CHAPTER 20
Magnetism

Figure 20.1 The magnificent spectacle of the Aurora Borealis, or northern lights, glows in the northern sky above Bear Lake near Eielson Air Force Base, Alaska. Shaped by Earth's magnetic field, this light is produced by radiation spewed from solar storms. (credit: Senior Airman Joshua Strang, Flickr)

Chapter Outline

INTRODUCTION You may have encountered magnets for the first time as a small child playing with magnetic toys or refrigerator magnets. At the time, you likely noticed that two magnets that repulse each other will attract each other if you flip one of them around. The force that acts across the air gaps between magnets is the same force that creates wonders such as the Aurora Borealis. In fact, magnetic effects pervade our lives in myriad ways, from electric motors to medical imaging and computer memory. In this chapter, we introduce magnets and learn how they work and how magnetic fields and electric currents interact.

20.1 Magnetic Fields, Field Lines, and Force

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Summarize properties of magnets and describe how some nonmagnetic materials can become magnetized
- Describe and interpret drawings of magnetic fields around permanent magnets and current-carrying wires
- Calculate the magnitude and direction of magnetic force in a magnetic field and the force on a current-carrying wire in a magnetic field

Section Key Terms

Curie temperature	domain	electromagnet	electromagnetism	ferromagnetic
magnetic dipole	magnetic field	magnetic pole	magnetized	north pole
permanent magnet	right-hand rule	solenoid	south pole	

Magnets and Magnetization

People have been aware of magnets and magnetism for thousands of years. The earliest records date back to ancient times, particularly in the region of Asia Minor called Magnesia—the name of this region is the source of words like *magnet*. Magnetic rocks found in Magnesia, which is now part of western Turkey, stimulated interest during ancient times. When humans first discovered magnetic rocks, they likely found that certain parts of these rocks attracted bits of iron or other magnetic rocks more strongly than other parts. These areas are called the *poles* of a magnet. A **magnetic pole** is the part of a magnet that exerts the strongest force on other magnets or magnetic material, such as iron. For example, the poles of the bar magnet shown in Figure 20.2 are where the paper clips are concentrated.

Figure 20.2 A bar magnet with paper clips attracted to the two poles.

If a bar magnet is suspended so that it rotates freely, one pole of the magnet will always turn toward the north, with the opposite pole facing south. This discovery led to the compass, which is simply a small, elongated magnet mounted so that it can rotate freely. An example of a compass is shown Figure 20.3. The pole of the magnet that orients northward is called the **north pole**, and the opposite pole of the magnet is called the **south pole**.

Figure 20.3 A compass is an elongated magnet mounted in a device that allows the magnet to rotate freely.

The discovery that one particular pole of a magnet orients northward, whereas the other pole orients southward allowed people to identify the north and south poles of any magnet. It was then noticed that the north poles of two different magnets repel each other, and likewise for the south poles. Conversely, the north pole of one magnet attracts the south pole of other magnets. This situation is analogous to that of electric charge, where like charges repel and unlike charges attract. In magnets, we simply replace charge with *pole*: Like poles repel and unlike poles attract. This is summarized in Figure 20.4, which shows how the force between magnets depends on their relative orientation.

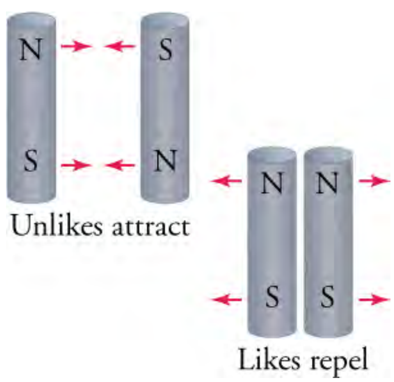


Figure 20.4 Depending on their relative orientation, magnet poles will either attract each other or repel each other.

Consider again the fact that the pole of a magnet that orients northward is called the north pole of the magnet. If unlike poles attract, then the magnetic pole of Earth that is close to the geographic North Pole must be a magnetic south pole! Likewise, the magnetic pole of Earth that is close to the geographic South Pole must be a magnetic north pole. This situation is depicted in Figure 20.5, in which Earth is represented as containing a giant internal bar magnet with its magnetic south pole at the geographic North Pole and vice versa. If we were to somehow suspend a giant bar magnet in space near Earth, then the north pole of the space magnet would be attracted to the south pole of Earth's internal magnet. This is in essence what happens with a compass needle: Its magnetic north pole is attracted to the magnet south pole of Earth's internal magnet.

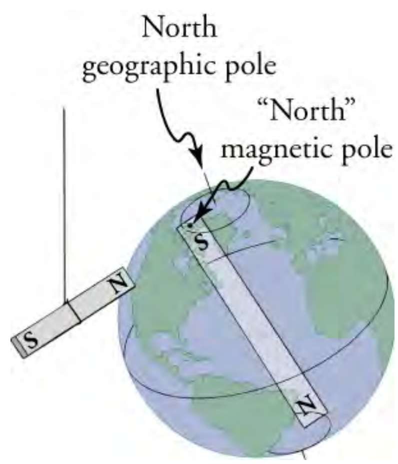


Figure 20.5 Earth can be thought of as containing a giant magnet running through its core. The magnetic south pole of Earth's magnet is at the geographic North Pole, so the north pole of magnets is attracted to the North Pole, which is how the north pole of magnets got their name. Likewise, the south pole of magnets is attracted to the geographic South Pole of Earth.

What happens if you cut a bar magnet in half? Do you obtain one magnet with two south poles and one magnet with two north poles? The answer is no: Each half of the bar magnet has a north pole and a south pole. You can even continue cutting each piece of the bar magnet in half, and you will always obtain a new, smaller magnet with two opposite poles. As shown in Figure 20.6, you can continue this process down to the atomic scale, and you will find that even the smallest particles that behave as magnets have two opposite poles. In fact, no experiment has ever found any object with a single magnetic pole, from the smallest subatomic particle such as electrons to the largest objects in the universe such as stars. Because magnets always have two poles, they are referred to as **magnetic dipoles**—*di* means *two*. Below, we will see that magnetic dipoles have properties that are analogous to electric dipoles.

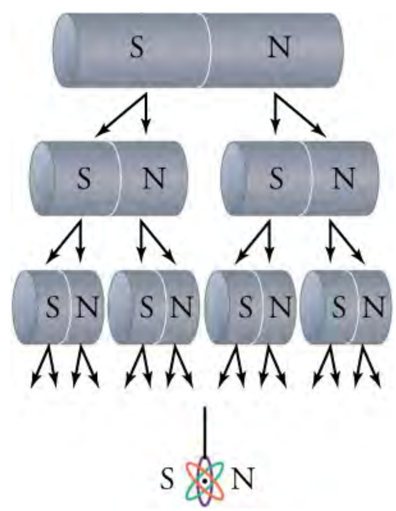


Figure 20.6 All magnets have two opposite poles, from the smallest, such as subatomic particles, to the largest, such as stars.

WATCH PHYSICS

Introduction to Magnetism

This video provides an interesting introduction to magnetism and discusses, in particular, how electrons around their atoms contribute to the magnetic effects that we observe.

Click to view content (https://www.openstax.org/l/28_intro_magn)

GRASP CHECK

Toward which magnetic pole of Earth is the north pole of a compass needle attracted?

a. The north pole of a compass needle is attracted to the north magnetic pole of Earth, which is located near the geographic North Pole of Earth.
b. The north pole of a compass needle is attracted to the south magnetic pole of Earth, which is located near the geographic North Pole of Earth.
c. The north pole of a compass needle is attracted to the north magnetic pole of Earth, which is located near the geographic South Pole of Earth.
d. The north pole of a compass needle is attracted to the south magnetic pole of Earth, which is located near the geographic South Pole of Earth.

Only certain materials, such as iron, cobalt, nickel, and gadolinium, exhibit strong magnetic effects. Such materials are called **ferromagnetic**, after the Latin word *ferrum* for iron. Other materials exhibit weak magnetic effects, which are detectable only with sensitive instruments. Not only do ferromagnetic materials respond strongly to magnets—the way iron is attracted to magnets—but they can also be **magnetized** themselves—that is, they can be induced to be magnetic or made into permanent magnets (Figure 20.7). A **permanent magnet** is simply a material that retains its magnetic behavior for a long time, even when exposed to demagnetizing influences.

Figure 20.7 An unmagnetized piece of iron is placed between two magnets, heated, and then cooled, or simply tapped when cold. The iron becomes a permanent magnet with the poles aligned as shown: Its south pole is adjacent to the north pole of the original magnet, and its north pole is adjacent to the south pole of the original magnet. Note that attractive forces are created between the central magnet and the outer magnets.

When a magnet is brought near a previously unmagnetized ferromagnetic material, it causes local magnetization of the material with unlike poles closest, as in the right side of Figure 20.7. This causes an attractive force, which is why unmagnetized iron is attracted to a magnet.

What happens on a microscopic scale is illustrated in Figure 7(a). Regions within the material called **domains** act like small bar magnets. Within domains, the magnetic poles of individual atoms are aligned. Each atom acts like a tiny bar magnet. Domains are small and randomly oriented in an unmagnetized ferromagnetic object. In response to an external magnetic field, the domains may grow to millimeter size, aligning themselves, as shown in Figure 7(b). This induced magnetization can be made permanent if the material is heated and then cooled, or simply tapped in the presence of other magnets.

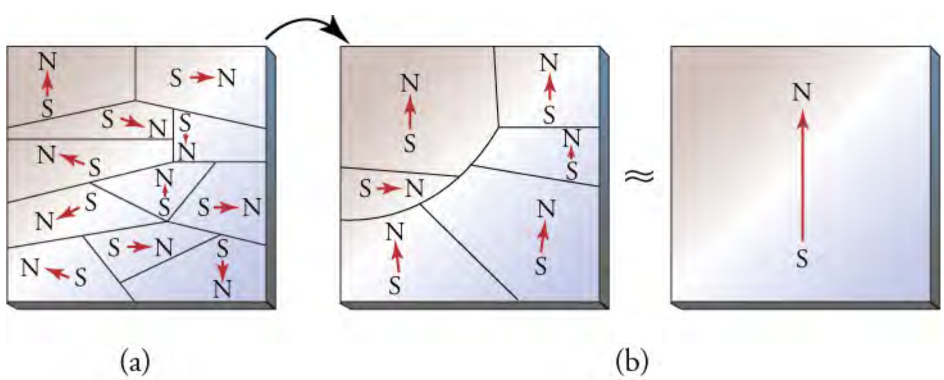


Figure 20.8 (a) An unmagnetized piece of iron—or other ferromagnetic material—has randomly oriented domains. (b) When magnetized by an external magnet, the domains show greater alignment, and some grow at the expense of others. Individual atoms are aligned within

domains; each atom acts like a tiny bar magnet.

Conversely, a permanent magnet can be demagnetized by hard blows or by heating it in the absence of another magnet. Increased thermal motion at higher temperature can disrupt and randomize the orientation and size of the domains. There is a well-defined temperature for ferromagnetic materials, which is called the **Curie temperature**, above which they cannot be magnetized. The Curie temperature for iron is 1,043 K (770 $^\circ\text{C}$), which is well above room temperature. There are several elements and alloys that have Curie temperatures much lower than room temperature and are ferromagnetic only below those temperatures.

Snap Lab

Refrigerator Magnets

We know that like magnetic poles repel and unlike poles attract. See if you can show this for two refrigerator magnets. Will the magnets stick if you turn them over? Why do they stick to the refrigerator door anyway? What can you say about the magnetic properties of the refrigerator door near the magnet? Do refrigerator magnets stick to metal or plastic spoons? Do they stick to all types of metal?

GRASP CHECK

You have one magnet with the north and south poles labeled. How can you use this magnet to identify the north and south poles of other magnets?

a. If the north pole of a known magnet is repelled by a pole of an unknown magnet on bringing them closer, that pole of unknown magnet is its north pole; otherwise, it is its south pole.
b. If the north pole of known magnet is attracted to a pole of an unknown magnet on bringing them closer, that pole of unknown magnet is its north pole; otherwise, it is its south pole.

