MAGNETISM AND ELECTROMAGNETISM

10

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Explain the principles of a magnetic field
- Explain the principles of electromagnetism
- Describe the principle of operation for several types of electromagnetic devices
- Explain magnetic hysteresis
- Discuss the principle of electromagnetic induction
- Explain how a dc generator works
- Explain how a dc motor works

KEY TERMS

- Magnetic field
- Lines of force
- Magnetic flux
- Weber (Wb)
- Tesla (T)
- Hall effect
- Electromagnetism
- Electromagnetic field
- Permeability
- Reluctance
- Magnetomotive force (mmf)
- Ampere-turn (At)
- Solenoid
- Relay
- Speaker
- Hysteresis
- Retentivity
- Induced voltage (v_{ind})
- Electromagnetic induction
- Induced current (i_{ind})
- Faraday's law
- Lenz's law

APPLICATION ACTIVITY PREVIEW

In this application activity, you will learn how electromagnetic relays can be used in security alarm systems, and you will develop a procedure to check out a basic alarm system.

VISIT THE COMPANION WEBSITE

Study aids for this chapter are available at
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INTRODUCTION

This chapter departs from the coverage of dc circuits and introduces the concepts of magnetism and electromagnetism. The operation of devices such as the relay, the solenoid, and the speaker is based partially on magnetic or electromagnetic principles. Electromagnetic induction is important in an electrical component called an inductor or coil, which is the topic in Chapter 13.

Two types of magnets are the permanent magnet and the electromagnet. The permanent magnet maintains a constant magnetic field between its two poles with no external excitation. The electromagnet produces a magnetic field only when there is current through it. The electromagnet is basically a coil of wire wound around a magnetic core material.

The chapter concludes with an introduction to dc generators and dc motors.

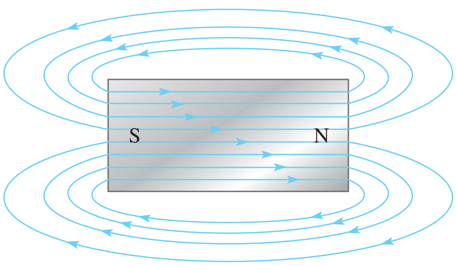
10–1 THE MAGNETIC FIELD

A permanent magnet has a magnetic field surrounding it. A **magnetic field** is visualized by **lines of force** that radiate from the north pole (N) to the south pole (S) and back to the north pole through the magnetic material.

After completing this section, you should be able to

- **Explain the principles of a magnetic field**
  - Define *magnetic flux*
  - Define *magnetic flux density*
  - Discuss how materials are magnetized
  - Explain how a magnetic switch works

A permanent magnet, such as the bar magnet shown in Figure 10–1, has a magnetic field surrounding it. All magnetic fields have their origin in moving charge, which in solid materials is caused by moving electrons. In certain materials such as iron, atoms can be aligned so that the electron motion is reinforced, creating a measurable field that extends in three dimensions. Even some electrical insulators can exhibit this behavior; ceramics (also known as ferrites) make excellent magnets but are electrical insulators. They are used in many applications including hard disk read/write heads, sensors, magnetic resonant imaging, and motors to name a few.



Blue lines represent only a few of the many magnetic lines of force in the magnetic field.

FIGURE 10–1

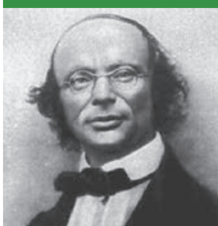
Magnetic lines of force around a bar magnet.

To illustrate magnetic fields, "lines of force" or flux lines are used to represent an unseen field. Flux lines are widely used as a description of a field, showing the strength and direction of the field. The flux lines never cross. When lines are close together, the field is more intense; when they are farther apart, the field is weaker. The flux lines are always drawn from the north pole (N) to the south pole (S) of a magnet. Even in weak magnets, the number of lines based on the mathematical definition is extremely large, so for clarity, only a few lines are generally shown in drawings of magnetic fields.

When unlike poles of two permanent magnets interact, their magnetic fields produce an attractive force, as indicated in Figure 10–2(a). When two like poles are brought close together, they repel each other, as shown in part (b).

When a nonmagnetic material such as paper, glass, wood, or plastic is placed in a magnetic field, the lines of force are unaltered, as shown in Figure 10–3(a). However, when a magnetic material such as iron is placed in the magnetic field, the lines of force tend to change course and pass through the iron rather than through the surrounding air. They do so because the iron provides a magnetic path that is more easily established than that of air. Figure 10–3(b) illustrates this principle. The fact

HISTORY NOTE

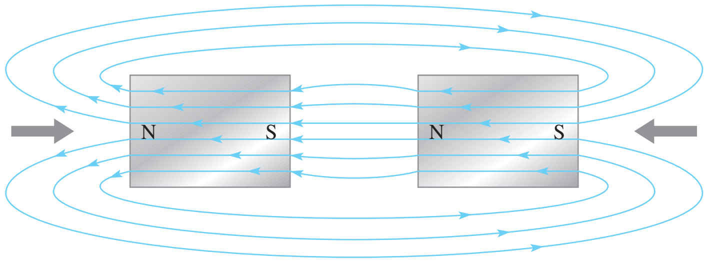


Wilhelm Eduard Weber 1804–1891

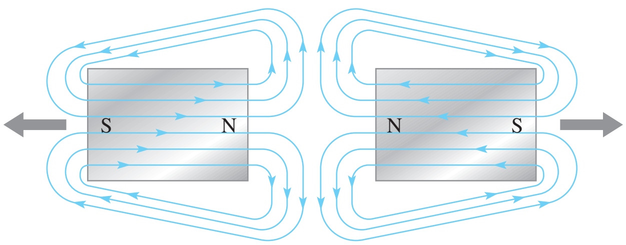
Weber was a German physicist who worked closely with Gauss, whose biography appears later. Independently, he established a system of absolute electrical units and also performed work that was crucial to the later development of the electromagnetic theory of light. The unit of magnetic flux is named in his honor.
(Photo credit: Library of Congress Prints and Photographs Division[LC-USZ62-100101].)

SAFETY NOTE

Many strong magnets are very brittle and can shatter on impact. Eye protection should always be worn when you work with strong magnets. Strong magnets are not toys and should not be given to children. People with pacemakers should stay away from strong magnets.



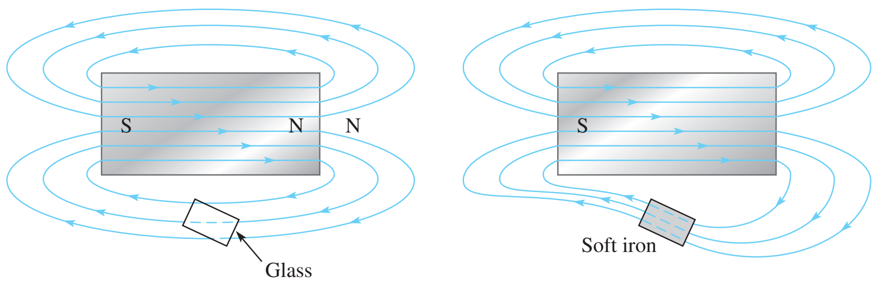
(a) Unlike poles attract.



(b) Like poles repel.

▲ **FIGURE 10–2**

Magnetic attraction and repulsion.



(a) (b)

▲ **FIGURE 10–3**

Effect of (a) nonmagnetic and (b) magnetic materials on a magnetic field.

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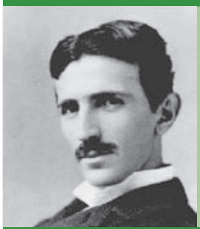


Nikola Tesla 1856–1943

Tesla was born in Croatia (then Austria-Hungary). He was an electrical engineer who invented the ac induction motor, polyphase ac systems, the Tesla coil transformer, wireless communications, and fluorescent lights. He worked for Edison when he first came to the United States in 1884 and later for Westinghouse. The SI unit of magnetic flux density is named in his honor. (Photo credit: Courtesy of the Nikola Tesla Museum, Belgrade, Yugoslavia.)

that magnetic lines of force follow a path through iron or other materials is a consideration in the design of shields that prevent stray magnetic fields from affecting sensitive circuits.

Magnetic Flux (ϕ)

The group of force lines going from the north pole to the south pole of a magnet is called the **magnetic flux**, symbolized by ϕ (the Greek letter phi). A stronger field is represented by more lines of force. Several factors determine the strength of a magnet, including the material and physical geometry as well as the distance from the magnet. Magnetic field lines tend to be more concentrated at the poles.

The unit of magnetic flux is the **weber (Wb)**. One weber equals 10^8 lines. The weber is a very large unit; thus, in most practical situations, the microweber (μWb) is used. One microweber equals 100 lines of magnetic flux.

Magnetic Flux Density (*B*)

The **magnetic flux density** is the amount of flux per unit area perpendicular to the magnetic field. Its symbol is B, and its SI unit is the **tesla (T)**. One tesla equals one weber per square meter (Wb/m^2). The following formula expresses the flux density:

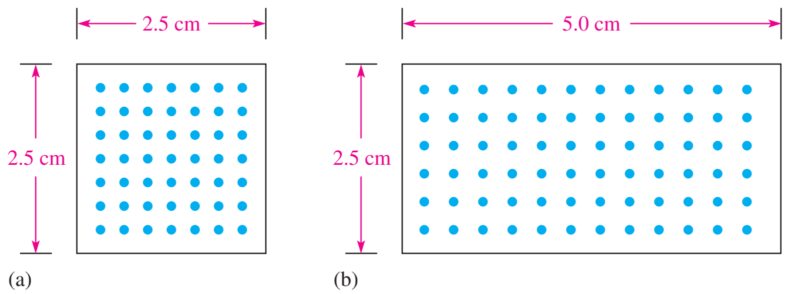
$$B = \frac{\phi}{A} \qquad \text{Equation 10–1}$$

where ϕ is the flux (Wb) and A is the cross-sectional area in square meters (m^2) of the magnetic field.

EXAMPLE 10–1

Compare the flux and the flux density in the two magnetic cores shown in Figure 10–4. The diagram represents the cross section of a magnetized material. Assume that each dot represents 100 lines or 1 μWb.

▶ FIGURE 10–4



Solution The flux is simply the number of lines. In Figure 10–4(a) there are 49 dots. Each represents 1 μWb, so the flux is 49 μWb. In Figure 10–4(b) there are 72 dots, so the flux is 72 μWb.

To calculate the flux density in Figure 10–4(a), first calculate the area in m^2.

$$A = l \times w = 0.025 \text{ m} \times 0.025 \text{ m} = 6.25 \times 10^{-4} \text{ m}^2$$

For Figure 10–4(b) the area is

$$A = l \times w = 0.025 \text{ m} \times 0.050 \text{ m} = 1.25 \times 10^{-3} \text{ m}^2$$

Use Equation 10–1 to calculate the flux density. For Figure 10–4(a) the flux density is

$$B = \frac{\phi}{A} = \frac{49\ \mu\text{Wb}}{6.25 \times 10^{-4} \text{ m}^2} = 78.4 \times 10^{-3} \text{ Wb/m}^2 = 78.4 \times 10^{-3} \text{ T}$$

For Figure 10–4(b) the flux density is

$$B = \frac{\phi}{A} = \frac{72\ \mu\text{Wb}}{1.25 \times 10^{-3} \text{ m}^2} = 57.6 \times 10^{-3} \text{ Wb/m}^2 = 57.6 \times 10^{-3} \text{ T}$$

The data in Table 10–1 compares the two cores. Note that the core with the largest flux does not necessarily have the highest flux density.

▶ TABLE 10–1

	FLUX (Wb)	AREA (m^2)	FLUX DENSITY (T)
Figure 10–4(a)	49 μWb	6.25×10^{-4} m^2	78.4×10^{-3} T
Figure 10–4(b)	72 μWb	1.25×10^{-3} m^2	57.6×10^{-3} T

*Related Problem** What happens to the flux density if the same flux shown in Figure 10–4(a) is in a core that is 5.0 cm × 5.0 cm?

*Answers are at the end of the chapter.

EXAMPLE 10–2

If the flux density in a certain magnetic material is 0.23 T and the area of the material is 0.38 in.^{2}, what is the flux through the material?

Solution First, 0.38 in.^{2} must be converted to square meters. 39.37 in. = 1 m; therefore,

$$A = 0.38\text{ in.}^2[1\text{ m}^2/(39.37\text{ in.})^2] = 245 \times 10^{-6}\text{ m}^2$$

The flux through the material is

$$\phi = BA = (0.23\text{ T})(245 \times 10^{-6}\text{ m}^2) = \mathbf{56.4\ \mu Wb}$$

Related Problem Calculate B if $A = 0.05$ in.^{2} and $\phi = 1{,}000\ \mu$Wb.

HISTORY NOTE

Karl Friedrich Gauss 1777–1855

Gauss, a German mathematician, disproved many 18th-century mathematical theories. Later, he worked closely with Weber on a worldwide system of stations for systematic observations of terrestrial magnetism. The most important result of their work in electromagnetism was the later development of telegraphy by others. The CGS unit of magnetic flux density is named in his honor. (Credit: Illustration by Steven S. Nau.)

The Gauss Although the tesla (T) is the mks SI unit for flux density, another unit called the **gauss**, **G**, from the CGS (centimeter-gram-second) system, is used (10^4 G = 1 T). In fact, the instrument used to measure flux density is the gaussmeter. A typical gaussmeter is shown in Figure 10–5. This particular gaussmeter is a portable unit with four ranges that can measure magnetic fields as small as the earth's field (about 0.5 G, but widely varies depending on location) to strong fields such as in an MRI unit (about 10,000 G or 1 T). The unit *gauss* is still in widespread use, so you should be familiar with it as well as the *tesla*.

To use a gaussmeter such as the one shown, the user first needs to calibrate the meter by zeroing it. For best results, the probe is inserted into a "zero gauss" chamber that shields the sensor from stray magnetic fields including the earth's magnetic field. The zero set controls are adjusted for a zero reading. The probe is then placed in the magnetic field and oriented to read the field. The probe shown in Figure 10–5 is a transverse probe; to measure a magnet's strength, it is placed flat on the magnet near the tip.

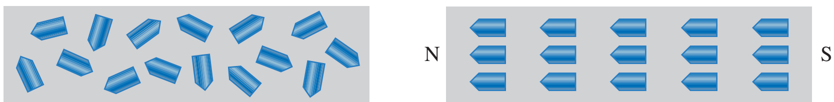
FIGURE 10–5

A dc gaussmeter. (Integrity Model IDR-329 distributed by Less EMF Inc.)

How Materials Become Magnetized

Ferromagnetic materials such as iron, nickel, and cobalt become magnetized when placed in the magnetic field of a magnet. We have all seen a permanent magnet pick up things like paper clips, nails, and iron filings. In these cases, the object becomes magnetized (that is, it actually becomes a magnet itself) under the influence of the permanent magnetic field and becomes attracted to the magnet. When removed from the magnetic field, the object tends to lose its magnetism.

Ferromagnetic materials have minute magnetic domains created within their atomic structure. These domains can be viewed as very small bar magnets with north and south poles. When the material is not exposed to an external magnetic field, the magnetic domains are randomly oriented, as shown in Figure 10–6(a). When the material is placed in a magnetic field, the domains align themselves as shown in part (b). Thus, the object itself effectively becomes a magnet.



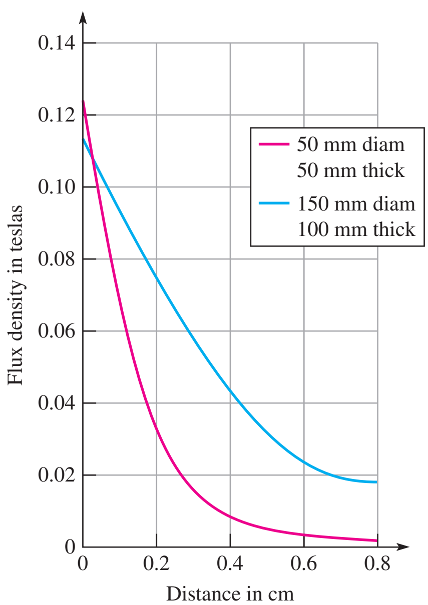
(a) The magnetic domains (N S) are randomly oriented in the unmagnetized material.

(b) The magnetic domains become aligned when the material is magnetized.

▲ **FIGURE 10–6**

Magnetic domains in (a) an unmagnetized and in (b) a magnetized material.

Effects of the Magnetic Material The magnetic material affects not only the magnetic flux density at the poles but also how the magnetic flux density falls off as distance from the poles increases. The physical size also affects the flux density. For example, two disk magnets that are made from alnico (an alloy of aluminum (Al), nickel (Ni), and cobalt (Co)) have very similar densities near the pole, but the larger magnet has much higher flux density, as you move away from the pole, as shown in Figure 10–7. Notice that the flux density falls off rapidly as you move away from the pole. This type of plot can illustrate if a given magnet is effective for a specific application that depends on the distance in which the magnet must work.



◀ **FIGURE 10–7**

Example of magnetic flux density for two disk alnico magnets as a function of distance. The blue curve represents the larger magnet.

The type of material is an important parameter for the actual flux density of magnets. Table 10–2 lists the flux densities of typical magnetic fields in teslas. For permanent magnets, the numbers given are based on the flux density of the field that is typical if measured close to the pole. As previously discussed, these values can drop significantly as distance from the poles is increased. The strongest field most people will ever experience is about 1 T (10,000 G) if they have an MRI exam. The strongest commercially available permanent magnets are neodymium-iron-boron composites (NdFeB), commonly abbreviated NIB. To find the flux density in gauss, multiply the values in teslas by 10^4 (10,000).

