domain, there might be another domain where the magnets, by chance, were aligned together but in a different orientation to the first domain. Interspersed throughout the box, there might be many domains of different sizes, strengths and orientations. In reality, the tiny magnets which make up the domains are actually the atoms or the molecules of the material.

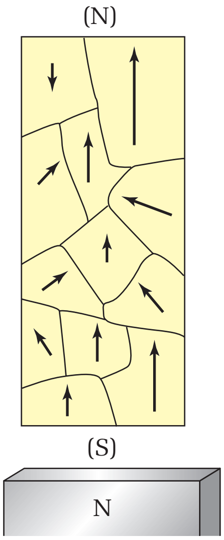


**Figure 16.3** The external magnet has caused the orientation of the domains to shift so that they are in greater alignment with its polarity.

Now imagine what would happen inside the box if an external magnet is brought near one end of the box. The pole of the external magnet that was near the box would exert a force on the domains and would try to align the domains. Even though the domains are not totally free to move, the force would shift domain orientations into greater alignment. In this way, the direction of the magnetic domains in the box would take on the same polarity in the same direction as the external magnet. The box is now a magnet that is attracted to the external magnet (see Figure 16.3). When the external magnet is removed, the domains would tend to sort themselves randomly again and the polarity of the box would become much weaker and even disappear completely.

In domain theory, the material is affected by the presence of a magnet if the atoms or molecules of the material are magnets. A domain is a group of adjacent atoms whose like poles have “like” orientation within the material. When the domains of a material are randomly oriented, the material shows no permanent magnetism. The presence of an external magnet can induce the domains to become aligned, more or less, with that of the external magnet. Thus, the material becomes a magnet in its own right.

In some magnetic materials, such as iron, the microscopic domains are easily reoriented in the direction parallel to an externally applied field. However, when the external magnet is removed, the domains return to their random orientations and the magnetism disappears. Thus, iron forms a **temporary magnet**. In other materials, such as steel, the internal domains are reoriented only with considerable difficulty. When the external magnet is removed, however random realignment of the domains is also difficult. Thus the material will retain its magnetic properties. These types of materials form **permanent magnets**.

Even though permanent magnets seem to be quite stable, they are fairly fragile. If a magnet is heated, its strength weakens but that strength will generally return when the magnet cools. However, if the magnet is heated above a certain temperature, called the **Curie point**, the magnet will be totally destroyed. Table 16.1 lists the Curie point for several materials displaying permanent magnetism.

**Table 16.1** Curie Points for Magnetic Materials

| Material | Curie Point (°C) |
|---|---|
| iron | 770 |
| cobalt | 1131 |
| nickel | 358 |
| magnetite | 620 |
| gadolinium | 16 |

**PHYSICS FILE**

The first magnetic compass is believed to have been created about C.E. 1000 in China and was used to navigate across the vast regions of Central Asia. By the thirteenth century, the compass was being used in Europe to aid navigation on the ocean. Until the arrival of the compass in Europe, sailors had to stay within sight of land in order to navigate. The invention of the compass enabled sailors to leave the coast and venture out into the ocean knowing they could find their way back with the compass. This resulted in the great global explorations of the fifteenth and sixteenth centuries, including the discovery of the "New World."

## Electric Charges and Magnetic Poles

In spite of the similarities between electricity and magnetism, early experimenters considered them to be two entirely separate phenomena. It is true that both electrostatic and magnetic forces of attraction and repulsion become weaker with separation. However, they display many fundamental differences. Electric charge, the source of the electric force, moves easily through conductors, while magnetic poles, the source of the magnetic force, cannot be conducted. Almost anything can be given an electric charge. However, magnetic poles are normally found in only ferromagnetic materials. Like magnetic poles, there are two kinds of electric charges. Objects displaying electric charge usually have only one type of charge on them, positive or negative. Magnetic poles seem always to come in pairs, hence the magnetic dipole. Overall, it seemed that the differences were far more significant than the similarities.

## Oersted's Discovery

In 1819, a Danish physicist, Hans Christian Oersted (1777–1851), was demonstrating the heating effects of an electric current in a wire to some friends and students. On his table he had some compasses ready for a demonstration he was doing later that day in magnetism. He noticed that when he closed the circuit, the needles of the compasses were deflected at right angles to the conductor. He kept this to himself until he had a chance to explore it further. It did not seem to make sense that the compass needle was neither attracted nor repelled by the current but deflected at right angles to it. Oersted had discovered that a current-carrying conductor caused the needle of a magnetic compass to deflect at right angles to the conductor. When he published his findings, it set off a flurry of research into the newly discovered phenomenon called **electromagnetism**. That is, moving electrons produce a magnetic field and a changing magnetic field will cause electrons to move.