Magnetic Fields

We have thus seen that forces can be applied between magnets and between magnets and ferromagnetic materials without any contact between the objects. This is reminiscent of electric forces, which also act over distances. Electric forces are described using the concept of the electric field, which is a force field around electric charges that describes the force on any other charge placed in the field. Likewise, a magnet creates a **magnetic field** around it that describes the force exerted on other magnets placed in the field. As with electric fields, the pictorial representation of magnetic field lines is very useful for visualizing the strength and direction of the magnetic field.

As shown in Figure 20.9, the direction of magnetic field lines is defined to be the direction in which the north pole of a compass needle points. If you place a compass near the north pole of a magnet, the north pole of the compass needle will be repelled and point away from the magnet. Thus, the magnetic field lines point away from the north pole of a magnet and toward its south pole.

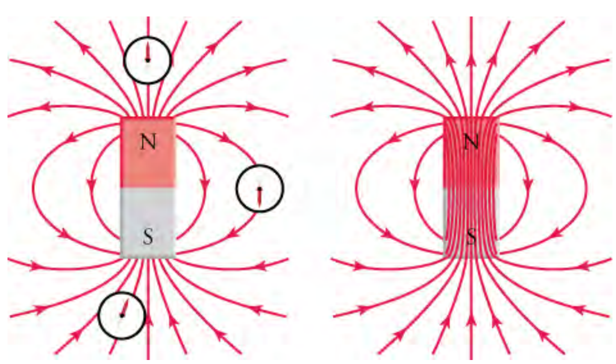


Figure 20.9 The black lines represent the magnetic field lines of a bar magnet. The field lines point in the direction that the north pole of a small compass would point, as shown at left. Magnetic field lines never stop, so the field lines actually penetrate the magnet to form complete loops, as shown at right.

Magnetic field lines can be mapped out using a small compass. The compass is moved from point to point around a magnet, and at each point, a short line is drawn in the direction of the needle, as shown in Figure 20.10. Joining the lines together then reveals the path of the magnetic field line. Another way to visualize magnetic field lines is to sprinkle iron filings around a magnet. The filings will orient themselves along the magnetic field lines, forming a pattern such as that shown on the right in Figure 20.10.

Virtual Physics

Using a Compass to Map Out the Magnetic Field

Click to view content (http://www.openstax.org/l/28magcomp)

This simulation presents you with a bar magnet and a small compass. Begin by dragging the compass around the bar magnet to see in which direction the magnetic field points. Note that the strength of the magnetic field is represented by the brightness of the magnetic field icons in the grid pattern around the magnet. Use the magnetic field meter to check the field strength at several points around the bar magnet. You can also flip the polarity of the magnet, or place Earth on the image to see how the compass orients itself.

GRASP CHECK

With the slider at the top right of the simulation window, set the magnetic field strength to 100 percent . Now use the magnetic field meter to answer the following question: Near the magnet, where is the magnetic field strongest and where is it weakest? Don't forget to check inside the bar magnet.

a. The magnetic field is strongest at the center and weakest between the two poles just outside the bar magnet. The magnetic field lines are densest at the center and least dense between the two poles just outside the bar magnet.
b. The magnetic field is strongest at the center and weakest between the two poles just outside the bar magnet. The magnetic field lines are least dense at the center and densest between the two poles just outside the bar magnet.
c. The magnetic field is weakest at the center and strongest between the two poles just outside the bar magnet. The magnetic field lines are densest at the center and least dense between the two poles just outside the bar magnet.
d. The magnetic field is weakest at the center and strongest between the two poles just outside the bar magnet and the magnetic field lines are least dense at the center and densest between the two poles just outside the bar magnet.

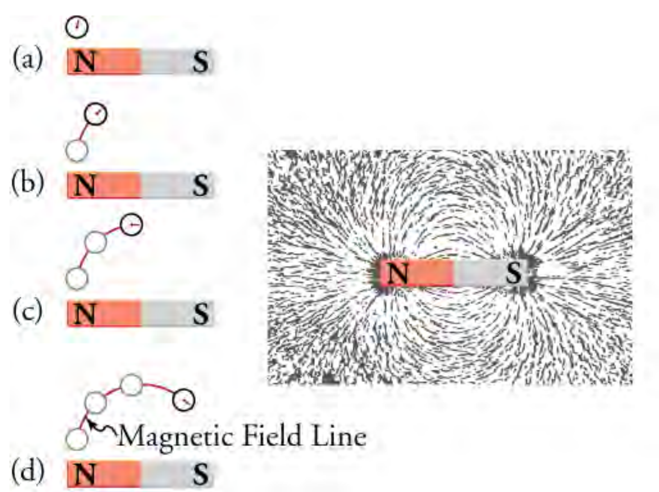


Figure 20.10 Magnetic field lines can be drawn by moving a small compass from point to point around a magnet. At each point, draw a short line in the direction of the compass needle. Joining the points together reveals the path of the magnetic field lines. Another way to visualize magnetic field lines is to sprinkle iron filings around a magnet, as shown at right.

When two magnets are brought close together, the magnetic field lines are perturbed, just as happens for electric field lines when two electric charges are brought together. Bringing two north poles together—or two south poles—will cause a repulsion, and the magnetic field lines will bend away from each other. This is shown in Figure 20.11, which shows the magnetic field lines created by the two closely separated north poles of a bar magnet. When opposite poles of two magnets are brought together, the magnetic field lines join together and become denser between the poles. This situation is shown in Figure 20.11.

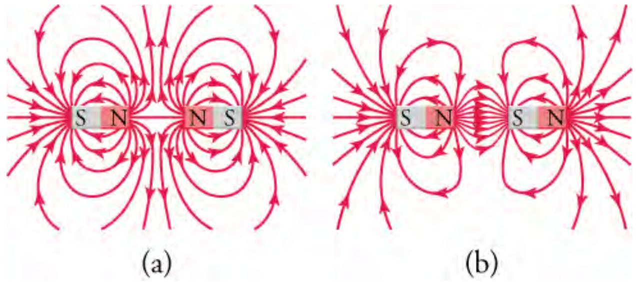


Figure 20.11 (a) When two north poles are approached together, the magnetic field lines repel each other and the two magnets experience a repulsive force. The same occurs if two south poles are approached together. (b) If opposite poles are approached together, the magnetic field lines become denser between the poles and the magnets experience an attractive force.

Like the electric field, the magnetic field is stronger where the lines are denser. Thus, between the two north poles in Figure 20.11, the magnetic field is very weak because the density of the magnetic field is almost zero. A compass placed at that point would essentially spin freely if we ignore Earth's magnetic field. Conversely, the magnetic field lines between the north and south poles in Figure 20.11 are very dense, indicating that the magnetic field is very strong in this region. A compass placed here would quickly align with the magnetic field and point toward the south pole on the right.

Note that magnets are not the only things that make magnetic fields. Early in the nineteenth century, people discovered that electrical currents cause magnetic effects. The first significant observation was by the Danish scientist Hans Christian Oersted (1777–1851), who found that a compass needle was deflected by a current-carrying wire. This was the first significant evidence that the movement of electric charges had any connection with magnets. An **electromagnet** is a device that uses electric current to make a magnetic field. These temporarily induced magnets are called electromagnets. Electromagnets are employed for everything from a wrecking yard crane that lifts scrapped cars to controlling the beam of a 90-km-circumference particle accelerator to the magnets in medical-imaging machines (see Figure 20.12).

Figure 20.12 Instrument for magnetic resonance imaging (MRI). The device uses a cylindrical-coil electromagnet to produce for the main magnetic field. The patient goes into the *tunnel* on the gurney. (credit: Bill McChesney, Flickr)

The magnetic field created by an electric current in a long straight wire is shown in Figure 20.13. The magnetic field lines form concentric circles around the wire. The direction of the magnetic field can be determined using the *right-hand rule*. This rule shows up in several places in the study of electricity and magnetism. Applied to a straight current-carrying wire, the **right-hand rule** says that, with your right thumb pointed in the direction of the current, the magnetic field will be in the direction in which your right fingers curl, as shown in Figure 20.13. If the wire is very long compared to the distance r from the wire, the strength B of the magnetic field is given by

$$B_{\text{straightwire}} = \frac{\mu_0 I}{2\pi r} \tag{20.1}$$

where I is the current in the wire in amperes. The SI unit for magnetic field is the tesla (T). The symbol μ_0 —read "mu-zero"—is a constant called the "permeability of free space" and is given by

$$\mu_0 = 4\pi \times 10^{-7}\,\text{T} \cdot \text{m/A}. \tag{20.2}$$

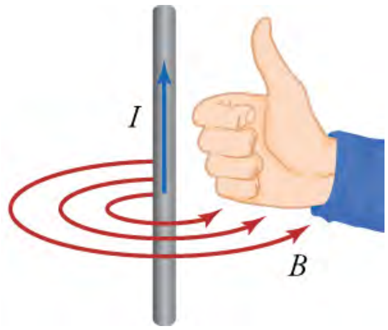


Figure 20.13 This image shows how to use the right-hand rule to determine the direction of the magnetic field created by current flowing through a straight wire. Point your right thumb in the direction of the current, and the magnetic field will be in the direction in which your fingers curl.

WATCH PHYSICS

Magnetic Field Due to an Electric Current

This video describes the magnetic field created by a straight current-carrying wire. It goes over the right-hand rule to determine the direction of the magnetic field, and presents and discusses the formula for the strength of the magnetic field due to a straight current-carrying wire.

Click to view content (https://www.openstax.org/l/28magfield)

GRASP CHECK

A long straight wire is placed on a table top and electric current flows through the wire from right to left. If you look at the wire end-on from the left end, does the magnetic field go clockwise or counterclockwise?

a. By pointing your right-hand thumb in the direction opposite of current, the right-hand fingers will curl counterclockwise, so the magnetic field will be in the counterclockwise direction.
b. By pointing your right-hand thumb in the direction opposite of current, the right-hand fingers will curl clockwise, so the magnetic field will be in the clockwise direction.
c. By pointing your right-hand thumb in the direction of current, the right-hand fingers will curl counterclockwise, so the magnetic field will be in the counterclockwise direction.
d. By pointing your right-hand thumb in the direction of current, the right-hand fingers will curl clockwise, so the magnetic field will be in the clockwise direction.

Now imagine winding a wire around a cylinder with the cylinder then removed. The result is a wire coil, as shown in Figure 20.14. This is called a **solenoid**. To find the direction of the magnetic field produced by a solenoid, apply the right-hand rule to several points on the coil. You should be able to convince yourself that, inside the coil, the magnetic field points from left to right. In fact, another application of the right-hand rule is to curl your right-hand fingers around the coil in the direction in which the current flows. Your right thumb then points in the direction of the magnetic field inside the coil: left to right in this case.

Figure 20.14 A wire coil with current running through as shown produces a magnetic field in the direction of the red arrow.

Each loop of wire contributes to the magnetic field inside the solenoid. Because the magnetic field lines must form closed loops, the field lines close the loop outside the solenoid. The magnetic field lines are much denser inside the solenoid than outside the solenoid. The resulting magnetic field looks very much like that of a bar magnet, as shown in Figure 20.15. The magnetic field strength deep inside a solenoid is

$$B_{\text{solenoid}} = \mu_0 \frac{NI}{\ell}, \tag{20.3}$$

where N is the number of wire loops in the solenoid and ℓ is the length of the solenoid.

