

UNIT 4

Magnetism

Why You Need to Know

Magnetism and electricity are inseparable. If you have one, the other can be produced. A list of devices that operate on magnetism is almost endless. Everything from a simple compass to the largest electric motor in industry operates on magnetism. This unit presents those basic principles and discusses the most common terms used to measure magnetism:

- flux density.
- reluctance.
- ampere-turns.
- the left-hand rule regarding electromagnets.

These concepts appear many times in the study of electricity.

Key Terms

Ampere-turns
Demagnetized
Electromagnets
Electron spin patterns
Flux
Flux density
Left-hand rule
Lines of flux
Lodestones
Magnetic domains
Magnetic molecules
Magnetomotive force (mmf)
Permanent magnets
Permeability
Reluctance
Residual magnetism
Saturation

Outline

- 4–1** The Earth Is a Magnet
- 4–2** Permanent Magnets
- 4–3** The Electron Theory of Magnetism
- 4–4** Magnetic Materials
- 4–5** Magnetic Lines of Force
- 4–6** Electromagnetics
- 4–7** Magnetic Measurement
- 4–8** Magnetic Polarity
- 4–9** Demagnetizing
- 4–10** Magnetic Devices

Objectives

After studying this unit, you should be able to

- discuss the properties of permanent magnets.
- discuss the difference between the axis poles of the earth and the magnetic poles of the earth.
- discuss the operation of electromagnets.
- determine the polarity of an electromagnet when the direction of the current is known.
- discuss the different systems used to measure magnetism.
- define terms used to describe magnetism and magnetic quantities.

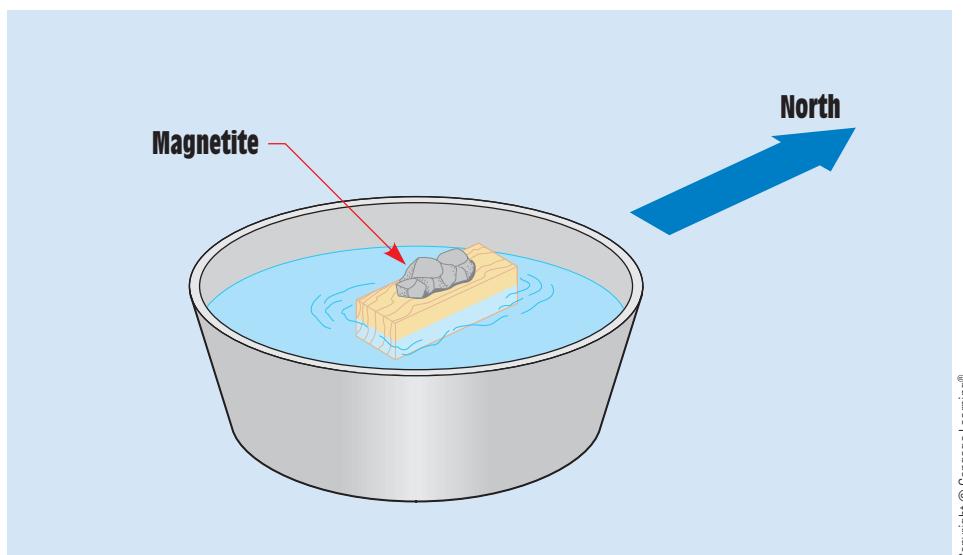
Preview

Magnetism is one of the most important phenomena in the study of electricity. It is the force used to produce most of the electrical power in the world. The force of magnetism has been known for over 2000 years. It was first discovered by the Greeks when they noticed that a certain type of stone was attracted to iron. This stone was first found in Magnesia in Asia Minor and was named magnetite. In the Dark Ages, the strange powers of the magnet were believed to be caused by evil spirits or the devil. ■

4-1

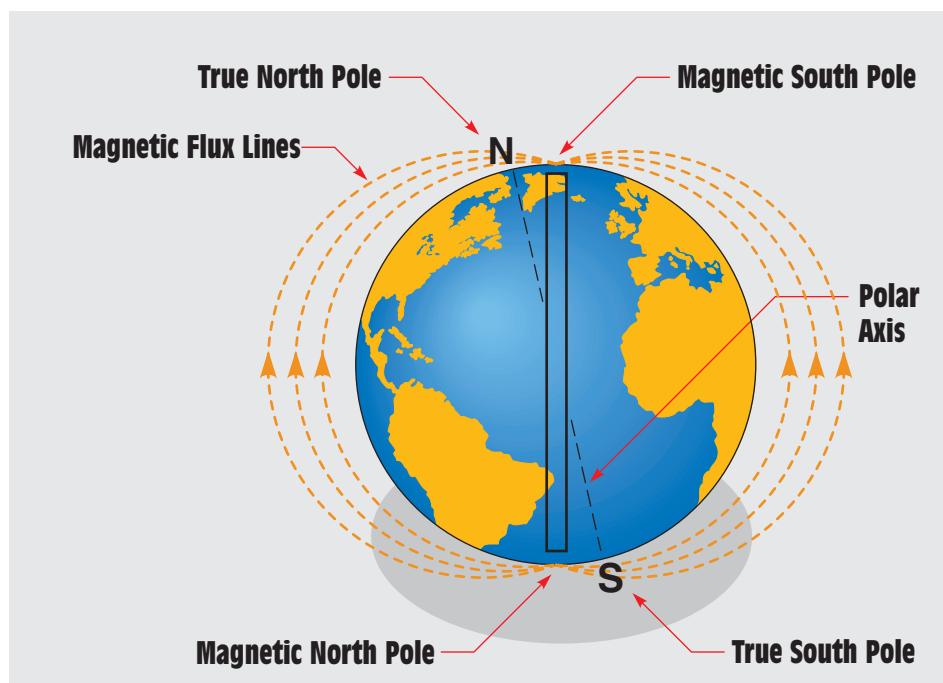
The Earth Is a Magnet

The first compass was invented when it was noticed that a piece of magnetite, a type of stone that is attracted to iron, placed on a piece of wood floating in water always aligned itself north and south (Figure 4-1). Because they are always able to align themselves north and south, natural magnets became known as “leading stones” or **lodestones**. The reason that the lodestone aligned itself north and south is because the earth itself contains magnetic



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FIGURE 4-1 The first compass.



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FIGURE 4-2 The earth is a magnet.

poles. Figure 4–2 illustrates the positions of the true North and South Poles, or the axis, of the earth and the positions of the magnetic poles. Notice that *magnetic north* is not located at the true North Pole of the earth. This is the reason that navigators must distinguish between true north and magnetic north. The angular difference between the two is known as the *angle of declination*. Although the illustration shows the magnetic lines of force to be only on each side of the earth, the lines actually surround the entire earth like a magnetic shell.

Also notice that the magnetic north pole is located near the southern polar axis and the magnetic south pole is located near the northern polar axis. The reason that the *geographic* poles (axes) are called north and south is because the north pole of a compass needle points in the direction of the north geographic pole. Because unlike magnetic poles attract, the north magnetic pole of the compass needle is attracted to the south magnetic pole of the earth.