## Right-hand Rule #1

Oersted's experiments convinced him that each point of a current-carrying conductor created a magnetic field around itself. The field lines were a set of concentric closed circles on planes perpendicular to the direction of the current. The direction of the field lines and thus the direction of the field could be determined using a "right-hand rule" (see Figure 16.4).

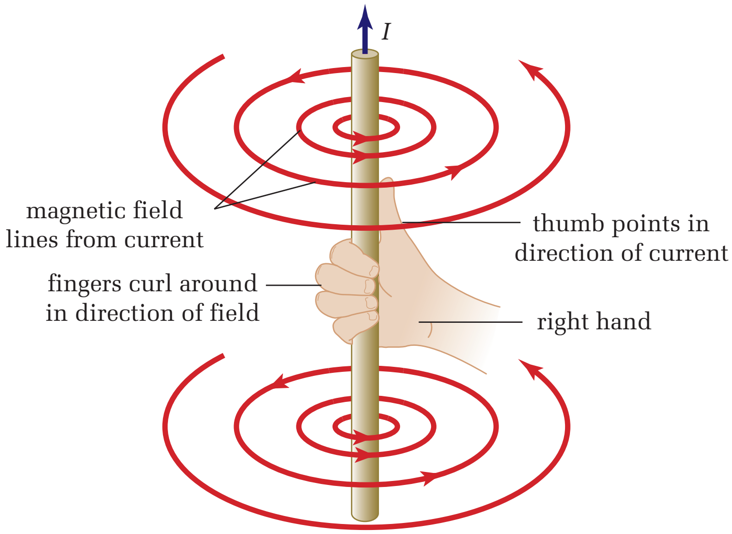
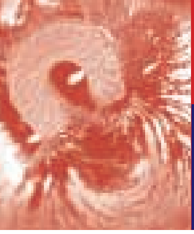


**Figure 16.4** **Right-hand rule #1** If you grasp a current-carrying conductor with your right hand so that the thumb lies along the conductor in the direction of the current, then the fingers of your hand will be encircling the conductor in the direction of the magnetic field lines caused by the current.

**PHYSICS FILE**

**Magnetic Monopoles**

Whether or not a magnetic monopole can exist is an interesting point. Classical field theory does not allow for the existence of magnetic monopoles. However, as you study Unit 7, you will discover that modern theories and observations have demonstrated the existence of several phenomena that were not predicted by classical theories. Some modern theories allow for the existence of magnetic monopoles. For many years, physicists have been searching for evidence of magnetic monopoles but have not yet had any success. Thus, the "jury is still out" on the topic of magnetic monopoles.



# INVESTIGATION 16-A

## Magnetic Field around a Straight Conductor

**TARGET SKILLS**

- **Performing and recording**
- **Modelling concepts**
- **Communicating results**

**CAUTION** In this experiment, you will be using circuits in which the only resistance is that of the wire. They are *short circuits*. To protect the power supply from damage, you should only connect them for very short periods of time.

### Problem

Develop an understanding of the relationship between a current and its magnetic field.

### Prediction

In the text it is noted that Oersted observed that the needle of the compass was deflected at right angles to the current. From this information, what can you predict about the shape of the field near the conductor?

### Equipment

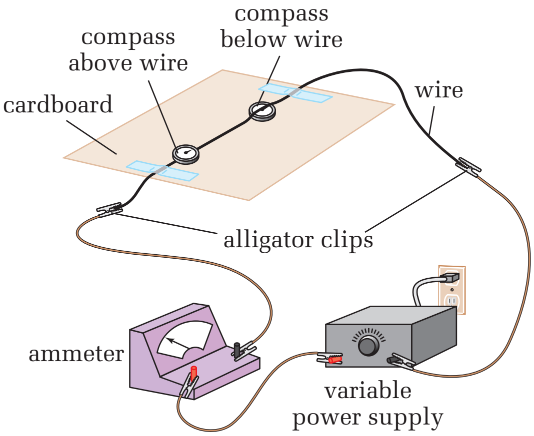
- ammeter (0–10 A)
- variable power supply (or fixed power supply with an external variable resistor)
- magnetic compass (2)
- wire (approximately 1 m)
- connecting leads
- cardboard square (approximately 20 cm × 20 cm)
- iron filings
- metre stick
- 1 kg mass (2)
- masking tape
- retort stand (2)
- ring clamp

### Part 1: Horizontal Conductor

### Procedure

1. Place the wire across the middle of the cardboard square and hold it in place at the edges of the cardboard with masking tape.
2. Connect the power supply and the ammeter, in series, with the wire.
3. Turn on the power supply very slightly to check that the ammeter is connected properly.
4. Once you have confirmed that the circuit is properly connected, place one compass under the wire and one compass above the wire. Rotate the cardboard until the wire lies along the direction of magnetic north and the compass needles are parallel to the conductor (see the figure below).

