Section 1 The Electricity and Magnetism Connection

What Do You See?

Learning Outcomes

In this section, you will

- **Map** a magnetic field by using a magnetic compass.
- **Look** for a relationship between an electric current and a magnetic field.

What Do You Think?

A compass helps travelers determine which way is north.

- **How is a compass affected by a bar magnet?**

Write your answer to this question in your *Active Physics* log. Be prepared to discuss your ideas with your small group and other members of your class.

Investigate

In the first part of this *Investigate*, you will use a bar magnet to explore magnetic forces between magnets and magnetic materials. You will also use a compass to explore the shape of a magnetic field around a bar magnet. In the second part, you will investigate if a relationship exists between magnetism and electricity.

Part A: Mapping a Magnetic Field

1. You will be given two bar magnets. Note that each bar magnet is labeled N (north) on one end and S (south) on the other end.

   a) Explore whether there are attractive forces or repulsive forces when the magnets are placed near each other. Record your results in your log.

b) Determine the strength of one of the bar magnets by measuring how many paper clips the magnet can lift.

2. The needle of a compass is a small bar magnet that is placed on a point so that it can rotate easily. It can be used as a magnetic-field detector. Any magnet or magnetic material will affect the compass. When the compass is not near any magnet or magnetic material, it aligns itself with Earth's *magnetic field* and indicates which direction is north.

Note the direction of the compass needle. Rotate the casing.

a) Did the compass needle change direction?

3. Set the magnetic compass on the table and bring another type of magnet, such as a bar magnet, into the area near the compass needle. But do not get them too close because a strong magnet can ruin a compass needle if it gets too close.

a) Describe your observations.

b) What happens to the dependable north-pointing property of the compass?

c) How dependable is the compass at pointing north when it is placed in a region where there are other magnetic effects, in addition to Earth's magnetic field?

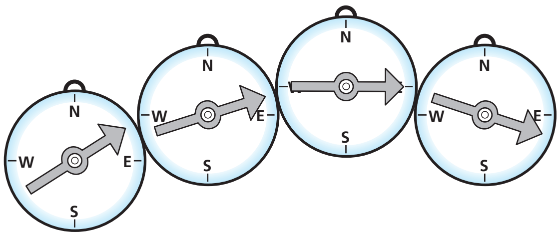
4. You will now make a map of the magnetic field of the rectangular bar magnet. Place the magnet on a piece of paper and trace its position. Label which end of the bar magnet is the N pole and which is the S pole. Keep the compass a centimeter or two away from the magnet to avoid ruining the compass. Place the compass at one location and mark the direction it points. Remove the compass.

Note: If the bar magnet is an extremely strong one, you should keep it close enough to the compass to see the effects, but not close enough to damage the compass.

a) Sketch a small arrow at the location from which you removed the compass to show the way it pointed. Pay attention to which end of the compass needle points to which pole of the magnet.

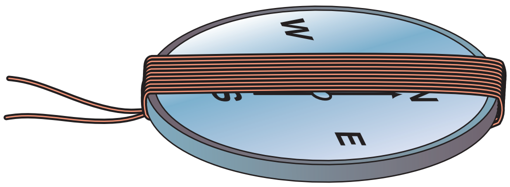
b) Place the compass at a second location near the tip of the first arrow you sketched. Remove the compass and sketch another small arrow in this location to show the way the compass pointed. See the diagram at the top of the following page.

c) Repeat the process at 10 or more locations to get a map of the magnetic field of a bar magnet. Tape or glue the map into your log.



Part B: Electric Currents and Magnetic Fields

1. Wrap a wire around the magnetic compass a few times to form a coil. Wrap the wire across the north-south markings of the compass scale, as shown in the diagram below. Hold the turns of wire in place with tape, or use the method recommended by your teacher. Use sandpaper to remove the insulation from a short section of the wire ends.



2. Connect a DC hand generator, a light bulb, and the compass/coil in a series circuit, as shown in the diagram at the bottom of the page. Rest the compass/coil so that the compass is horizontal, with the needle balanced, pointing north, and free to rotate. Also, turn the compass within, if necessary, so that the compass needle is parallel to the turns of wire. You might wedge some paper under the edges of the compass to make it rest level.