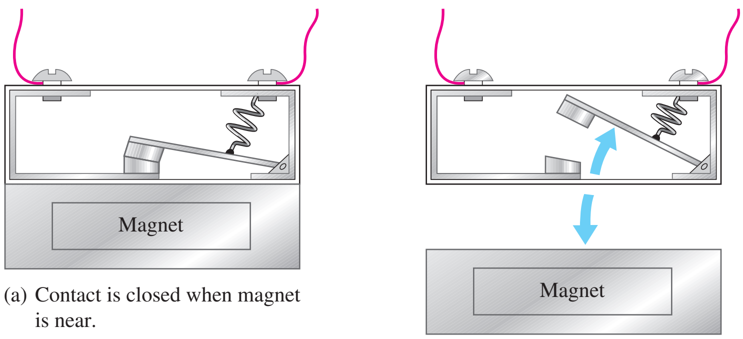
▶ TABLE 10–2

Flux density of various magnetic fields.

SOURCE	TYPICAL FLUX DENSITY IN TESLAS (T)
Earth's magnetic field	4×10^{-5} (varies with location)
Small "refrigerator" magnets	0.08 to 0.1
Ceramic magnets	0.2 to 0.3
Alnico 5 reed switch magnet	0.1 to 0.2
Neodymium magnets	0.3 to 0.52
Magnetic resonance imaging (MRI)	1
The strongest steady magnetic field ever achieved in a laboratory	45

Applications

Permanent magnets are widely used in brushless motors (discussed in Section 10–7), magnetic separators, speakers, microphones, automobiles and devices that use ion beams in electronic manufacturing, physics research, and certain medical devices. They are also commonly used in switches, such as the normally closed switch illustrated in Figure 10–8. When the magnet is near the switch mechanism, as in Figure 10–8(a), the switch is closed. When the magnet is moved away, as in part (b), the spring pulls the arm open. Magnetic switches are widely used in security systems.



(a) Contact is closed when magnet is near.

(b) Contact opens when magnet is moved away.

▲ FIGURE 10–8

Operation of a magnetic switch.

Another important application of permanent magnets is in sensors that take advantage of an effect known as the Hall effect. The **Hall effect** is the occurrence of a small voltage (a few μV) that is generated on opposite sides of a thin current-carrying conductor or semiconductor (the Hall element) in a magnetic field. A voltage called the Hall voltage appears across the Hall element, as illustrated in Figure 10–9. This voltage is proportional to the magnetic field strength, B. The Hall voltage is due to the forces exerted on the electrons as they traverse the magnetic field, causing an excess of charge on one side of the Hall element. Although the effect was first noticed in a conductor, it

HISTORY NOTE

Edwin Herbert Hall (1855–1938)

The Hall effect was discovered by Hall in 1879 while he worked on his doctoral thesis in physics at Johns Hopkins University. Hall's experiments consisted of exposing thin gold leaf on a glass plate to a magnetic field and accessing tap points on the gold leaf at points down its length. After applying a current through the gold leaf, he observed a tiny voltage across the tap points. (Photo credit: Voltiana, Como, Italy-September 10, 1927 issue, courtesy AIP Emilio Segre Visual Archives.)

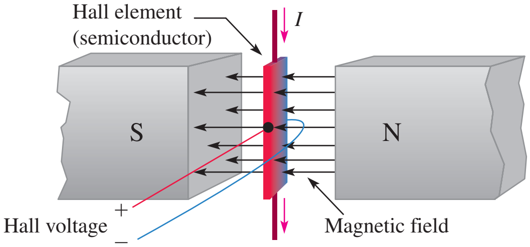


FIGURE 10–9

The Hall effect. The Hall voltage is induced across the Hall element. For illustration, the positive side is shown in red and the negative side is shown in blue.

is more pronounced in semiconductors, which are normally used in Hall-effect sensors. Notice that the magnetic field, the electric current, and the Hall voltage are all at right angles to each other. This voltage is amplified and can be used to detect the presence of the magnetic field. The detection of a magnetic field is useful in sensor applications.

Hall-effect sensors are widely used because they are small, inexpensive, and have no moving parts. In addition, they are noncontacting sensors, so they can last for billions of repeated operations, a clear advantage over contacting sensors that can wear out. Hall-effect sensors can detect the nearby presence of a magnet by sensing its magnetic field. For this reason, they can be used for position measurements or for sensing motion. They are used in conjunction with other sensor elements to measure current, temperature, or pressure.

There are many applications for Hall-effect sensors. In automobiles, Hall-effect sensors are used to measure various parameters such as throttle angle, crankshaft and camshaft positions, distributor position, tachometer, power seat, and rear-view mirror positions. As a current sensor, they are used in motor control (see Section 10–7), switch mode power supplies, and load control. An example of a current sensor using a Hall-effect sensor is the Allegro ACS723. A few other applications for Hall-effect sensors include measuring parameters for rotating devices such as drills, fans, vanes in flow meters, and disk speed detection.

SECTION 10–1 CHECKUP
Answers are at the end of the chapter.

1. When the north poles of two magnets are placed close together, do they repel or attract each other?
2. What is the difference between magnetic flux and magnetic flux density?
3. What are two units for measuring magnetic flux density?
4. What is the flux density when $\phi = 4.5\ \mu\text{Wb}$ and $A = 5 \times 10^{-3}\ \text{m}^2$?
5. How can the Hall effect be used to detect proximity?

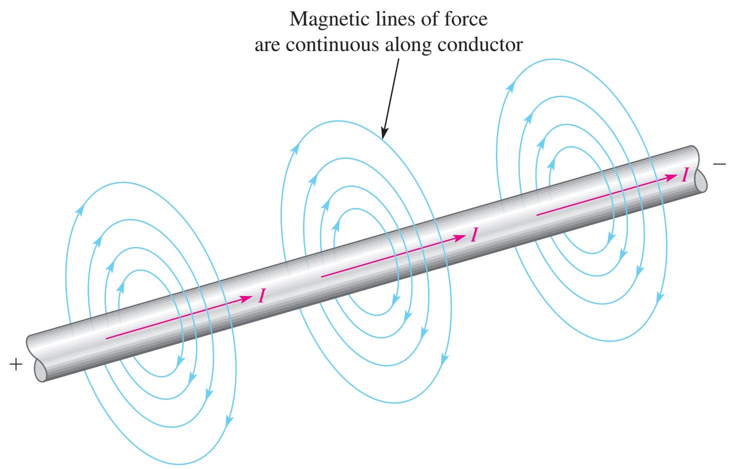
10–2 ELECTROMAGNETISM

Electromagnetism is the production of a magnetic field by current in a conductor.

After completing this section, you should be able to

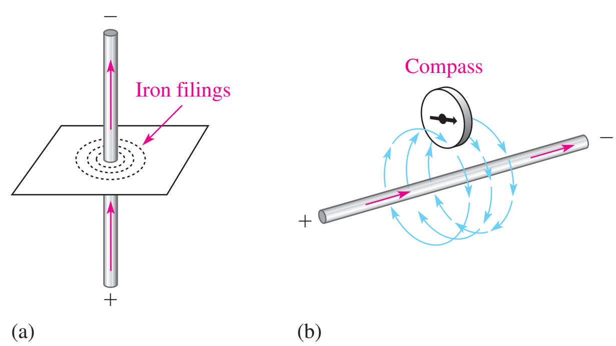
- **Explain the principles of electromagnetism**
  - Determine the direction of the magnetic lines of force
  - Define *permeability*
  - Define *reluctance*
  - Define *magnetomotive force*
  - Describe a basic electromagnet

Current produces a magnetic field, called an **electromagnetic field**, around a conductor, as illustrated in Figure 10–10. The invisible lines of force of the magnetic field form a concentric circular pattern around the conductor and are continuous along its length. Unlike the bar magnet, the magnetic field surrounding a wire does not have a north or south pole. The direction of the lines of force surrounding the conductor shown in the figure is for conventional current. The lines are in a clockwise direction. When current is reversed, the magnetic field lines are in a counterclockwise direction.



▲ **FIGURE 10–10**

Magnetic field around a current-carrying conductor. The red arrows indicate the direction of conventional (+ to −) current.

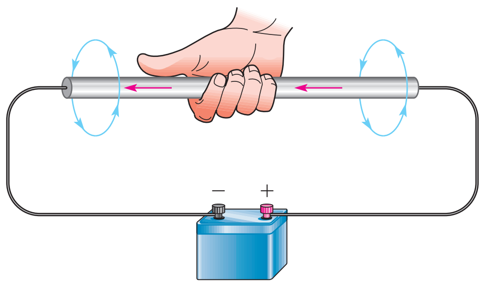


▲ **FIGURE 10–11**

Visible effects of an electromagnetic field.

Although the magnetic field cannot be seen, it is capable of producing visible effects. For example, if a current-carrying wire is inserted through a sheet of paper in a perpendicular direction, iron filings placed on the surface of the paper arrange themselves along the magnetic lines of force in concentric rings, as illustrated in Figure 10–11(a). Part (b) of the figure illustrates that the north pole of a compass placed in the electromagnetic field will point in the direction of the lines of force. The field is stronger closer to the conductor and becomes weaker with increasing distance from the conductor.

Right-Hand Rule An aid to remembering the direction of the lines of force is illustrated in Figure 10–12. Imagine that you are grasping the conductor with your right hand, with your thumb pointing in the direction of current. Your fingers point in the direction of the magnetic lines of force.



◄ FIGURE 10–12

Illustration of right-hand rule. The right-hand rule is used for conventional current (+ to −).

Electromagnetic Properties

Several important properties are related to electromagnetic fields.

***Permeability* (μ)** The ease with which a magnetic field can be established in a given material is measured by the **permeability** of that material. The higher the permeability, the more easily a magnetic field can be established.

The symbol of permeability is μ (the Greek letter mu), and its value varies depending on the type of material. The permeability of a vacuum (μ_0) is $4\pi \times 10^{-7}$ Wb/At·m (webers/ampere-turn·meter) and is used as a reference. Ferromagnetic materials typically have permeabilities hundreds of times larger than that of a vacuum, indicating that a magnetic field can be set up with relative ease in these materials. Ferromagnetic materials include iron, steel, nickel, cobalt, and their alloys.

The *relative permeability* (μ_r) of a material is the ratio of its absolute permeability to the permeability of a vacuum (μ_0).

$$\mu_r = \frac{\mu}{\mu_0}$$

Equation 10–2

Because it is a ratio of permeabilities, μ_r is dimensionless. Typical magnetic materials, such as iron, have a relative permeability of a few hundred. Highly permeable materials can have a relative permeability as high as 100,000.

***Reluctance* ($\mathcal{R}$)** The opposition to the establishment of a magnetic field in a material is called **reluctance**. The value of reluctance is directly proportional to the length (l) of the magnetic path and inversely proportional to the permeability (μ) and to the cross-sectional area (A) of the material, as expressed by the following equation:

$$\mathcal{R} = \frac{l}{\mu A}$$

Equation 10–3

Reluctance in magnetic circuits is analogous to resistance in electric circuits. The unit of reluctance can be derived using l in meters, A (area) in square meters, and μ in Wb/At·m as follows:

$$\mathcal{R} = \frac{l}{\mu A} = \frac{\cancel{\text{m}}}{(\text{Wb/At}\cdot\cancel{\text{m}})(\cancel{\text{m}^2})} = \frac{\text{At}}{\text{Wb}}$$

At/Wb is ampere-turns/weber.

Equation 10–3 is analogous to Equation 2–6 for determining wire resistance. Recall that Equation 2–6 is

$$R = \frac{\rho l}{A}$$

The reciprocal of resistivity (ρ) is conductivity (σ). By substituting $1/\sigma$ for ρ, Equation 2–6 can be written as

$$R = \frac{l}{\sigma A}$$

Compare this last equation for wire resistance with Equation 10–3. The length (l) and the area (A) have the same meaning in both equations. The conductivity (σ) in electrical circuits is analogous to permeability (μ) in magnetic circuits. Also, resistance (R) in electric circuits is analogous to reluctance ($\mathcal{R}$) in magnetic circuits; both are oppositions. Typically, the reluctance of a magnetic circuit is 50,000 At/Wb or more, depending on the size and type of material.

EXAMPLE 10–3

Calculate the reluctance of a torus (a doughnut-shaped core) made of low-carbon steel. The inner radius of the torus is 1.75 cm and the outer radius of the torus is 2.25 cm. Assume the permeability of low-carbon steel is 2×10^{-4} Wb/At·m.

Solution You must convert centimeters to meters before you calculate the area and length. From the dimensions given, the thickness (diameter) is 0.5 cm = 0.005 m. Thus, the cross-sectional area is

$$A = \pi r^2 = \pi(0.0025)^2 = 1.96 \times 10^{-5}\ \text{m}^2$$

The length is equal to the circumference of the torus measured at the average radius of 2.0 cm or 0.020 m.

$$l = C = 2\pi r = 2\pi(0.020\ \text{m}) = 0.125\ \text{m}$$

Substituting values into Equation 10–3,

$$\mathcal{R} = \frac{l}{\mu A} = \frac{0.125\ \text{m}}{(2 \times 10^{-4}\ \text{Wb/At}\cdot\text{m})(1.96 \times 10^{-5}\ \text{m}^2)} = \mathbf{32.0 \times 10^6\ At/Wb}$$

Related Problem What happens to the reluctance if cast steel with a permeability of 5×10^{-4} Wb/At·m is substituted for the cast iron core?

EXAMPLE 10–4

Mild steel has a relative permeability of 800. Calculate the reluctance of a mild steel core that has a length of 10 cm and has a cross section of 1.0 cm × 1.2 cm.

Solution First, determine the permeability of mild steel.

$$\mu = \mu_0\mu_r = (4\pi \times 10^{-7}\ \text{Wb/At}\cdot\text{m})(800) = 1.00 \times 10^{-3}\ \text{Wb/At}\cdot\text{m}$$

Next, convert the length to meters and the area to square meters.

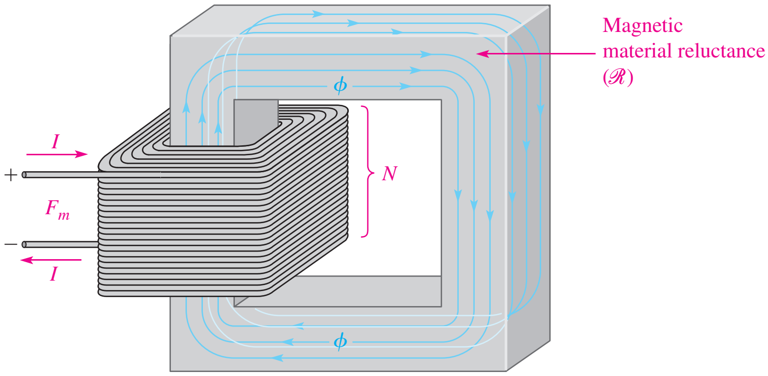
$$l = 10\ \text{cm} = 0.10\ \text{m}$$
$$A = 0.010\ \text{m} \times 0.012\ \text{m} = 1.2 \times 10^{-4}\ \text{m}^2$$

Substituting values into Equation 10–3,

$$\mathcal{R} = \frac{l}{\mu A} = \frac{0.10\ \text{m}}{(1.00 \times 10^{-3}\ \text{Wb/At}\cdot\text{m})(1.2 \times 10^{-4}\ \text{m}^2)} = \mathbf{8.29 \times 10^5\ At/Wb}$$

Related Problem What happens to the reluctance if the core is made from 78 Permalloy with a relative permeability of 4,000?

Magnetomotive Force (mmf) As you have learned, current in a conductor produces a magnetic field. The cause of a magnetic field is called the **magnetomotive force (mmf)**. Magnetomotive force is something of a misnomer because in a physics sense mmf is not really a force, but rather it is a direct result of the movement of charge (current).



◄ **FIGURE 10–13**

A basic magnetic circuit.

The unit of mmf, the **ampere-turn (At)**, is established on the basis of the current in a single loop (turn) of wire. The formula for mmf is

$$F_m = NI$$

Equation 10–4

where F_m is the magnetomotive force, N is the number of turns of wire, and I is the current in amperes.

Figure 10–13 illustrates that a number of turns of wire carrying a current around a magnetic material creates the mmf that sets up flux lines through the magnetic path. The amount of flux depends on the magnitude of the mmf and on the reluctance of the material, as expressed by the following equation:

$$\phi = \frac{F_m}{\mathcal{R}}$$

Equation 10–5

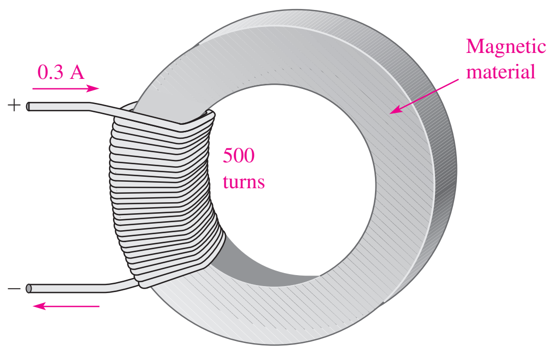
Equation 10–5 is known as *Ohm's law for magnetic circuits* because the flux (ϕ) is analogous to current, the mmf (F_m) is analogous to voltage, and the reluctance ($\mathcal{R}$) is analogous to resistance. Like other phenomena in science, the flux is an effect, the mmf is a cause, and the reluctance is an opposition. In magnetic circuits the cause of flux is current (and number of turns), whereas in electric circuits the cause of current is voltage.