4-2**Permanent Magnets**

Permanent magnets are magnets that do not require any power or force to maintain their field. They are an excellent example of one of the basic laws of magnetism that states that *energy is required to create a magnetic field, but no energy is required to maintain a magnetic field*. Man-made permanent magnets are much stronger and can retain their magnetism longer than natural magnets.

4-3**The Electron Theory of Magnetism**

Only three substances actually form natural magnets: iron, nickel, and cobalt. Why these materials form magnets has been the subject of complex scientific investigations, resulting in an explanation of magnetism based on **electron spin patterns**. It is believed that electrons spin on their axes as they orbit around the nucleus of the atom. This spinning motion causes each electron to become a tiny permanent magnet. Although all electrons spin, they do not all spin in the same direction. In most atoms, electrons that spin in opposite

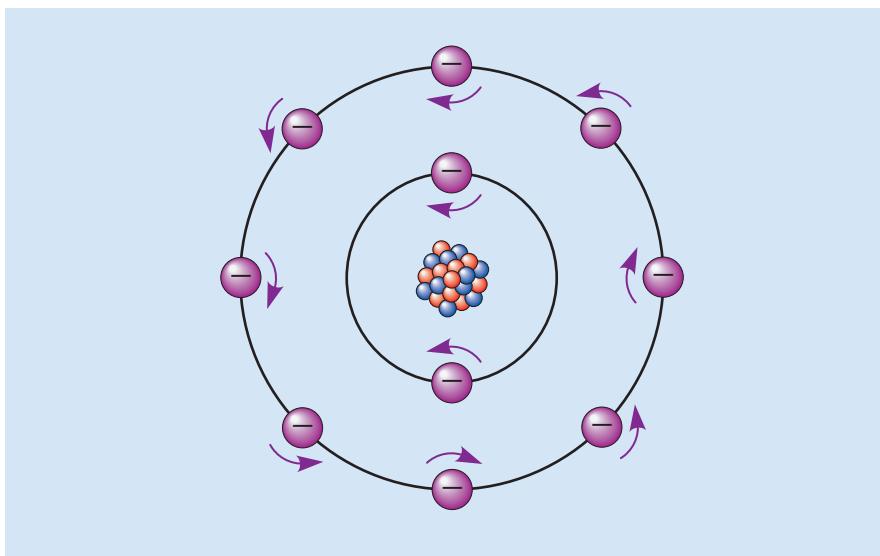


FIGURE 4–3 Electron pairs generally spin in opposite directions.

directions tend to form pairs (*Figure 4–3*). Because the electron pairs spin in opposite directions, their magnetic effects cancel each other out as far as having any effect on distant objects. In a similar manner, two horseshoe magnets connected together would be strongly attracted to each other but would have little effect on surrounding objects (*Figure 4–4*).

An atom of iron contains 26 electrons. Of these 26, 22 are paired and spin in opposite directions, canceling each other's magnetic effect. In the next to the outermost shell, however, 4 electrons are not paired and spin in the same direction. These 4 electrons account for the magnetic properties of iron. At a temperature of 1420°F, or 771.1°C, the electron spin patterns rearrange themselves and iron loses its magnetic properties.

When the atoms of most materials combine to form molecules, they arrange themselves in a manner that produces a total of eight valence electrons. The electrons form a spin pattern that cancels the magnetic field of the material. When the atoms of iron, nickel, and cobalt combine, however, the magnetic field is not canceled. Their electrons combine so that they share valence electrons in such a way that their spin patterns are in the same direction, causing their magnetic fields to add instead of cancel. The additive effect forms regions in the molecular structure of the metal called **magnetic domains** or **magnetic molecules**. These magnetic domains act like small permanent magnets.

A piece of nonmagnetized metal has its molecules in a state of disarray (*Figure 4–5*). When the metal is magnetized, its molecules align themselves in an orderly pattern

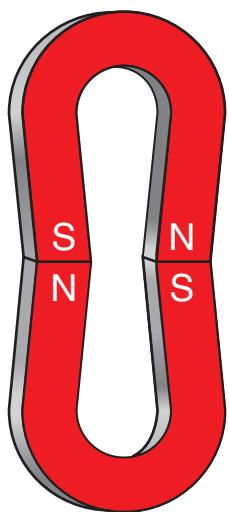


FIGURE 4–4 Two horseshoe magnets attract each other.

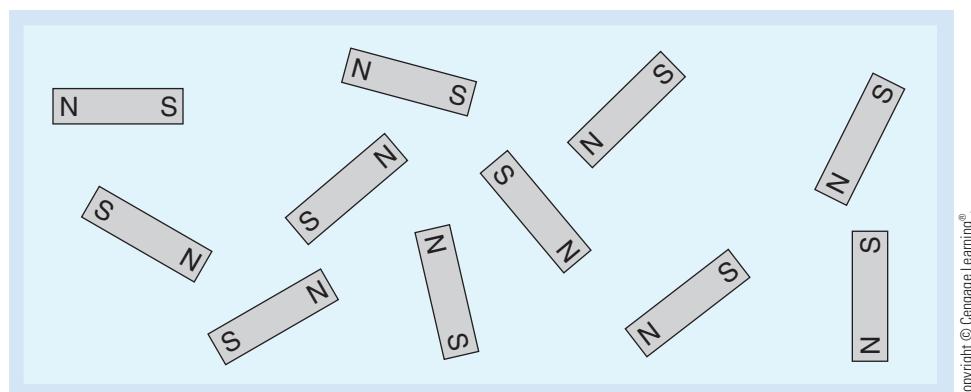
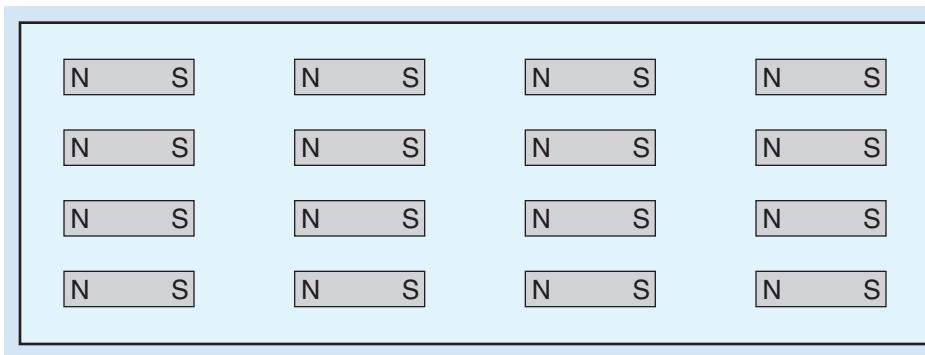
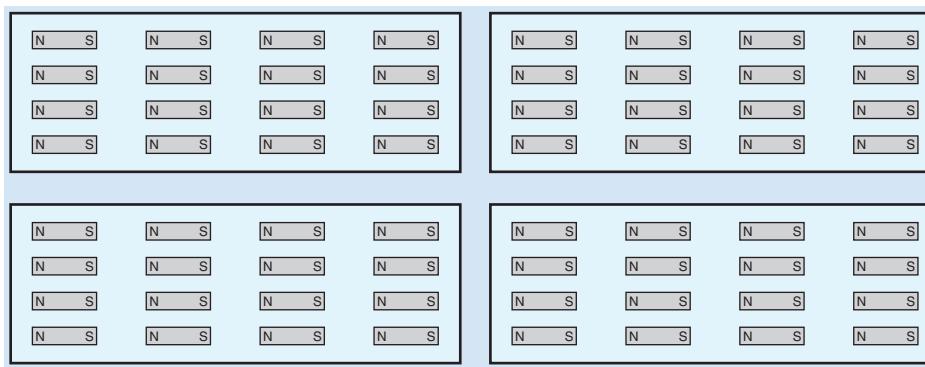


FIGURE 4–5 The atoms are disarrayed in a piece of nonmagnetized metal.



