8.1 Natural Magnetism and Electromagnetism

A systematic study of magnetism has been going on for the past two hundred years, yet physicists are still not able to fully explain the magnetic characteristics of the neutron and proton, and they are still puzzled about the origin of Earth's magnetic field. And while there are currently many applications of the principles of magnetism and electromagnetism in nature and society, scientists are continuously discovering new ways to use them.

DID YOU KNOW ?

Magnets

Early investigators of magnets used the mineral lodestone (magnetite), an oxide of iron that is naturally magnetized. Now artificial magnets, containing iron, nickel, cobalt, and gadolinium in alloys or ceramics, are used instead.

Magnets

When a bar magnet is dipped into iron filings, the filings are attracted to it, accumulating most noticeably around regions at each end of the magnet—the **poles**. When the bar magnet is allowed to rotate freely the pole that tends to seek the northerly direction is called the north-seeking pole, or simply, the N-pole. The other is called the south-seeking pole, or S-pole.

poles the regions at the end of a magnetized body at which magnetic attraction is strongest

By placing two bar magnets first with similar poles together, then with opposite poles together, you can demonstrate the *law of magnetic poles* (**Figure 1**):

Law of Magnetic Poles

Opposite magnetic poles attract. Similar magnetic poles repel.

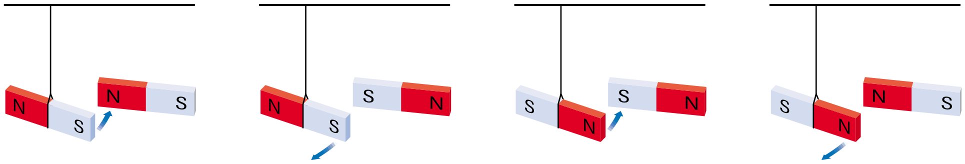


Figure 1
The law of magnetic poles

Magnetic Fields

Since an iron filing experiences a force when placed near a magnet, then, by definition, a magnet is surrounded by a **magnetic force field**. This field is often detected by its effect on a small test compass (magnetized needle). It is visually depicted by drawing magnetic field lines that show the direction in which the N-pole of the test compass points at all locations in the field. Experimentally, the lines in a magnetic field can easily be traced by sprinkling iron filings on a sheet of paper placed in the field. The filings behave like many tiny compasses and line up in the direction of the field at all points. They produce a "picture" of the magnetic field, as shown in **Figure 2**.

magnetic force field the area around a magnet in which magnetic forces are exerted

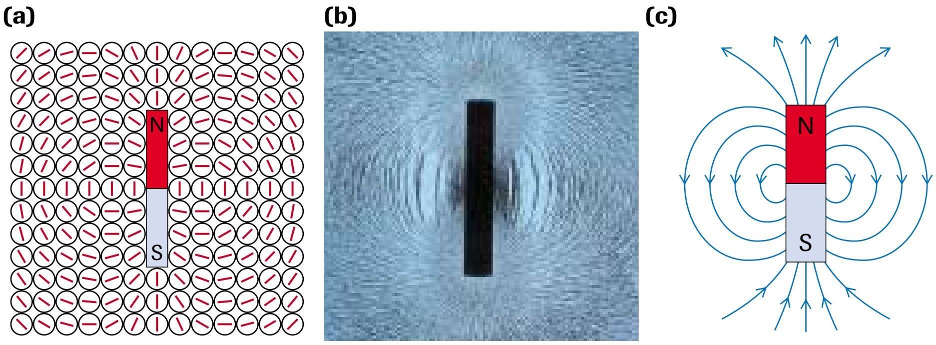


Figure 2
(a) The magnetic field of a single bar magnet is revealed by a number of compasses.
(b) Iron filings show the field clearly but do not reveal the pole orientation.
(c) The field in one plane is represented by a series of directed lines that by convention emerge from the N-pole and curve toward the S-pole.

Since iron filings have no marked north or S-poles, they reveal only the pattern of the magnetic field lines, not their direction (**Figure 3**). The relative strength of the magnetic field is indicated by the spacing of adjacent field lines: where lines are close together, the magnetic field is strong.