One important difference between an electric circuit and a magnetic circuit is that in magnetic circuits, Equation 10–5 is only valid up to a certain point before the magnetic material saturates (flux becomes a maximum). You will see this when you look at magnetization curves in Section 10–4. Another difference that was already noted is that flux does occur in permanent magnets with no source of mmf. In a permanent magnet, the flux is due to internal electron motion rather than an external current. No equivalent effect occurs in electric circuits.

EXAMPLE 10–5

How much flux is established in the magnetic path of Figure 10–14 if the reluctance of the material is 2.8×10^5 At/Wb?

► **FIGURE 10–14**



Solution

$$\phi = \frac{F_m}{\mathcal{R}} = \frac{NI}{\mathcal{R}} = \frac{(500\text{ t})(0.300\text{ A})}{2.8 \times 10^5\text{ At/Wb}} = \mathbf{536\ \mu Wb}$$

Related Problem How much flux is established in the magnetic path of Figure 10–14 if the reluctance is 7.5×10^3 At/Wb, the number of turns is 300, and the current is 0.18 A?

EXAMPLE 10–6

There is 0.1 A of current through a coil with 400 turns.

(a) What is the mmf?

(b) What is the reluctance of the circuit if the flux is 250 μWb?

Solution

(a) $N = 400$ and $I = 0.1$ A

$F_m = NI = (400\text{ t})(0.1\text{ A}) = \mathbf{40\ At}$

(b) $$\mathcal{R} = \frac{F_m}{\phi} = \frac{40\text{ At}}{250\ \mu\text{Wb}} = \mathbf{1.60 \times 10^5\ At/Wb}$$

Related Problem Rework the example for $I = 85$ mA and $N = 500$. The flux is 500 μWb.

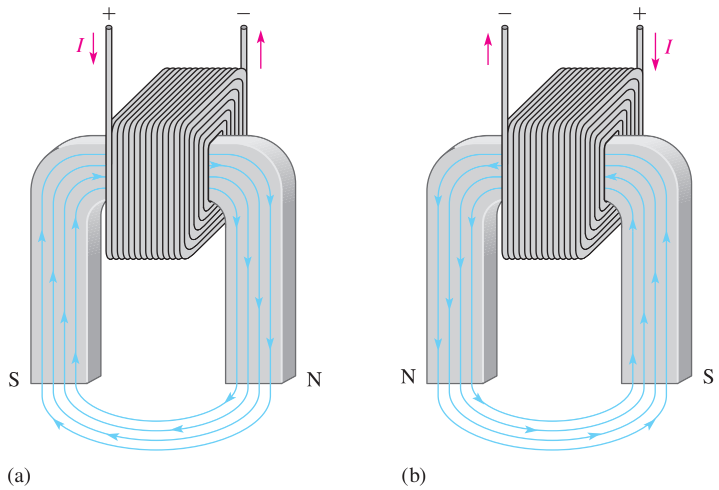
In many magnetic circuits, the core is not continuous. For example, if an air gap is cut into the core, it will increase the reluctance of the magnetic circuit. This means that more current is required to establish the same flux as before because an air gap represents a significant opposition to establishing flux. The situation is analogous to a series electrical circuit; the total reluctance of the magnetic circuit is the sum of the reluctance of the core and the reluctance of the air gap. There are various reasons to have an air gap in a core. For example, one reason is to prevent core saturation, where an increase in current does *not* lead to an increase in flux.

A widely used core material is composed of a ferrite material. **Ferrites** are crystalline compounds composed of iron oxides and other materials that can be selected for specific desired properties. Hard ferrites are widely used to make permanent magnets. Another class of ferrites are called soft ferrites that have properties useful in inductors, high frequency transformers, antennas, and other electronic components. (Inductors are discussed in Chapter 13; transformers are discussed in Chapter 14.)

The Electromagnet

An electromagnet is based on the properties that you have just learned. A basic electromagnet is simply a coil of wire wound around a core material that can be easily magnetized.

The shape of an electromagnet can be designed for various applications. For example, Figure 10–15 shows a U-shaped magnetic core. When the coil of wire is connected to a battery and there is current, as shown in part (a), a magnetic field is established as indicated. If the current is reversed, as shown in part (b), the direction of the magnetic field is also reversed. The closer the north and south poles are brought together, the smaller the air gap between them becomes, and the easier it becomes to establish a magnetic field because the reluctance is lessened.



▲ FIGURE 10–15

Reversing the current in the coil causes the electromagnetic field to reverse.

SECTION 10–2 CHECKUP

1. Explain the difference between magnetism and electromagnetism.
2. What happens to the magnetic field in an electromagnet when the current through the coil is reversed?
3. State Ohm's law for a magnetic circuit.
4. Compare each quantity in Question 3 to its electrical counterpart.
5. What happens to the reluctance of a magnetic core if an air gap is added?

10–3 Electromagnetic Devices

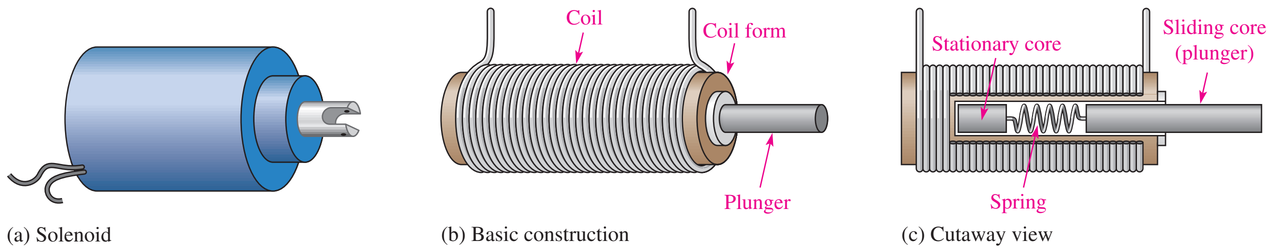
Many types of useful devices such as magnetic storage devices, electric motors, speakers, solenoids, and relays are based on electromagnetism.

After completing this section, you should be able to

- **Describe the principle of operation for several types of electromagnetic devices**
  - Discuss how a solenoid and a solenoid valve work
  - Discuss how a relay and a contactor work
  - Discuss how a speaker works
  - Discuss the basic analog meter movement
  - Explain a magnetic disk and tape Read/Write operation
  - Explain the basic operation of Magnetoresistive Random Access Memory

The Solenoid

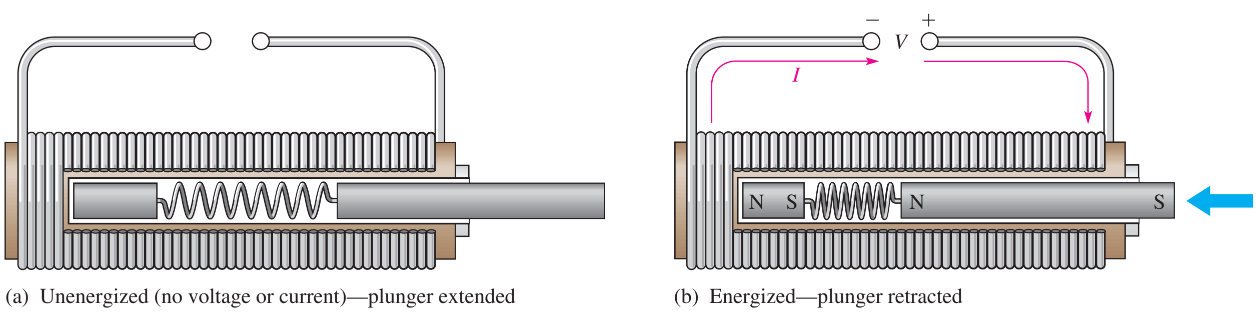
The **solenoid** is a type of electromagnetic device that has a movable iron core called a *plunger*. The movement of this iron core depends on both an electromagnetic field and a mechanical spring force. The basic structure of a solenoid is shown in Figure 10–16. It consists of a cylindrical coil of wire wound around a nonmagnetic hollow form. A stationary iron core is fixed in position at the end of the shaft and a sliding iron core (plunger) is attached to the stationary core with a spring.



▲ **FIGURE 10–16**

Basic solenoid structure.

The basic solenoid operation is illustrated in Figure 10–17 for the unenergized and the energized conditions. In the at-rest (or unenergized) state, the plunger is extended. The solenoid is energized by current through the coil, which sets up an electromagnetic field that magnetizes both iron cores. The south pole of the stationary core attracts the north pole of the movable core causing it to slide inward, thus retracting the plunger and compressing the spring. As long as there is coil current, the plunger remains retracted by the attractive force of the magnetic fields. When the current is cut off, the magnetic fields collapse and the force of the compressed spring pushes the plunger back out. The solenoid is used for applications such as opening and closing valves and automobile door locks.



▲ **FIGURE 10–17**

Basic solenoid operation.

The Solenoid Valve In industrial controls, **solenoid valves** are widely used to control the flow of air, water, steam, oils, refrigerants, and other fluids. Solenoid valves are used in both pneumatic (air) and hydraulic (oil) systems, common in machine controls. Solenoid valves are also common in the aerospace and medical fields. Solenoid valves can either move a plunger to open or close a port or can rotate a blocking flap a fixed amount.

A solenoid valve consists of two functional units: a solenoid coil that provides the magnetic field to provide the required movement to open or close the valve and a valve body, which is isolated from the coil assembly via a leakproof seal and includes a pipe and butterfly valve. Figure 10–18 shows a cutaway of one type of solenoid valve. When the solenoid is energized, the butterfly valve is turned to open a normally closed (NC) valve or to close a normally open (NO) valve.

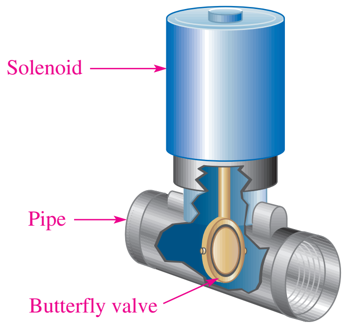


FIGURE 10–18

A basic solenoid valve structure.

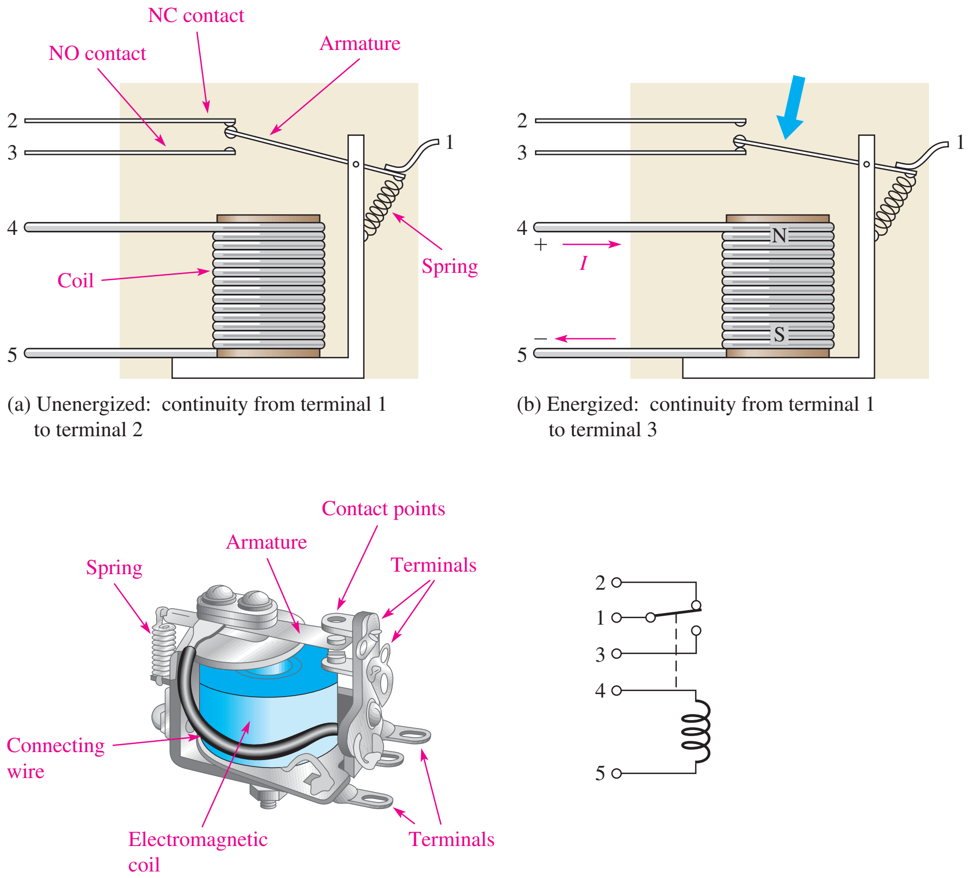
Solenoid valves are available with a wide variety of configurations including normally open or normally closed valves. They are rated for different types of fluids (for example, gas or water), pressures, number of pathways, sizes, and more. The same valve may control more than one line and may have more than one solenoid to move.

The Relay

The **relay** uses the mechanical motion of a solenoid to open and close electrical contacts. Figure 10–19 shows the basic operation of an *armature-type relay* with one normally open (NO) contact and one normally closed (NC) contact (single pole–double throw). When there is no coil current, the armature is held against the upper contact by the spring, thus providing continuity from terminal 1 to terminal 2, as shown in part (a) of the figure. When energized with coil current, the armature is pulled down by the attractive force of the electromagnetic field and makes connection with the lower contact to provide continuity from terminal 1 to terminal 3, as shown in Figure 10–19(b). A typical armature relay is shown in part (c), and the schematic symbol is shown in part (d).

Another widely used type of relay is the *reed relay,* which is shown in Figure 10–20. The reed relay, like the armature relay, uses an electromagnetic coil. The contacts are thin reeds of magnetic material and are usually located inside the coil. When there is no coil current, the reeds are in the open position as shown in part (b). When there is current through the coil, the reeds make contact because they are magnetized and attract each other as shown in part (c).

Closely related to relays are **contactors**, which are electrically controlled switches that function like a relay but are designed to switch higher currents (15 A or more) to a load. With contactors, the load is connected directly to the contacts so the contacts need to be designed to minimize problems with arcing. In general, contactors have larger contact points than relays are designed to open and close rapidly to minimize time for arcs to heat the contacts. In high voltage applications, insulation between contacts is used to prevent arcing between contacts. Contactors are found in industrial applications, where the contacts are connected to a load such as a large motor or heating element.



(a) Unenergized: continuity from terminal 1 to terminal 2

(b) Energized: continuity from terminal 1 to terminal 3

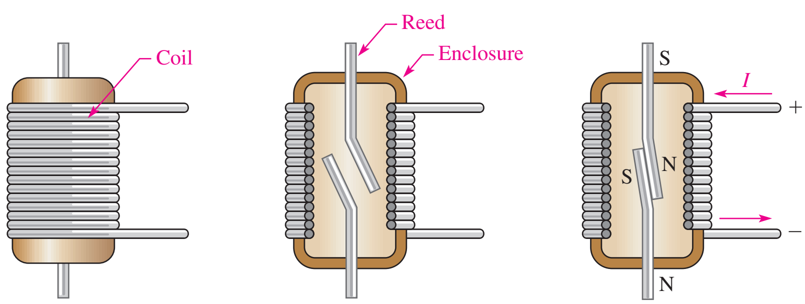
(c) Typical relay structure

(d) Symbol

▶ FIGURE 10–19

Basic structure of a single-pole–double-throw armature relay.

Another type of relay is the reed relay, which is based on the reed switch. Reed relays are simple, fast, and highly reliable relays that are basically one or more reed switches controlled by an external magnet. The contacts for the reed switch are mounted on magnetic reeds that are inside a sealed glass tube. They are opened or closed by an external magnetic field, so there is no armature. They generally are rated for lower currents than armature relays and are susceptible to shock and vibration and can "bounce" when contacts are closed. Applications include pulse counting, position sensors, alarm systems, and overload protection.



(a)

(b) Unenergized

(c) Energized

▲ FIGURE 10–20

Basic structure of a reed relay.

The Speaker

A **speaker** is an electromagnetic device that converts electrical signals into sound. Essentially, it is a linear motor that alternately attracts and repels an electromagnet to and from a permanent magnet called a donut magnet. Figure 10–21 shows the key parts of a speaker. The audio signal is connected using very flexible wires to a cylindrical coil called the voice coil. The voice coil and its movable core form an electromagnet, which is suspended in an accordion-like structure called the spider. The spider acts like an accordion spring, keeping the voice coil in the center and restoring it to the rest position when there is no input signal.

Current from the audio input alternates back and forth and powers the electromagnet; when there is more current, the attraction or repulsion is greater. When the input current reverses direction, the polarity of the electromagnet reverses direction also, faithfully following the input signal. The voice coil and its moving magnet are firmly attached to the cone. The cone is a flexible diaphragm that vibrates to produce sound.

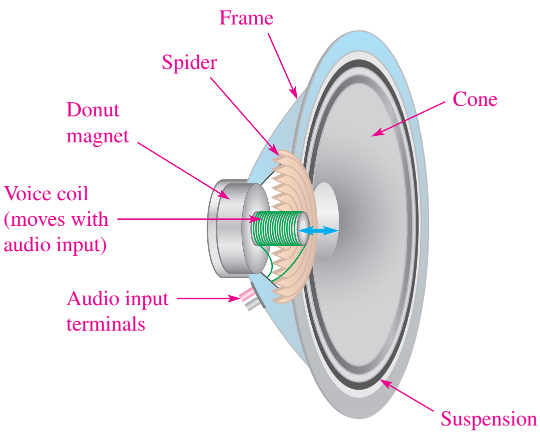


FIGURE 10–21

Key parts of a speaker (cutaway view).