   (**Note:** Place the compasses far enough apart so that they do not strongly interact with each other. Tap them gently to make sure that their needles are able to move freely.)



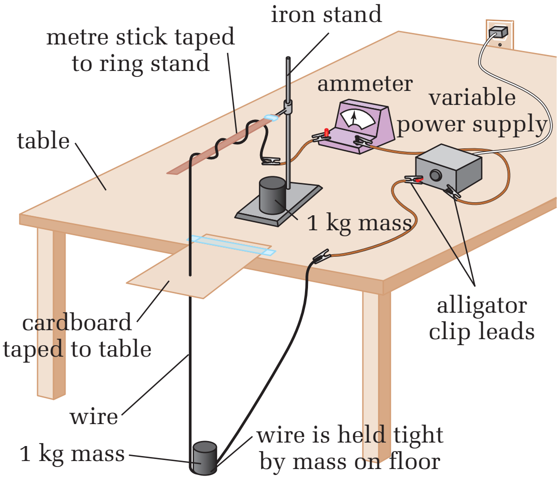
5. Turn the power on and increase the current (to about 5 A) until the needle of the compass shows a strong reaction to the current. Quickly disconnect the lead at the *anode* of the power supply. (In this way, you will not have to reset the power level each time you want to start and stop the current.) Next, momentarily touch, but do not attach, the lead to the anode of the power supply and note the reaction of the compass needles.

6. Draw a sketch of the orientation of the apparatus, including the direction of the current and the direction of the N-pole of the compasses before and after the current was turned on. (Remember that a magnetic dipole aligns itself with the net magnetic field. Also, the N-pole of a magnet is used as a reference to determine the direction of the magnetic field.) As a reference, include an arrow in your sketch to show the direction of Earth's magnetic field.
7. Draw a sketch of your observation of the reaction of the compass needles to the current.
8. Turn the cardboard 45° clockwise and repeat steps 5 through 7.
9. Turn the cardboard another 45° clockwise and repeat steps 5 through 7.
10. Turn the cardboard another 45° clockwise and repeat steps 5 through 7.
11. Without changing the power setting on the supply, reverse the connection of the leads connected to the wire on the cardboard so that the current in the wire is reversed. Reorient the cardboard to its original position. Momentarily turn on the current and note the reaction of the compass needles to the current. Draw a sketch of your observations.

## Part 2: Vertical Conductor

### Procedure

1. Assemble the apparatus as shown below. Notice that the vertical wire passes through a hole in the cardboard.
2. Connect the power supply and ammeter to the wire and turn the current on very slightly to check that the ammeter is connected correctly.



3. Place a compass on the cardboard platform to the north of the conductor so that it is very close to, but not touching, the wire.
4. As in Part 1, momentarily turn on the current and increase it until the compass reacts to the current. Once again, a current of about 5 A should be adequate. (If you want to increase the current beyond that level, consult with your teacher.) Observe and note the reaction of the compass to the current.
5. Draw a sketch of the result, showing the position of the compass needle before and after the current was turned on. As a reference, include an arrow to show the direction of Earth's magnetic field.
6. Move the magnet 45° clockwise around the wire and repeat steps 4 and 5. Record your result on the sketch you drew for the first trial.

7. Continue to move the compass around the conductor in 45° angles until it has returned to its original position, repeating steps 4 and 5 after each move.

8. Cut a slit in a piece of paper from its edge to its centre and use it to cover the cardboard square. Sprinkle iron filings on the paper around the conductor.

9. Connect the circuit and gently tap the cardboard. Observe the effect of the current on the position of the filings. Draw a sketch of the result.

### Analyze and Conclude

1. For all trials in Part 1, determine the greatest angle that the current caused the compass needle to deflect? What is the significance of this? Remember that the compass needle points in the direction of the sum of the magnetic fields from the Earth and from the current.

2. In Part 1, what is the significance of the fact that the compass needles above and below the current deflected in opposite directions?

3. In Part 1, when you reversed the current without changing the orientation of the wire, what happened? Why is that significant?

4. In Part 1, based on the information that you have gathered, what is your prediction for the shape of the magnetic field near a current? Explain.

5. Do the results from Part 2 of the investigation confirm the hypothesis you made about the shape of the field in Part 1?