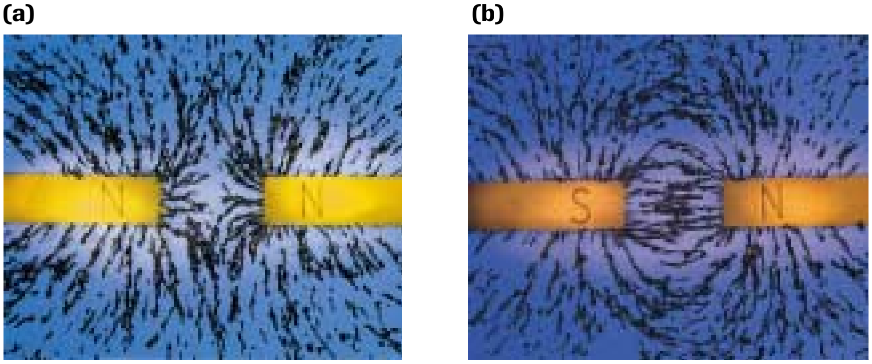


Figure 3
(a) Similar poles face each other.
(b) Opposite poles face each other.

The magnetic field at any point is a vector quantity, represented by the symbol $\vec{B}$. The magnitude B is given by the magnitude of the torque (or turning action) on a small test compass not aligned with the direction of the field. We will make a more precise definition of B later in this chapter, when we examine electromagnetism.

Earth's Magnetic Field

A pivoted magnet will rotate and point north–south because of its interaction with the magnetic field of Earth. As early as the 16th century, Sir William Gilbert, the distinguished English physicist, had devised a model to describe Earth's magnetism. He determined that Earth's magnetic field resembled the field of a large bar magnet, inclined at a slight angle to Earth's axis, with its S-pole in the northern hemisphere. **Figure 4(a)** shows this field and the bar magnet that was thought, in Gilbert's time, to be responsible for it.

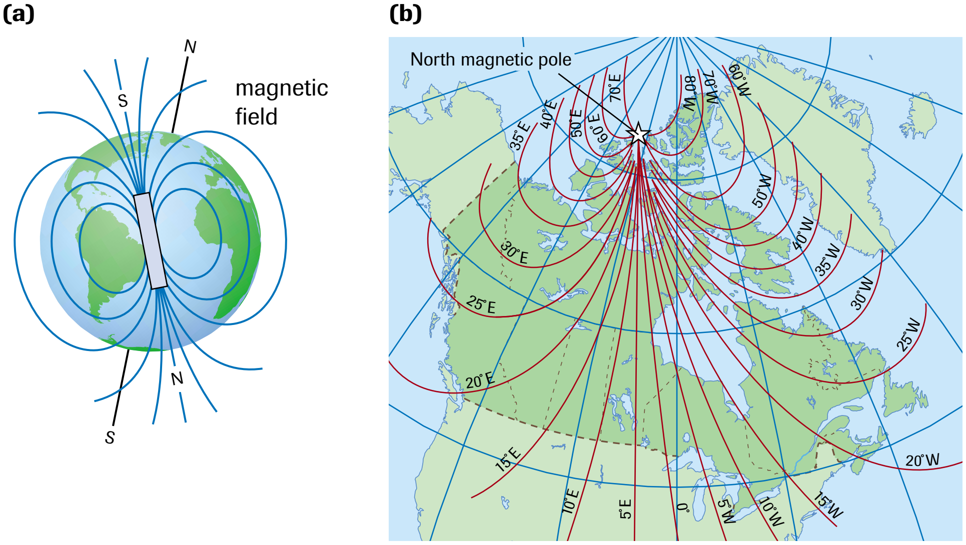


Figure 4
(a) The magnetic field of Earth closely resembles the field of a large bar magnet.
(b) Lines of magnetic declination in Canada

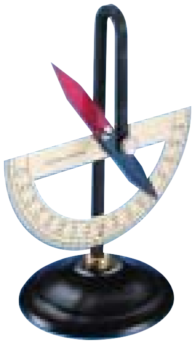


Figure 5
A dipping needle is a compass pivoted at its centre of gravity and free to rotate in a vertical plane. When aligned with a horizontal compass pointing north, it points in the direction of Earth's magnetic field. The angle of inclination is then read directly from the attached protractor.