Meter Movement

The d'Arsonval meter movement is the most common type used in analog multimeters. In this type of meter movement, the pointer is deflected in proportion to the amount of current through a coil. Figure 10–22 shows a basic d'Arsonval meter movement. It consists of a coil of wire wound on a bearing-mounted assembly that is placed

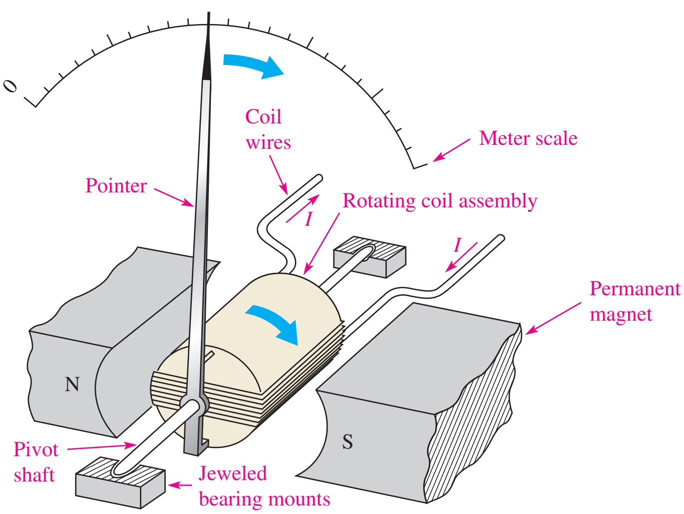


FIGURE 10–22

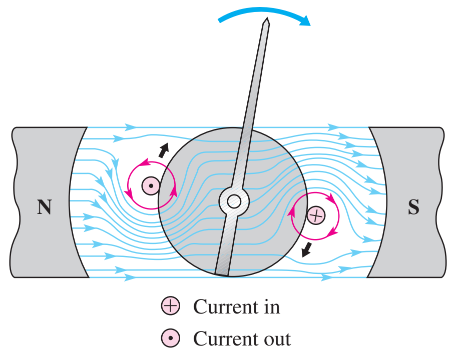
The basic d'Arsonval meter movement.

between the poles of a permanent magnet. A pointer is attached to the moving assembly. With no current through the coil, a spring mechanism keeps the pointer at its left-most (zero) position. When there is current through the coil, electromagnetic forces act on the coil, causing a rotation to the right. The amount of rotation depends on the amount of current.

Figure 10–23 illustrates how the interaction of magnetic fields produces rotation of the coil assembly. Current is inward at the "cross" and outward at the "dot" in the single winding shown. The inward current produces a clockwise electromagnetic field that reinforces the permanent magnetic field above it. The result is a downward force on the right side of the coil as shown. The outward current produces a counterclockwise electromagnetic field that reinforces the permanent magnetic field below it. The result is an upward force on the left side of the coil as shown. These forces produce a clockwise rotation of the coil assembly and are opposed by a spring mechanism. The indicated forces and the spring force are balanced at the value of the current. When current is removed, the spring force returns the pointer to its zero position.

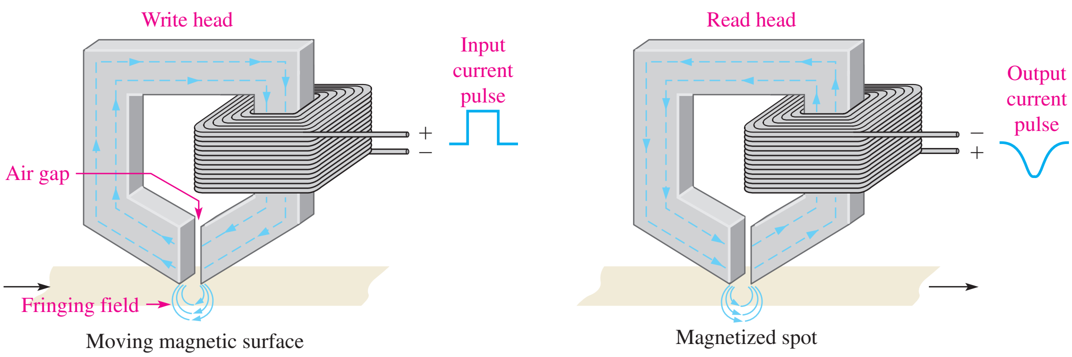
▶ **FIGURE 10–23**

When the electromagnetic field interacts with the permanent magnetic field, forces are exerted on the rotating coil assembly, causing it to move clockwise and thus deflecting the pointer.



Magnetic Disk and Tape Read/Write Head

A simplified and greatly magnified diagram of a magnetic disk or tape surface read/write operation is shown in Figure 10–24. A data bit (1 or 0) is written on the magnetic surface by the magnetization of a tiny segment of the surface as it moves by the write head. The direction of the magnetic flux lines is controlled by the direction of the current pulse in the winding, as shown in Figure 10–24(a). At the air gap in the write head, the magnetic flux takes the lower reluctance path through the magnetic surface of the storage device. This magnetizes a tiny spot on the surface in the direction of the field. A magnetized spot of one polarity represents a binary 1, and one of



(a) The magnetic flux from the write head follows the low reluctance path through the moving magnetic surface.

(b) When read head passes over a magnetized spot, an induced voltage appears at the output.

▲ **FIGURE 10–24**

Read/write function on a magnetic surface.

the opposite polarity represents a binary 0. Over the years, the size of the magnetized spot has decreased dramatically allowing higher storage densities. The bit density is determined by the ability of the read/write head to localize the magnetic field. Today, hard disk drives with 20 terabytes of storage are available to consumers.

In older read heads, the magnetized spot flies under a read head and induces a magnetic flux that follows the low reluctance path through the read head as shown in Figure 10–24(b). The direction of the induced current depends on the direction of the magnetized spot. Some older read/write heads combined reading and writing in the same head but normally the reading and writing functions are done with separate heads.

Modern hard disk read heads use magnetoresistive heads that are more sensitive than the older type that generate a current in a coil. Magnetoresistive read heads use a special material that changes its resistance in the presence of a magnetic field. The resistance depends on the direction of the field and special sensors can convert the resistance back into the data bits that were written on the media. Figure 10–25 shows a magnetoresistive read head used with a hard drive. This type of head (called a Giant Magnetoresistive head or GMR) enables much higher data densities in the magnetic material. The GMR head uses a device called a spin valve whose resistance depends on the relative alignment of the magnetization between two internal layers.

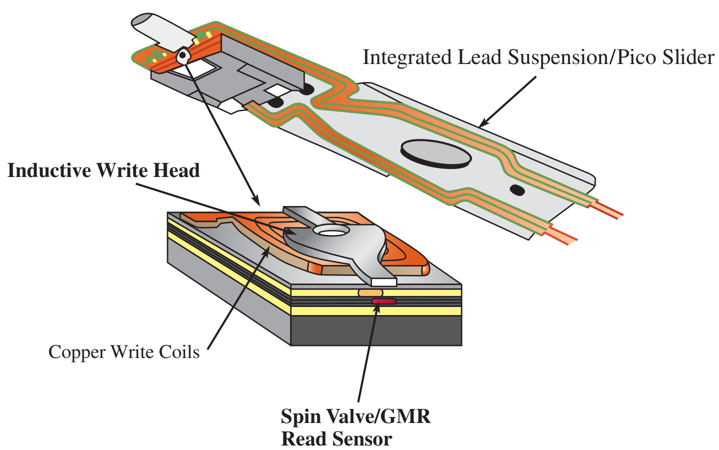


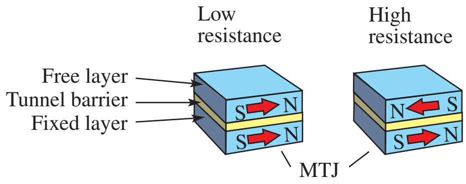
FIGURE 10–25

Magnetoresistive Random Access Memory (MRAM)

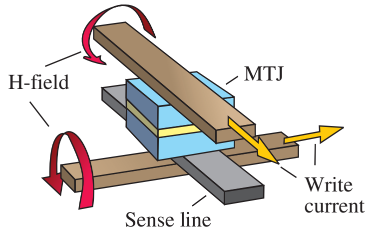
Magnetoresistive Random Access Memory (MRAM) is a new technology that stores binary states (0 or 1) in a ferromagnetic material integrated with silicon circuitry. Because it is magnetic, the data are stored when power is removed, an important advantage. Bits are stored in an array that has a magnetic tunnel junction cell as a storage unit. Two magnetic layers are separated by an extremely thin insulating layer called a tunnel barrier forming a sandwich called the magnetic tunnel junction (MTJ), as illustrated in Figure 10–26(a). The bottom layer is a fixed permanent magnetic layer that is set at the time of manufacture; the top layer is a free magnetic layer. The polarity of the magnetic poles in the free layer changes the resistance of the cell (high or low resistance), which determines if a 1 or 0 is stored. This resistance does not change when power is removed, which means the data are nonvolatile. This is an important advantage to this type of memory.

There are currently two technologies for writing the polarity of each magnetic storage cell. In "toggle" MRAM, shown in Figure 10–26(b), writing can be controlled by direction of a current at the intersection of perpendicular lines. Both lines must be active to write to a given cell, a technology that has roots in old core memory from the 1950s.

▶ FIGURE 10–26



(a) MTJ



(b) Basic toggle MRAM technology

The magnetic field associated with the write current in each of the two write lines determines the polarity and hence the resistance of the MTJ. There are limits to bit density with this method because one cell's magnetism can interfere with an adjacent cell if they are too close to each other. Toggle MRAMs have been in production since 2003.

A second-generation technology, called *spin-torque* (ST), uses the spin state of electrons to read or write to the cell and overcomes some of the drawbacks to toggle MRAMs. Spin is the property of electrons (or other charge carriers) to behave as tiny spinning tops, thus carrying angular momentum. Normal current has a 50–50 mix of spin-up or spin-down electrons. In polarized spin current, the majority of change carriers have the same spin. The polarized spin current has the ability to flip the magnetic state of the cells. This technology allows higher density that toggle MRAM because magnetic interference is greatly reduced. A significant research effort is currently ongoing for ST-MRAMs that may eventually become the ideal memory. Currently, a number of manufacturers are engaged in research.

To read the stored data in an MRAM cell, a transistor that is part of the cell is activated. The resistance of the cell depends on the polarity of the magnetic poles in the free layer. If the polarity matches the polarity of the fixed layer, the resistance is low; otherwise it is high. There are many advantages to MRAM. In addition to being nonvolatile, it is fast, reliable, low-power, and has no wear-out mechanism as there are no moving parts.

SECTION 10–3 CHECKUP

1. Explain the difference between a solenoid and a relay.
2. What is the movable part of a solenoid called?
3. What is the movable part of a relay called?
4. Upon what basic principle is the d'Arsonval meter movement based?
5. What is the function of the spider in a speaker?
6. Describe the basic storage cell of MRAM.

10–4 MAGNETIC HYSTERESIS

When a magnetizing force is applied to a material, the flux density in the material changes in a certain way.

After completing this section, you should be able to

- **Explain magnetic hysteresis**
  - State the formula for magnetic field intensity
  - Discuss a hysteresis curve
  - Define *retentivity*

Magnetic Field Intensity (*H*)

The **magnetic field intensity** (also called *magnetizing force*) in a material is defined to be the magnetomotive force (F_m) per unit length (l) of the material, as expressed by the following equation. The unit of magnetic field intensity (H) is ampere-turns per meter (At/m).

$$H = \frac{F_m}{l}$$

Equation 10–6

where $F_m = NI$. Note that the magnetic field intensity depends on the number of turns (N) of the coil of wire, the current (I) through the coil, and the length (l) of the material. It does not depend on the type of material.

Since $\phi = F_m/\mathcal{R}$, as F_m increases, the flux increases. Also, the magnetic field intensity (H) increases. Recall that the flux density (B) is the flux per unit cross-sectional area ($B = \phi/A$), so B is also proportional to H. The curve showing how these two quantities (B and H) are related is called the B-H curve or the hysteresis curve. The parameters that influence both B and H are illustrated in Figure 10–27.

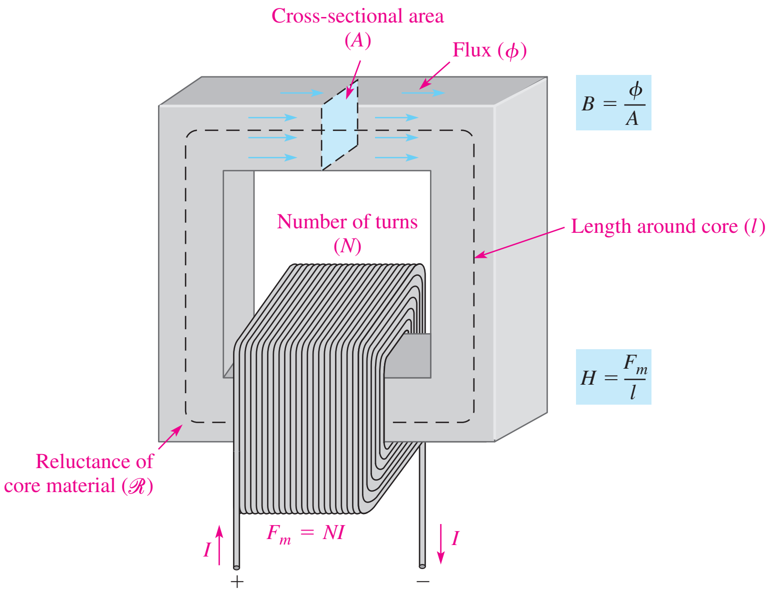


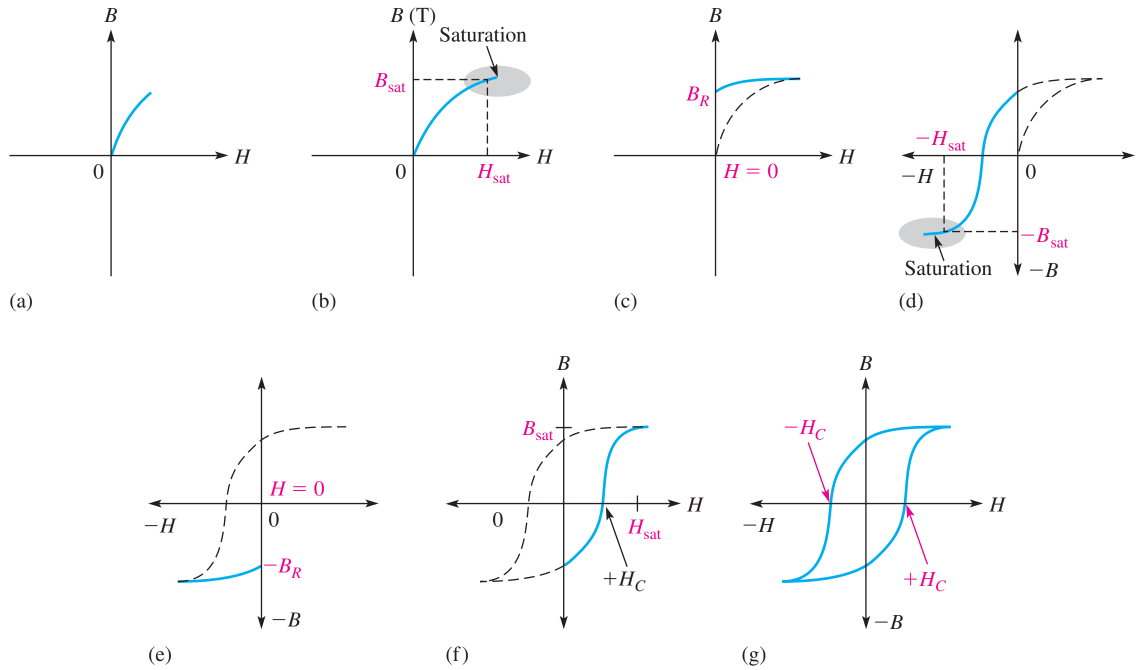
FIGURE 10–27 Parameters that determine the magnetic field intensity (*H*) and the flux density (*B*).

The Hysteresis Curve and Retentivity

Hysteresis is a characteristic of a magnetic material whereby a change in magnetization lags the application of the magnetic field intensity. The magnetic field intensity (H) can be readily increased or decreased by varying the current through the coil of wire, and it can be reversed by reversing the voltage polarity across the coil.

Figure 10–28 illustrates the development of the hysteresis curve. Let's start by assuming a magnetic core is unmagnetized so that $B = 0$. As the magnetic field intensity (H) is increased from zero, the flux density (B) increases proportionally, as indicated by the curve in Figure 10–28(a). When H reaches a certain value, B begins to level off. As H continues to increase, B reaches a saturation value (B_{sat}) when H reaches a value (H_{sat}), as illustrated in Figure 10–28(b). Once saturation is reached, a further increase in H will not increase B.

Now, if H is decreased to zero, B will fall back along a different path to a residual value (B_R), as shown in Figure 10–28(c). This indicates that the material continues to be magnetized even when the magnetic field intensity is zero ($H = 0$). The ability of a material to maintain a magnetized state without magnetic field intensity is called **retentivity**.



▲ **FIGURE 10–28**

Development of a magnetic hysteresis curve.

The retentivity of a material represents the maximum flux that can be retained after the material has been magnetized to saturation and is indicated by the ratio of B_R to B_{sat}.

Reversal of the magnetic field intensity is represented by negative values of H on the curve and is achieved by reversing the current in the coil of wire. An increase in H in the negative direction causes saturation to occur at a value ($-H_{sat}$) where the flux density is at its maximum negative value, as indicated in Figure 10–28(d).