3. Crank the DC generator and observe the compass needle.

   a) Record your observations.

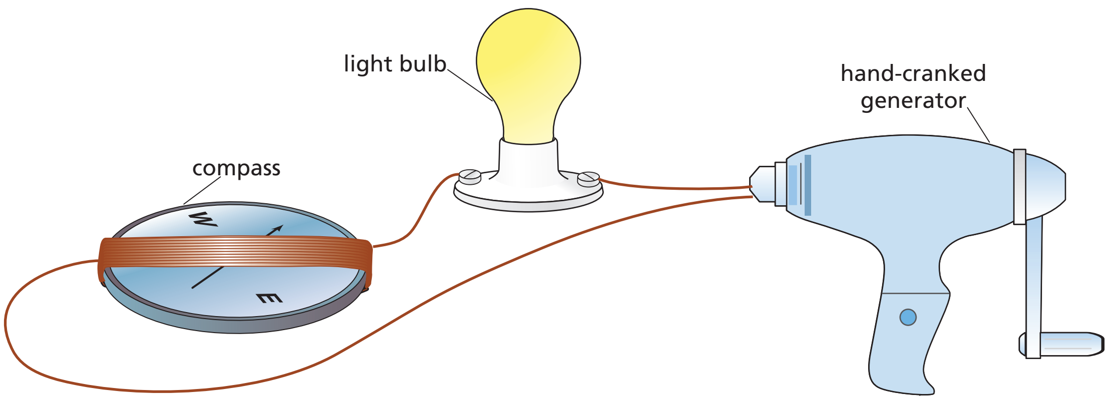
4. Reverse the direction of the current in the wire by reversing the direction you crank the DC generator.

   a) Describe the results in your log.

   b) What evidence do you now have that electric currents can produce magnetic fields?

5. Notice that the compass does not need to be in contact with the wire to experience a force due to the current in the wire. This illustrates the general phenomenon of "action at a distance."

   a) In your log, describe how this is similar to the force of gravity.



6. The "action at a distance," of the magnetic field is used to bridge the "gap" between the wire and the compass. In short, the current running through the wire produces a magnetic field in the space surrounding it. When a compass is placed in a region of space where a magnetic field exists, it experiences a force. The magnetic field defines both the strength and the direction of the force.

a) Using a similar explanation, describe what a gravitational field of Earth may be like.

b) What is the direction of the gravitational force and how does its strength change as you move further from Earth?

7. The concept of a field is an example of a model used in physics to help you understand natural phenomena. Physicists use a ray model to describe how light travels. Chemists use balls and sticks as a model to represent molecules. Magnetic fields are depicted as lines surrounding the current-carrying wire or the magnet.

a) How does this model help you to understand or describe the properties of a bar magnet?

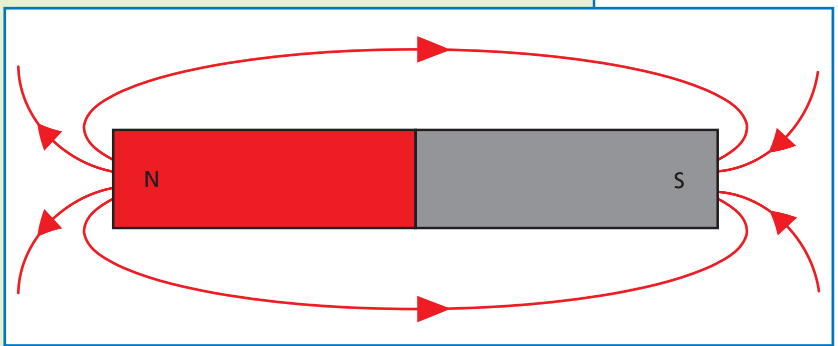
Physics Talk

MAGNETISM AND ELECTRICITY

Magnetic Fields

People have been fascinated by the invisible tug of one magnet on another magnet for hundreds of years. In the first part of the investigation, you found that when the north pole of one magnet is placed near the north pole of a second magnet, the two magnets repel. This can be summarized by stating that "like poles repel." In contrast, you found that when the north pole of one magnet is placed near the south pole of a second magnet, the two magnets attract. This can be summarized by stating that "unlike poles attract."