A compass points toward Earth's magnetic N-pole, rather than toward its geographic north pole (the north end of Earth's axis of rotation). The angle, or *magnetic declination*, between magnetic north and geographic north varies from position to position on the surface of Earth (**Figure 4(b)**). In navigating by compass, the angle of declination for a particular location must be known so that true north can be determined.

In addition, Earth's magnetic field is three-dimensional, with both a horizontal and a vertical component. A magnetic compass on a horizontal surface reveals only the horizontal component. The angle between Earth's magnetic field, at any point, and the horizontal is called the *magnetic inclination*, or "dip," and is measured with a magnetic dipping needle (**Figure 5**).

Inclination and declination charts must be revised from time to time because Earth's magnetic field is slowly changing. It is believed that these changes result from the rotation of the magnetic field about Earth's axis; one complete rotation takes about 1000 years (**Figure 6**).

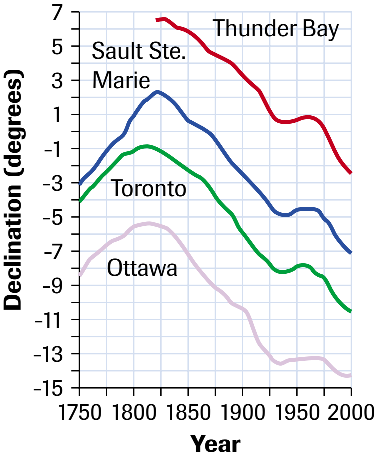


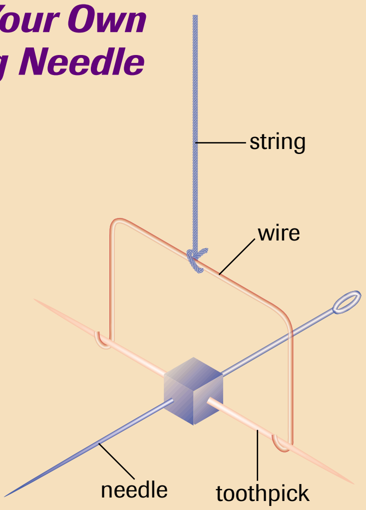
Figure 6
This chart shows how the magnetic declination in Ontario has changed since 1750 at Thunder Bay, Sault Ste Marie, Ottawa, and Toronto. The negative signs indicate a westerly declination.

Source: Natural Resources Canada

TRY THIS activity

Make Your Own Dipping Needle

Bend a piece of wire into a stirrup, and tie a piece of string to the middle of it as shown. Push a needle through a small cube of Styrofoam. Then push a round toothpick through the Styrofoam, perpendicular to the needle, balancing the toothpick on the wire stirrup. Magnetize the needle, balancing the setup as a combined compass and dipping needle. Explain how your device works.



The Domain Theory of Magnetism

Although not normally magnetized, some *ferromagnetic* materials, such as iron, nickel, cobalt, and gadolinium, may become magnetized under certain circumstances. How they are able to acquire magnetic properties may be explained by the **domain theory of magnetism**.

domain theory of magnetism theory that describes, in terms of tiny magnetically homogeneous regions ("domains"), how a material can become magnetized: each domain acts like a bar magnet

Ferromagnetic substances are composed of a large number of tiny regions called *magnetic domains*. Each domain behaves like a tiny bar magnet, with its own N- and S-poles. When a specimen of the material is unmagnetized, these millions of domains are oriented at random, with their magnetic effects cancelling each other out, as in **Figure 7**.

However, if a piece of ferromagnetic material is placed in a sufficiently strong magnetic field, some domains rotate to align with the external field, while others, already aligned, tend to increase in size at the expense of neighbouring nonaligned domains (**Figure 8**). The net result is a preferred orientation of the domains (in the same direction as the external field), causing the material to behave like a magnet. When the external field is removed, this orientation will either remain for a long time or disappear almost immediately, depending on the material. When magnets are made in this way, they are known as *induced* magnets.