6. In the previous sections of this chapter, you saw magnetic fields pointing from the N-pole of a magnet to the S-pole. Where are the poles for this magnetic field? Where do the magnetic field lines begin and end? Could a magnetic field exist in the absence of magnetic poles?

7. Does the magnetic field from the current maintain its strength as you move away from the current? What evidence is there to support your answer?

8. What is your conclusion about the shape of the magnetic field that results from a current?

### Apply and Extend

9. What would be the effect if a second wire was positioned alongside the wire in your apparatus and was carrying a current in (a) the same direction or (b) the opposite direction as the wire in your apparatus? Form a partnership with another lab group, and combine your apparatuses to run two wires side by side. Using two power supplies to produce equal currents in the wires, repeat steps 4 and 5 of the previous procedure. Does this arrangement have an effect on the strength of the field around the wires? Try it with currents running in the same and in the opposite directions.

10. What do the results tell you about the nature of magnetic fields around conductors?

## Magnetic Field of a Current-carrying Coil

Consider a coil of wire carrying a current as shown in Figure 16.5. What type of magnetic field should there be around the wire? Oersted's discovery predicts that there are circular magnetic lines of force perpendicular to the coil at each point on the coil. Inside the coil, all the magnetic field lines pass through the plane of the coil in the same direction as determined using right-hand rule #1. Outside the coil, all field lines pass through the plane of the coil in the opposite direction that they passed through inside the coil.

In the region outside of the coil, the magnetic field lines spread out and therefore the field becomes weaker. Further inspection of Figure 16.5 will reveal another reason why the magnetic field intensity outside of the coil is very small. Study the left side of the coil where the magnetic field lines are going into the page. Then consider the circular field lines around the right side of the coil. Imagine these circles becoming larger and larger. Eventually the circles from the right side will reach the region outside of the coil on the left. These magnetic field lines generated by the current on the right side of the coil will be coming out of the page opposing the lines generated by the left side of the coil. These field lines will cancel each other, reducing the intensity of the field.

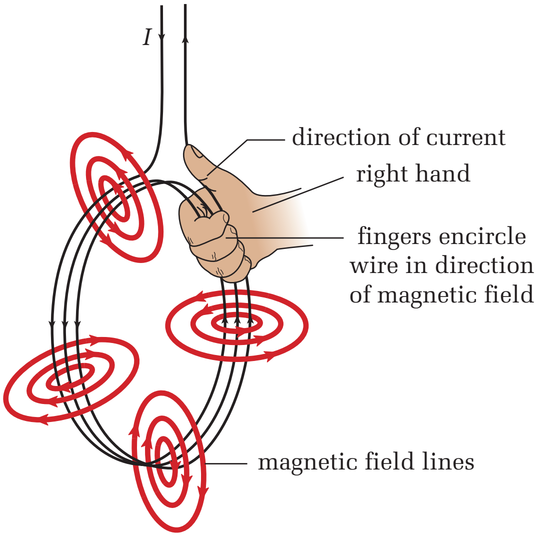


**Figure 16.5** Using right-hand rule #1, we can show that, inside the coil, all the field lines point in the same direction. The total strength of the magnetic field inside the coil is the vector sum of all the individual fields. Since all field lines point in the same direction, the net magnetic field inside the coil is quite strong.

Next examine the situation inside the coil. A remarkable thing happens. The field lines from all points on the coil pass through the plane of the coil in the same direction. Thus, the magnetic fields inside the coil combine together constructively. As you move away from one edge of the coil, along any diameter, the field strength from that edge weakens. However, as you move away from one edge, you move closer to the opposite edge, and the field from the opposite edge gets stronger at just the right rate to exactly compensate for the loss in strength from the other edge. The net effect is that the field is exactly uniform in strength.

When you draw the magnetic field for a coil, the field lines should still be closed loops. Inside the coil, they should be uniformly spaced to represent the uniform nature of the field. Outside the coil, the magnetic field lines should spread out to indicate the weakened field in that region. Figure 16.6 demonstrates this property if the coil was viewed in cross section. Figure 16.7 illustrates the same property of the coil when viewed in the plane of the coil from either face.

For the two current-carrying coils, dots and crosses represent the directions of the magnetic fields in the plane of the page. In the coil at right (b), the current is counter-clockwise, thus the magnetic field lines point out of the page inside the coil and into the page outside the coil. In the coil at left (a), the reverse is true. Inside the coils, the spacing of the magnetic field lines is uniform to indicate the uniform nature of the field. Outside the coils, the spacing of the lines increases as the distance from the coil increases to indicate that the magnetic field intensity is decreasing as you move away from the coil.