When the magnetic field intensity is removed ($H = 0$), the flux density goes to its negative residual value ($-B_R$), as shown in Figure 10–28(e). From the $-B_R$ value, the flux density follows the curve indicated in part (f) back to its maximum positive value when the magnetic field intensity equals H_{sat} in the positive direction.

The complete *B-H* curve is shown in Figure 10–28(g) and is called the *hysteresis curve.* The magnetic field intensity required to make the flux density zero is called the *coercive force,* H_C.

Materials with a low retentivity do not retain a magnetic field very well, while those with high retentivities exhibit values of B_R very close to the saturation value of B. Depending on the application, retentivity in a magnetic material can be an advantage or a disadvantage. In permanent magnets and magnetic tape, for example, high retentivity is required; while in tape recorder read/write heads, low retentivity is necessary. In ac motors, retentivity is undesirable because the residual magnetic field must be overcome each time the current reverses, thus wasting energy.

SECTION 10–4 CHECKUP

1. For a given wirewound core, how does an increase in current through the coil affect the flux density?
2. Define *retentivity*.
3. Why is low retentivity required for tape recorder read/write heads but high retentivity is required for magnetic tape?

10–5 Electromagnetic Induction

In this section, electromagnetic induction is introduced. The principle of electromagnetic induction is what makes transformers, electrical generators, and many other devices possible.

After completing this section, you should be able to

- **Discuss the principle of electromagnetic induction**
  - Explain how voltage is induced in a conductor in a magnetic field
  - Determine polarity of an induced voltage
  - Discuss forces on a conductor in a magnetic field
  - State Faraday's law
  - State Lenz's law
  - Explain how a crankshaft position sensor works

Relative Motion

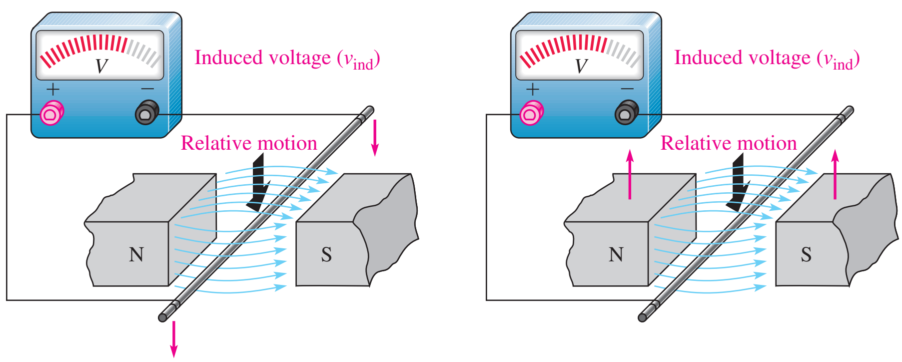
When a straight conductor is moved perpendicular to a magnetic field, there is a relative motion between the conductor and the magnetic field. Likewise, when a magnetic field is moved past a stationary conductor, there is also relative motion. In either case, this relative motion results in an **induced voltage (v_{ind})** in the conductor, as Figure 10–29 indicates. This principle is known as **electromagnetic induction**. The lowercase v stands for instantaneous voltage. Voltage is only induced when the conductor "cuts" magnetic lines as shown. The amount of the induced voltage (v_{ind}) depends on the flux density (B), the length of the conductor (l) that is exposed to the magnetic field, and the rate at which the conductor and the magnetic field move with respect to each other. The faster the relative speed, the greater the induced voltage. The equation for induced voltage in a straight conductor is

$$v_{ind} = B_{\perp} lv \qquad \text{Equation 10–7}$$

where v_{ind} is the induced voltage, $B_{\perp}$ is the portion of the flux density in teslas that is perpendicular to the motion, l is the length of the conductor exposed to the magnetic field in meters, and v is the relative velocity in meters per second.

Polarity of the Induced Voltage

If the conductor in Figure 10–29 is moved first one way and then another in the magnetic field, a reversal of the polarity of the induced voltage will be observed. As the

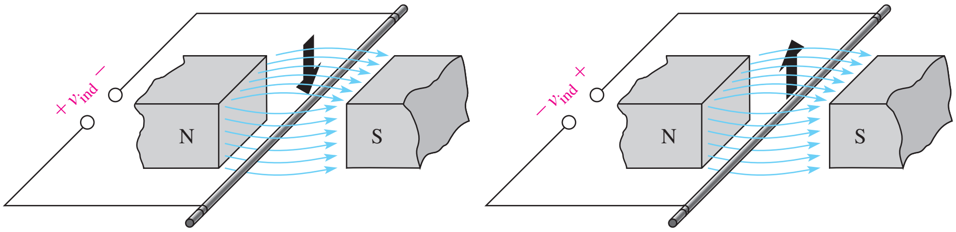


(a) Conductor moving downward (b) Magnetic field moving upward

◀ **FIGURE 10–29**

Relative motion between a straight conductor and a magnetic field.

conductor is moved downward, a voltage is induced with the polarity indicated in Figure 10–30(a). As the conductor is moved upward, the polarity is as indicated in part (b) of the figure.



(a) Downward relative motion (b) Upward relative motion

FIGURE 10–30

Polarity of induced voltage depends on direction of motion.

EXAMPLE 10–7

Assume the conductor in Figure 10–30 is 10 cm long and the pole face of the magnet is 5.0 cm wide. The flux density is 0.5 T, and the conductor is moved upward at a velocity of 0.8 m/s. What voltage is induced in the conductor?

Solution Although the conductor is 10 cm, only 5.0 cm (0.05 m) is in the magnetic field because of the size of the pole faces. Therefore,

$$v_{ind} = B_{\perp} lv = (0.5\text{ T})(0.05\text{ m})(0.8\text{ m/s}) = \mathbf{20\text{ mV}}$$

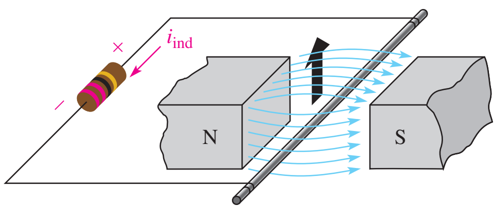
Related Problem What is the induced voltage if the velocity is doubled?

Induced Current

When a load resistor is connected to the conductor in Figure 10–30, the voltage induced by the relative motion in the magnetic field will cause a current in the load, as shown in Figure 10–31. This current is called the **induced current (i_{ind})**. The lowercase *i* stands for instantaneous current.

FIGURE 10–31

Induced current in a load as the conductor moves through the magnetic field.



The action of producing a voltage and a resulting current in a load by moving a conductor across a magnetic field is the basis for electrical generators. A single conductor will have a small induced current, so practical generators use coils with many turns. This effectively increases the length of the conductor that is exposed to the magnetic field. The property of an electrical conductor to produce an emf when there is relative motion between the conductor and magnetic field is the basis for inductance in an electric circuit.

HISTORY NOTE

Michael Faraday 1791–1867

Faraday was an English physicist and chemist who is best remembered for his contribution to the understanding of electromagnetism. He discovered that electricity could be produced by moving a magnet inside a coil of wire, and he was able to build the first electric motor. He later built the first electromagnetic generator and transformer. The statement of the principles of electromagnetic induction is known today as Faraday's law. Also, the unit of capacitance, the *farad*, is named after him. (Photo credit: Library of Congress.)

Faraday's law

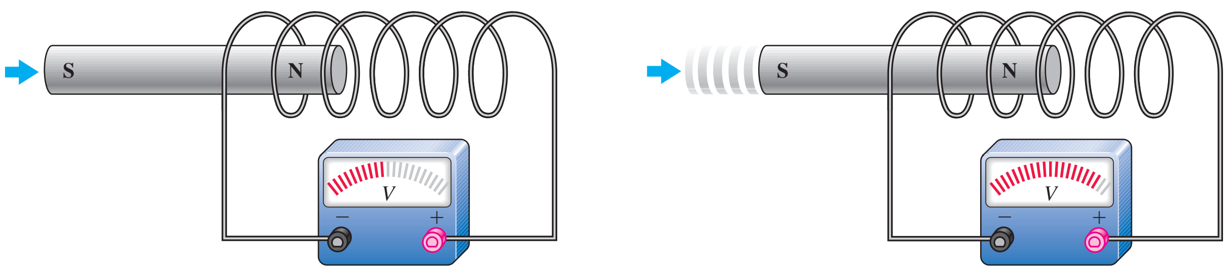
Michael Faraday discovered the principle of electromagnetic induction in 1831. The key idea behind Faraday's law is that a changing magnetic field can induce a voltage in a conductor. Sometimes Faraday's law is stated as Faraday's law of induction. Faraday experimented with coils, and his law is an extension of the principle of electromagnetic induction for straight conductors discussed previously.

When a conductor is coiled into multiple turns, more conductors can be exposed to the magnetic field, increasing the induced voltage. When the magnetic flux is caused to change by any means, an induced voltage will result. The change in the magnetic field can be caused by relative motion between the magnetic field and the coil. Faraday's observations can be stated as follows:

1. The amount of voltage induced in a coil is directly proportional to the rate of change of the magnetic field with respect to the coil ($d\phi/dt$).
2. The amount of voltage induced in a coil is directly proportional to the number of turns of wire in the coil (N).

Faraday's first observation is demonstrated in Figure 10–32, where a bar magnet is moved through a coil, thus creating a changing magnetic field. In part (a) of the figure, the magnet is moved at a certain rate, and a certain induced voltage is produced as indicated. In part (b), the magnet is moved at a faster rate through the coil, creating a greater induced voltage.

Faraday's second observation is demonstrated in Figure 10–33. In part (a), the magnet is moved through the coil and a voltage is induced as shown. In part (b), the magnet is moved at the same speed through a coil that has a greater number of turns. The greater number of turns creates a greater induced voltage.

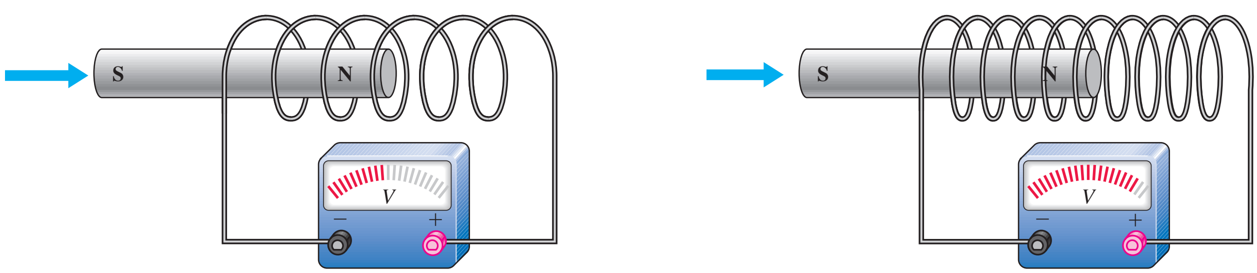


(a) As the magnet moves slowly to the right, its magnetic field is changing with respect to the coil, and a voltage is induced.

(b) As the magnet moves more rapidly to the right, its magnetic field is changing more rapidly with respect to the coil, and a greater voltage is induced.

▲ **FIGURE 10–32**

A demonstration of Faraday's first observation: The amount of induced voltage is directly proportional to the rate of change of the magnetic field with respect to the coil.



(a) Magnet moves through a coil and induces a voltage.

(b) Magnet moves at same rate through a coil with more turns (loops) and induces a greater voltage.

▲ **FIGURE 10–33**

A demonstration of Faraday's second observation: The amount of induced voltage is directly proportional to the number of turns in the coil.

Faraday's law is stated as follows:

The voltage induced across a coil equals the number of turns in the coil times the rate of change of the magnetic flux.

Faraday's law is expressed in equation form as

Equation 10–8

$$v_{ind} = N\left(\frac{d\phi}{dt}\right)$$

where v_{ind} is the induced voltage, N is the number of turns in the coil, and $d\phi/dt$ is the rate of change of the magnetic flux in Wb/s.

EXAMPLE 10–8

Apply Faraday's law to find the induced voltage across a coil with 500 turns that is located in a magnetic field that is changing at a rate of 8,000 μWb/s.

Solution

$$v_{ind} = N\left(\frac{d\phi}{dt}\right) = (500\text{ t})(8{,}000\ \mu\text{Wb/s}) = \mathbf{4.0\ V}$$

Related Problem Find the induced voltage across a 250 turn coil in a magnetic field that is changing at 50 μWb/s.

HISTORY NOTE

Heinrich F. E. Lenz 1804–1865

Lenz was born in Estonia (then Russia) and became a professor at the University of St. Petersburg. He carried out many experiments following Faraday's lead and formulated the principle of electromagnetism, which defines the polarity of induced voltage in a coil. The statement of this principle is named in his honor. (Photo credit: AIP Emilio Segré Visual Archives, E. Scott Barr Collection.)

Any *relative* motion between the magnetic field and the coil will produce the changing magnetic field that will induce a voltage in the coil. The changing magnetic field can even be induced by ac applied to an electromagnet, just as if there were motion. This type of changing magnetic field is the basis for transformer action in ac circuits, as you will see in Chapter 14.

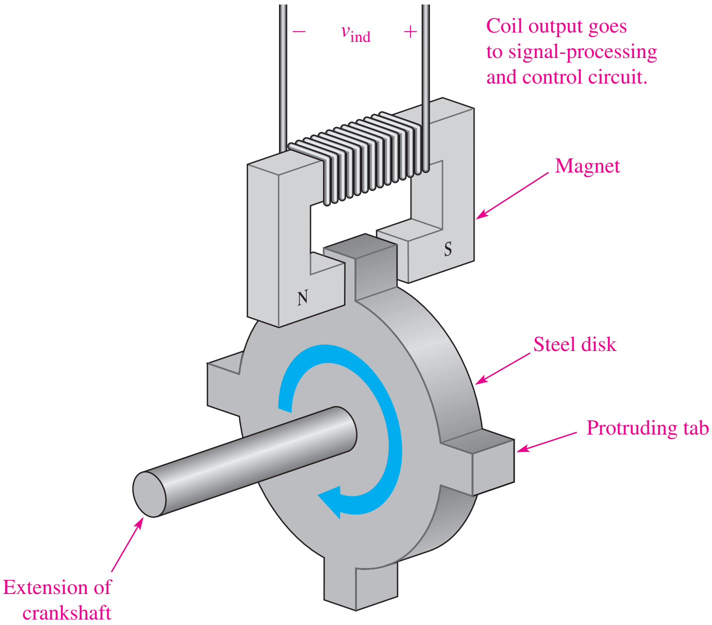
Lenz's Law

Faraday's law states that a changing magnetic field induces a voltage in a coil that is directly proportional to the rate of change of the magnetic field and the number of turns in the coil. **Lenz's law** defines the polarity or direction of the induced voltage.

When the current through a coil changes, an induced voltage is created as a result of the changing electromagnetic field and the polarity of the induced voltage is such that it always opposes the change in current.

An Application of Electromagnetic Induction

In automobiles, it is necessary to know the position of the crankshaft to control ignition timing and sometimes to adjust the fuel mixture. As mentioned previously, a Hall-effect sensor is one method to determine the position of the crankshaft (or camshaft). Another widely used method is to detect a change in the magnetic field as a metallic tab moves though the air gap in a magnetic assembly. A basic concept is shown in Figure 10–34. A steel disk with protruding tabs is connected to the end of the crankshaft. As the crankshaft turns, the tabs move through the magnetic field. Steel has a much lower reluctance than does air, so the magnetic flux increases when a tab is in the air gap. This change in the magnetic flux causes an induced voltage to appear across the coil, indicating the position of the crankshaft.



◀ **FIGURE 10–34**

A crankshaft position sensor that produces a voltage when a tab passes through the air gap of the magnet.

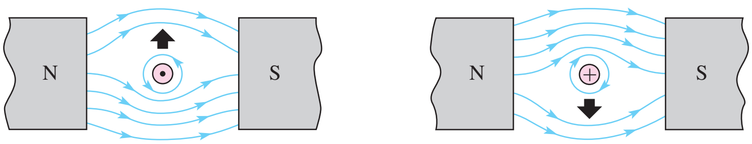
HISTORY NOTE

James Clerk Maxwell 1831–1879

James Clerk Maxwell (1831–1879) was a Scottish physicist who unified the apparently diverse fields of electricity, light, and magnetism in series of four equations. Essentially his equations laid the foundation for 20th-century physics, including special relativity and quantum mechanics. His equations started with the work of Faraday and Gauss, but he went further and was able to show that light consisted of oscillating electric and magnetic fields. This work is considered to be the greatest accomplishments of 19th-century physics.

Forces on a Current-Carrying Conductor in a Magnetic Field (Motor Action)

When two bar magnets are placed next to each other so that the north and south poles of one are next to like poles of the other, the flux from the adjacent magnets will have the same polarity (i.e., point in the same direction) and the magnets will repel. If the magnets are placed next to each other so that the north and south poles of one magnet are next to the opposite poles of the other, the flux from the adjacent magnets will have opposite polarity (i.e., point in different directions) and the magnets will attract. In a motor, when current flows through the conductor, it creates a circular field whose polarity is determined by right-hand rule, as shown in Figure 10–35(a) and (b).



(a) Upward force: weak field above, strong field below.

(b) Downward force: strong field above, weak field below

⊙ Current out
⊕ Current in

◀ **FIGURE 10–35**

Forces on a current-carrying conductor in a magnetic field (motor action).

In Figure 10–35(a) the current through the conductor is out of the page and creates a magnetic field with a counterclockwise polarity. Note that the polarity of the flux above the conductor is opposite to that of the fixed magnetic field, so that the force between them attracts the conductor just as for bar magnets with opposite orientations. Conversely, the polarity of the flux below the conductor is the same as the polarity of the fixed magnetic field, so that the force between them repels the conductor just as for bar magnets with the same orientation. In both cases, the force exerted on the conductor is upward.