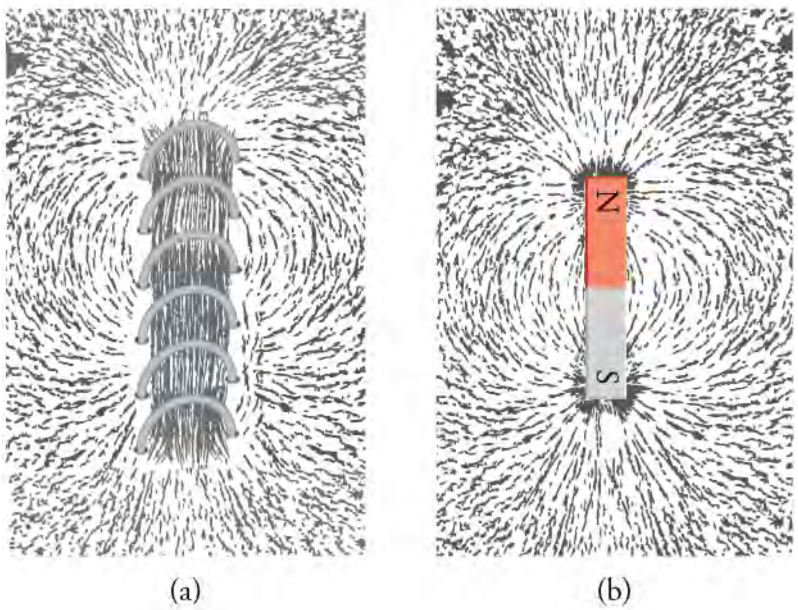


Figure 20.15 Iron filings show the magnetic field pattern around (a) a solenoid and (b) a bar magnet. The fields patterns are very similar, especially near the ends of the solenoid and bar magnet.

Virtual Physics

Electromagnets

[Click to view content (http://www.openstax.org/l/28elec_magnet)](http://www.openstax.org/l/28elec_magnet)

Use this simulation to visualize the magnetic field made from a solenoid. Be sure to click on the tab that says Electromagnet. You can drive AC or DC current through the solenoid by choosing the appropriate current source. Use the field meter to measure the strength of the magnetic field and then change the number of loops in the solenoid to see how this affects the magnetic field strength.

GRASP CHECK

Choose the battery as current source and set the number of wire loops to four. With a nonzero current going through the solenoid, measure the magnetic field strength at a point. Now decrease the number of wire loops to two. How does the magnetic field strength change at the point you chose?

a. There will be no change in magnetic field strength when number of loops reduces from four to two.
b. The magnetic field strength decreases to half of its initial value when number of loops reduces from four to two.
c. The magnetic field strength increases to twice of its initial value when number of loops reduces from four to two.
d. The magnetic field strength increases to four times of its initial value when number of loops reduces from four to two.

Magnetic Force

If a moving electric charge, that is electric current, produces a magnetic field that can exert a force on another magnet, then the reverse should be true by Newton's third law. In other words, a charge moving through the magnetic field produced by another object should experience a force—and this is exactly what we find. As a concrete example, consider Figure 20.16, which shows a charge q moving with velocity $\vec{v}$ through a magnetic field $\vec{B}$ between the poles of a permanent magnet. The magnitude F of the force experienced by this charge is

$$F = qvB\sin\theta, \tag{20.4}$$

where θ is the angle between the velocity of the charge and the magnetic field.

The direction of the force may be found by using another version of the right-hand rule: First, we join the tails of the velocity vector and a magnetic field vector, as shown in step 1 of Figure 20.16. We then curl our right fingers from $\vec{v}$ to $\vec{B}$, as indicated in step (2) of Figure 20.16. The direction in which the right thumb points is the direction of the force. For the charge in Figure 20.16, we find that the force is directed into the page.

Note that the factor $\sin\theta$ in the equation $F = qvB\sin\theta$ means that zero force is applied on a charge that moves parallel to a magnetic field because $\theta = 0$ and $\sin 0 = 0$. The maximum force a charge can experience is when it moves perpendicular to the magnetic field, because $\theta = 90°$ and $\sin 90° = 1$.

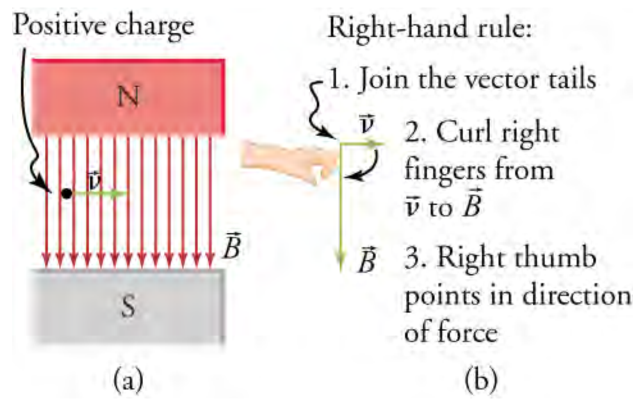


Figure 20.16 (a) An electron moves through a uniform magnetic field. (b) Using the right-hand rule, the force on the electron is found to be directed into the page.

LINKS TO PHYSICS

Magnetohydrodynamic Drive

In Tom Clancy's Cold War novel "The Hunt for Red October," the Soviet Union built a submarine (see Figure 20.17) with a magnetohydrodynamic drive that was so silent it could not be detected by surface ships. The only conceivable purpose to build such a submarine was to give the Soviet Union first-strike capability, because this submarine could sneak close to the coast of the United States and fire its ballistic missiles, destroying key military and government installations to prevent an American counterattack.

Figure 20.17 A Typhoon-class Russian ballistic-missile submarine on which the fictional submarine Red October was based.

A magnetohydrodynamic drive is supposed to be silent because it has no moving parts. Instead, it uses the force experienced by charged particles that move in a magnetic field. The basic idea behind such a drive is depicted in Figure 20.18. Salt water flows through a channel that runs from the front to the back of the submarine. A magnetic field is applied horizontally across the channel, and a voltage is applied across the electrodes on the top and bottom of the channel to force a downward electric current through the water. The charge carriers are the positive sodium ions and the negative chlorine ions of salt. Using the right-hand rule, the force on the charge carriers is found to be toward the rear of the vessel. The accelerated charges collide with water molecules and transfer their momentum, creating a jet of water that is propelled out the rear of the channel. By Newton's third law, the vessel experiences a force of equal magnitude, but in the opposite direction.

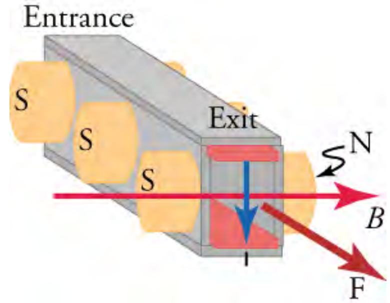


Figure 20.18 A schematic drawing of a magnetohydrodynamic drive showing the water channel, the current direction, the magnetic field direction, and the resulting force.

Fortunately for all involved, it turns out that such a propulsion system is not very practical. Some back-of-the-envelope calculations show that, to power a submarine, either extraordinarily high magnetic fields or extraordinarily high electric currents would be required to obtain a reasonable thrust. In addition, prototypes of magnetohydrodynamic drives show that they are anything but silent. Electrolysis caused by running a current through salt water creates bubbles of hydrogen and oxygen, which makes this propulsion system quite noisy. The system also leaves a trail of chloride ions and metal chlorides that can easily be detected to locate the submarine. Finally, the chloride ions are extremely reactive and very quickly corrode metal parts, such as the electrode or the water channel itself. Thus, the Red October remains in the realm of fiction, but the physics involved is quite real.

GRASP CHECK

If the magnetic field is downward, in what direction must the current flow to obtain rearward-pointing force?

a. The current must flow vertically from up to down when viewed from the rear of the boat.
b. The current must flow vertically from down to up when viewed from the rear of the boat.
c. The current must flow horizontally from left to right when viewed from the rear of the boat.
d. The current must flow horizontally from right to left when viewed from the rear of the boat.

Instead of a single charge moving through a magnetic field, consider now a steady current I moving through a straight wire. If we place this wire in a uniform magnetic field, as shown in Figure 20.19, what is the force on the wire or, more precisely, on the electrons in the wire? An electric current involves charges that move. If the charges q move a distance ℓ in a time t, then their speed is $v = \ell/t$. Inserting this into the equation $F = qvB\sin\theta$ gives

$$\begin{aligned} F &= q\left(\frac{\ell}{t}\right)B\sin\theta \\ &= \left(\frac{q}{t}\right)\ell B\sin\theta. \end{aligned} \tag{20.5}$$

The factor q/t in this equation is nothing more than the current in the wire. Thus, using $I = q/t$, we obtain

$$F = I\ell B\sin\theta(1.4). \tag{20.6}$$

This equation gives the force on a straight current-carrying wire of length ℓ in a magnetic field of strength B. The angle θ is the angle between the current vector and the magnetic field vector. Note that ℓ is the length of wire that is in the magnetic field and for which $\theta \neq 0$, as shown in Figure 20.19.

The direction of the force is determined in the same way as for a single charge. Curl your right fingers from the vector for I to the vector for B, and your right thumb will point in the direction of the force on the wire. For the wire shown in Figure 20.19, the force is directed into the page.

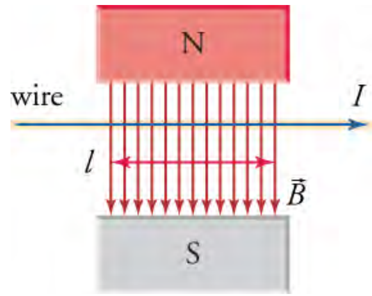


Figure 20.19 A straight wire carrying current I in a magnetic field B. The force exerted on the wire is directed into the page. The length ℓ is the length of the wire that is *in* the magnetic field.

Throughout this section, you may have noticed the symmetries between magnetic effects and electric effects. These effects all fall under the umbrella of **electromagnetism**, which is the study of electric and magnetic phenomena. We have seen that electric charges produce electric fields, and moving electric charges produce magnetic fields. A magnetic dipole produces a magnetic field, and, as we will see in the next section, moving magnetic dipoles produce an electric field. Thus, electricity and magnetism are two intimately related and symmetric phenomena.

WORKED EXAMPLE

Trajectory of Electron in Magnetic Field

A proton enters a region of constant magnetic field, as shown in Figure 20.20. The magnetic field is coming out of the page. If the electron is moving at $3.0 \times 10^6 \,\text{m/s}$ and the magnetic field strength is 2.0 T, what is the magnitude and direction of the force on the proton?

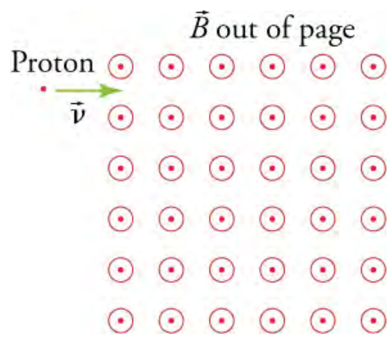


Figure 20.20 A proton enters a region of uniform magnetic field. The magnetic field is coming out of the page—the circles with dots represent vector arrow heads coming out of the page.

STRATEGY

Use the equation $F = qvB \sin\theta$ to find the magnitude of the force on the proton. The angle between the magnetic field vectors and the velocity vector of the proton is $90°$. The direction of the force may be found by using the right-hand rule.

Solution

The charge of the proton is $q = 1.60 \times 10^{-19}\,\text{C}$. Entering this value and the given velocity and magnetic field strength into the equation $F = qvB \sin\theta$ gives

$$\begin{aligned} F &= qvB \sin\theta \\ &= \left(1.60 \times 10^{-19}\text{C}\right)\left(3.0 \times 10^6\text{m/s}\right)(2.0\text{ T})\sin(90°) \\ &= 9.6 \times 10^{-13}\text{N}. \end{aligned} \quad (20.7)$$

To find the direction of the force, first join the velocity vector end to end with the magnetic field vector, as shown in Figure 20.21. Now place your right hand so that your fingers point in the direction of the velocity and curl them upward toward the magnetic field vector. The force is in the direction in which your thumb points. In this case, the force is downward in the plane of the paper in the $\hat{z}$ -direction, as shown in Figure 20.21.