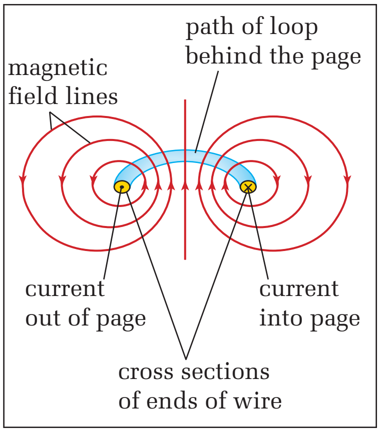


**Figure 16.6** The field lines around the edges of a coil are closed loops. Inside the coil, the line spacing indicates that the field is uniform. Outside the coil, the line spacing indicates that the field is getting weaker as the distance from the coil increases.

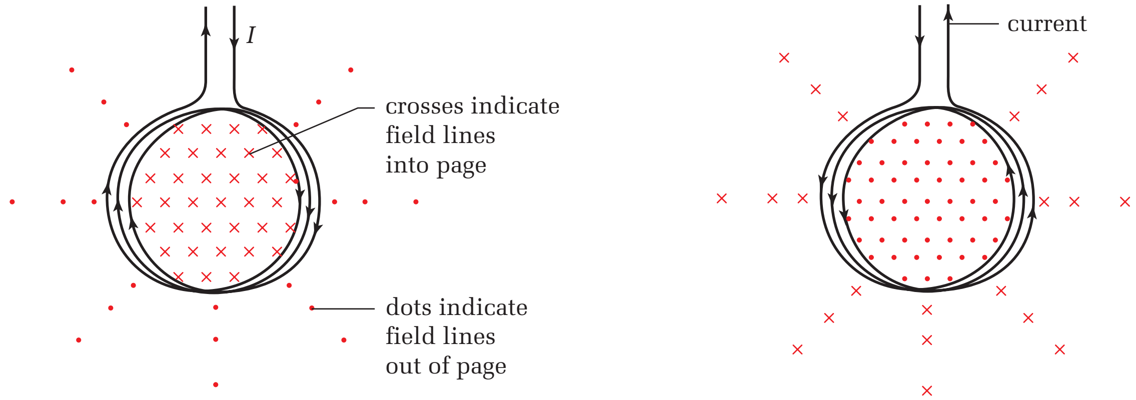


**Figure 16.7** **(A)** Magnetic fields with a clockwise current

**(B)** Magnetic fields with a counter-clockwise current

# INVESTIGATION 16-B

## Magnetic Field around a Helix

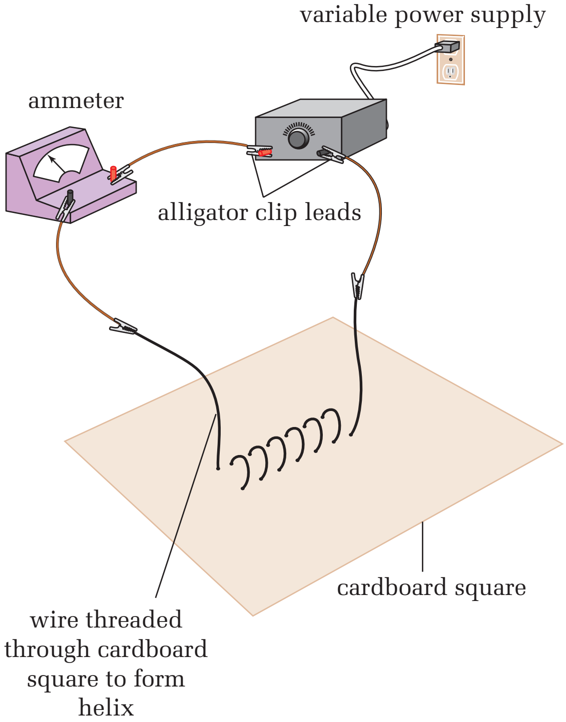
**TARGET SKILLS**

- Hypothesizing
- Conducting research
- Performing and recording

The purpose of this investigation is to plot the shape of the magnetic field around a helix. A helix is formed when a coil of wire is stretched so that there is space between the adjacent loops of wire. When a wire is formed into a helix and current flows through it, the magnetic field is similar to that of a coil, except that it is longer.

### Hypothesis

Based on the information that you have about the magnetic field around a single coil of wire, draw a sketch to predict the shape of the magnetic field around the helix.



### Equipment and Materials

- wire for helix (approx. 1 m)
- cardboard square (approx. 20 cm × 20 cm)
- power supply
- ammeter (0–10 A)
- compass
- iron filings

### Procedure

1. Thread the wire through the cardboard square as shown in Figure 14.35. A helix of about 10 turns, with loops that are two centimetres in diameter spaced about one centimetre apart, works reasonably well. Connect the power supply and the ammeter in series with the helix.