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FIGURE 4-6 The atoms are aligned in an orderly fashion in a piece of magnetized metal.

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FIGURE 4-7 When a magnet is cut apart, each piece becomes a separate magnet.

(Figure 4–6). In theory, each molecule of a magnetic material is itself a small magnet. If a permanent magnet is cut into pieces, each piece is a separate magnet (Figure 4–7).

4-4 Magnetic Materials

Magnetic materials can be divided into three basic classifications:

- *Ferromagnetic materials* are metals that are easily magnetized. Examples of these materials are iron, nickel, cobalt, and manganese.
- *Paramagnetic materials* are metals that can be magnetized, but not as easily as ferromagnetic materials. Some examples of paramagnetic materials are platinum, titanium, and chromium.
- *Diamagnetic materials* are either metal or nonmetal materials that cannot be magnetized. The magnetic lines of force tend to go around them instead of through them. Some examples of these materials are copper, brass, and antimony.

Some of the best materials for the production of permanent magnets are alloys. One of the best permanent magnet materials is Alnico 5, which is made from a combination of aluminum, nickel, cobalt, copper, and iron. Another type of permanent magnet material is made from a combination of barium ferrite and strontium ferrite. Ferrites can have an advantage in some situations because they are insulators and not conductors. They have a resistivity of approximately 1,000,000 ohm-centimeters. Barium ferrite and strontium

ferrite can be powdered. The powder is heated to the melting point and then rolled and heat treated. This treatment changes the grain structure and magnetic properties of the material. The new type of material has a property more like stone than metal and is known as a *ceramic magnet*. Ceramic magnets can be powdered and mixed with rubber, plastic, or liquids. Ceramic magnetic materials mixed with liquids can be used to make magnetic ink, which is used on checks. Another frequently used magnetic material is iron oxide, which is used to make magnetic recording tape and computer disks.

4-5 Magnetic Lines of Force

Magnetic lines of force are called **flux**. The symbol used to represent flux is the Greek letter phi (Φ). Flux lines can be seen by placing a piece of cardboard on a magnet and sprinkling iron filings on the cardboard. The filings will align themselves in a pattern similar to the one shown in *Figure 4-8*. The pattern produced by the iron filings forms a two-dimensional figure, but the flux lines actually surround the entire magnet (*Figure 4-9*). Magnetic **lines of flux** repel each other and never cross. Although magnetic lines of flux do not flow, it is assumed they are in a north to south direction because that is the direction that a compass needle would point. Flux lines are stronger near the poles of the magnet and become weaker as they move farther away.

A basic law of magnetism states that *unlike poles attract and like poles repel*. *Figure 4-10* illustrates what happens when a piece of cardboard is placed over two magnets with their north and south poles facing each other and iron filings are sprinkled on the cardboard.

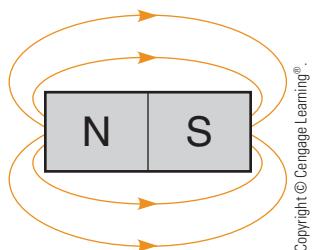


FIGURE 4-8 Magnetic lines of force are called lines of flux.

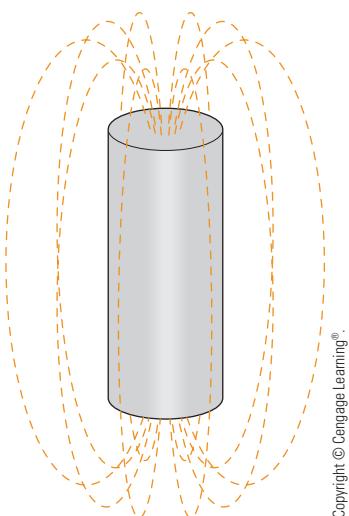


FIGURE 4-9 Magnetic lines of flux surround the entire magnet.

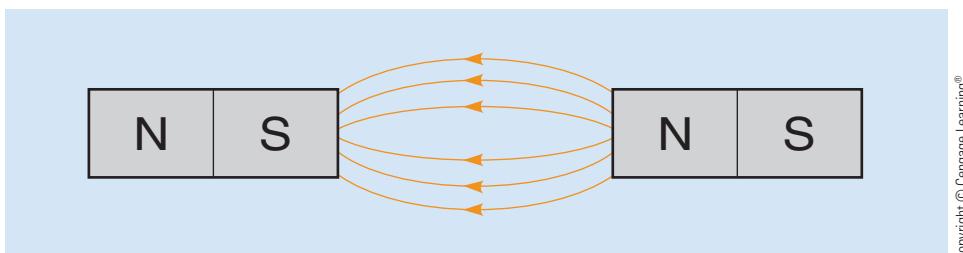
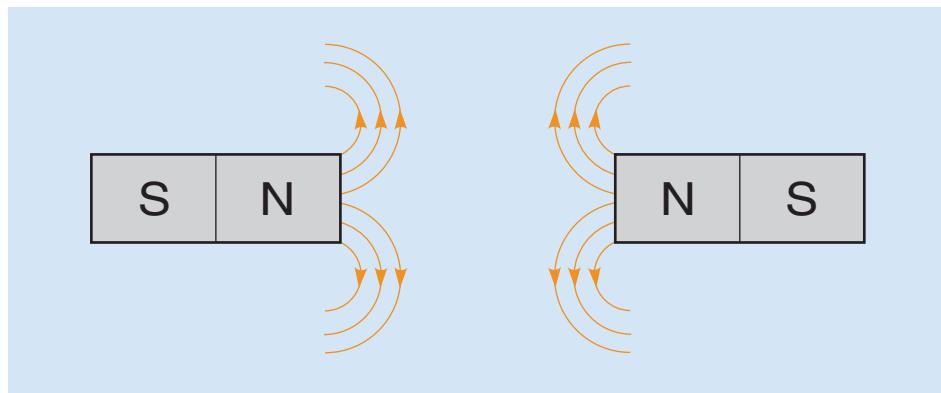
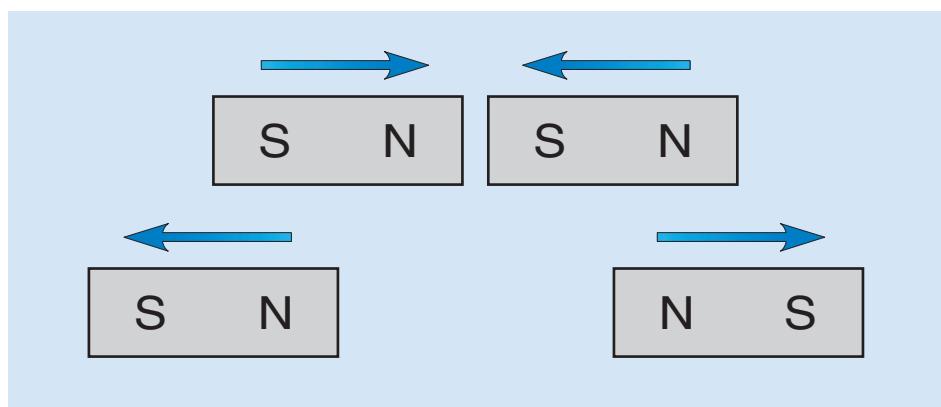