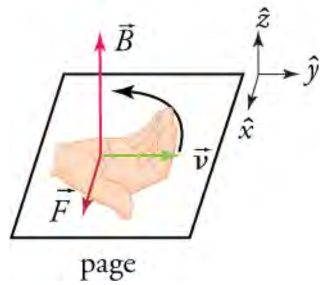


Figure 20.21 The velocity vector and a magnetic field vector from Figure 20.20 are placed end to end. A right hand is shown with the fingers curling up from the velocity vector toward the magnetic field vector. The thumb points in the direction of the resulting force, which is the $\hat{z}$ -direction in this case.

Thus, combining the magnitude and the direction, we find that the force on the proton is $\left(9.6 \times 10^{-13}\text{N}\right)\hat{z}$.

Discussion

This seems like a very small force. However, the proton has a mass of $1.67 \times 10^{-27}\text{kg}$, so its acceleration is $a = \frac{F}{m} = \frac{9.6 \times 10^{-13}\text{N}}{1.67 \times 10^{-27}\text{kg}} = 5.7 \times 10^{14}\ \text{m/s}^2$, or about ten thousand billion times the acceleration due to gravity!

We found that the proton's initial acceleration as it enters the magnetic field is downward in the plane of the page. Notice that, as the proton accelerates, its velocity remains perpendicular to the magnetic field, so the magnitude of the force does not change. In addition, because of the right-hand rule, the direction of the force remains perpendicular to the velocity. This force is nothing more than a centripetal force: It has a constant magnitude and is always perpendicular to the velocity. Thus, the magnitude of the velocity does not change, and the proton executes circular motion. The radius of this circle may be found by using the kinematics relationship.

$$\begin{aligned} F &= ma = m\frac{v^2}{r} \\ a &= \frac{v^2}{r} \\ r &= \frac{v^2}{a} = \frac{\left(3.0 \times 10^6\text{m/s}\right)^2}{5.7 \times 10^{14}\ \text{m/s}^2} = 1.6\ \text{cm} \end{aligned} \tag{20.8}$$

The path of the proton in the magnetic field is shown in Figure 20.22.

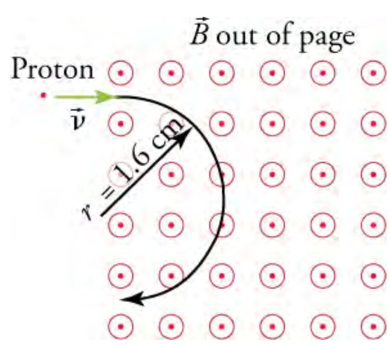
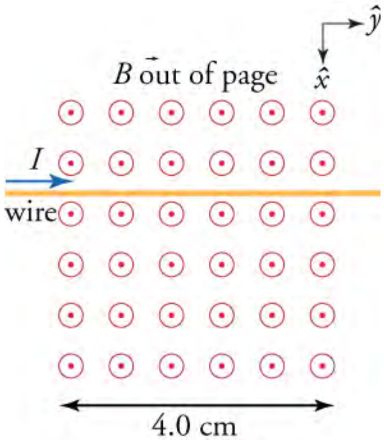


Figure 20.22 When traveling perpendicular to a constant magnetic field, a charged particle will execute circular motion, as shown here for a proton.

WORKED EXAMPLE

Wire with Current in Magnetic Field

Now suppose we run a wire through the uniform magnetic field from the previous example, as shown. If the wire carries a current of 1.0 A in the $\hat{y}$ -direction, and the region with magnetic field is 4.0 cm long, what is the force on the wire?



STRATEGY

Use equation $F = I\ell B \sin\theta$ to find the magnitude of the force on the wire. The length of the wire inside the magnetic field is 4.0 cm, and the angle between the current direction and the magnetic field direction is 90°. To find the direction of the force, use the right-hand rule as explained just after the equation $F = I\ell B \sin\theta$.

Solution

Insert the given values into equation $F = I\ell B \sin\theta$ to find the magnitude of the force

$$F = I\ell B \sin\theta = (1.5\ \text{A})\,(0.040\ \text{m})\,(2.0\ \text{T}) = 0.12\ \text{N}. \tag{20.9}$$

To find the direction of the force, begin by placing the current vector end to end with a vector for the magnetic field. The result is as shown in the figure in the previous Worked Example with $\vec{v}$ replaced by $\vec{I}$. Curl your right-hand fingers from $\vec{I}$ to $\vec{B}$ and your right thumb points down the page, again as shown in the figure in the previous Worked Example. Thus, the direction of the force is in the $\hat{x}$ -direction. The complete force is thus $(0.12\ \text{N})\,\hat{x}$.

Discussion

The direction of the force is the same as the initial direction of the force was in the previous example for a proton. However, because the current in a wire is confined to a wire, the direction in which the charges move does not change. Instead, the entire wire accelerates in the $\hat{x}$ -direction. The force on a current-carrying wire in a magnetic field is the basis of all electrical motors, as we will see in the upcoming sections.

Practice Problems

1. What is the magnitude of the force on an electron moving at 1.0 × 106 m/s perpendicular to a 1.0-T magnetic field?
   a. 0.8×10^{-13} N
   b. 1.6×10^{-14} N
   c. 0.8×10^{-14} N
   d. 1.6×10^{-13} N

2. A straight 10 cm wire carries 0.40 A and is oriented perpendicular to a magnetic field. If the force on the wire is 0.022 N, what is the magnitude of the magnetic field?
   a. 1.10×10^{-2} T
   b. 0.55×10^{-2} T
   c. 1.10 T
   d. 0.55 T

Check Your Understanding

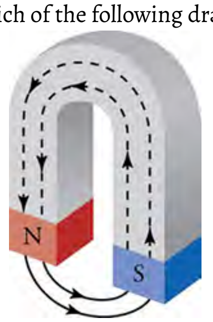
3. If two magnets repel each other, what can you conclude about their relative orientation?
   a. Either the south pole of magnet 1 is closer to the north pole of magnet 2 or the north pole of magnet 1 is closer to the south pole of magnet 2.
   b. Either the south poles of both the magnet 1 and magnet 2 are closer to each other or the north poles of both the magnet 1

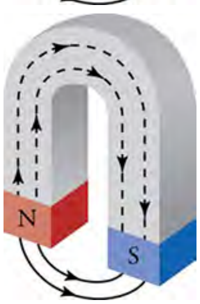
and magnet 2 are closer to each other.

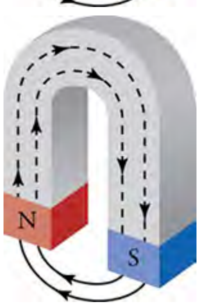
4. Describe methods to demagnetize a ferromagnet.
   a. by cooling, heating, or submerging in water
   b. by heating, hammering, and spinning it in external magnetic field
   c. by hammering, heating, and rubbing with cloth
   d. by cooling, submerging in water, or rubbing with cloth

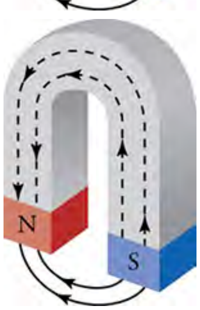
5. What is a magnetic field?
   a. The directional lines present inside and outside the magnetic material that indicate the magnitude and direction of the magnetic force.
   b. The directional lines present inside and outside the magnetic material that indicate the magnitude of the magnetic force.
   c. The directional lines present inside the magnetic material that indicate the magnitude and the direction of the magnetic force.
   d. The directional lines present outside the magnetic material that indicate the magnitude and the direction of the magnetic force.

6. Which of the following drawings is correct?

a. 

b. 

c. 

d. 

20.2 Motors, Generators, and Transformers

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain how electric motors, generators, and transformers work
- Explain how commercial electric power is produced, transmitted, and distributed

Section Key Terms

electric motor	generator	transformer

Electric Motors, Generators, and Transformers

As we learned previously, a current-carrying wire in a magnetic field experiences a force—recall $F = I\ell B \sin\theta$. **Electric motors**, which convert electrical energy into mechanical energy, are the most common application of magnetic force on current-carrying wires. Motors consist of loops of wire in a magnetic field. When current is passed through the loops, the magnetic field exerts a torque on the loops, which rotates a shaft. Electrical energy is converted to mechanical work in the process. Figure 20.23 shows a schematic drawing of an electric motor.

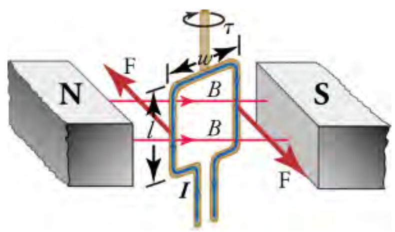


Figure 20.23 Torque on a current loop. A vertical loop of wire in a horizontal magnetic field is attached to a vertical shaft. When current is passed through the wire loop, torque is exerted on it, making it turn the shaft.

Let us examine the force on each segment of the loop in Figure 20.23 to find the torques produced about the axis of the vertical shaft—this will lead to a useful equation for the torque on the loop. We take the magnetic field to be uniform over the rectangular loop, which has width w and height ℓ, as shown in the figure. First, consider the force on the top segment of the loop. To determine the direction of the force, we use the right-hand rule. The current goes from left to right into the page, and the magnetic field goes from left to right in the plane of the page. Curl your right fingers from the current vector to the magnetic field vector and your right thumb points down. Thus, the force on the top segment is downward, which produces no torque on the shaft. Repeating this analysis for the bottom segment—neglect the small gap where the lead wires go out—shows that the force on the bottom segment is upward, again producing no torque on the shaft.

Consider now the left vertical segment of the loop. Again using the right-hand rule, we find that the force exerted on this segment is perpendicular to the magnetic field, as shown in Figure 20.23. This force produces a torque on the shaft. Repeating this analysis on the right vertical segment of the loop shows that the force on this segment is in the direction opposite that of the force on the left segment, thereby producing an equal torque on the shaft. The total torque on the shaft is thus twice the toque on one of the vertical segments of the loop.

To find the magnitude of the torque as the wire loop spins, consider Figure 20.24, which shows a view of the wire loop from above. Recall that torque is defined as $\tau = rF\sin\theta$, where F is the applied force, r is the distance from the pivot to where the force is applied, and θ is the angle between r and F. Notice that, as the loop spins, the current in the vertical loop segments is always perpendicular to the magnetic field. Thus, the equation $F = I\ell B \sin\theta$ gives the magnitude of the force on each vertical segment as $F = I\ell B$. The distance r from the shaft to where this force is applied is $w/2$, so the torque created by this force is

$$\tau_{\text{segment}} = rF\sin\theta = w/2I\ell B\sin\theta = (w/2)\,I\ell B\sin\theta. \tag{20.10}$$

Because there are two vertical segments, the total torque is twice this, or

$$\tau = wI\ell B\sin\theta. \tag{20.11}$$

If we have a multiple loop with N turns, we get N times the torque of a single loop. Using the fact that the area of the loop is $A = w\ell$; the expression for the torque becomes

$$\tau = NIAB \sin \theta. \tag{20.12}$$

This is the torque on a current-carrying loop in a uniform magnetic field. This equation can be shown to be valid for a loop of any shape.

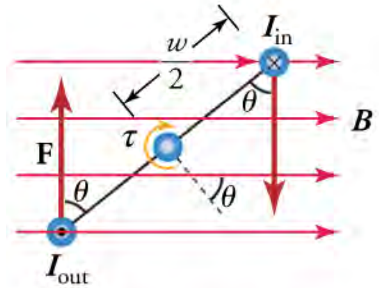


Figure 20.24 View from above of the wire loop from Figure 20.23. The magnetic field generates a force *F* on each vertical segment of the wire loop, which generates a torque on the shaft. Notice that the currents I_{in} and I_{out} have the same magnitude because they both represent the current flowing in the wire loop, but I_{in} flows into the page and I_{out} flows out of the page.

From the equation $\tau = NIAB \sin \theta$, we see that the torque is zero when $\theta = 0$. As the wire loop rotates, the torque increases to a maximum positive torque of $w\ell B$ when $\theta = 90°$. The torque then decreases back to zero as the wire loop rotates to $\theta = 180°$. From $\theta = 180°$ to $\theta = 360°$, the torque is negative. Thus, the torque changes sign every half turn, so the wire loop will oscillate back and forth.