**CAUTION** Since the circuit has no resistance other than that of the coil, it is a short circuit. To protect the power supply from damage, the coil should only be connected to the circuit for very short periods of time.

2. Increase the power output of the supply very slightly to check that the ammeter has been connected correctly.
3. When the connections are correct, increase the output of the power supply until the current is about 5 A, and then disconnect the lead from the anode of the power supply.
4. Place a compass near the end of the helix and briefly connect the circuit. Notice the orientation of the compass needle.

5. Draw a sketch to record your observations. Include the coils, the direction of the current in the coils, and the orientation of the compass needle before and after the current was on. This will be used later in your analysis.

6. Repeat steps 4 and 5, placing the compass at various locations around the helix. Include all the results on the sketch made in step 5.

7. Sprinkle iron filings on the cardboard. Make sure there are filings inside the helix as well as outside it.

8. Briefly connect the circuit. Tap the cardboard to assist the filings to become aligned with the magnetic field of the helix. After a few seconds, disconnect the lead from the anode. **Do not disturb the filings on the cardboard.**

9. Give the power supply a period of time to cool down and repeat step 8 to enhance the result of the trial. (This step may be repeated again if necessary.)

10. Draw an accurate sketch of the pattern of the iron filings observed in step 9.

11. From your sketch of the pattern of iron filings, and the directions of the compasses, make a drawing of the magnetic field lines for the helix as seen in the pattern of the iron filings. Include the pattern of the lines inside the helix. Using the information from the compass sketch in step 5, place arrows on the lines of force to indicate the direction of the field.

### Analyze and Conclude

1. Does the magnetic field pattern resemble the one in your hypothesis? If not, try to explain why the actual field differs from your hypothetical field.

2. Is the magnetic field around a helix similar to any magnetic field observed previously? If yes, describe the similarities and the differences between this field and the previously observed field.

### Apply and Extend

3. What would be the effect on the magnetic field around the helix if the number of loops was increased without the helix getting longer? This would, in effect, make the turns tighter together.

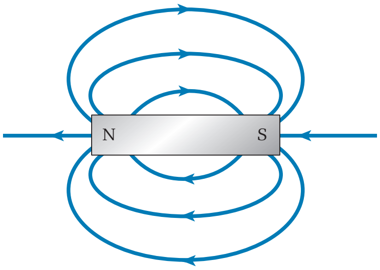


**Figure 16.8** From two-dimensional drawings of iron filings around magnets, you can create idealized two-dimensional images of the magnetic field. Notice how the lines get farther apart where the field is weaker.

## Magnetic Field around a Solenoid

A **solenoid** is a closely wound helix. The main difference between the field from a solenoid and the field from a helix is that the field from a solenoid is more uniform. Also, because there are so many coils of wire, it is much stronger for any given current. Outside the solenoid, the magnetic field closely resembles that of a bar magnet. Inside a solenoid, all the magnetic field lines form closed loops. The field lines leave one end of the solenoid, circle around and enter the other end of the solenoid, and then pass through the solenoid to their starting point.

With a bar magnet, classical field theory predicts that the lines of force entering one end of a magnet are the same ones that exit the other end. Compare the magnetic field around the solenoid as shown in Figure 16.9 with that of the bar magnet as shown in Figure 16.8.

If the N-pole of a compass or bar magnet were placed near the end of the solenoid at which the lines of force exit, it would experience a force pushing it away from that end, just as if that end were an N-pole of a solid magnet. Similarly, the S-pole of a bar magnet placed near the end of the solenoid, at which the lines of force exit, would be pulled toward the solenoid. In other words, the solenoid acts just like a hollow bar magnet. The similarity between a solenoid and a bar magnet is just one of many clues that the lines of force in all magnets are closed loops that pass through the magnet.

If magnetic lines of force are always closed loops, it explains why magnets are always dipoles. As we have seen, the end of the magnet where the lines of force exit is the N-pole, and where they re-enter the magnet is the S-pole. To have a magnetic monopole, let's say an N-monopole, the magnetic lines of force would have to