FIGURE 4-10 Opposite magnetic poles attract each other.



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FIGURE 4-11 Like magnetic poles repel each other.

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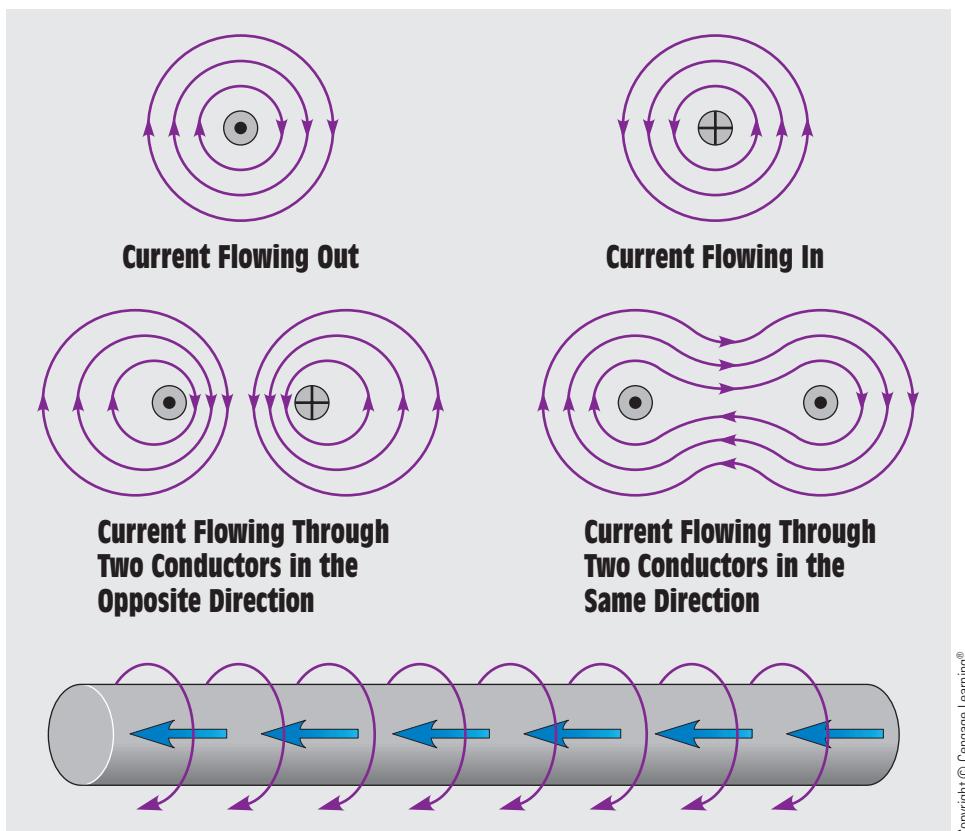
FIGURE 4-12 Opposite poles of a magnet attract, and like poles repel.

The filings form a pattern showing that the magnetic lines of flux are attracted to each other. *Figure 4-11* illustrates the pattern formed by the iron filings when the cardboard is placed over two magnets with like poles facing each other. The filings show that the magnetic lines of flux repel each other.

If the opposite poles of two magnets are brought close to each other, they are attracted to each other (*Figure 4-12*). If like poles of the two magnets are brought together, they repel each other.

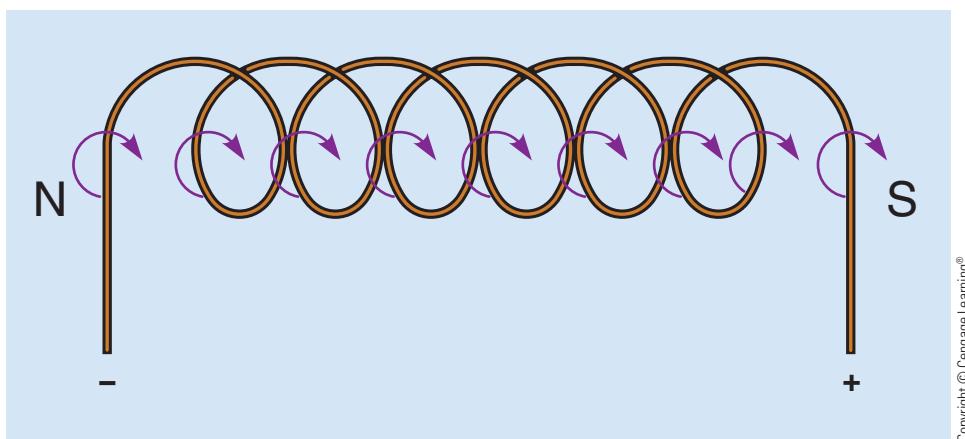
4-6**Electromagnetics**

A basic law of physics states that *whenever an electric current flows through a conductor, a magnetic field is formed around the conductor*. Electromagnets depend on electric current flow to produce a magnetic field. They are generally designed to produce a magnetic field only as long as the current is flowing; they do not retain their magnetism when current flow stops. Electromagnets operate on the principle that current flowing through a conductor produces a magnetic field around the conductor (*Figure 4-13*). If the conductor is wound into a coil (*Figure 4-14*), the magnetic lines of flux add to produce a stronger magnetic field. A coil with 10 turns of wire produces a magnetic field that is 10 times as strong as the magnetic field around a single conductor.



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FIGURE 4-13 Current flowing through a conductor produces a magnetic field around the conductor.



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FIGURE 4-14 Winding the wire into a coil increases the strength of the magnetic field.

Another factor that affects the strength of an electromagnetic field is the amount of current flowing through the wire. An increase in current flow causes an increase in magnetic field strength. The two factors that determine the number of flux lines produced by an electromagnet are the number of turns of wire and the amount of current flow through the wire. The strength of an electromagnet is proportional to its **ampere-turns**. Ampere-turns are determined by multiplying the number of turns of wire by the current flow.