The domain model provides a simple explanation for many properties of induced magnets:

1. A needle is magnetized by rubbing it in one direction with a strong permanent magnet. This aligns the domains with the field of the permanent magnet.
2. When a bar magnet is broken in two, two smaller magnets result, each with its own N- and S-poles. It is impossible to produce an isolated N- or S-pole by breaking a bar magnet.
3. Induced magnets made of "soft" iron demagnetize as soon as the external field is removed. Examples include temporary magnets such as lifting electromagnets. In contrast, hard steel or alloys remain magnetized indefinitely. These include permanent magnets such as magnetic door catches. Impurities in the alloys seem to "lock" the aligned domains in place and prevent them from relaxing to their random orientation.
4. Heating or dropping a magnet can cause it to lose its magnetization, jostling the domains sufficiently to allow them to move and resume their random orientation. Each ferromagnetic material has a critical temperature above which it becomes demagnetized and remains demagnetized even upon cooling.
5. A strong external magnetic field can reverse the magnetism in a bar magnet, causing the former south-seeking pole to become north-seeking. This occurs when the domains reverse their direction of orientation by 180° due to the influence of the strong external field in the opposite direction.
6. Ships' hulls, columns and beams in buildings, and many other steel structures are often found to be magnetized by the combined effects of Earth's magnetic field and the vibrations imposed during construction. The effect is similar to stroking a needle with a strong magnet, in that the domains within the metals are caused to line up with Earth's magnetic field. Vibrations during construction aid in the realignment of the domains.

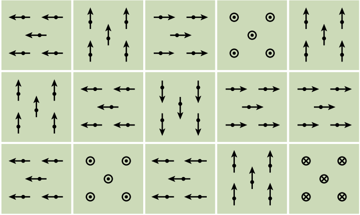


Figure 7
The atomic dipoles are lined up in each domain. The domains point in random directions. The magnetic material is unmagnetized.

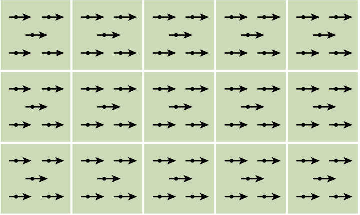


Figure 8
The atomic dipoles (not the domains) turn so that all domains point in the direction of the magnetizing field. The magnetic material is fully magnetized.

Prior to the nineteenth century, electricity and magnetism, although similar in many respects, were generally considered separate phenomena. It was left to an accidental discovery by the Danish physicist Hans Christian Oersted (1777–1851), while teaching at the University of Copenhagen, to reveal a relationship between the two. Observing that a magnetic compass needle was deflected by an electric current flowing through a nearby wire, Oersted formulated the basic *principle of electromagnetism:*

Principle of Electromagnetism

Moving electric charges produce a magnetic field.

Magnetic Field of a Straight Conductor

When an electric current flows through a long, straight conductor, the resulting magnetic field consists of field lines that are concentric circles, centred on the conductor (**Figure 9**).

You can remember the direction of these field lines (as indicated by the N-pole of a small test compass) if you use the *right-hand rule for a straight conductor:*

Right-Hand Rule for a Straight Conductor

If a conductor is grasped in the right hand, with the thumb pointing in the direction of the current, the curled fingers point in the direction of the magnetic field lines.