For the coil to continue rotating in the same direction, the current is reversed as the coil passes through $\theta = 0$ and$\theta = 180°$ using automatic switches called *brushes*, as shown in Figure 20.25.

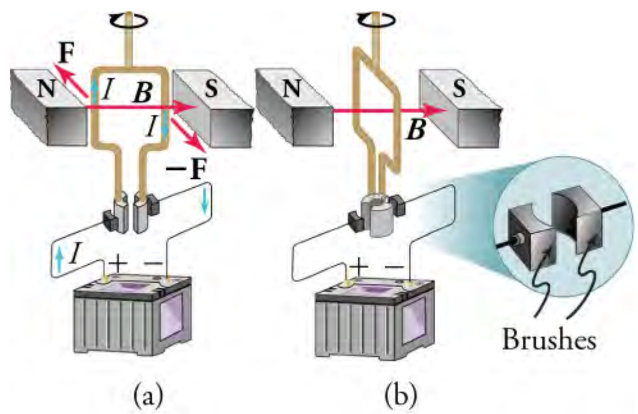


Figure 20.25 (a) As the angular momentum of the coil carries it through $\theta = 0$, the brushes reverse the current and the torque remains clockwise. (b) The coil rotates continuously in the clockwise direction, with the current reversing each half revolution to maintain the clockwise torque.

Consider now what happens if we run the motor in reverse; that is, we attach a handle to the shaft and mechanically force the coil to rotate within the magnetic field, as shown in Figure 20.26. As per the equation $F = qvB \sin \theta$—where θ is the angle between the vectors $\vec{v}$ and $\vec{B}$—charges in the wires of the loop experience a magnetic force because they are moving in a magnetic field. Again using the right-hand rule, where we curl our fingers from vector $\vec{v}$ to vector $\vec{B}$, we find that charges in the top and bottom segments feel a force perpendicular to the wire, which does not cause a current. However, charges in the vertical wires experience forces parallel to the wire, causing a current to flow through the wire and through an external circuit if one is connected. A device such as this that converts mechanical energy into electrical energy is called a **generator**.

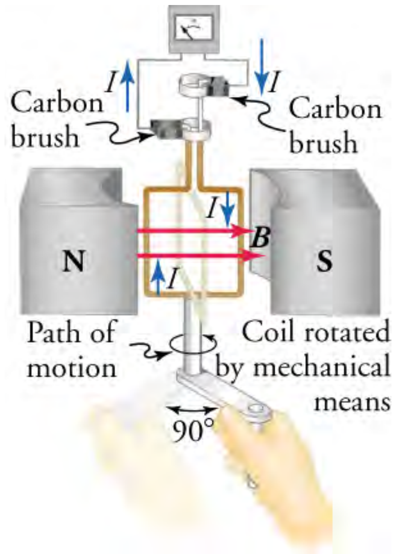


Figure 20.26 When this coil is rotated through one-fourth of a revolution, the magnetic flux Φ changes from its maximum to zero, inducing an emf, which drives a current through an external circuit.

Because current is induced only in the side wires, we can find the induced emf by only considering these wires. As explained in Induced Current in a Wire, motional emf in a straight wire moving at velocity v through a magnetic field B is $E = B\ell v$, where the velocity is perpendicular to the magnetic field. In the generator, the velocity makes an angle θ with B (see Figure 20.27), so the velocity component perpendicular to B is $v \sin\theta$. Thus, in this case, the emf induced on each vertical wire segment is $E = B\ell v \sin\theta$, and they are in the same direction. The total emf around the loop is then

$$E = 2B\ell v \sin\theta. \tag{20.13}$$

Although this expression is valid, it does not give the emf as a function of time. To find how the emf evolves in time, we assume that the coil is rotated at a constant angular velocity ω. The angle θ is related to the angular velocity by $\theta = \omega t$, so that

$$E = 2B\ell v \sin\omega t. \tag{20.14}$$

Recall that tangential velocity v is related to angular velocity ω by $v = r\omega$. Here, $r = w/2$, so that $v = (w/2)\,\omega$ and

$$E = 2B\ell\left(\frac{w}{2}\omega\right)\sin\omega t = B\ell w\omega \sin\omega t. \tag{20.15}$$

Noting that the area of the loop is $A = \ell w$ and allowing for N wire loops, we find that

$$E = NAB\omega \sin\omega t \tag{20.16}$$

is the emf induced in a generator coil of N turns and area A rotating at a constant angular velocity ω in a uniform magnetic field B. This can also be expressed as

$$E = E_0 \sin\omega t \tag{20.17}$$

where

$$E_0 = NAB\omega \tag{20.18}$$

is the maximum (peak) emf.

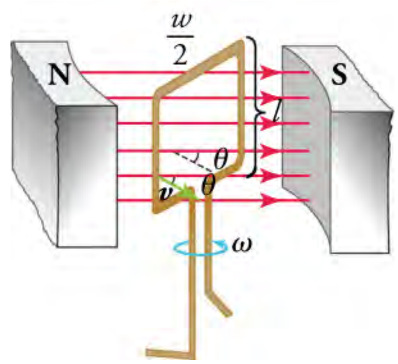


Figure 20.27 The instantaneous velocity of the vertical wire segments makes an angle θ with the magnetic field. The velocity is shown in the figure by the green arrow, and the angle θ is indicated.

Figure 20.28 shows a generator connected to a light bulb and a graph of the emf vs. time. Note that the emf oscillates from a positive maximum of E_0 to a negative maximum of $-E_0$. In between, the emf goes through zero, which means that zero current flows through the light bulb at these times. Thus, the light bulb actually flickers on and off at a frequency of $2f$, because there are two zero crossings per period. Since alternating current such as this is used in homes around the world, why do we not notice the lights flickering on and off? In the United States, the frequency of alternating current is 60 Hz, so the lights flicker on and off at a frequency of 120 Hz. This is faster than the refresh rate of the human eye, so you don't notice the flicker of the lights. Also, other factors prevent various different types of light bulbs from switching on and off so fast, so the light output is *smoothed out* a bit.

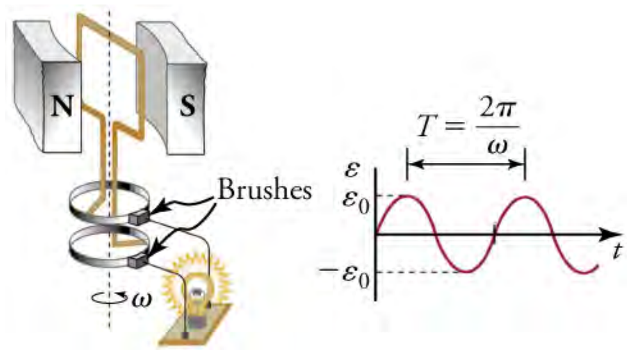


Figure 20.28 The emf of a generator is sent to a light bulb with the system of rings and brushes shown. The graph gives the emf of the generator as a function of time. E_0 is the peak emf. The period is $T = 1/f = 2\pi/\omega$, where f is the frequency at which the coil is rotated in the magnetic field.

Virtual Physics

Generator

Click to view content (http://www.openstax.org/l/28gen)

Use this simulation to discover how an electrical generator works. Control the water supply that makes a water wheel turn a magnet. This induces an emf in a nearby wire coil, which is used to light a light bulb. You can also replace the light bulb with a voltmeter, which allows you to see the polarity of the voltage, which changes from positive to negative.

GRASP CHECK

Set the number of wire loops to three, the bar-magnet strength to about 50 percent, and the loop area to 100 percent. Note the maximum voltage on the voltmeter. Assuming that one major division on the voltmeter is 5V, what is the maximum voltage when using only a single wire loop instead of three wire loops?

a. 5 V
b. 15 V

c. 125 V
d. 53 V

In real life, electric generators look a lot different than the figures in this section, but the principles are the same. The source of mechanical energy that turns the coil can be falling water—hydropower—steam produced by the burning of fossil fuels, or the kinetic energy of wind. Figure 20.29 shows a cutaway view of a steam turbine; steam moves over the blades connected to the shaft, which rotates the coil within the generator.

Figure 20.29 Steam turbine generator. The steam produced by burning coal impacts the turbine blades, turning the shaft which is connected to the generator. (credit: Nabonaco, Wikimedia Commons)

Another very useful and common device that exploits magnetic induction is called a **transformer**. Transformers do what their name implies—they transform voltages from one value to another; the term voltage is used rather than emf because transformers have internal resistance. For example, many cell phones, laptops, video games, power tools, and small appliances have a transformer built into their plug-in unit that changes 120 V or 240 V AC into whatever voltage the device uses. Figure 20.30 shows two different transformers. Notice the wire coils that are visible in each device. The purpose of these coils is explained below.

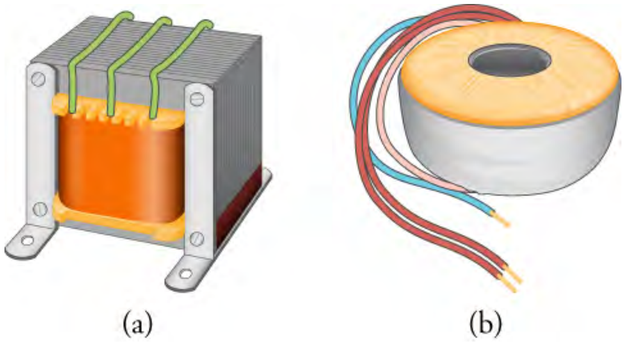


Figure 20.30 On the left is a common laminated-core transformer, which is widely used in electric power transmission and electrical appliances. On the right is a toroidal transformer, which is smaller than the laminated-core transformer for the same power rating but is more expensive to make because of the equipment required to wind the wires in the doughnut shape.

Figure 20.31 shows a laminated-coil transformer, which is based on Faraday's law of induction and is very similar in construction to the apparatus Faraday used to demonstrate that magnetic fields can generate electric currents. The two wire coils are called the primary and secondary coils. In normal use, the input voltage is applied across the primary coil, and the secondary produces the transformed output voltage. Not only does the iron core trap the magnetic field created by the primary coil, but also its magnetization increases the field strength, which is analogous to how a dielectric increases the electric field strength in a capacitor. Since the input voltage is AC, a time-varying magnetic flux is sent through the secondary coil, inducing an AC output voltage.

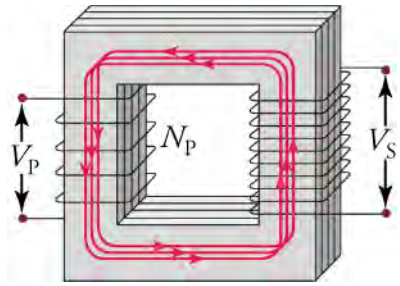


Figure 20.31 A typical construction of a simple transformer has two coils wound on a ferromagnetic core. The magnetic field created by the primary coil is mostly confined to and increased by the core, which transmits it to the secondary coil. Any change in current in the primary coil induces a current in the secondary coil.

LINKS TO PHYSICS

Magnetic Rope Memory

To send men to the moon, the Apollo program had to design an onboard computer system that would be robust, consume little power, and be small enough to fit onboard the spacecraft. In the 1960s, when the Apollo program was launched, entire buildings were regularly dedicated to housing computers whose computing power would be easily outstripped by today's most basic handheld calculator.

To address this problem, engineers at MIT and a major defense contractor turned to *magnetic rope memory*, which was an offshoot of a similar technology used prior to that time for creating random access memories. Unlike random access memory, magnetic rope memory was read-only memory that contained not only data but instructions as well. Thus, it was actually more than memory: It was a hard-wired computer program.

The components of magnetic rope memory were wires and iron rings—which were called *cores*. The iron cores served as transformers, such as that shown in the previous figure. However, instead of looping the wires multiple times around the core, individual wires passed only a single time through the cores, making these single-turn transformers. Up to 63 *word* wires could pass through a single core, along with a single *bit* wire. If a word wire passed through a given core, a voltage pulse on this wire would induce an emf in the bit wire, which would be interpreted as a *one*. If the word wire did not pass through the core, no emf would be induced on the bit wire, which would be interpreted as a *zero*.