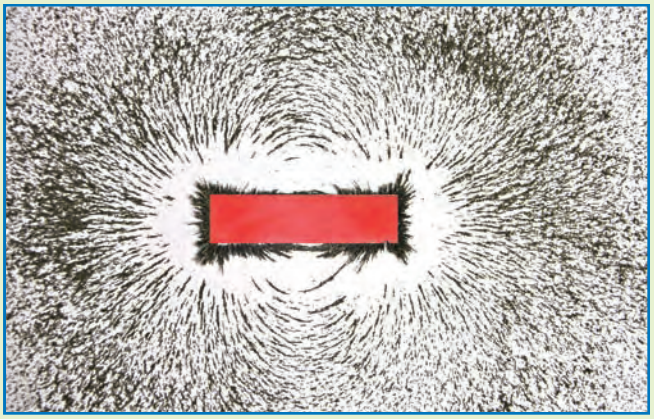
A compass is usually used to determine which way is north. The compass needle is actually a tiny bar magnet. Earth has the equivalent of a large magnet beneath its surface and the compass needle is attracted to Earth's interior magnet. [redacted]

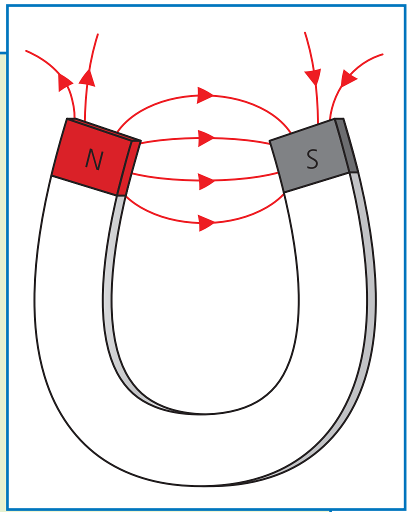


The compass can be used as a magnetic-field detector. It can indicate if a magnet (in addition to Earth's magnet) is in the vicinity of the compass. You used the compass to map the **magnetic field** of a bar magnet. That field is sketched to the right.

Physics Words

magnetic field: a region of space where magnetic forces act on objects.





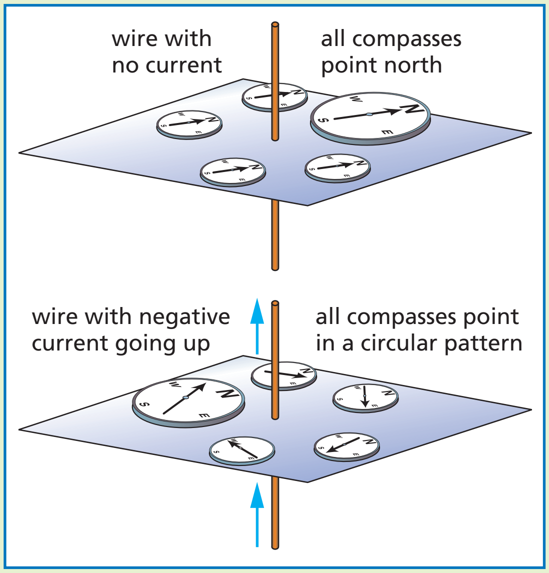
Notice that the north end of the compass points away from the north end of the bar magnet and toward the south end of the bar magnet. A magnetic field of a horseshoe magnet is drawn above. The field, once again, points away from the north end and toward the south end.

These magnetic field lines are a model to help describe the magnet and its effect on objects near it. The field is at all points near the magnet but only a few lines are drawn to show the shape of the field.