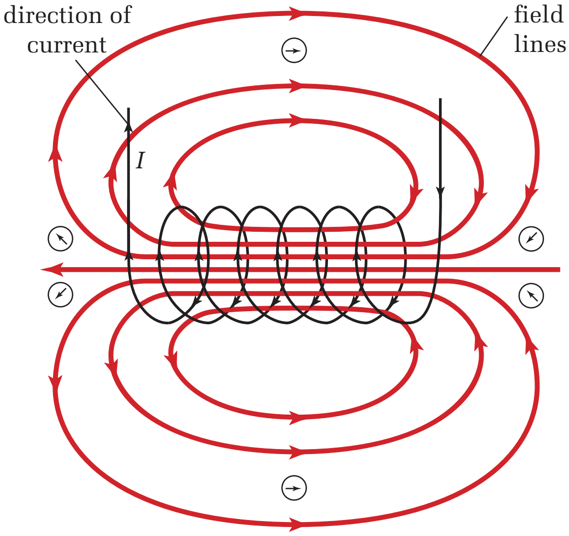


**Figure 16.9** The pattern of the magnetic lines of force around a solenoid is very similar to the pattern of lines of force around a bar magnet.

exit the material but never re-enter it. If, as classical field theory suggests, field lines are closed loops, they must come back and enter the material at some point. That point is the S-pole of the material. When you break a magnet into pieces, you just shorten the path of the loops for each piece. They still are loops and each piece is still a magnetic dipole.

## Right-hand Rule #2

How does the magnetic polarity of a coil or solenoid relate to the direction of the current in the coils? To find the N-pole of a coil of wire as shown in Figure 16.10, you can use right-hand rule #1. When you find the face of the coil where the field lines exit, you have found the N-pole of the coil. Grasp the coil at some point with your right hand so that your thumb lies along the coil in the direction of the current, and your fingers encircle the wire in the direction of the magnetic field lines. The face of the coil where your fingers exit is the N-pole of the coil.

To make this process simpler, a second right-hand rule was invented. It is actually just a variation of right-hand rule #1. **Right-hand rule #2**: Place the fingers of your right hand along the wire of the coil so that your fingers point in the direction of the current in the coil. When you extend your thumb at right angles to the plane of the coil, it will indicate the direction of the field lines as they pass through the coil, and thus indicate the face of the coil that acts as the N-pole of the coil (Figure 16.11). The same rule will obviously apply to a solenoid or any other system where the current is moving in a circle.

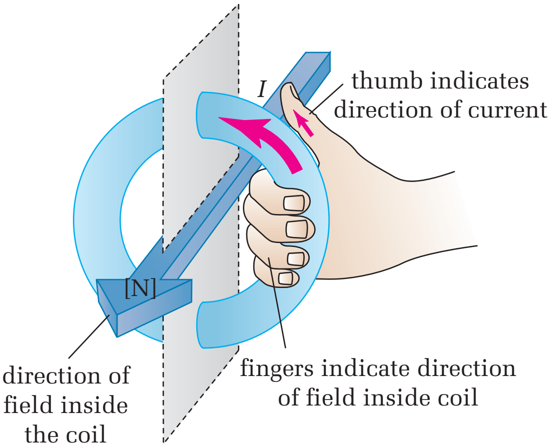


**Figure 16.10** Right-hand rule #1 can be used to identify the direction of the field lines through the coil and thus the locations of the N-pole and the S-pole of the coil.

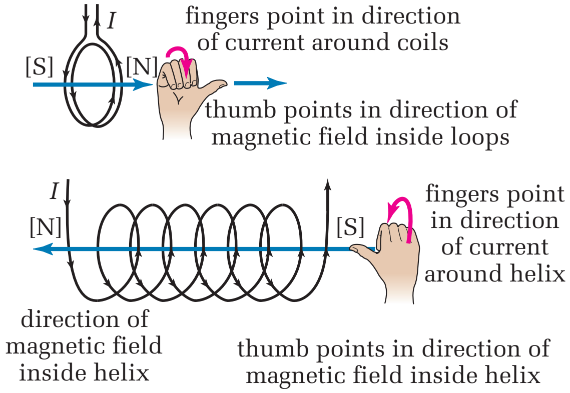


**Figure 16.11** When the fingers of the right hand lie along a coil in the direction of the current in the coil, the thumb points in the direction of the magnetic field lines inside the coil. The face of the coil where the magnetic field lines exit acts like the N-pole of a magnet.

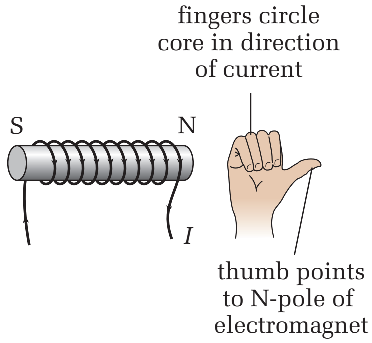


**Figure 16.12** Right-hand rule #2 is used to locate the N-pole of an electromagnet.

## Electromagnets

If a core of ferromagnetic material, such as iron, is placed inside a solenoid, the magnetic field strength inside the solenoid is greatly increased. Because the magnetic field easily penetrates the iron, the field lines within the solenoid crowd into the iron core. This has two effects. First, the crowding concentrates the field lines from the solenoid; the closer together the field lines, the stronger the field. Second, the field lines from the solenoid induce the domains of the iron core to align so that ferromagnetic material becomes a magnet whose field supplements the field of the solenoid.