LEARNING TIP

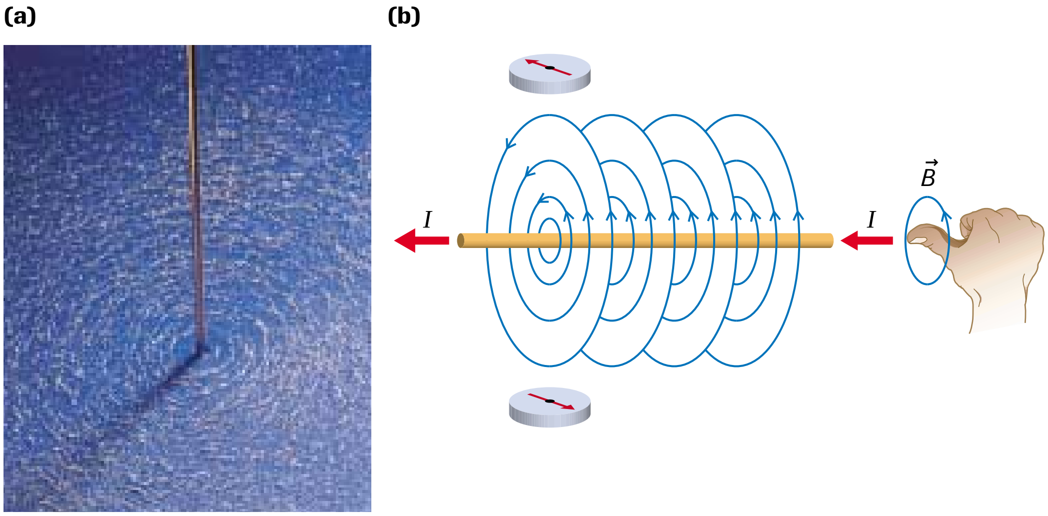
Current Direction

Conventional current direction is being used, not electron flow direction.

Figure 9

(a) Iron filings reveal the circular pattern of the magnetic field around a conductor with a current.

(b) If the right thumb points in the direction of the current, then the fingers curl around the wire in the direction of the magnetic field lines.



Magnetic Field of a Current Loop

When a straight wire is formed into a circular loop, its magnetic field will appear as shown in **Figure 10**. Note that the field lines inside the loop are closer together, indicating a stronger magnetic field than on the outside of the loop.