In Figure 10–35(b) the situation is reversed. The current through the conductor is into the page and creates a magnetic field with a clockwise polarity. The polarity of the flux above the conductor is the same as that of the fixed magnetic field, so that the force between them repels the conductor. Conversely, the polarity of the flux below the conductor is opposite to that of the fixed magnetic field, so that the force between them attracts the conductor. In both cases, the force exerted on the conductor is downward.

The force on a current carrying conductor is given by the equation

Equation 10–9

$$F = BIl \sin\theta$$

where F is the force in newtons, B is the magnetic flux density in teslas, I is the current in amperes, l is the length of the conductor exposed to the magnetic field in meters, and θ is the angle between the conductor and the field. When the angle between the conductor and the field is 90°, $\sin\theta = 1$ and the equation simplifies to $F = BIl$. (This is the case for the conductor in Figure 10–35, with the current in and out of the page.)

EXAMPLE 10–9

Assume a magnetic pole face is a square that is 3.0 cm on a side. Find the force on a conductor that has a current of 2 A if the conductor is perpendicular to the field and the flux density is 0.35 T.

Solution Because the conductor is perpendicular to the field, $\sin\theta = 1$ and $F = BIl$. The length of conductor exposed to the magnetic flux is 3.0 cm (0.030 m). Therefore,

$$F = BIl = (0.35\text{ T})(2.0\text{ A})(0.03\text{ m}) = \mathbf{0.21\ N}$$

Related Problem What is the direction of the force if the field is directed up (along the y axis) and the current is directed inward (along the z axis)?

Although the force in Example 10–9 is relatively small, it can be multiplied many times by simply coiling the conductor and exposing a much longer length of the conductor to the magnetic field.

SECTION 10–5 CHECKUP

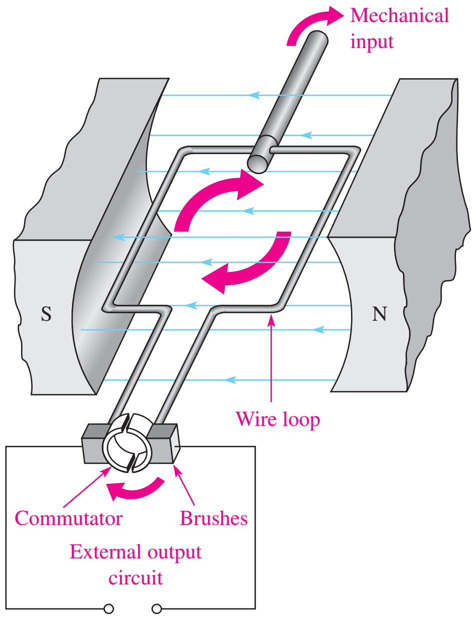
1. What is the induced voltage across a stationary conductor in a stationary magnetic field?
2. When the speed at which a conductor is moved through a magnetic field is increased, does the induced voltage increase, decrease, or remain the same?
3. When there is current through a conductor in a magnetic field, what happens?
4. If the steel disk in the crankshaft position sensor has stopped with a tab in the magnet's air gap, what is the induced voltage?

10–6 The DC Generator

DC generators produce a voltage that is proportional to the magnetic flux and the rotational speed of the armature.

After completing this section, you should be able to

- **Explain how a dc generator works**
    - Draw an equivalent circuit for a self-excited shunt-type dc generator
    - Discuss the parts of a dc generator

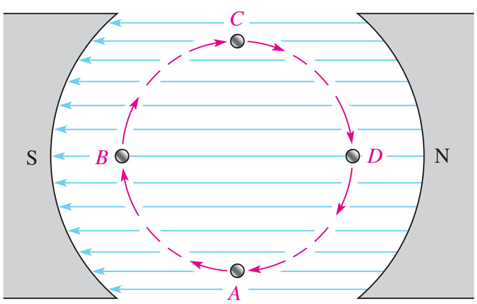


◀ **FIGURE 10–36**

A simplified dc generator.

Figure 10–36 shows a simplified dc generator consisting of a single loop of wire in a permanent magnetic field. Notice that each end of the wire loop is connected to a split-ring arrangement. This conductive metal ring is called a *commutator.* As the wire loop rotates in the magnetic field, the split commutator ring also rotates. Each half of the split ring rubs against the fixed contacts, called *brushes,* and connects the wire loop to an external circuit.

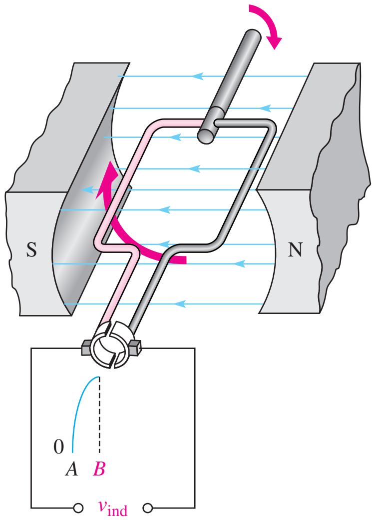
As the wire loop rotates through the magnetic field, it cuts through the flux lines at varying angles, as illustrated in Figure 10–37. At position *A* in its rotation, the loop of wire is effectively moving parallel with the magnetic field. Therefore, at this instant, the rate at which it is cutting through the magnetic flux lines is zero. As the loop moves from position *A* to position *B*, it cuts through the flux lines at an increasing rate. At position *B*, it is moving effectively perpendicular to the magnetic field and thus is cutting through a maximum number of lines per unit time. As the loop rotates from position *B* to position *C*, the rate at which it cuts the flux lines decreases to minimum (zero) at *C.* From position *C* to position *D*, the rate at which the loop cuts the flux lines increases to a maximum at *D* and then back to a minimum again at *A*.



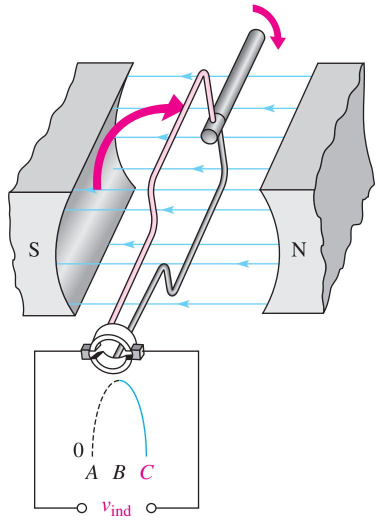
◀ **FIGURE 10–37**

End view of wire loop cutting through the magnetic field.

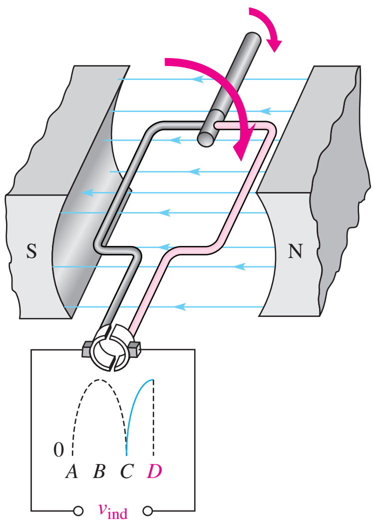
As you have learned, when a wire moves through a magnetic field, a voltage is induced, and by Faraday's law, the amount of induced voltage is proportional to the number of loops (turns) in the wire and the rate at which it is moving with respect to the magnetic field. The angle at which the wire moves with respect to the magnetic flux lines determines the amount of induced voltage because the rate at which the wire cuts through the flux lines depends on the angle of motion.



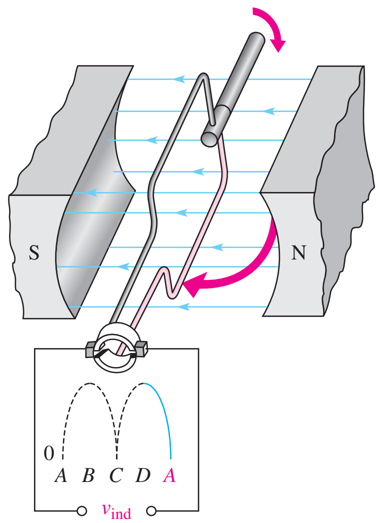
Position *B*: Loop is moving perpendicular to flux lines, and voltage is maximum.



Position *C*: Loop is moving parallel with flux lines, and voltage is zero.



Position *D*: Loop is moving perpendicular to flux lines, and voltage is maximum.



Position *A*: Loop is moving parallel with flux lines, and voltage is zero.

▲ **FIGURE 10–38**

Operation of a basic dc generator.

Figure 10–38 illustrates how a voltage is induced in the external circuit as the single loop rotates in the magnetic field. Assume that the loop is in its instantaneous horizontal position, so the induced voltage is zero. As the loop continues in its rotation, the induced voltage builds up to a maximum at position *B*, as shown in part (a) of the figure. Then, as the loop continues from *B* to *C*, the voltage decreases to zero at position *C*, as shown in part (b).

During the second half of the revolution, shown in Figure 10–38(c) and (d), the brushes switch to opposite commutator sections, so the polarity of the voltage remains the same across the output. Thus, as the loop rotates from position *C* to position *D* and then back to position *A*, the voltage increases from zero at *C* to a maximum at *D* and back to zero at *A*.

Figure 10–39 shows how the induced voltage varies as the wire loop in the dc generator goes through several rotations (three in this case). This voltage is a dc voltage because its polarities do not change. However, the voltage is pulsating between zero and its maximum value.

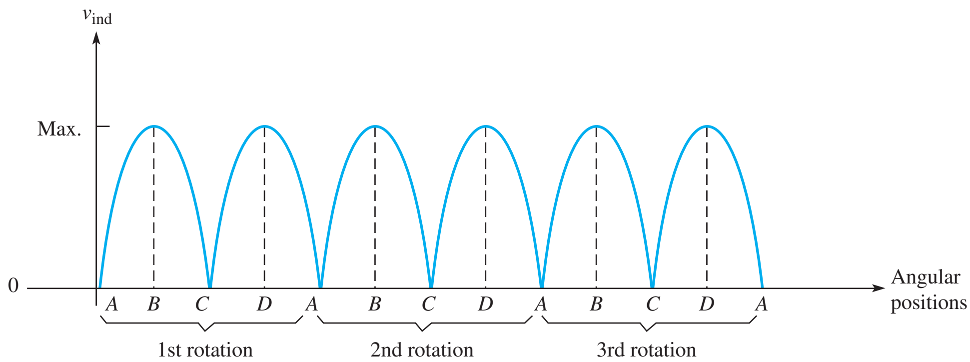


FIGURE 10–39

Induced voltage over three rotations of the wire loop in the dc generator.

In practical generators, multiple coils are pressed into slots in a ferromagnetic-core assembly. The entire assembly, called the **rotor**, is connected to bearings and rotates in the magnetic field. Figure 10–40 is a diagram of the rotor core with no wire loops (coils) shown. The commutator is divided into segments, with each pair of segments connected to the end of a coil. With more coils, the voltages from several coils are combined because the brushes can contact more than one of the commutator segments at once. The loops do not reach maximum voltage at the same time, so the pulsating output voltage is much smoother than is the case with only one coil or loop shown previously. The variations can be further smoothed by filters to produce a nearly constant dc output. (Filters are discussed in Chapter 18.)

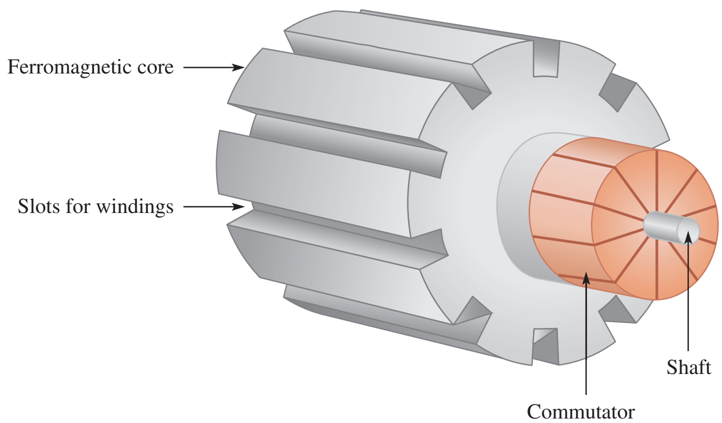


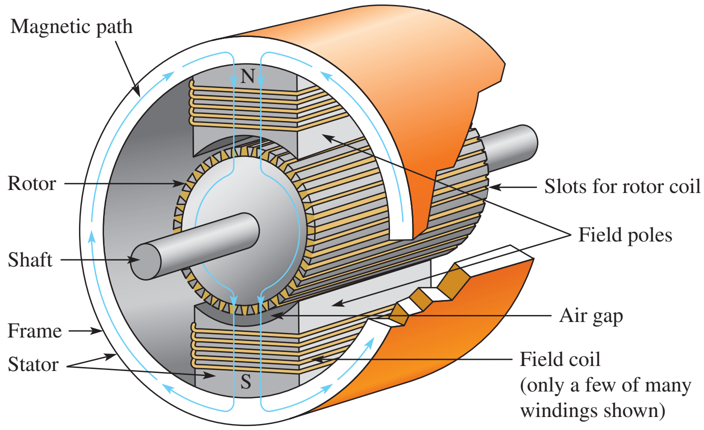
FIGURE 10–40

A simplified rotor core. The coils are pressed into the slots and connected to the commutator.

Instead of permanent magnets, most generators use electromagnets to provide the required magnetic field. One advantage to this is that flux density can be controlled, thus controlling the output voltage of the generator. The windings for the electromagnets, called field windings, require current to produce the magnetic field.

The current for the field windings can be provided from a separate voltage source, but this is a disadvantage. A better method is to use the generator itself to provide the current for the electromagnets; this is called a **self-excited generator.** The generator starts because there is normally enough residual magnetism in the field magnets due to hysteresis that causes a small initial field and allows the generator to start producing a voltage. In cases where a generator has not been used for a long time, it may be necessary to provide an external source to the field windings to start it.

The stationary part of a generator (or motor) includes all of the nonmoving parts and is called the **stator**. Figure 10–41 illustrates a simplified two-pole dc generator



▲ **FIGURE 10–41**

The magnetic structure of a generator or motor. In this case, the rotor is also the armature because it produces the power.

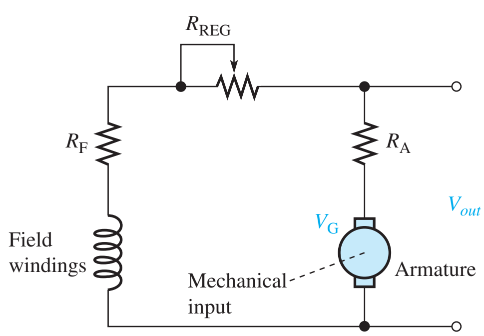
showing the magnetic paths (end caps, bearings, and commutator are not shown). Notice that the frame is part of the magnetic path for the field magnets. To make a generator have high efficiency, the air gap is kept as small as possible. The **armature** is the power-producing component and can be either on the rotor or the stator. In the dc generator described previously, the armature is the rotor because power is produced in the moving conductors and taken from the rotor via the commutator.

Equivalent Circuit for a DC Generator

A self-excited generator can be represented by a basic dc circuit with a coil to produce the magnetic field and a mechanically driven generator, as shown in Figure 10–42. There are other configurations of dc generators, but this represents a common one. In the case shown, the field windings are in parallel with the source; this configuration is called a *shunt-wound generator*. The resistance of the field windings is shown as R_F. For the equivalent circuit, this resistance is shown in series with the field windings. The armature is driven by a mechanical input, causing it to spin; it looks like a voltage source of V_G. The armature resistance is shown as the series resistance, R_A. The rheostat, R_{REG}, is in series with the field winding resistance and regulates the output voltage by controlling the current to the field windings and thus the flux density.

► **FIGURE 10–42**

Equivalent circuit for a self-excited shunt dc generator.



When a load is connected to the output, current in the armature is shared between the load and the field windings. The efficiency of the generator can be calculated as the ratio of the power delivered to the load (P_L) to the total power (P_T), which includes the losses in the armature and the resistance in the field circuit.

MHD Generator A **magnetohydrodynamic (MHD) generator** causes a voltage to be generated from a conducting fluid (it can be a very hot ionized gas, plasma, liquid metal, or salt water). The gas is hot enough to ionize the atoms in the gas, which means the gas becomes a good electrical conductor. The concept is illustrated in Figure 10–43. The hot gas is passed through a transverse field of a very strong electromagnet (of several tesla strength). This generates dc at the output, which is taken from electrodes that are perpendicular to the magnetic field as illustrated. To date, the process has not been cost effective for adoption in large-scale power generation; however, there are applications for MHD phenomena in flow control and metal processing. There is considerable interest in government, academia, and research labs in developing cost-effective MHD generators because they have the potential to be very efficient with reduced pollution and with no moving parts they should have high reliability.

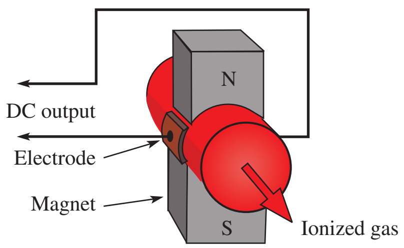


FIGURE 10–43

A magnetohydrodynamic generator.

One potential application for an MHD generator is combining it with concentrated solar power (CSP). Concentrated solar power systems work by focusing solar energy on a receiver, producing very high temperatures, which are high enough to provide ionization required by MHD generators. MHD generators can use the integrating CSP to gain higher efficiencies than are currently realized with standard power generation methods.