[redacted]

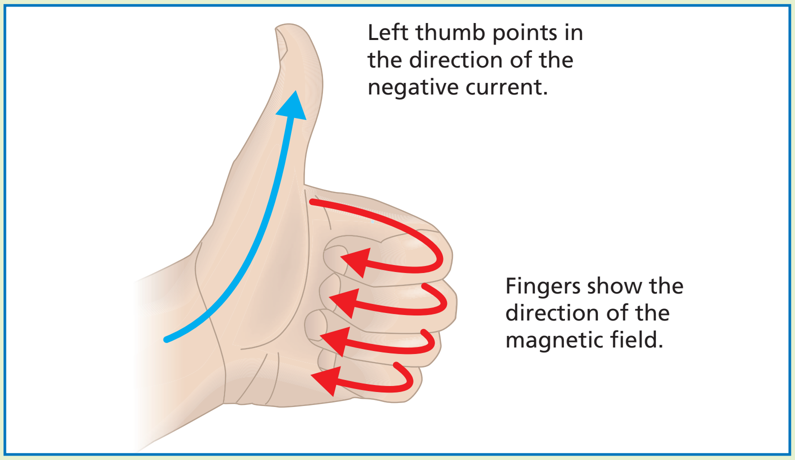
In 1820, the Danish physicist Hans Christian Oersted placed a long, straight, horizontal wire on top of a magnetic compass. [redacted]. In order to create a demonstration for his students, Oersted then sent a current through the wire. [redacted] Oersted noticed something that became one of the greatest discoveries in physics. The compass needle moved. The discovery was that a current can produce a magnetic field. This connection between [redacted] electricity and magnetism resulted in changes across the globe. Motors, electricity for everyday use, communication through cellular phones, and the development of the Internet are all a result of Oersted's discovery that electric currents produce magnetic fields.

You reproduced this famous experiment using a hand generator, some wire and a compass needle. Rather than having a single wire near the compass, you wound the wire around the compass. A related experiment maps out the magnetic field by surrounding a single current-carrying wire with compasses.



In the diagram at the right, you can see that when no current is flowing in the wire, all the compass needles point north. When a current is flowing, the compass needles all point in different directions.

The important concept is that the current-carrying wire can produce a magnetic field that can be detected with compasses. The magnetic field is circular about the wire. The direction of the magnetic field can be found experimentally with a compass. This direction can be recalled by using the left-hand rule. Point your left thumb in the direction of the current (the electron current travels from the negative terminal of a battery to the positive terminal). The direction of the curve of your fingers indicates the direction of the circular magnetic field.



Notice that the compass does not need to be in contact with the wire to experience a force due to the current in the wire. This situation illustrates the general phenomenon of "action at a distance." In other words, the current produces a force (an action) without touching (at a distance). In order to better understand how this occurs, the concept of the magnetic field is introduced to describe the empty space between the wire and the compass. The current in the wire produces a magnetic field in the space surrounding it. When a compass is placed in a region of space where a magnetic field exists, it experiences a force.

Checking Up

1. Describe the direction of the magnetic field around a current-carrying wire.
2. Toward which pole of a magnet does the north end of a compass point?
3. Compare the magnetic field of a magnet with the gravitational field of Earth.

Unlike "force fields" you may have seen in a movie, a real field does not end abruptly like some sort of shield or invisible wall. Instead, it just gets weaker and weaker as you move away from the source of the field. Other examples of fields are the electric field around charges and the gravitational fields around masses. Earth has a gravitational field that can pull on objects that are above Earth. When you drop a ball, the ball accelerates down. This can be described by saying that there is an invisible force of gravity that pulls the ball down. You can also say that Earth has a gravitational field that surrounds it. When the ball is placed in that field, it experiences a downward force. You are very familiar with the effects due to the gravitational field of Earth. Now you are aware that magnets respond to another field produced by Earth, namely its magnetic field. The concept of a field is an example of a model used in physics to help you understand natural phenomena.