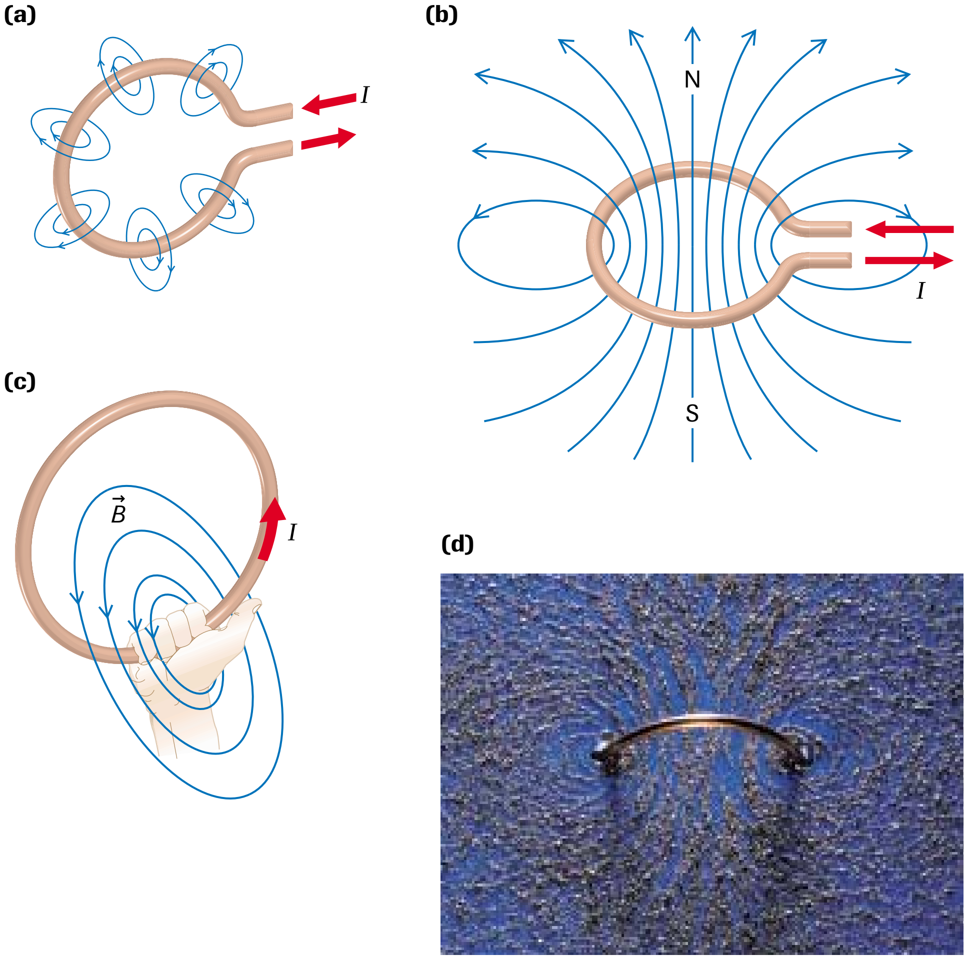
Figure 10

(a) Each individual segment produces its own magnetic field, in the manner of a straight conductor.

(b) The individual fields combine to form a net field similar to the three-dimensional field of a bar magnet.

(c) The right-hand rule for straight conductors gives the direction of the magnetic field of a single loop.

(d) Iron filings reveal the magnetic field pattern.



Magnetic Field of a Coil or Solenoid

A **solenoid** is a long conductor wound into a coil of many loops. The magnetic field of a solenoid (**Figure 11**) is the sum of the magnetic fields of all of its loops. The field inside the coil can consequently be very strong. If the coil is tightly wound, the field lines are nearly straight and very close together (**Figure 12**).

solenoid a coiled conductor used to produce a magnetic field; when a current is passed through the wire, a magnetic field is produced inside the coil

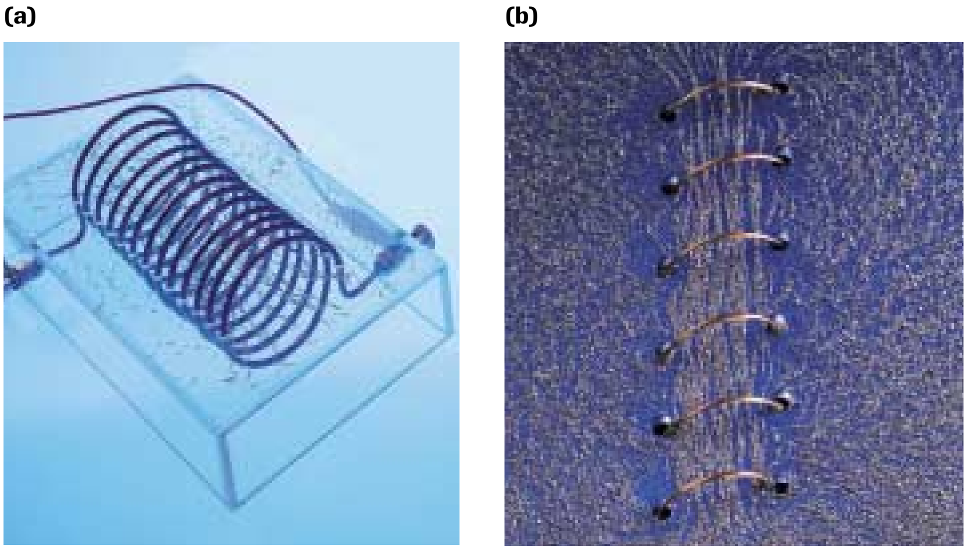


Figure 11
(a) A solenoid
(b) Iron filings reveal the field lines in and around a solenoid.