SECTION 10–6 CHECKUP

1. What is the moving part of a generator called?
2. What is the purpose of a commutator?
3. How does greater resistance in the field windings of a generator affect the output voltage?
4. What is meant by a self-excited generator?

10–7 THE DC MOTOR

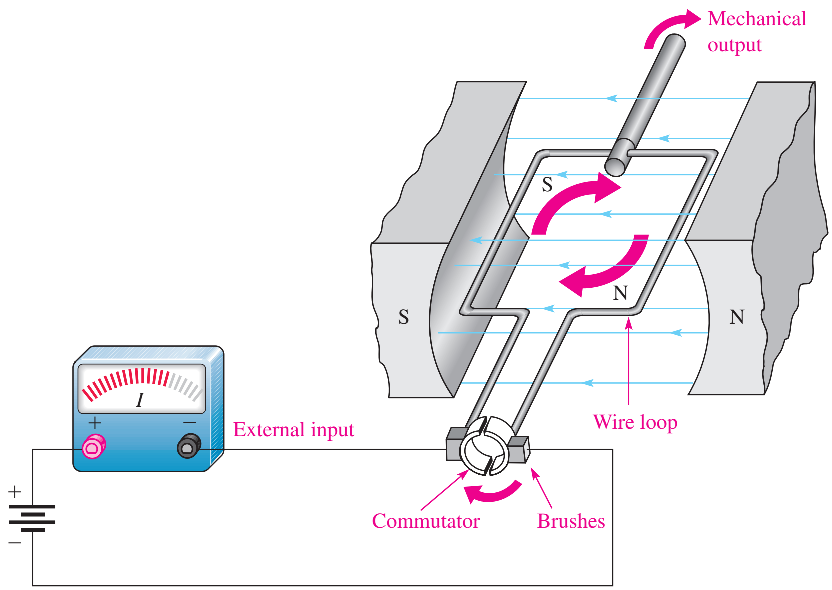
Motors convert electrical energy to mechanical motion by taking advantage of the force produced when a current-carrying conductor is in a magnetic field. A dc motor operates from a dc source and can use either an electromagnet or a permanent magnet to supply the field.

After completing this section, you should be able to

- **Explain how a dc motor works**
  - Draw an equivalent circuit for a series and a shunt-type dc motor
  - Discuss back emf and how it reduces armature current
  - Discuss power rating of motors

Basic Operation

As in the case of generators, motor action is the result of the interaction of magnetic fields. In a dc motor, the rotor field interacts with the magnetic field of the stator. The rotor in all dc motors contains the armature winding, which sets up a magnetic field. The rotor moves because of the attractive force between opposite poles and the repulsive force between like poles, as illustrated in the simplified diagram of Figure 10–44. The rotor moves because of the attraction of its north pole with the south pole of the stator (and vice versa). As the two poles near each other, the polarity of the rotor current is suddenly switched by the commutator, reversing the magnetic poles of the rotor. The commutator serves as a mechanical switch to reverse the current in the armature just as the unlike poles are near each other, continuing the rotation of the rotor.



▲ FIGURE 10–44

Simplified dc motor.

Brushless DC Motors

Many dc motors do not use a commutator to reverse the polarity of the current. Instead of supplying current to a moving armature, the magnetic field is rotated in the stator windings using an electronic controller. The direction of current in the field coils is periodically reversed by the controller by producing an ac waveform (or modified ac waveform) from the dc input. This causes the stator field to rotate, and the permanent magnet rotor moves in the same direction to keep up with the rotating field. A common way to sense the position of the rotating magnet is to use a Hall-effect sensor, which provides the controller with position information. Brushless motors have higher reliability than traditional brushed motors because they do not need to have periodic brush replacement, but have the added complexity of the electronic controller. Figure 10–45 shows a cutaway view of a brushless dc motor.

Back EMF

When a dc motor is first started, a magnetic field is present from the field windings. Armature current develops another magnetic field that interacts with the one from

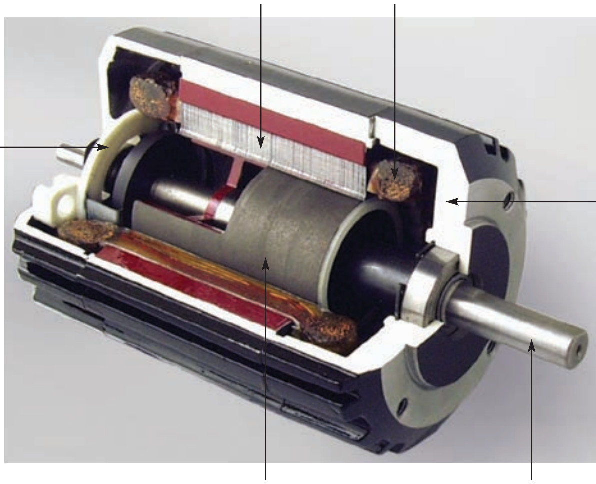


FIGURE 10–45

Cutaway view of a brushless dc motor. (Courtesy of Bodine Electric Company)

the field windings and starts the motor turning. The armature windings are now spinning in the presence of the magnetic field, so generator action occurs. In effect, the spinning armature has a voltage developed across it that opposes the original applied voltage in accordance with Lenz's law. This self-generated voltage is called **back emf** (electromotive force). The term *emf* was once common for voltage but is not favored because voltage is not a "force" in the physics sense, but back emf still refers to the self-generated voltage in motors. Back emf, also called *counter emf*, serves to significantly reduce the armature current when the motor is turning at constant speed.

Motor Ratings

Some motors are rated by the torque they can provide, others are rated by the power they produce. Torque and power are important parameters for any motor. Although torque and power are different physical parameters, if one is known, the other can be obtained.

Torque tends to rotate an object. In a dc motor, the torque is proportional to the amount of flux and to the armature current. Torque, T, in a dc motor can be calculated from the equation

$$T = K\phi I_A$$

Equation 10–10

where T is torque in newton-meters (N-m), K is a constant that depends on physical parameters of the motor, ϕ is magnetic flux in webers (Wb), and I_A is armature current in amperes (A).

Recall that power is defined as the rate of doing work. To calculate power from torque, you must know the speed of the motor in rpm for the torque that you measured. The equation to determine the power, given the torque at a certain speed, is

$$P = 0.105Ts$$

Equation 10–11

where P is power in W, T is torque in N-m, and s is speed of motor in rpm.

EXAMPLE 10–10 What is the power developed by a motor that turns at 350 rpm when the torque is 3.6 N-m?

Solution Substitute into Equation 10–11.

$$P = 0.105Ts = 0.105(3.6 \text{ N-m})(350 \text{ rpm}) = \mathbf{132\ W}$$

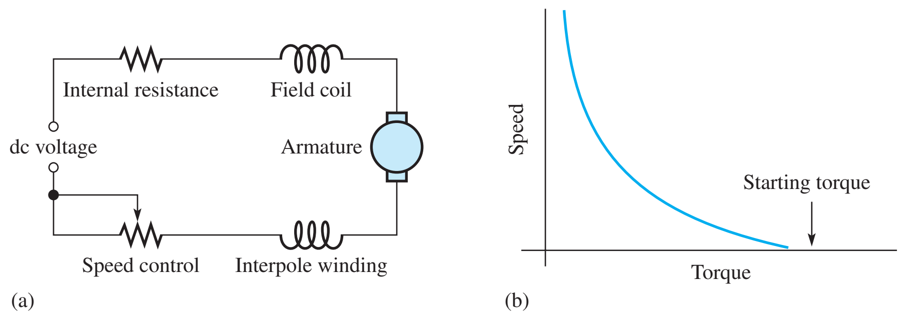
Related Problem Determine the power produced by a motor if $T = 5$ N-m and $s = 1{,}000$ rpm.

TECH NOTE

One characteristic of dc motors is that if they are allowed to run without a load, the torque can cause the motor to "run away" to a speed beyond the manufacturer's rating. Therefore, dc motors should always be operated with a load to prevent self-destruction.

The Series DC Motor

The series dc motor has the field coil windings and the armature coil windings in series. A schematic of this arrangement is shown in Figure 10–46(a). The internal resistance is generally small and consists of field coil resistance, armature winding resistance, and brush resistance. As in the case of generators, dc motors may also contain an interpole winding, as shown, and current limiting for speed control. The interpole winding is an auxiliary winding to overcome the effects of the armature reactance. In a series dc motor, the armature current, field current, and line current are all the same.



▲ **FIGURE 10–46**

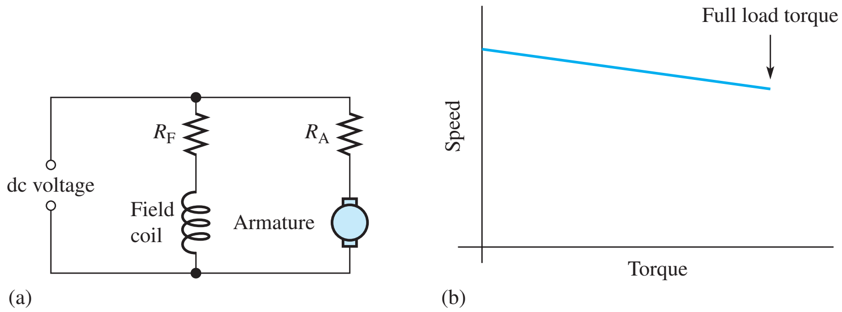
Simplified schematic and torque-speed characteristic for a series dc motor.

As you know, magnetic flux is proportional to the current in a coil. The magnetic flux created by the field windings is proportional to armature current because of the series connection. Thus, when the motor is started, there is no back emf and the high starting current implies high magnetic flux. Recall that Equation 10–10 showed that the torque in a dc motor is proportional to both the armature current and the magnetic flux. Thus, the series-wound motor will have a very high starting torque when the current is high because flux and armature current are high. For this reason, series dc motors are used when high starting torques are required (such as a starter motor in a car).

The plot of the torque and motor speed for a series dc motor is shown in Figure 10–46(b). The starting torque is at its maximum value. At low speeds, the torque is still very high, but drops off dramatically as the speed increases. As you can see, the speed can be very high if the torque is low; for this reason, the series-wound dc motor always is operated with a load.

The Shunt DC Motor

A shunt dc motor has the field coil in parallel with the armature, as shown in the equivalent circuit in Figure 10–47(a). In the shunt motor, the field coil is supplied by a



▲ FIGURE 10–47

Simplified schematic and torque-speed characteristic for a shunt dc motor.

constant voltage source, so the magnetic field set up by the field coils is constant. The armature resistance and the back emf produced by generator action in the armature determine the armature current.

The torque-speed characteristic for a shunt dc motor is quite different than for a series dc motor. When a load is applied, the shunt motor will slow down, causing the back emf to be reduced and the armature current to increase. The increase in armature current tends to compensate for the added load by increasing the torque of the motor. Although the motor has slowed because of the additional load, the torque-speed characteristic is nearly a straight line for the shunt dc motor as shown in Figure 10–47(b). At full load, the shunt dc motor still has high torque.

SECTION 10–7 CHECKUP

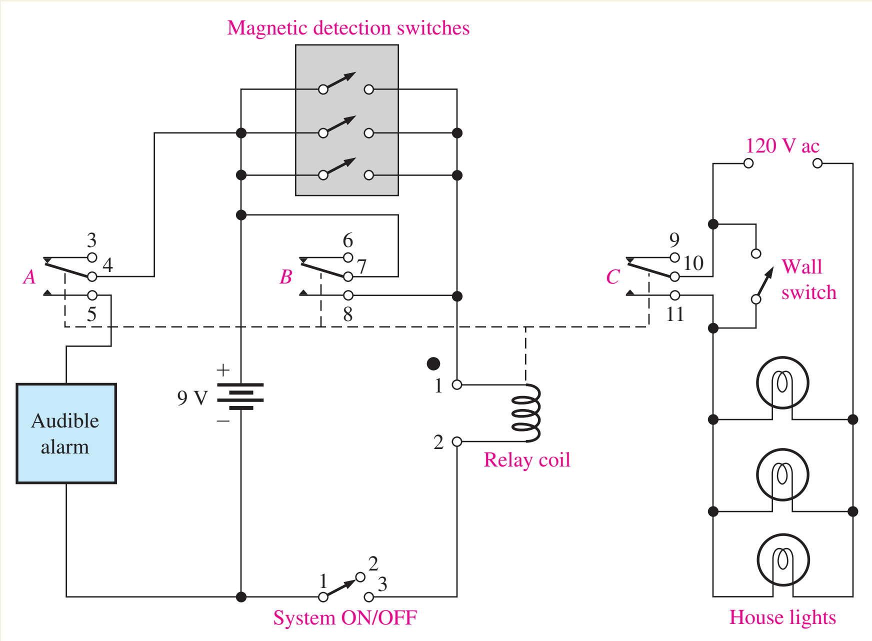
1. What creates back emf?
2. How does back emf affect armature current as the motor comes up to speed?
3. What type of dc motor has the highest starting torque?
4. What is the major advantage of a brushless motor over a brushed motor?

Application Activity

The relay is a common type of electromagnetic device that is used in many types of control applications. With a relay, a lower voltage, such as from a battery, can be used to switch a much higher voltage, such as the 120 V from an ac outlet. You will see how a relay can be used in a basic security alarm system.

The schematic in Figure 10–48 shows a simplified intrusion alarm system that uses a relay to turn on an audible alarm (siren) and lights. The system operates from a 9 V battery so that even if power to the house is off, the audible alarm will still work.

The detection switches are normally open (NO) magnetic switches that are parallel connected and located in the windows and doors. The relay is a triple-pole–double-throw device that operates with a coil voltage of 9 V dc and draws approximately 50 mA. When an intrusion occurs, one of the switches closes and allows current from the battery to the relay coil, which energizes the relay and causes the three sets of normally open contacts to close. Closure of contact



▲ **FIGURE 10–48**

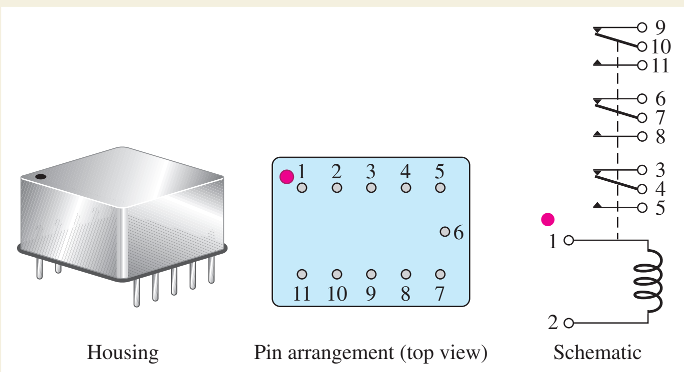
Simplified burglar alarm system.

A turns on the alarm, which draws 2 A from the battery. Closure of contact *C* turns on a light circuit in the house. Closure of contact *B* latches the relay and keeps it energized even if the intruder closes the door or window through which entry was made. If not for contact *B* in parallel with the detection switches, the alarm and lights would shut off as soon as the window or door was shut behind the intruder.

The relay contacts are not physically remote in relation to the coil as the schematic indicates. The schematic is drawn this way for functional clarity. The entire relay is housed in the package shown in Figure 10–49. Also shown are the pin diagram and internal schematic for the relay.

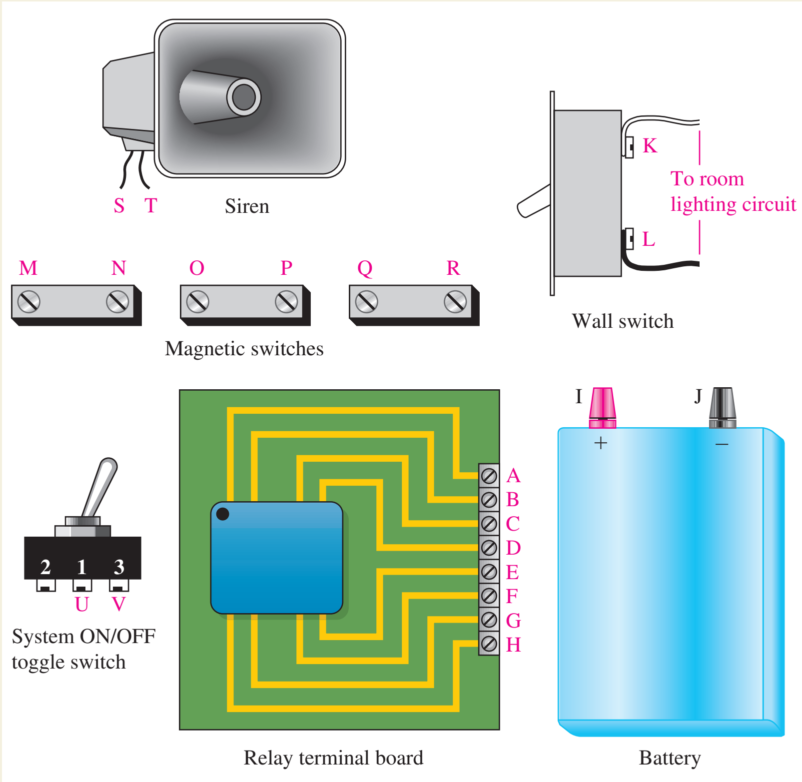
System Interconnections

1. Develop a connection block diagram and point-to-point wire list for interconnecting the components in Figure 10–50 to create the alarm system shown in the schematic of Figure 10–48. The connection points on the components are indicated by letters.



▲ **FIGURE 10–49**

Triple-pole–double-throw relay.



▲ FIGURE 10–50

Array of security alarm components.