Core Material

Coils can be wound around any type of material to form an electromagnet. The base material is called the *core material*. When a coil is wound around a nonmagnetic material such as wood or plastic, it is known as an *air-core magnet*. When a coil is wound around a magnetic material such as iron or soft steel, it is known as an *iron-core magnet*. The addition of magnetic material to the center of the coil can greatly increase the strength of the magnet. If the core material causes the magnetic field to become 10 times stronger, the core material has a **permeability** of 10 (Figure 4–15). Permeability is a measure of a material's ability to become magnetized. The number of flux lines produced is proportional to the ampere-turns. The magnetic core material provides an easy path for the flow of magnetic lines in much the same way a conductor provides an easy path for the flow of electrons. This increased permeability permits the flux lines to be concentrated in a smaller area, which increases the number of flux lines per square inch or per square centimeter. In a similar manner, a person using a garden hose with an adjustable nozzle attached can adjust the nozzle to spray the water in a fine mist that covers a large area or in a concentrated stream that covers a small area.

Another common magnetic measurement is **reluctance**. Reluctance is resistance to magnetism. A material such as soft iron or steel has a high permeability and low reluctance because it is easily magnetized. A material such as copper has a low permeability and high reluctance.

If the current flow in an electromagnet is continually increased, the magnet eventually reaches a point where its strength increases only slightly with an increase in current. When

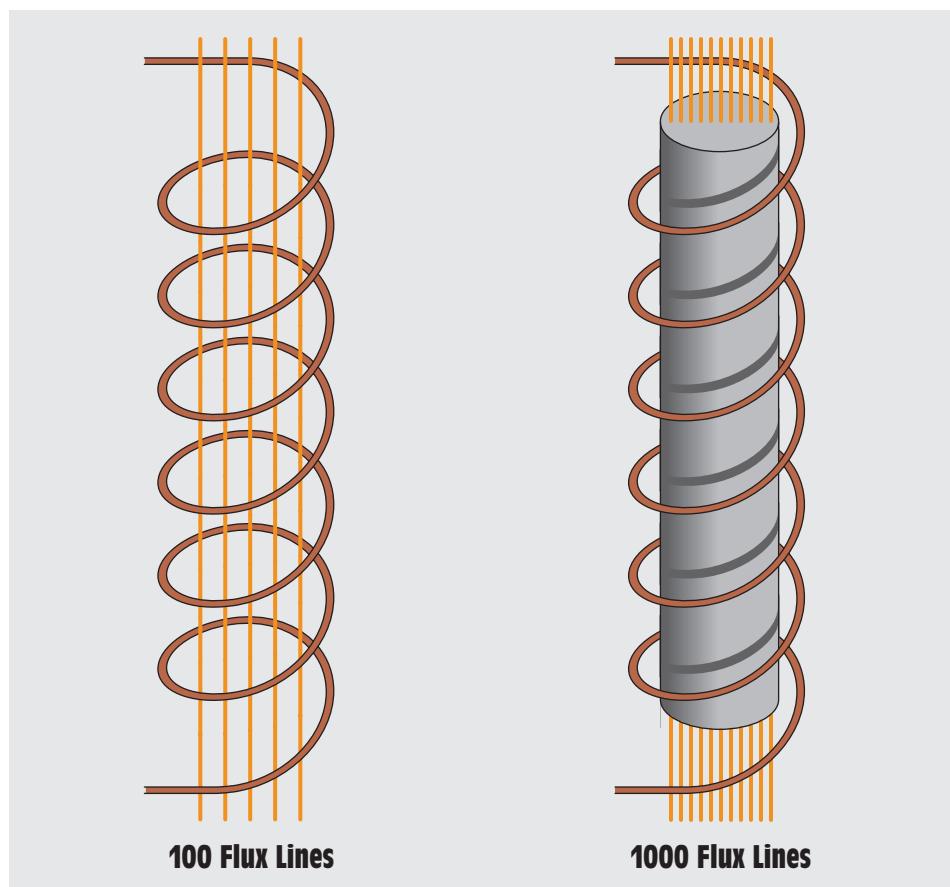


FIGURE 4–15 An iron core increases the number of flux lines per square inch.

this condition occurs, the magnetic material is at a point of **saturation**. Saturation occurs when all the molecules of the magnetic material are lined up. Saturation is similar to pouring 5 gallons of water into a 5-gallon bucket. Once the bucket is full, it simply cannot hold any more water. If it became necessary to construct a stronger magnet, a larger piece of core material would be required.

When the current flow through the coil of a magnet is stopped, some magnetism may be left in the core material. The amount of magnetism left in a material after the magnetizing force has stopped is called **residual magnetism**. If the residual magnetism of a piece of core material is hard to remove, the material has a high coercive force. *Coercive force* is a measure of a material's ability to retain magnetism. A high coercive force is desirable in materials that are intended to be used as permanent magnets. A low coercive force is generally desirable for materials intended to be used as electromagnets. Coercive force is measured by determining the amount of current flow through the coil in the opposite direction that is required to remove the residual magnetism. Another term that is used to describe a material's ability to retain magnetism is *retentivity*.

4-7

Magnetic Measurement

The terms used to measure the strength of a magnetic field are determined by the system that is being used. Three different systems are used to measure magnetism: the English system, the CGS system, and the MKS or SI system.

The English System

In the English system of measure, magnetic strength is measured in a term called **flux density**. Flux density is measured in lines per square inch. As the Greek letter phi (Φ) is used to measure flux, the letter B is used to represent flux density. The following formula is used to determine flux density:

$$B \text{ (flux density)} = \frac{\Phi \text{ (flux lines)}}{A \text{ (area)}}$$

In the English system, the term used to describe the total force producing a magnetic field, or flux, is **magnetomotive force (mmf)**. Magnetomotive force can be computed using the formula

$$\text{mmf} = \Phi \times \text{rel (reluctance)}$$

The following formula can be used to determine the strength of the magnet:

$$\text{Pull (in pounds)} = \frac{B \times A}{72,000,000}$$

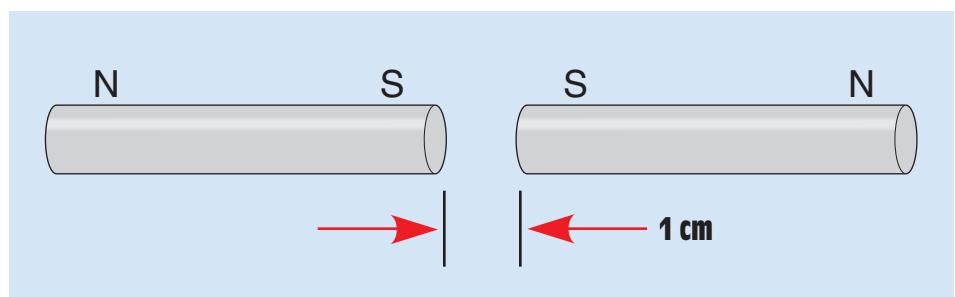
where

B = flux density in lines per square inch

A = area of the magnet.