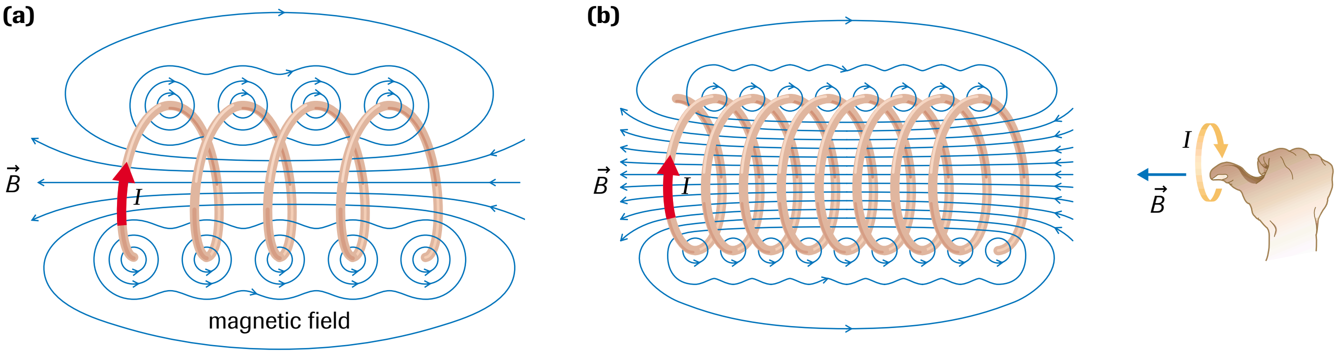


Figure 12
(a) When the solenoid is loosely wound, field lines within the coil are curved.
(b) The field becomes stronger and straighter inside the coil when the coil is wound tighter. The right-hand rule for solenoids (a corollary of the right-hand rule for a straight conductor) gives the direction of the field inside the coil.

A solenoid has a magnetic field very similar to the field of a bar magnet, with the convenient additional feature that the field can be switched off and on. To remember the direction of the magnetic field of a solenoid, we apply a special right-hand rule for a solenoid:

Right-Hand Rule for a Solenoid

If a solenoid is grasped in the right hand, with the fingers curled in the direction of the electric current, the thumb points in the direction of the magnetic field lines in its core.

Note that the right-hand rule for a solenoid is consistent with the right-hand rule for a straight conductor if we point our thumb along, or tangent to, the curved wire of the coil.

DID YOU KNOW?

Strength Outside the Coil

The field lines outside the coil have an enormous volume of space to fill; therefore, they spread out so much that the field strength is negligible.

Using Electromagnets and Solenoids

If a piece of a ferromagnetic material, such as iron, is placed in the core of a solenoid, the magnetic field can become stronger, even by a factor of several thousand. The domains in the iron are aligned by the magnetic field of the coil, with the total magnetic field now the sum of the field due to the coil and the field due to the magnetized core material. The ratio of magnetic field strength for a particular core material to magnetic field strength in the absence of the material is called the *relative permeability* of the material. In other words, permeability is a measure of the extent to which a material is affected by a magnetic field. A high permeability of a material means that the magnitude of the magnetic field will be high when using that material; a low permeability (close to 1) means that the magnitude of the magnetic field will be close to that of a vacuum. **Table 1** lists relative magnetic permeabilities of some common materials. It shows that the magnetic field with a nickel core will be 1000 times stronger than a vacuum core.

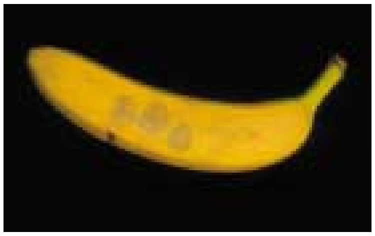
Typical engineering applications demand that the iron in a solenoid core be "magnetically soft," or free of impurities that tend to lock domains into place after the external field disappears. Iron-core solenoids that lose their magnetism the instant the current is disconnected are useful not only in lifting electromagnets, but in many other devices, such as bells, relays, and magnetic speakers.

Table 1 Relative Magnetic Permeabilities of Common Materials

Material	Relative Magnetic Permeability
copper	0.999 99
water	0.999 999
vacuum	1.000 000
oxygen	1.000 002
aluminum	1.000 02
cobalt	170
nickel	1 000
steel	2 000
iron	6 100
permalloy	100 000

DID YOU KNOW ?

Magnetism and Fingerprinting



The fingerprints on this banana are revealed by magnetic fingerprint powder, a new invention used to detect fingerprints on surfaces impossible to check by conventional means. The powder consists of tiny iron flakes with an organic coating that makes them stick to the greasy residue in a fingerprint. Excess powder is removed by a magnet, eliminating the need for brushing and therefore leaving the delicate fingerprints intact. The technique gives sharper results than traditional methods and works on difficult surfaces including plastic bags, magazine covers, wallpaper, and wood.