Engineers would create programs that would be hard wired into these magnetic rope memories. The wiring process could take as long as a month to complete as workers painstakingly threaded wires through some cores and around others. If any mistakes were made either in the programming or the wiring, debugging would be extraordinarily difficult, if not impossible.

These modules did their job quite well. They are credited with correcting an astronaut mistake in the lunar landing procedure, thereby allowing Apollo 11 to land on the moon. It is doubtful that Michael Faraday ever imagined such an application for magnetic induction when he discovered it.

GRASP CHECK

If the bit wire were looped twice around each core, how would the voltage induced in the bit wire be affected?

a. If number of loops around the wire is doubled, the emf is halved.
b. If number of loops around the wire is doubled, the emf is not affected.
c. If number of loops around the wire is doubled, the emf is also doubled.
d. If number of loops around the wire is doubled, the emf is four times the initial value.

For the transformer shown in Figure 20.31, the output voltage V_S from the secondary coil depends almost entirely on the input voltage V_P across the primary coil and the number of loops in the primary and secondary coils. Faraday's law of induction for the secondary coil gives its induced output voltage V_S to be

$$V_S = -N_S \frac{\Delta\Phi}{\Delta t}, \tag{20.19}$$

where N_S is the number of loops in the secondary coil and $\Delta\Phi/\Delta t$ is the rate of change of magnetic flux. The output voltage equals the induced emf $(V_S = E_S)$, provided coil resistance is small—a reasonable assumption for transformers. The cross-sectional area of the coils is the same on each side, as is the magnetic field strength, and so $\Delta\Phi/\Delta t$ is the same on each side. The input primary voltage V_P is also related to changing flux by

$$V_P = -N_P \frac{\Delta\Phi}{\Delta t}. \tag{20.20}$$

Taking the ratio of these last two equations yields the useful relationship

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}(3.07). \tag{20.21}$$

This is known as the transformer equation. It simply states that the ratio of the secondary voltage to the primary voltage in a transformer equals the ratio of the number of loops in secondary coil to the number of loops in the primary coil.

Transmission of Electrical Power

Transformers are widely used in the electric power industry to increase voltages—called *step-up* transformers—before long-distance transmission via high-voltage wires. They are also used to decrease voltages—called *step-down* transformers—to deliver power to homes and businesses. The overwhelming majority of electric power is generated by using magnetic induction, whereby a wire coil or copper disk is rotated in a magnetic field. The primary energy required to rotate the coils or disk can be provided by a variety of means. Hydroelectric power plants use the kinetic energy of water to drive electric generators. Coal or nuclear power plants create steam to drive steam turbines that turn the coils. Other sources of primary energy include wind, tides, or waves on water.

Once power is generated, it must be transmitted to the consumer, which often means transmitting power over hundreds of kilometers. To do this, the voltage of the power plant is increased by a step-up transformer, that is stepped up, and the current decreases proportionally because

$$P_{\text{transmitted}} = I_{\text{transmitted}} V_{\text{transmitted}}. \tag{20.22}$$

The lower current $I_{\text{transmitted}}$ in the transmission wires reduces the *Joule losses*, which is heating of the wire due to a current flow. This heating is caused by the small, but nonzero, resistance R_{wire} of the transmission wires. The power lost to the environment through this heat is

$$P_{\text{lost}} = I^2_{\text{transmitted}} R_{\text{wire}}, \tag{20.23}$$

which is proportional to the current *squared* in the transmission wire. This is why the transmitted current $I_{\text{transmitted}}$ must be as small as possible and, consequently, the voltage must be large to transmit the power $P_{\text{transmitted}}$.

Voltages ranging from 120 to 700 kV are used for transmitting power over long distances. The voltage is stepped up at the exit of the power station by a step-up transformer, as shown in Figure 20.32.

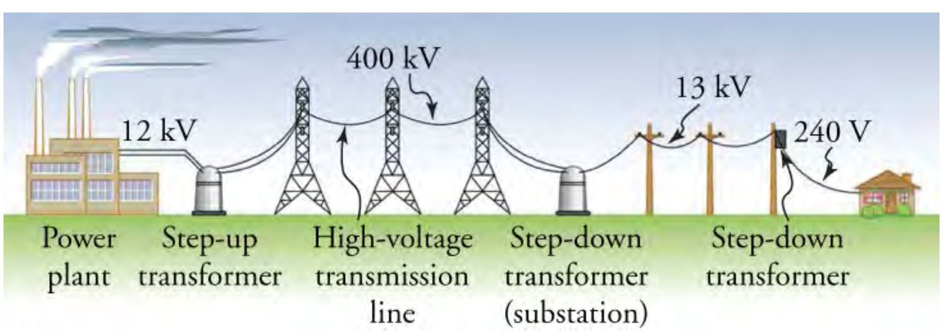


Figure 20.32 Transformers change voltages at several points in a power distribution system. Electric power is usually generated at greater than 10 kV, and transmitted long distances at voltages ranging from 120 kV to 700 kV to limit energy losses. Local power distribution to neighborhoods or industries goes through a substation and is sent short distances at voltages ranging from 5 to 13 kV. This is reduced to 120, 240, or 480 V for safety at the individual user site.

Once the power has arrived at a population or industrial center, the voltage is stepped down at a substation to between 5 and 30 kV. Finally, at individual homes or businesses, the power is stepped down again to 120, 240, or 480 V. Each step-up and step-down transformation is done with a transformer designed based on Faradays law of induction. We've come a long way since Queen Elizabeth asked Faraday what possible use could be made of electricity.

Check Your Understanding

7. What is an electric motor?
   a. An electric motor transforms electrical energy into mechanical energy.
   b. An electric motor transforms mechanical energy into electrical energy.
   c. An electric motor transforms chemical energy into mechanical energy.
   d. An electric motor transforms mechanical energy into chemical energy.

8. What happens to the torque provided by an electric motor if you double the number of coils in the motor?
   a. The torque would be doubled.
   b. The torque would be halved.
   c. The torque would be quadrupled.
   d. The torque would be tripled.

9. What is a step-up transformer?
   a. A step-up transformer decreases the current to transmit power over short distance with minimum loss.
   b. A step-up transformer increases the current to transmit power over short distance with minimum loss.
   c. A step-up transformer increases voltage to transmit power over long distance with minimum loss.
   d. A step-up transformer decreases voltage to transmit power over short distance with minimum loss.

10. What should be the ratio of the number of output coils to the number of input coil in a step-up transformer to increase the voltage fivefold?
    a. The ratio is five times.
    b. The ratio is 10 times.
    c. The ratio is 15 times.
    d. The ratio is 20 times.

20.3 Electromagnetic Induction

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain how a changing magnetic field produces a current in a wire
- Calculate induced electromotive force and current

Section Key Terms

emf induction magnetic flux

Changing Magnetic Fields

In the preceding section, we learned that a current creates a magnetic field. If nature is symmetrical, then perhaps a magnetic field can create a current. In 1831, some 12 years after the discovery that an electric current generates a magnetic field, English scientist Michael Faraday (1791–1862) and American scientist Joseph Henry (1797–1878) independently demonstrated that magnetic fields can produce currents. The basic process of generating currents with magnetic fields is called **induction**; this process is also called magnetic induction to distinguish it from charging by induction, which uses the electrostatic Coulomb force.

When Faraday discovered what is now called Faraday's law of induction, Queen Victoria asked him what possible use was electricity. “Madam,” he replied, “What good is a baby?” Today, currents induced by magnetic fields are essential to our technological society. The electric generator—found in everything from automobiles to bicycles to nuclear power plants—uses magnetism to generate electric current. Other devices that use magnetism to induce currents include pickup coils in electric guitars, transformers of every size, certain microphones, airport security gates, and damping mechanisms on sensitive chemical balances.

One experiment Faraday did to demonstrate magnetic induction was to move a bar magnet through a wire coil and measure the resulting electric current through the wire. A schematic of this experiment is shown in Figure 20.33. He found that current is induced only when the magnet moves with respect to the coil. When the magnet is motionless with respect to the coil, no current is induced in the coil, as in Figure 20.33. In addition, moving the magnet in the opposite direction (compare Figure 20.33 with Figure 20.33) or reversing the poles of the magnet (compare Figure 20.33 with Figure 20.33) results in a current in the opposite direction.

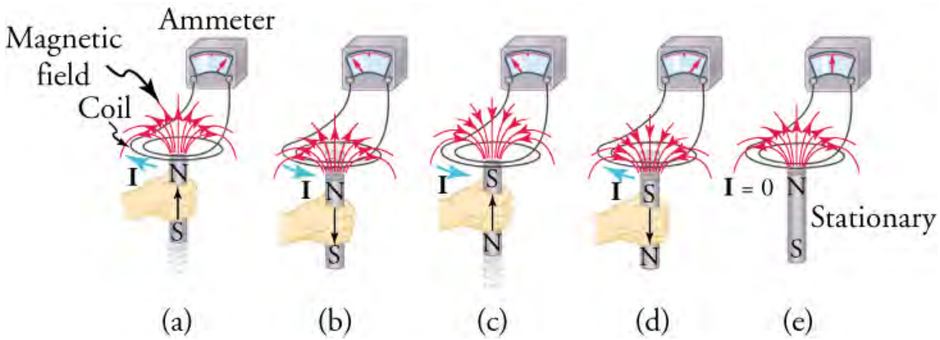


Figure 20.33 Movement of a magnet relative to a coil produces electric currents as shown. The same currents are produced if the coil is moved relative to the magnet. The greater the speed, the greater the magnitude of the current, and the current is zero when there is no motion. The current produced by moving the magnet upward is in the opposite direction as the current produced by moving the magnet downward.

Virtual Physics

Faraday's Law

Click to view content (http://www.openstax.org/l/faradays-law)

Try this simulation to see how moving a magnet creates a current in a circuit. A light bulb lights up to show when current is flowing, and a voltmeter shows the voltage drop across the light bulb. Try moving the magnet through a four-turn coil and through a two-turn coil. For the same magnet speed, which coil produces a higher voltage?

GRASP CHECK

With the north pole to the left and moving the magnet from right to left, a positive voltage is produced as the magnet enters the coil. What sign voltage will be produced if the experiment is repeated with the south pole to the left?

a. The sign of voltage will change because the direction of current flow will change by moving south pole of the magnet to the left.
b. The sign of voltage will remain same because the direction of current flow will not change by moving south pole of the magnet to the left.
c. The sign of voltage will change because the magnitude of current flow will change by moving south pole of the magnet to the left.
d. The sign of voltage will remain same because the magnitude of current flow will not change by moving south pole of the magnet to the left.

Induced Electromotive Force

If a current is induced in the coil, Faraday reasoned that there must be what he called an *electromotive force* pushing the charges through the coil. This interpretation turned out to be incorrect; instead, the external source doing the work of moving the magnet adds energy to the charges in the coil. The energy added per unit charge has units of volts, so the electromotive force is actually a potential. Unfortunately, the name electromotive force stuck and with it the potential for confusing it with a real force. For this reason, we avoid the term *electromotive force* and just use the abbreviation *emf*, which has the mathematical symbol ε. The **emf** may be defined as the rate at which energy is drawn from a source per unit current flowing through a circuit. Thus, emf is the energy per unit charge *added* by a source, which contrasts with voltage, which is the energy per unit charge *released* as the charges flow through a circuit.

To understand why an emf is generated in a coil due to a moving magnet, consider Figure 20.34, which shows a bar magnet moving downward with respect to a wire loop. Initially, seven magnetic field lines are going through the loop (see left-hand image). Because the magnet is moving away from the coil, only five magnetic field lines are going through the loop after a short time Δt (see right-hand image). Thus, when a change occurs in the number of magnetic field lines going through the area defined by the wire loop, an emf is induced in the wire loop. Experiments such as this show that the induced emf is proportional to the *rate of change* of the magnetic field. Mathematically, we express this as

$$\varepsilon \propto \frac{\Delta B}{\Delta t}, \tag{20.24}$$

where ΔB is the change in the magnitude in the magnetic field during time Δt and A is the area of the loop.