The CGS System

In the CGS (centimeter-gram-second) system of measurement, one magnetic line of force is known as a *maxwell*. A gauss represents a magnetic force of 1 maxwell per square centimeter. A gauss is also equal to 6.4516 lines of flux per square inch. In the English or SI system, magnetomotive force is measured in ampere-turns. In the



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FIGURE 4-16 A unit magnetic pole produces a force of one dyne.

CGS system, gilberts are used to represent the same measurement. Because the main difference between these two systems of measurement is that they use different units of measure, a conversion factor can be employed to help convert one set of units to another:

$$\begin{aligned}1 \text{ gilbert} &= 1.256 \text{ ampere-turns} \\1 \text{ ampere-turn} &= 0.7905 \text{ gilbert}\end{aligned}$$

In the CGS system, a standard called the *unit magnetic pole* is used. In *Figure 4-16*, two magnets are separated by a distance of 1 centimeter. These magnets repel each other with a force of 1 dyne. The dyne is a very weak unit of force. One dyne is equal to $\frac{1}{27,800}$ of an ounce, or it requires 27,800 dynes to equal a force of 1 ounce. When the two magnets separated by a distance of 1 centimeter exert a force of 1 dyne, they are considered to be a unit magnetic pole. Magnetic force can then be determined using the formula

$$\text{Force (in dynes)} = \frac{M_1 \times M_2}{D^2}$$

where

M_1 = strength of first magnet in unit magnetic poles

M_2 = strength of second magnet in unit magnetic poles

D = distance between the poles in centimeters

The MKS or SI System

The MKS or SI system employs the units of measure of the MKS (meter-kilogram-second) system. In the SI system, the unit of force is the newton. One newton is equal to 0.2248 pounds, or it requires 4.448 newtons to equal a force of 1 pound. The weber is used to measure magnetic flux. One weber equals 100,000,000 lines of flux or 10^8 maxwells. The main unit of measure in the SI system is the Tesla. One tesla is equal to one weber per square meter. *Table 4-1* lists different magnetic units of measure and the conversion factor to other magnetic units of measure.

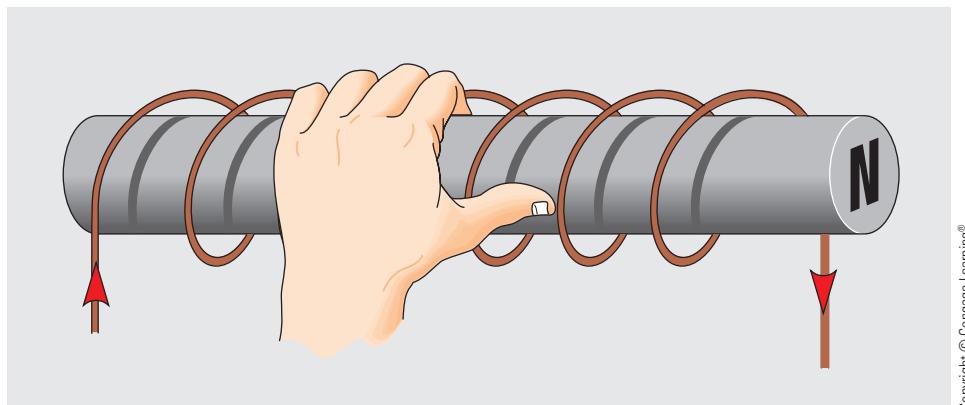
4-8

Magnetic Polarity

The polarity of an electromagnet can be determined using the **left-hand rule**. When the fingers of the left hand are placed around the windings in the direction of electron current flow, the thumb points to the north magnetic pole (*Figure 4-17*).

1 Gauss	=	6.4516 lines/sq. in.
1 Gauss	=	0.0001 Tesla
1 Tesla	=	10,000 Gauss
1 Tesla	=	64,516 lines/sq. in.
1 Tesla	=	1 Weber/sq. meter
1 Weber	=	100,000,000 lines of flux
1 line/sq. in.	=	0.155 Gauss
1 line/sq. in.	=	0.0000155 Tesla
1 Gilbert	=	0.7959949 Ampere Turns
1 Ampere Turn	=	1.256637 Gilberts

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TABLE 4-1 Magnetic Units of Measure

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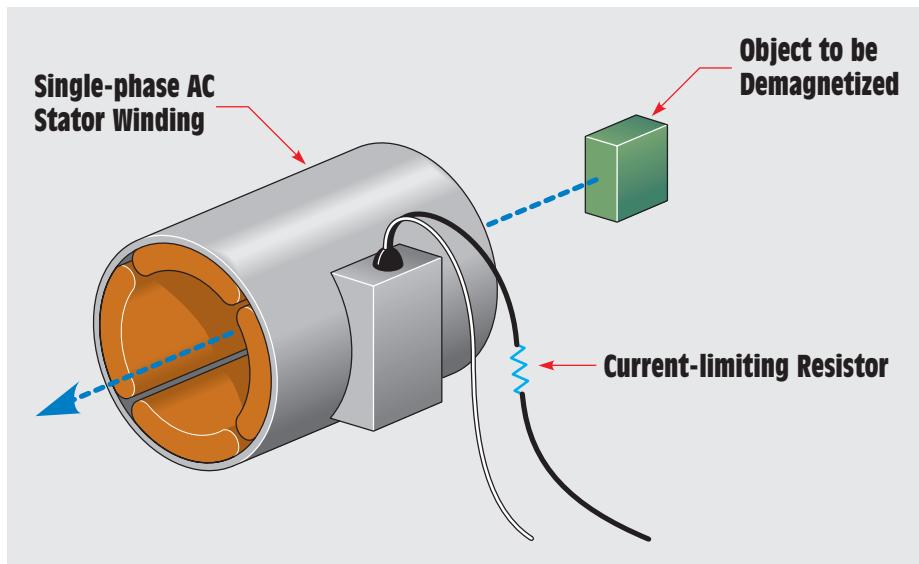
FIGURE 4-17 The left-hand rule can be used to determine the polarity of an electromagnet.

If the direction of current flow is reversed, the polarity of the magnetic field also reverses.