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
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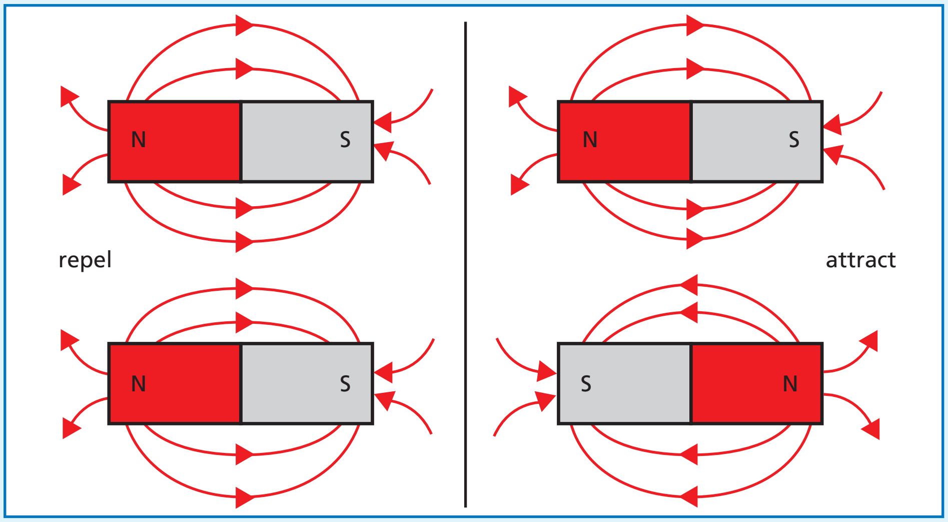
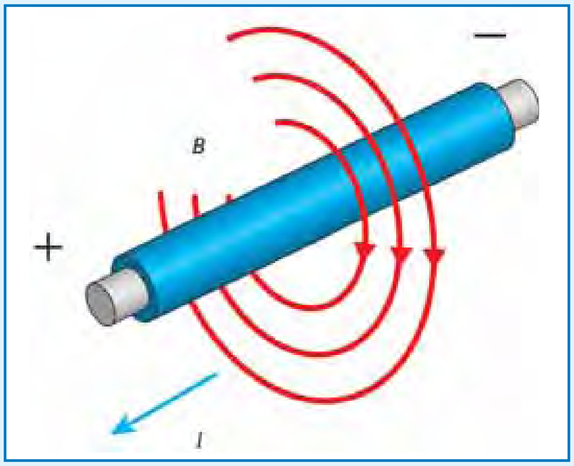
Observing the Sum of Magnetic Fields

Another way of describing the attraction and repulsion of bar magnets is to notice the sum of the magnetic field lines between the magnets.

In the diagram below, note that when the bar magnets repel, the field lines from the two magnets are in the same direction. When the bar magnets attract, the field lines from the two magnets are in opposite directions.

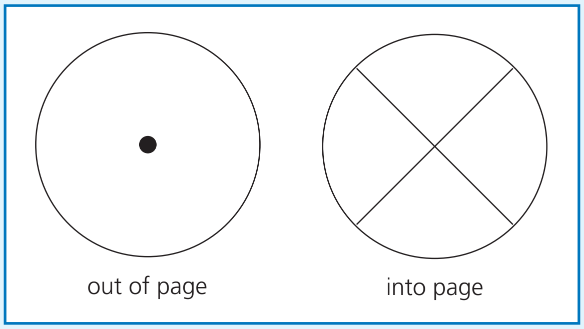


Below is a wire carrying a negative current, labeled *I*. Its magnetic field, labeled *B*, is shown as circles.



A useful convention for showing three dimensions on a sheet of paper is to draw the diagram in two dimensions. Then, use a dot in the circle representing the wire to denote "out of the page." A cross in the circle denotes "into the page."

If you think of an arrow piercing the page, this can help you remember the convention. If an arrow were coming out of the page, you would see its tip — a dot. If an arrow were going into the page, you would see the feathers — an X.



1. a) Draw a diagram that shows the magnetic-field lines for two parallel wires that are both carrying currents in the same direction.
   b) Compare the magnetic fields between the wires with the magnetic fields between the bar magnets above.
   c) On the basis of these diagrams, would you predict that these current-carrying wires attract or repel each other?
2. Repeat this exercise with parallel wires that are carrying currents in the opposite directions.