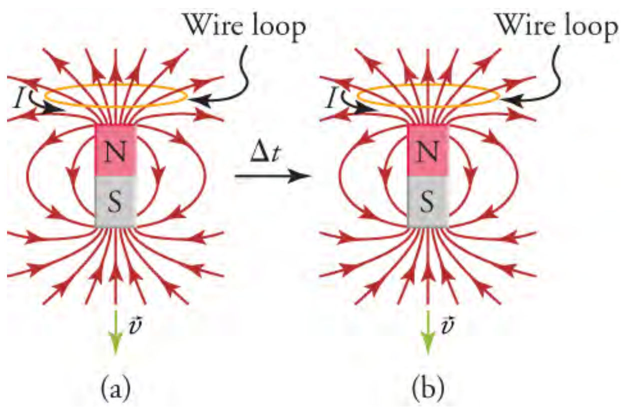


Figure 20.34 The bar magnet moves downward with respect to the wire loop, so that the number of magnetic field lines going through the loop decreases with time. This causes an emf to be induced in the loop, creating an electric current.

Note that magnetic field lines that lie in the plane of the wire loop do not actually pass through the loop, as shown by the left-most loop in Figure 20.35. In this figure, the arrow coming out of the loop is a vector whose magnitude is the area of the loop and whose direction is perpendicular to the plane of the loop. In Figure 20.35, as the loop is rotated from $\theta = 90°$ to $\theta = 0°$, the contribution of the magnetic field lines to the emf increases. Thus, what is important in generating an emf in the wire loop is the component of the magnetic field that is *perpendicular* to the plane of the loop, which is $B \cos \theta$.

This is analogous to a sail in the wind. Think of the conducting loop as the sail and the magnetic field as the wind. To maximize the force of the wind on the sail, the sail is oriented so that its surface vector points in the same direction as the winds, as in the right-most loop in Figure 20.35. When the sail is aligned so that its surface vector is perpendicular to the wind, as in the left-most loop in Figure 20.35, then the wind exerts no force on the sail.

Thus, taking into account the angle of the magnetic field with respect to the area, the proportionality $E \propto \Delta B/\Delta t$ becomes

$$E \propto \frac{\Delta B \cos \theta}{\Delta t}. \tag{20.25}$$

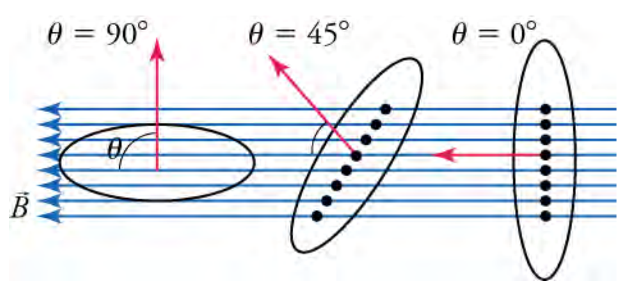


Figure 20.35 The magnetic field lies in the plane of the left-most loop, so it cannot generate an emf in this case. When the loop is rotated so that the angle of the magnetic field with the vector perpendicular to the area of the loop increases to $90°$ (see right-most loop), the magnetic field contributes maximally to the emf in the loop. The dots show where the magnetic field lines intersect the plane defined by the loop.

Another way to reduce the number of magnetic field lines that go through the conducting loop in Figure 20.35 is not to move the magnet but to make the loop smaller. Experiments show that changing the area of a conducting loop in a stable magnetic field induces an emf in the loop. Thus, the emf produced in a conducting loop is proportional to the rate of change of the *product* of the perpendicular magnetic field and the loop area

$$\varepsilon \propto \frac{\Delta\left[(B\cos\theta)A\right]}{\Delta t}, \tag{20.26}$$

where $B\cos\theta$ is the perpendicular magnetic field and A is the area of the loop. The product $BA\cos\theta$ is very important. It is proportional to the number of magnetic field lines that pass perpendicularly through a surface of area A. Going back to our sail analogy, it would be proportional to the force of the wind on the sail. It is called the **magnetic flux** and is represented by Φ .

$$\Phi = BA\cos\theta \tag{20.27}$$

The unit of magnetic flux is the weber (Wb), which is magnetic field per unit area, or T/m^2. The weber is also a volt second (Vs).

The induced emf is in fact proportional to the rate of change of the magnetic flux through a conducting loop.

$$\varepsilon \propto \frac{\Delta\Phi}{\Delta t} \tag{20.28}$$

Finally, for a coil made from N loops, the emf is N times stronger than for a single loop. Thus, the emf induced by a changing magnetic field in a coil of N loops is

$$\varepsilon \propto N\frac{\Delta B\cos\theta}{\Delta t}\mathrm{A}.$$

The last question to answer before we can change the proportionality into an equation is “In what direction does the current flow?” The Russian scientist Heinrich Lenz (1804–1865) explained that the current flows in the direction that creates a magnetic field that tries to keep the flux constant in the loop. For example, consider again Figure 20.34. The motion of the bar magnet causes the number of upward-pointing magnetic field lines that go through the loop to decrease. Therefore, an emf is generated in the loop that drives a current in the direction that creates more upward-pointing magnetic field lines. By using the right-hand rule, we see that this current must flow in the direction shown in the figure. To express the fact that the induced emf acts to counter the change in the magnetic flux through a wire loop, a minus sign is introduced into the proportionality $\varepsilon \propto \Delta\Phi/\Delta t.$, which gives Faraday’s law of induction.

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} \tag{20.29}$$

Lenz’s law is very important. To better understand it, consider Figure 20.36, which shows a magnet moving with respect to a wire coil and the direction of the resulting current in the coil. In the top row, the north pole of the magnet approaches the coil, so the magnetic field lines from the magnet point toward the coil. Thus, the magnetic field $\vec{B}_{\text{mag}} = B_{\text{mag}}\,(\hat{x})$ pointing to the right increases in the coil. According to Lenz’s law, the emf produced in the coil will drive a current in the direction that creates a magnetic field $\vec{B}_{\text{coil}} = B_{\text{coil}}\,(-\hat{x})$ inside the coil pointing to the left. This will counter the increase in magnetic flux pointing to the right. To see which way the current must flow, point your right thumb in the desired direction of the magnetic field $\vec{B}_{\text{coil}},$ and the current will flow in the direction indicated by curling your right fingers. This is shown by the image of the right hand in the top row of Figure 20.36. Thus, the current must flow in the direction shown in Figure 4(a).

In Figure 4(b), the direction in which the magnet moves is reversed. In the coil, the right-pointing magnetic field $\vec{B}_{\text{mag}}$ due to the moving magnet decreases. Lenz’s law says that, to counter this decrease, the emf will drive a current that creates an additional right-pointing magnetic field $\vec{B}_{\text{coil}}$ in the coil. Again, point your right thumb in the desired direction of the magnetic field, and the current will flow in the direction indicate by curling your right fingers (Figure 4(b)).

Finally, in Figure 4(c), the magnet is reversed so that the south pole is nearest the coil. Now the magnetic field $\vec{B}_{\text{mag}}$ points toward the magnet instead of toward the coil. As the magnet approaches the coil, it causes the left-pointing magnetic field in the coil to increase. Lenz’s law tells us that the emf induced in the coil will drive a current in the direction that creates a magnetic field pointing to the right. This will counter the increasing magnetic flux pointing to the left due to the magnet. Using the right-hand rule again, as indicated in the figure, shows that the current must flow in the direction shown in Figure 4(c).

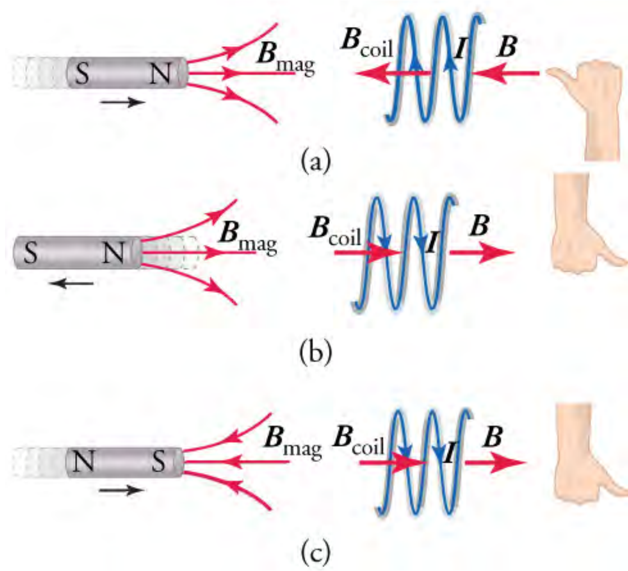


Figure 20.36 Lenz's law tells us that the magnetically induced emf will drive a current that resists the change in the magnetic flux through a circuit. This is shown in panels (a)–(c) for various magnet orientations and velocities. The right hands at right show how to apply the right-hand rule to find in which direction the induced current flows around the coil.

Virtual Physics

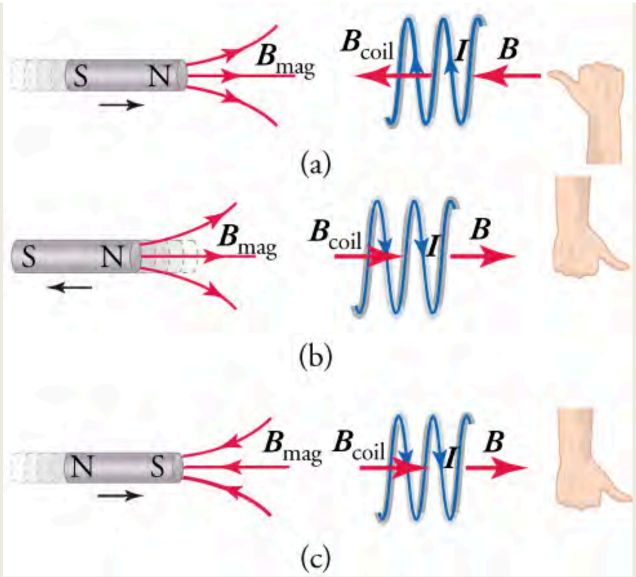
Faraday's Electromagnetic Lab

[Click to view content (http://www.openstax.org/l/Faraday-EM-lab)](http://www.openstax.org/l/Faraday-EM-lab)

This simulation proposes several activities. For now, click on the tab Pickup Coil, which presents a bar magnet that you can move through a coil. As you do so, you can see the electrons move in the coil and a light bulb will light up or a voltmeter will indicate the voltage across a resistor. Note that the voltmeter allows you to see the sign of the voltage as you move the magnet about. You can also leave the bar magnet at rest and move the coil, although it is more difficult to observe the results.

GRASP CHECK

Orient the bar magnet with the north pole facing to the right and place the pickup coil to the right of the bar magnet. Now move the bar magnet toward the coil and observe in which way the electrons move. This is the same situation as depicted below. Does the current in the simulation flow in the same direction as shown below? Explain why or why not.



a. Yes, the current in the simulation flows as shown because the direction of current is opposite to the direction of flow of electrons.
b. No, current in the simulation flows in the opposite direction because the direction of current is same to the direction of flow of electrons.

WATCH PHYSICS

Induced Current in a Wire

This video explains how a current can be induced in a straight wire by moving it through a magnetic field. The lecturer uses the *cross product*, which a type of vector multiplication. Don't worry if you are not familiar with this, it basically combines the right-hand rule for determining the force on the charges in the wire with the equation $F = qvB \sin \theta$.