4-9**Demagnetizing**

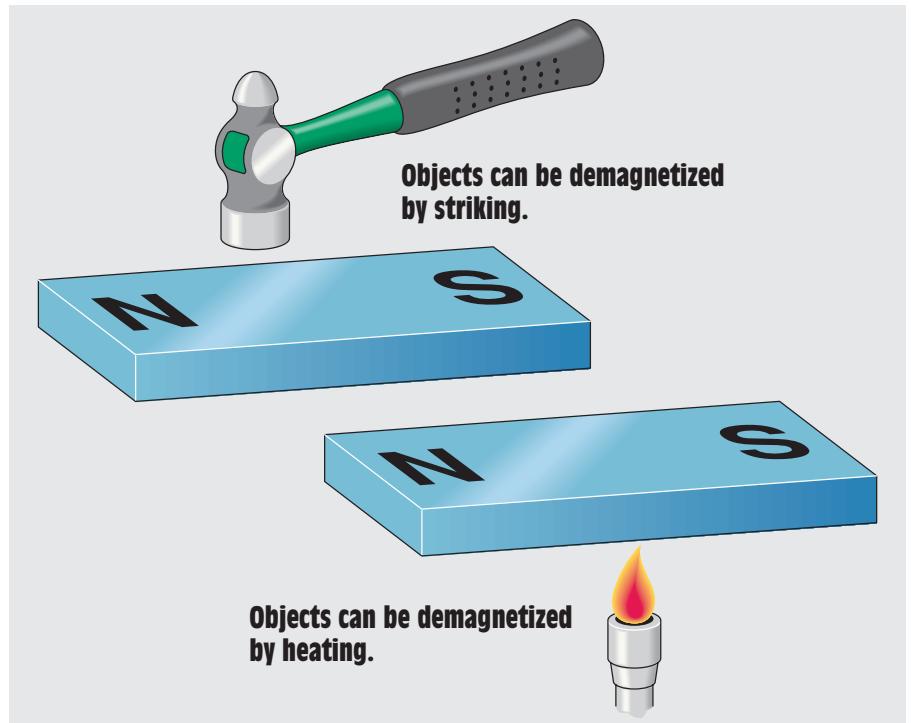
When an object is to be **demagnetized**, its molecules must be disarranged as they are in a nonmagnetized material. This can be done by placing the object in the field of a strong electromagnet connected to an AC line. Because the magnet is connected to AC, the polarity of the magnetic field reverses each time the current changes direction. The molecules of the object to be demagnetized are therefore aligned first in one direction and then in the other. If the object is pulled away from the AC magnetic field, the effect of the field becomes weaker as the object is moved farther away (*Figure 4-18*). The weakening of the magnetic field causes the molecules of the object to be left in a state of disarray. The ease or difficulty with which an object can be demagnetized depends on the strength of the AC magnetic field and the coercive force of the object.

An object can be demagnetized in two other ways (*Figure 4-19*). If a magnetized object is struck, the vibration often causes the molecules to rearrange themselves in a disordered



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FIGURE 4-18 Demagnetizing an object.



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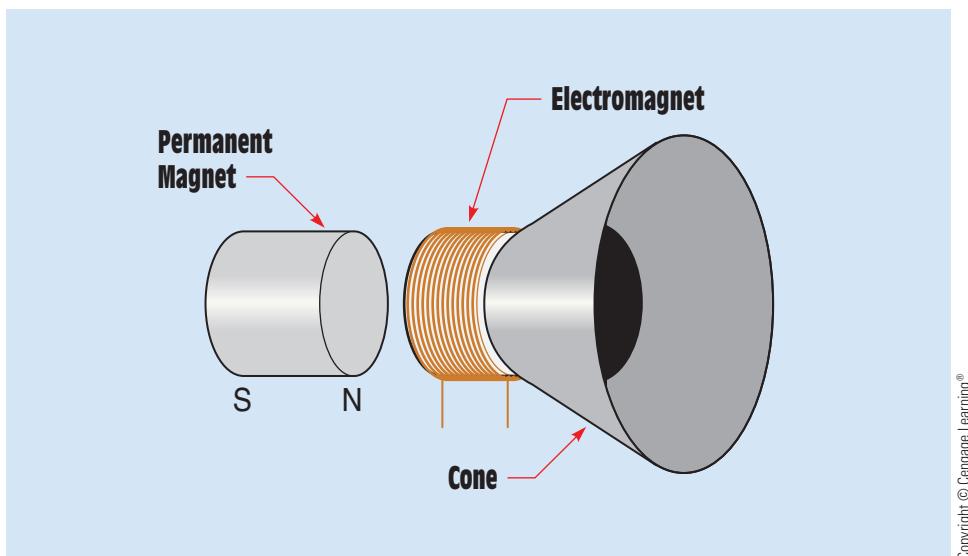
FIGURE 4-19 Other methods for demagnetizing objects.

fashion. It may be necessary to strike the object several times. Heating also demagnetizes an object. When the temperature becomes high enough, the molecules rearrange themselves in a disordered fashion.

4-10

Magnetic Devices

A list of devices that operate on magnetism would be very long indeed. Some of the more common devices are electromagnets, measuring instruments, inductors, transformers, and motors.



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FIGURE 4–20 A speaker uses both an electromagnet and a permanent magnet.

The Speaker

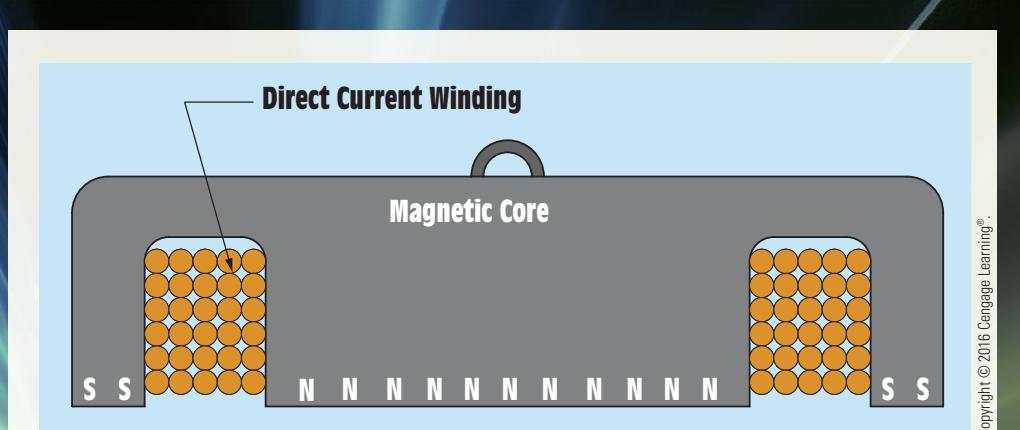
The speaker is a common device that operates on the principle of magnetism (*Figure 4–20*). The speaker produces sound by moving a cone; the movement causes a displacement of air. The tone is determined by how fast the cone vibrates. Low or bass sounds are produced by vibrations in the range of 20 cycles per second. High sounds are produced when the speaker vibrates in the range of 20,000 cycles per second.

The speaker uses two separate magnets. One is a permanent magnet, and the other is an electromagnet. The permanent magnet is held stationary, and the electromagnet is attached to the speaker cone. When current flows through the coil of the electromagnet, a magnetic field is produced. The polarity of the field is determined by the direction of current flow. When the electromagnet has a north polarity, it is repelled away from the permanent magnet, causing the speaker cone to move outward and displace air. When the current flow reverses through the coil, the electromagnet has a south polarity and is attracted to the permanent magnet. The speaker cone then moves inward and again displaces air. The number of times per second that the current through the coil reverses determines the tone of the speaker.