Is There an Equation for the Strength of a Magnetic Field?

When you investigated the magnetic field due to a current-carrying wire, you might have noticed that the field weakens as you move the compass away from the wire. An approximate formula for the magnetic field near a long current-carrying wire is

$$B = \frac{\mu_0 I}{2\pi d}$$

where B is the strength of the magnetic field measured in tesla,

μ_0 is a constant equal to $4\pi \times 10^{-7}$ newton/ampere^2,

I is the current in amperes, and

d is the distance to the wire in meters.

From the equation, you can see one tesla is equal to one newton/(ampere × meter). A magnetic field of one tesla is a strong magnetic field.

The strength of the magnetic field of Earth at its surface is roughly 0.00005 T (tesla) or 5×10^{-5} T. On the other hand, magnetic resonance imaging (MRI) requires a magnetic field of about one tesla.

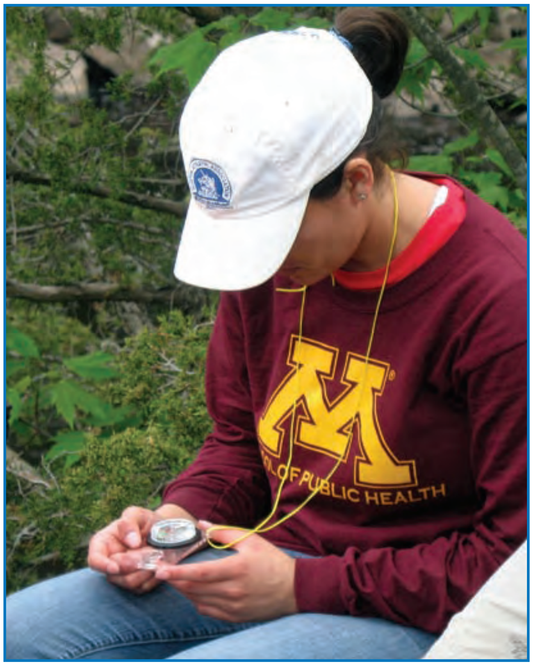
1. Calculate the strength of the magnetic field at three distances (0.5 cm, 1.0 cm, and 1.5 cm) from a straight vertical current-carrying wire with 3 A flowing through it. At approximately what distance does the magnetic field of the wire have the same strength as the magnetic field of Earth?
2. Draw a sketch showing the approximate direction the compass needle points when it is 1.0 cm from the straight wire carrying 3 A and located in four positions surrounding the wire.

What Do You Think Now?

At the beginning of this section, you were asked the following:

- **How is a compass affected by a bar magnet?**

Based on what you learned in your investigation, how would you answer this question now? Use what you learned in this section to describe how a compass is affected by a current-carrying wire.



Physics
Essential Questions

What does it mean?

Electricity is all about currents in wires. Magnetism is all about magnets. What is the connection between electricity and magnetism?

How do you know?

What did you observe that makes it clear that there is a connection between electricity and magnetism?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Electricity and magnetism	Models	* Parsimonious - maximum of generality for minimum of primary concepts

* Physics helps make sense of the world by attempting to describe different phenomena with a single explanation. How does Oersted's discovery help make the explanation of the world "simpler"?

Why should you care?

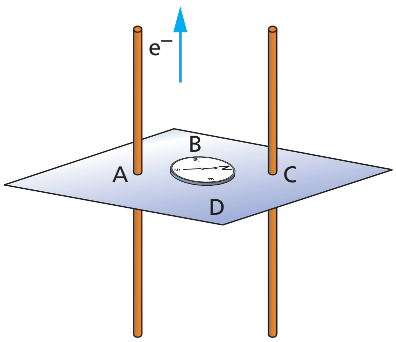
A motor is useful because it can make things move. The electric current can make a compass needle move. A motor can make a clothes dryer or a mixing blade spin. How are these motors similar to and different from the compass needle near the current?