SUMMARY Natural Magnetism and Electromagnetism

- The law of magnetic poles states that opposite magnetic poles attract and similar magnetic poles repel.
- A magnet is surrounded by a magnetic force field.
- The domain theory states that ferromagnetic substances are composed of a large number of tiny regions called magnetic domains, with each domain acting like a tiny bar magnet. These domains can be aligned by an external magnetic field.
- The principle of electromagnetism states that moving electric charges produce a magnetic field.

Section 8.1 Questions

Understanding Concepts

1. Explain why a piece of iron can be magnetized but a piece of copper cannot.
2. (a) What will happen to the iron filings in a long glass tube if they are gently shaken in the presence of a strong magnetic field and then the tube is carefully removed from the magnetic field?
   (b) What will happen if the glass tube is shaken again?
   (c) How is this process related to a solid bar of iron as described by the domain theory?
3. In the section discussing "The Domain Theory of Magnetism," a list of explanations for many properties of magnets is provided. Draw diagrams to illustrate "before" and "after" scenarios for each of the cases listed.
4. Compare the magnetic, electric, and gravitational fields of Earth in a table of similarities and differences.
5. Consider the magnetic field around a long, straight conductor with a steady current.
   (a) How is this field related to the field around a loop of wire?
   (b) How is the field around a loop of wire related to the field around a long coil of wire?

Applying Inquiry Skills

6. The equipment shown in **Figure 13** was used by James Clerk Maxwell to confirm the nature of the magnetic field around a long, straight conductor. He found that no matter how large the current through the wire, the disk did not rotate at all.
   (a) Explain how this device can be used to determine the nature of the magnetic field around a conductor with a steady current.
   (b) Outline the steps you would use in an experiment of this nature.

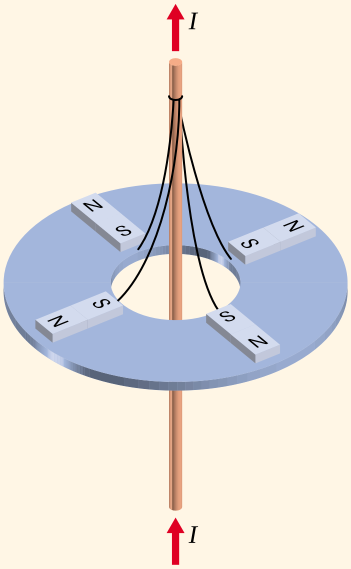


Figure 13
Equipment used by Maxwell

7. Examine the diagram of the electric doorbell in **Figure 14** and explain how it works.

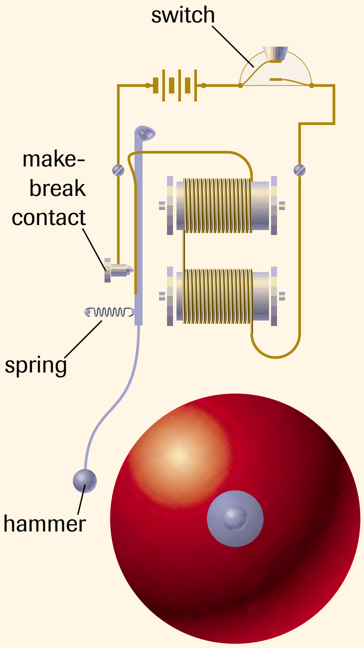


Figure 14

Making Connections

8. **Figure 15** is a micrograph of a magnetotactic bacterium. Prominent in this image is a row of dark, circular dots, in reality a chain of magnetite crystals. What purpose do you think the crystals serve? How could you test your hypothesis? Research the bacterium to check your answer.

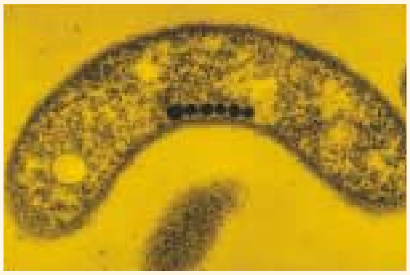


Figure 15
A magnetotactic bacterium