A Test Procedure

2. Develop a detailed step-by-step procedure to check out the completely wired security alarm system.

Review

3. What is the purpose of the detection switches?
4. What is the purpose of contact *B* in the relay in Figure 10–48?

SUMMARY

- Unlike magnetic poles attract each other, and like poles repel each other.
- Materials that can be magnetized are called *ferromagnetic.*
- When there is current through a conductor, it produces an electromagnetic field around the conductor.
- You can use the right-hand rule to establish the direction of the electromagnetic lines of force around a conductor.
- An electromagnet is basically a coil of wire around a magnetic core.
- When a conductor moves within a magnetic field, or when a magnetic field moves relative to a conductor, a voltage is induced across the conductor.
- The faster the relative motion between a conductor and a magnetic field, the greater the induced voltage.
- Table 10–3 summarizes the quantities and units used in this chapter.
- Hall-effect sensors use current to sense the presence of a magnetic field.
- DC generators convert mechanical power to dc electrical power.

▶ TABLE 10–3

SYMBOL	QUANTITY	SI UNIT
B	Magnetic flux density	Tesla (T)
ϕ	Magnetic flux	Weber (Wb)
μ	Permeability	Webers/ampere-turn · meter (Wb/At · m)
$\mathcal{R}$	Reluctance	Ampere-turns/weber (At/Wb)
F_m	Magnetomotive force (mmf)	Ampere-turn (At)
H	Magnetic field intensity	Ampere-turns/meter (At/m)
F	Force	Newton (N)
T	Torque	Newton-meter (N-m)

- The moving part of a generator or motor is called the *rotor*; the stationary part is called the *stator*.
- DC motors convert electrical power to mechanical power.
- Brushless dc motors use a permanent magnet as the rotor, and the stator is the armature.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Ampere-turn (At) The current in a single loop (turn) of wire.

Electromagnetic field A formation of a group of magnetic lines of force surrounding a conductor created by electrical current in the conductor.

Electromagnetic induction The phenomenon or process by which a voltage is produced in a conductor when there is relative motion between the conductor and a magnetic or electromagnetic field.

Electromagnetism The production of a magnetic field by current in a conductor.

Faraday's law A law stating that the voltage induced across a coil equals the number of turns in the coil times the rate of change of the magnetic flux.

Hall effect A change in current across a conductor or semiconductor when current in the material is perpendicular to a magnetic field. The change in current produces a small transverse voltage in the material called the *Hall voltage*.

Hysteresis A characteristic of a magnetic material whereby a change in magnetization lags the application of the magnetic field intensity.

Induced current (i_{ind}) A current induced in a conductor when the conductor moves through a magnetic field.

Induced voltage (v_{ind}) Voltage produced as a result of a changing magnetic field.

Lenz's law A law that states when the current through a coil changes, the polarity of the induced voltage created by the changing magnetic field is such that it always opposes the change in current that caused it. The current cannot change instantaneously.

Lines of force Magnetic flux lines in a magnetic field radiating from the north pole to the south pole.

Magnetic field A force field radiating from the north pole to the south pole of a magnet.

Magnetic flux The lines of force between the north and south poles of a permanent magnet or an electromagnet.

Magnetomotive force (mmf) The cause of a magnetic field, measured in ampere-turns.

Permeability The measure of ease with which a magnetic field can be established in a material.

Relay An electromagnetically controlled mechanical device in which electrical contacts are opened or closed by a magnetizing current.

Reluctance The opposition to the establishment of a magnetic field in a material.

Retentivity The ability of a material, once magnetized, to maintain a magnetized state without the presence of a magnetizing force.

Solenoid An electromagnetically controlled device in which the mechanical movement of a shaft or plunger is activated by a magnetizing current.

Speaker An electromagnetic device that converts electrical signals to sound waves.

Tesla (T) The mks SI unit for magnetic flux density.

Weber (Wb) The SI unit of magnetic flux, which represents 10^8 lines.

FORMULAS

10–1	$B = \frac{\phi}{A}$	Magnetic flux density
10–2	$\mu_r = \frac{\mu}{\mu_0}$	Relative permeability
10–3	$\mathcal{R} = \frac{l}{\mu A}$	Reluctance
10–4	$F_m = NI$	Magnetomotive force
10–5	$\phi = \frac{F_m}{R}$	Magnetic flux
10–6	$H = \frac{F_m}{l}$	Magnetic field intensity
10–7	$v_{ind} = B_{\perp} lv$	Induced voltage across a moving conductor perpendicular to a magnetic field
10–8	$v_{ind} = N\left(\frac{d\phi}{dt}\right)$	Faraday's law
10–9	$F = BIl \sin \theta$	Force on a current-carrying conductor
10–10	$T = K\phi I_A$	Torque in a dc motor
10–11	$P = 0.105Ts$	Power from torque

TRUE/FALSE QUIZ

Answers are at the end of the chapter.

1. The tesla (T) and the gauss (G) are both units for magnetic flux density.
2. The Hall-effect voltage is proportional to the magnetic field strength, B.
3. The unit for measuring magnetomotive force (mmf) is the volt.
4. Ohm's law for a magnetic circuit gives the relationship between flux density, magnetomotive force, and reluctance.
5. A solenoid is a form of electromagnetic switch that opens and closes mechanical contacts.
6. A hysteresis curve is a plot of flux density (B) as a function of field intensity (H).
7. The magnetic field intensity required to make the flux density zero is called the inverse force.
8. To produce an induced voltage in a coil, the magnetic field surrounding it can be changed.
9. MRAM uses resistance differences as a basic way to store bits.
10. The speed of a generator can be controlled with a rheostat in the field windings.
11. A self-excited dc generator will normally have enough residual magnetism in the field magnets to start the generator producing voltage at the output when it is first turned on.
12. The power developed by a motor is proportional to its torque.
13. In a brushless motor, the magnetic field is supplied by permanent magnets.
14. Brushless dc motors use a coil wrapped on an iron core to develop the magnetic field in the rotor.

SELF-TEST

Answers are at the end of the chapter.

1. When the south poles of two bar magnets are brought close together, there will be
(a) a force of attraction **(b)** a force of repulsion
(c) an upward force **(d)** no force

2. A magnetic field is made up of
(a) positive and negative charges **(b)** magnetic domains
(c) flux lines **(d)** magnetic poles

3. The direction of a magnetic field is from
(a) north pole to south pole **(b)** south pole to north pole
(c) inside to outside the magnet **(d)** front to back

4. Reluctance in a magnetic circuit is analogous to
(a) voltage in an electric circuit **(b)** current in an electric circuit
(c) power in an electric circuit **(d)** resistance in an electric circuit

5. The unit of magnetic flux is the
(a) tesla **(b)** weber
(c) ampere-turn **(d)** ampere-turns/weber

6. The unit of magnetomotive force is the
(a) tesla **(b)** weber
(c) ampere-turn **(d)** ampere-turns/weber

7. The unit of flux density is the
(a) tesla **(b)** weber
(c) ampere-turn **(d)** electron-volt

8. The electromagnetic activation of a movable shaft is the basis for
(a) relays **(b)** circuit breakers
(c) magnetic switches **(d)** solenoids

9. When there is current through a wire placed in a magnetic field,
(a) the wire will overheat
(b) the wire will become magnetized
(c) a force is exerted on the wire
(d) the magnetic field will be cancelled

10. A coil of wire is placed in a changing magnetic field. If the number of turns in the coil is increased, the voltage induced across the coil will
(a) remain unchanged **(b)** decrease
(c) increase **(d)** be excessive

11. If a conductor is moved back and forth at a constant rate in a constant magnetic field, the voltage induced in the conductor will
(a) remain constant **(b)** reverse polarity
(c) be reduced **(d)** be increased

12. In the crankshaft position sensor in Figure 10–34, the induced voltage across the coil is caused by
(a) current in the coil
(b) rotation of the steel disk
(c) a tab passing through the magnetic field
(d) acceleration of the steel disk's rotational speed

13. The purpose of the commutator in a generator or motor is to
    (a) change the direction of the current to the rotor as it spins
    (b) change the direction of the current to the stator windings
    (c) support the motor or generator shaft
    (d) provide the magnetic field for the motor or generator
14. In a motor, back emf serves to
    (a) increase the power from the motor
    (b) increase the flux
    (c) increase the current in the field windings
    (d) decrease the current in the armature
15. The torque of a motor is proportional to the
    (a) amount of flux
    (b) armature current
    (c) both of the above
    (d) none of the above

PROBLEMS

More difficult problems are indicated by an asterisk (*).
Answers to odd-numbered problems are at the end of the book.

SECTION 10–1 The Magnetic Field

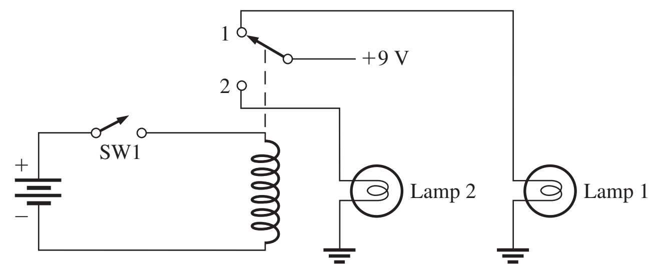
1. The cross-sectional area of a magnetic field is increased, but the flux remains the same. Does the flux density increase or decrease?
2. In a certain magnetic field the cross-sectional area is 0.5 m^2 and the flux is 1,500 μWb. What is the flux density?
3. What is the flux in a magnetic material when the flux density is $2{,}500 \times 10^{-6}$ T and the cross-sectional area is 150 cm^2?
4. At a given location, assume the earth's magnetic field is 0.6 G. Express this flux density in tesla.
5. A very strong permanent magnet has a magnetic field of 100,000 μT. Express this flux density in gauss.

SECTION 10–2 Electromagnetism

6. What happens to the compass needle in Figure 10–11 when the current through the conductor is reversed?
7. What is the relative permeability of a ferromagnetic material whose absolute permeability is 750×10^{-6} Wb/At·m?
8. Determine the reluctance of a material with a length of 0.28 m and a cross-sectional area of 0.08 m^2 if the absolute permeability is 150×10^{-7} Wb/At·m.
9. What is the magnetomotive force in a 50 turn coil of wire when there are 3 A of current through it?

SECTION 10–3 Electromagnetic Devices

10. Typically, when a solenoid is activated, is the plunger extended or retracted?
11. (a) What force moves the plunger when a solenoid is activated?
    (b) What force causes the plunger to return to its at-rest position?
12. Explain the sequence of events in the circuit of Figure 10–51 starting when switch 1 (SW1) is closed.
13. What causes the pointer in a d'Arsonval movement to deflect when there is current through the coil?

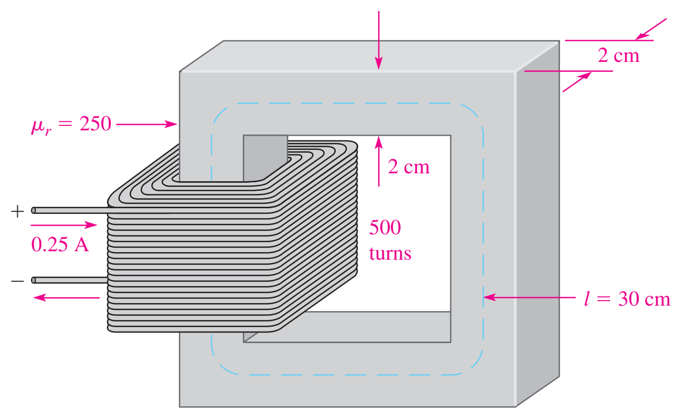


▲ FIGURE 10–51

SECTION 10–4 Magnetic Hysteresis

14. What is the magnetizing force in Problem 9 if the length of the core is 0.2 m?

15. How can the flux density in Figure 10–52 be changed without altering the physical characteristics of the core?

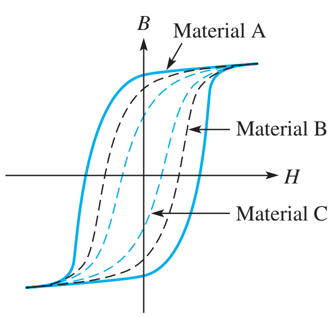


▲ FIGURE 10–52

16. In Figure 10–52, there are 500 turns. Determine

(a) H **(b)** ϕ **(c)** B

17. Determine from the hysteresis curves in Figure 10–53 which material has the most retentivity.



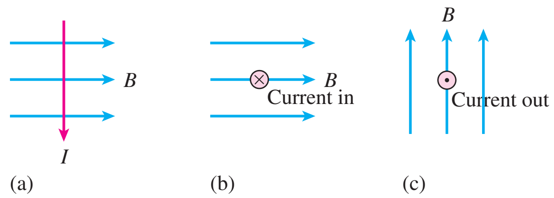
▲ FIGURE 10–53

SECTION 10–5 Electromagnetic Induction

18. According to Faraday's law, what happens to the induced voltage across a given coil if the rate of change of magnetic flux doubles?

19. What are three factors that determine the voltage in a conductor that is moving perpendicular to a magnetic field?

20. A magnetic field is changing at a rate of $3,500 \times 10^{-3}$ Wb/s. How much voltage is induced across a 50 turn coil that is placed in the magnetic field?
21. How does Lenz's law complement Faraday's law?
22. In Figure 10–34, why is there no induced voltage when the steel disk is not rotating?
23. Determine the direction of force for each part in Figure 10–54.



▲ FIGURE 10–54

24. A conductor carrying 6.5 A of current makes a 45° angle with a 0.90 T field. If 10.0 cm of the conductor is in the field, what force does it experience?

SECTION 10–6 The DC Generator

25. Explain the purpose of the commutator and brushes in Figure 10–36.

*26. A basic one-loop dc generator is rotated at 60 rev/s. How many times each second does the dc output voltage peak (reach a maximum)?

*27. Assume that another loop, 90 degrees from the first loop, is added to the dc generator in Problem 26. Make a graph of voltage versus time to show how the output voltage appears. Let the maximum voltage be 10 V.

28. Assume the self-excited shunt dc generator in Figure 10–42 has a load connected to it that draws 12 A. If the field windings draw 1.0 A, what is the armature current?
29. **(a)** If the output voltage in Problem 26 is 14 V, what power is supplied to the load?
    (b) What power is dissipated in the field resistance?

SECTION 10–7 The DC Motor

30. **(a)** What power is developed by a motor that turns at 1,200 rpm and has a torque of 3.0 N-m?
    (b) What is the horsepower rating of the motor? (746 W = 1 hp)
31. Assume a motor dissipates 12 W internally when it delivers 50 W to a load. What is the efficiency?

ANSWERS

SECTION CHECKUPS

SECTION 10–1 The Magnetic Field

1. North poles repel.
2. Magnetic flux is the group of lines of force that makes up a magnetic field. Magnetic flux density is a measure of the concentration of magnetic flux.
3. Gauss and tesla
4. $B = \phi/A = 900\ \mu T$
5. The voltage that is induced across the sensor is proportional to the distance to a magnet.

SECTION 10–2 Electromagnetism

1. Electromagnetism is produced by current through a conductor. An electromagnetic field exists only when there is current. A magnetic field exists independently of current.
2. When current reverses, the direction of the magnetic field also reverses.
3. Flux (ϕ) equals magnetomotive force (F_m) divided by reluctance ($\mathcal{R}$).
4. Flux: current, mmf: voltage, reluctance: resistance.
5. The reluctance increases.

SECTION 10–3 Electromagnetic Devices

1. A solenoid produces a movement only. A relay provides an electrical contact closure.
2. The movable part of a solenoid is the plunger.
3. The movable part of a relay is the armature.
4. The d'Arsonval movement is based on the interaction of magnetic fields.
5. The spider acts as a spring to return and support the coil in its rest position.
6. The cell is a sandwich of two magnetic layers are separated by an extremely thin insulating layer called a tunnel barrier.

SECTION 10–4 Magnetic Hysteresis

1. An increase in current increases the flux density.
2. Retentivity is the ability of a material to remain magnetized after removal of the magnetizing force.
3. Heads should not remain magnetized after magnetic force is removed, but tape should.

SECTION 10–5 Electromagnetic Induction

1. Zero voltage is induced.
2. Induced voltage increases.
3. A force is exerted on the conductor when there is current.
4. The induced voltage is zero.

SECTION 10–6 The DC Generator

1. The rotor
2. The commutator reverses the current in the rotating coil.
3. Greater resistance will reduce the magnetic flux, causing the output voltage to drop.
4. A generator in which the field windings derive their current from the output

SECTION 10–7 The DC Motor

1. Back emf is a voltage developed in a motor because of generator action as the rotor turns. It opposes the original supply voltage.
2. Back emf reduces the armature current.
3. A series-wound motor
4. Higher reliability because there are no brushes to wear out

RELATED PROBLEMS FOR EXAMPLES

10–1 Flux density will decrease.
10–2 31.0 T
10–3 The reluctance is reduced to 12.8×10^6 At/Wb.
10–4 1.66×10^5 At/Wb
10–5 7.2 mWb
10–6 **(a)** $F_m = 42.5$ At
(b) $\mathcal{R} = 85 \times 10^3$ At/Wb
10–7 40 mV
10–8 12.5 mV
10–9 The direction is along the negative x axis.
10–10 525 W

TRUE/FALSE QUIZ

1. T	2. T	3. F	4. F
5. F	6. T	7. F	8. T
9. T	10. F	11. T	12. T
13. F	14. F		

SELF-TEST

1. (b)	2. (c)	3. (a)	4. (d)
5. (b)	6. (c)	7. (a)	8. (d)
9. (c)	10. (c)	11. (b)	12. (c)
13. (a)	14. (d)	15. (c)	