PRACTICAL APPLICATIONS

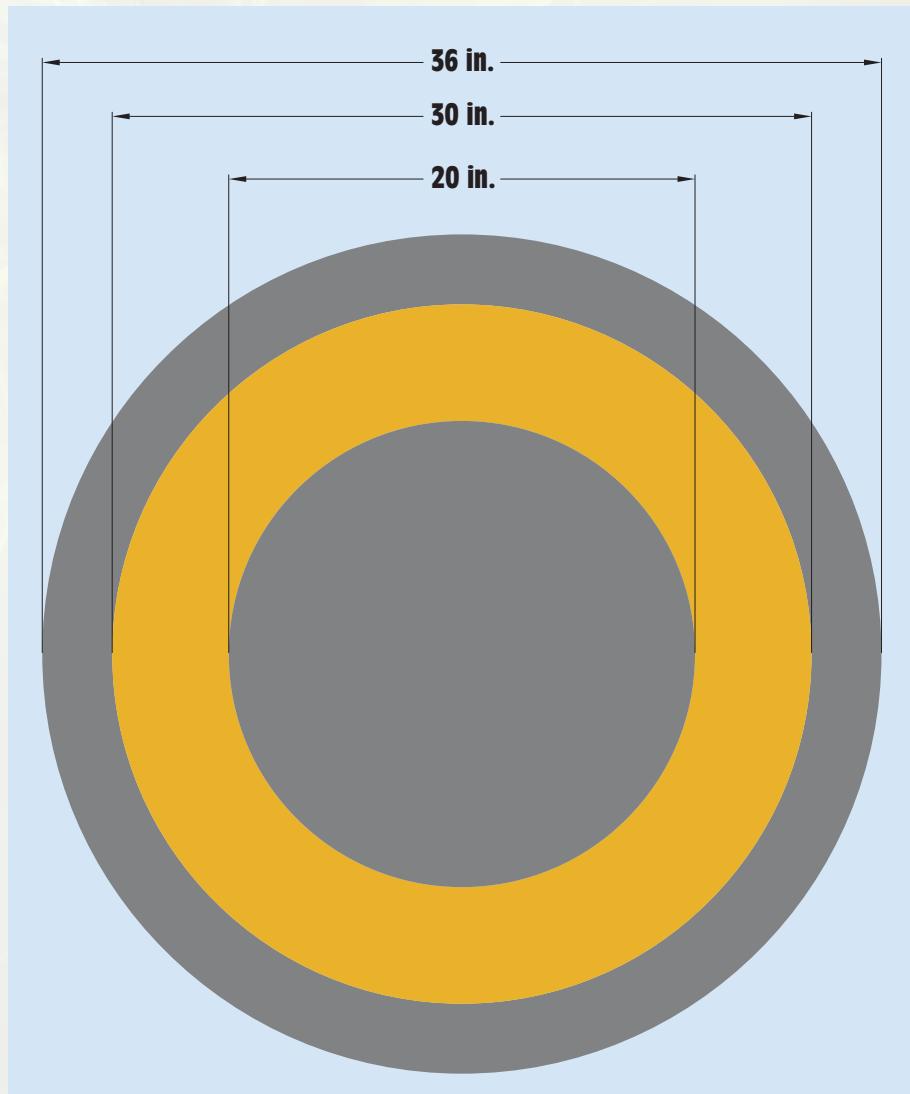
Industry often employs the use of an electromagnet to pick up metal objects. These large magnets are called round horseshoe magnets. They contain a center core surrounded by an outer core. A direct current winding of magnetic wire is wound around the center core. An illustration of a round horseshoe magnet that has been cut in half is shown in *Figure 4–21*. When direct current flows through the winding, the magnetic field produces the polarities as shown. The dimensions of the magnet are shown in *Figure 4–22*. It is assumed that the magnetic field developed has a flux density of 2 webers per square inch. Determine the maximum pulling force of the magnet.

SECTION 1 Safety, Basic Electricity, and Ohm's Law



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FIGURE 4-21 A round horseshoe magnet contains magnetic wire wound around a center core.



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FIGURE 4-22 Dimensions of a round horseshoe magnet.

Solution

The first step is to determine the surface area of the magnet. The maximum area of the magnet can be determined using the formula: The magnet has a diameter of 36 inches. The radius is one-half the diameter.

$$\begin{aligned} A &= \pi r^2 \\ A &= 3.1416 \times 18 \times 18 \\ A &= 1017.89 \text{ sq. in.} \end{aligned}$$

The next dimension is a circle 30 inches in diameter.

$$\begin{aligned} A &= 3.1416 \times 15 \times 15 \\ A &= 706.86 \text{ sq. in.} \end{aligned}$$

The surface area of the outer ring can be determined by subtracting these two dimensions.

$$1017.89 - 706.86 = 311.03 \text{ sq. in.}$$

The area of the center part of the magnet can be determined using the formula for the area of a circle.

$$\begin{aligned} A &= 3.1416 \times 10 \times 10 \\ A &= 314.16 \text{ sq. in.} \end{aligned}$$

The total surface area of the magnet is the sum of the two areas.

$$311.03 + 314.16 = 626.19 \text{ sq. in.}$$

The problem stated that the magnet produces a flux density 2 webers per square inch. A weber is equal to 100,000,000 lines of magnetic flux. The pulling force of the magnet can be determined using the formula:

$$\begin{aligned} \text{Pounds pull} &= \frac{B \times A}{72,000,000} \\ \text{Pounds pull} &= \frac{200,000,000 \times 626.19}{72,000,000} \\ \text{Pounds pull} &= 1739.42 \blacksquare \end{aligned}$$

SUMMARY

- Early natural magnets were known as lodestones.
- The earth has a north and a south magnetic pole.
- The magnetic poles of the earth and the axes poles are not the same.
- Like poles of a magnet repel each other, and unlike poles attract each other.
- Some materials have the ability to become better magnets than others.

- Three basic types of magnetic material are
 - a. Ferromagnetic
 - b. Paramagnetic
 - c. Diamagnetic
- When current flows through a wire, a magnetic field is created around the wire.
- The direction of current flow through the wire determines the polarity of the magnetic field.
- The strength of an electromagnet is determined by the ampere-turns.
- The type of core material used in an electromagnet can increase its strength.
- Three different systems are used to measure magnetic values:
 - a. The English system
 - b. The CGS system
 - c. The SI system
- An object can be demagnetized by placing it in an AC magnetic field and pulling it away, by striking, and by heating.

REVIEW QUESTIONS

1. Is the north magnetic pole of the earth a north polarity or a south polarity?
2. What were early natural magnets known as?
3. The south pole of one magnet is brought close to the south pole of another magnet. Will the magnets repel or attract each other?
4. How can the polarity of an electromagnet be determined if the direction of current flow is known?
5. Define the following terms:
 - Flux density
 - Permeability
 - Reluctance
 - Saturation
 - Coercive force
 - Residual magnetism
6. A force of 1 ounce is equal to how many dynes?