The N-pole and S-pole of the electromagnet are located using right-hand rule #2. Grasp the electromagnet so that the fingers of your right hand encircle the magnet in the direction of the current around the core, and with your thumb parallel to the axis of the magnet. Your thumb points to the N-pole of the magnet (see Figure 16.12).

**PHYSICS FILE**

Magnetic recording equipment and the material on which it records is very sensitive to magnetism. Computer disks, audio tapes and VCR tapes all store data in the form of magnetic fields. The unwanted presence of a magnetic field near any of these media could easily erase all the stored data. For this reason, electronic engineers must design methods to protect the recording medium from the effects of the magnetic fields generated by the motors which run the systems.

## Electromagnet Design

It is possible to make very strong electromagnets. Three factors affect the strength of an electromagnet: the size of the current, the number of turns, and the permeability of the core — the extent to which the magnetic field penetrates the core material. For a core of a given material, it would seem that you just put more and more turns of wire around the core and increase the current. Unfortunately, it's not quite so simple.

Think back to your studies of electricity in the previous chapter. As the number of turns of wire around the core of a magnet increases, the resistance of the coil also increases ($R \propto l$). For a fixed potential difference, doubling the number of coils of wire around the core of an electromagnet doubles the resistance of the coils and halves the current through the coils. The result is no increase in the strength of the magnet. One solution is to use heavier wire. If the size of the magnet was not a factor, that solution might have merit. If size is a factor, then using heavier wire means that you cannot put as many turns around the magnet. Moreover, heavier wire would increase the mass of the coil and the cost of making it.

Another solution might be to increase the potential difference of the power supply to increase the current. This results in an increase in the power and thus the cost to operate the magnet. The increase in current to the coils of the electromagnet also means an increase in the amount of electrical energy that is converted to heat by the coils. Considering the importance of electromagnets to today's technology, finding the most efficient design for electromagnets is a formidable challenge.

If very strong magnetic fields are required, the magnets have to be super-cooled to the point where the coils become superconductors. At that point the coils lose their resistance and very large currents can flow through them. Many technical applications, such as high speed MAGLEV trains, magnetic resonance imaging (MRI) machines and particle accelerators, require the use of superconducting magnets.

**Figure 16.13** Superconductors allow physicists to generate extremely powerful magnetic fields.

**PHYSICS FILE**

There is evidence to show that Earth's magnetic field undergoes periodic reversals. It is not known whether the reversals occur gradually or rapidly. When lava containing ferromagnetic material cools below its Curie point, the domains within the rock tend to line up with Earth's magnetic field. In 1906, a French physicist, Bernard Brunhes, found some ancient lava rocks that were polarized opposite to Earth's magnetic field. He suggested that when these rocks solidified, Earth's magnetic field must have been reversed. Studies of lava around the world indicate that the last reversal occurred about 780 000 years ago, even though the time lapse between reversals seems to be about 200 000 years.

## 16.1 Section Review

1. C In each case, assume that the magnitudes of the currents in the conductors are the same. Indicate the relative field strengths on the diagrams by the spacing of the lines of force.
   - **(a)** Draw a conductor in cross-section as seen end on. Indicate a current flowing directly towards you (out of the page). Draw the lines of force for the magnetic field resulting from the current in the conductor.
   - **(b)** Draw a similar diagram to that in part (a), but showing a set of two conductors right next to each other. Indicate that the current in each conductor flows towards the viewer. Draw the lines of force diagram for the magnetic field that results from the current in the conductors.
   - **(c)** Draw a set of two conductors, as in part (b). Indicate that the current flows toward the viewer in one conductor and away from the viewer in the other conductor. Draw the lines of force diagram for the magnetic field that results from the currents in the conductors.
2. K/U When electromagnets are constructed, what types of materials should be used in the core to make the strongest magnet? Explain why it is an advantage to use one of these materials for the core of the electromagnet rather than just having an air-core solenoid as the magnet.
3. MC A conductor is aligned with Earth's magnetic field lines. Thus, the compass set above the conductor points in a line parallel to the conductor. A DC power supply is connected to form a closed circuit with the conductor. Explain how this set-up could be used to identify the anode and the cathode for the power supply.