Click to view content (https://www.openstax.org/l/induced-current)

GRASP CHECK

What emf is produced across a straight wire 0.50 m long moving at a velocity of (1.5 m/s) $\hat{x}$ through a uniform magnetic field (0.30 T)$\hat{z}$? The wire lies in the $\hat{y}$-direction. Also, which end of the wire is at the higher potential—let the lower end of the wire be at $y = 0$ and the upper end at $y = 0.5$ m)?

a. 0.15 V and the lower end of the wire will be at higher potential
b. 0.15 V and the upper end of the wire will be at higher potential
c. 0.075 V and the lower end of the wire will be at higher potential
d. 0.075 V and the upper end of the wire will be at higher potential

WORKED EXAMPLE

EMF Induced in Conducing Coil by Moving Magnet

Imagine a magnetic field goes through a coil in the direction indicated in Figure 20.37. The coil diameter is 2.0 cm. If the magnetic field goes from 0.020 to 0.010 T in 34 s, what is the direction and magnitude of the induced current? Assume the coil has a resistance of 0.1 Ω.

Figure 20.37 A coil through which passes a magnetic field *B*.

STRATEGY

Use the equation $\varepsilon = -N\Delta\Phi/\Delta t$ to find the induced emf in the coil, where $\Delta t = 34\ \mathrm{s}$. Counting the number of loops in the solenoid, we find it has 16 loops, so $N = 16$. Use the equation $\Phi = BA\cos\theta$ to calculate the magnetic flux

$$\Phi = BA\cos\theta = B\pi\left(\frac{d}{2}\right)^2, \tag{20.30}$$

where d is the diameter of the solenoid and we have used $\cos 0° = 1$. Because the area of the solenoid does not vary, the change in the magnetic of the flux through the solenoid is

$$\Delta\Phi = \Delta B\pi\left(\frac{d}{2}\right)^2. \tag{20.31}$$

Once we find the emf, we can use Ohm's law, $\varepsilon = IR$, to find the current.

Finally, Lenz's law tells us that the current should produce a magnetic field that acts to oppose the decrease in the applied magnetic field. Thus, the current should produce a magnetic field to the right.

Solution

Combining equations $\varepsilon = -N\Delta\Phi/\Delta t$ and $\Phi = BA\cos\theta$ gives

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} = -N\frac{\Delta B\pi d^2}{4\ \Delta t}. \tag{20.32}$$

Solving Ohm's law for the current and using this result gives

$$\begin{aligned} I &= \tfrac{\varepsilon}{R} = -N\tfrac{\Delta B\pi d^2}{4R\Delta t} \\ &= -16\frac{(-0.010\ \mathrm{T})\pi(0.020\ \mathrm{m})^2}{4(0.10\ \Omega)(34\ \mathrm{s})} \\ &= 15\ \mu\mathrm{A} \end{aligned} \tag{20.33}$$

Lenz's law tells us that the current must produce a magnetic field to the right. Thus, we point our right thumb to the right and curl our right fingers around the solenoid. The current must flow in the direction in which our fingers are pointing, so it enters at the left end of the solenoid and exits at the right end.

Discussion

Let's see if the minus sign makes sense in Faraday's law of induction. Define the direction of the magnetic field to be the positive direction. This means the change in the magnetic field is negative, as we found above. The minus sign in Faraday's law of induction negates the negative change in the magnetic field, leaving us with a positive current. Therefore, the current must flow in the direction of the magnetic field, which is what we found.

Now try defining the positive direction to be the direction opposite that of the magnetic field, that is positive is to the left in Figure 20.37. In this case, you will find a negative current. But since the positive direction is to the left, a negative current must flow to the right, which again agrees with what we found by using Lenz's law.

WORKED EXAMPLE

Magnetic Induction due to Changing Circuit Size

The circuit shown in Figure 20.38 consists of a U-shaped wire with a resistor and with the ends connected by a sliding conducting rod. The magnetic field filling the area enclosed by the circuit is constant at 0.01 T. If the rod is pulled to the right at speed $v = 0.50\ \mathrm{m/s}$, what current is induced in the circuit and in what direction does the current flow?

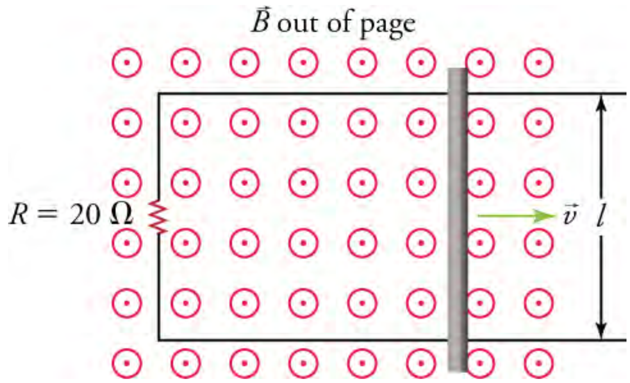


Figure 20.38 A slider circuit. The magnetic field is constant and the rod is pulled to the right at speed *v*. The changing area enclosed by the circuit induces an emf in the circuit.

STRATEGY

We again use Faraday's law of induction, $E = -N\frac{\Delta\Phi}{\Delta t}$, although this time the magnetic field is constant and the area enclosed by the circuit changes. The circuit contains a single loop, so $N = 1$. The rate of change of the area is $\frac{\Delta A}{\Delta t} = v\ell$. Thus the rate of change of the magnetic flux is

$$\frac{\Delta\Phi}{\Delta t} = \frac{\Delta\,(BA\cos\theta)}{\Delta t} = B\frac{\Delta A}{\Delta t} = Bv\ell, \tag{20.34}$$

where we have used the fact that the angle θ between the area vector and the magnetic field is 0°. Once we know the emf, we can find the current by using Ohm's law. To find the direction of the current, we apply Lenz's law.

Solution

Faraday's law of induction gives

$$E = -N\frac{\Delta\Phi}{\Delta t} = -Bv\ell. \tag{20.35}$$

Solving Ohm's law for the current and using the previous result for emf gives

$$I = \frac{E}{R} = \frac{-Bv\ell}{R} = \frac{-\,(0.010\text{ T})\,(0.50\text{ m/s})\,(0.10\text{ m})}{20\ \Omega} = 25\ \mu\text{A}. \tag{20.36}$$

As the rod slides to the right, the magnetic flux passing through the circuit increases. Lenz's law tells us that the current induced will create a magnetic field that will counter this increase. Thus, the magnetic field created by the induced current must be into the page. Curling your right-hand fingers around the loop in the clockwise direction makes your right thumb point into the page, which is the desired direction of the magnetic field. Thus, the current must flow in the clockwise direction around the circuit.

Discussion

Is energy conserved in this circuit? An external agent must pull on the rod with sufficient force to just balance the force on a current-carrying wire in a magnetic field—recall that $F = I\ell B\sin\theta$. The rate at which this force does work on the rod should be balanced by the rate at which the circuit dissipates power. Using $F = I\ell B\sin\theta$, the force required to pull the wire at a constant speed v is

$$F_{\text{pull}} = I\ell B\sin\theta = I\ell B, \tag{20.37}$$

where we used the fact that the angle θ between the current and the magnetic field is $90°$. Inserting our expression above for the current into this equation gives

$$F_{\text{pull}} = I\ell B = -\frac{Bv\ell}{R}(\ell B) = -\frac{B^2v\ell^2}{R}. \tag{20.38}$$

The power contributed by the agent pulling the rod is $F_{\text{pull}}v$, or

$$P_{\text{pull}} = F_{\text{pull}} v = -\frac{B^2 v^2 \ell^2}{R}. \tag{20.39}$$

The power dissipated by the circuit is

$$P_{\text{dissipated}} = I^2 R = \left(\frac{-Bv\ell}{R}\right)^2 R = \frac{B^2 v^2 \ell^2}{R}. \tag{20.40}$$

We thus see that $P_{\text{pull}} + P_{\text{dissipated}} = 0$, which means that power is conserved in the system consisting of the circuit and the agent that pulls the rod. Thus, energy is conserved in this system.

Practice Problems

11. The magnetic flux through a single wire loop changes from 3.5 Wb to 1.5 Wb in 2.0 s. What emf is induced in the loop?
   a. −2.0 V
   b. −1.0 V
   c. +1.0 V
   d. +2.0 V

12. What is the emf for a 10-turn coil through which the flux changes at 10 Wb/s?
   a. −100 V
   b. −10 V
   c. +10 V
   d. +100 V

Check Your Understanding

13. Given a bar magnet, how can you induce an electric current in a wire loop?
   a. An electric current is induced if a bar magnet is placed near the wire loop.
   b. An electric current is induced if wire loop is wound around the bar magnet.
   c. An electric current is induced if a bar magnet is moved through the wire loop.
   d. An electric current is induced if a bar magnet is placed in contact with the wire loop.

14. What factors can cause an induced current in a wire loop through which a magnetic field passes?
   a. Induced current can be created by changing the size of the wire loop only.
   b. Induced current can be created by changing the orientation of the wire loop only.
   c. Induced current can be created by changing the strength of the magnetic field only.
   d. Induced current can be created by changing the strength of the magnetic field, changing the size of the wire loop, or changing the orientation of the wire loop.

KEY TERMS

Curie temperature well-defined temperature for ferromagnetic materials above which they cannot be magnetized

domain region within a magnetic material in which the magnetic poles of individual atoms are aligned

electric motor device that transforms electrical energy into mechanical energy

electromagnet device that uses electric current to make a magnetic field

electromagnetism study of electric and magnetic phenomena

emf rate at which energy is drawn from a source per unit current flowing through a circuit

ferromagnetic material such as iron, cobalt, nickel, or gadolinium that exhibits strong magnetic effects

generator device that transforms mechanical energy into electrical energy

induction rate at which energy is drawn from a source per unit current flowing through a circuit

magnetic dipole term that describes magnets because they always have two poles: north and south

magnetic field directional lines around a magnetic material that indicates the direction and magnitude of the magnetic force

magnetic flux component of the magnetic field perpendicular to the surface area through which it passes and multiplied by the area

magnetic pole part of a magnet that exerts the strongest force on other magnets or magnetic material

magnetized material that is induced to be magnetic or that is made into a permanent magnet

north pole part of a magnet that orients itself toward the geographic North Pole of Earth

permanent magnet material that retains its magnetic behavior for a long time, even when exposed to demagnetizing influences

right-hand rule rule involving curling the right-hand fingers from one vector to another; the direction in which the right thumb points is the direction of the resulting vector

solenoid uniform cylindrical coil of wire through which electric current is passed to produce a magnetic field

south pole part of a magnet that orients itself toward the geographic South Pole of Earth

transformer device that transforms voltages from one value to another

SECTION SUMMARY

20.1 Magnetic Fields, Field Lines, and Force

- All magnets have two poles: a north pole and a south pole. If the magnet is free to move, its north pole orients itself toward the geographic North Pole of Earth, and the south pole orients itself toward the geographic South Pole of Earth.
- A repulsive force occurs between the north poles of two magnets and likewise for two south poles. However, an attractive force occurs between the north pole of one magnet and the south pole of another magnet.
- A charged particle moving through a magnetic field experiences a force whose direction is determined by the right-hand rule.
- An electric current generates a magnetic field.
- Electromagnets are magnets made by passing a current through a system of wires.

20.2 Motors, Generators, and Transformers

- Electric motors contain wire loops in a magnetic field. Current is passed through the wire loops, which forces them to rotate in the magnetic field. The current is reversed every half rotation so that the torque on the loop is always in the same direction.
- Electric generators contain wire loops in a magnetic field. An external agent provides mechanical energy to force the loops to rotate in the magnetic field, which produces an AC voltage that drives an AC current through the loops.
- Transformers contain a ring made of magnetic material and, on opposite sides of the ring, two windings of wire wrap around the ring. A changing current in one wire winding creates a changing magnetic field, which is trapped in the ring and thus goes through the second winding and induces an emf in the second winding. The voltage in the second winding is proportional to the ratio of the number of loops in each winding.
- Transformers are used to step up and step down the voltage for power transmission.
- Over long distances, electric power is transmitted at high voltage to minimize the current and thereby minimize the Joule losses due to resistive heating.

20.3 Electromagnetic Induction

- **Faraday's law of induction** states that a changing magnetic flux that occurs within an area enclosed by a conducting loop induces an electric current in the loop.
- **Lenz' law** states that an induced current flows in the direction such that it opposes the change that induced it.