Reflecting on the Section and the Challenge

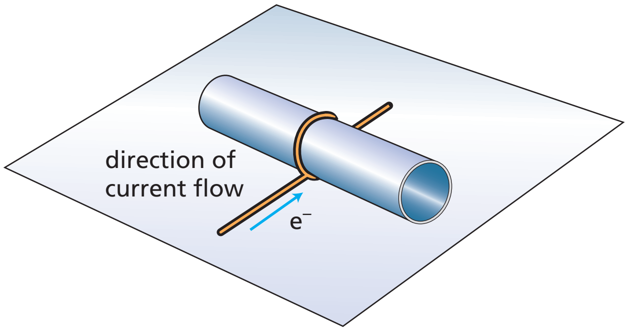
This section has provided you with knowledge about a critical link between electricity and magnetism, which is deeply involved in your challenge to make a working electric motor or generator. The response of the compass needle to a nearby electric current showed that an electric current itself has a magnetic effect that can cause a magnet, in this case a compass needle, to experience a force. You still have a way to go to understand and be able to be "in control" of electric motors and generators, but you have started along a path that will get you there.

Physics to Go

1. Sketch a bar magnet. Show the orientation of a compass placed at 10 different locations near the bar magnet.
2. Compare Oersted's experiment with a single wire and compass and your investigation with a wire and compass.
3. Suppose 100 compasses were placed on a horizontal surface to surround a vertical current-carrying wire. Describe the pattern of directions in which the 100 compasses would point in each of the following situations. (Pretend that one compass does not affect any other one.)
   a) No current is in the wire.
   b) A weak current is upwards in the wire.
   c) A strong current is upwards in the wire.
4. If a vertical wire carrying a strong current penetrated the floor of a room, and if you were using a compass to "navigate" in the room by always walking in the direction indicated by the north-seeking pole of the compass needle, describe the "walk" you would take.
5. Use the rule mentioned in the *Physics Talk* for the relationship between the direction of the current in a wire and the direction of the magnetic field near the wire to make a sketch showing the direction of the magnetic field near a wire which has a current:
   a) downward
   b) horizontally
6. Active Physics *Plus* Imagine that a second vertical wire is placed in the original apparatus used in this investigation, but not touching the first wire. There is room to place a magnetic compass between the wires without touching either wire. If a compass were placed between the wires, describe in what direction the compass would point if the wires carry equal currents:
   a) flowing in the same direction
   b) flowing in opposite directions



7. A hollow, transparent plastic tube is placed on a horizontal surface as shown in the diagram. A wire carrying a current is wound once around the tube to form a circular loop in the wire. In what direction would a compass placed inside the tube point? (Plastic does not affect a compass; only the current in the wire loop affects the compass.)



8. ***Preparing for the Chapter Challenge***

The challenge for you in this chapter is to develop a toy that contains either a motor or generator for a child. All motors and generators use either permanent magnets (like bar magnets) or electromagnets. All children find magnets fascinating. The instructions you include for assembling the toy may allow the students to explore the magnetic fields around any permanent magnets that you include in the kit. Write a brief description of at least three interesting things a child can do with the permanent magnets before assembling them to operate the toy.

Inquiring Further

Searching for magnetic fields

Use a compass to search for magnetic effects and magnetic "stuff." As you know, a compass needle usually aligns in a north-south direction. If a compass needle does not align north-south, a magnetic effect in addition to that of Earth is the cause, and the needle is responding to both Earth's magnetism and some other source of magnetism. Use a compass as a probe for magnetic effects. Try to find magnetic effects in a variety of places and near a variety of things where you suspect magnetism may be present. Try inside a car, bus, or subway. The structural steel in some buildings is magnetized and may cause a compass to give a "wrong" reading. Try near the speaker of a radio; try near electric motors, both operating and not operating.

Do not bring a strong magnet close to a compass, because the magnet may change the magnetic alignment of the compass needle, ruining the compass.

Make a list of the objects that are magnetic in nature and objects that affect a magnet that you find in your search.