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.

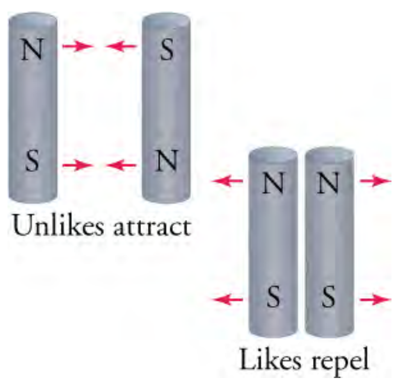


Figure 20.4 Depending on their relative orientation, magnet poles will either attract each other or repel each other.

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.

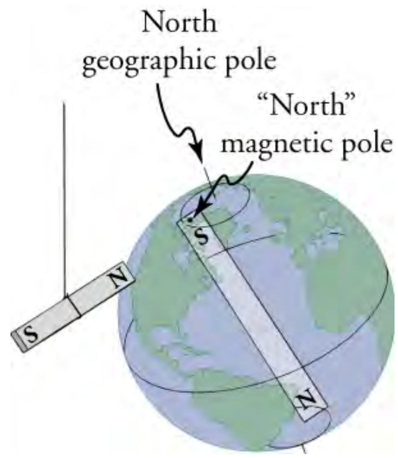


Figure 20.5 Earth can be thought of as containing a giant magnet running through its core. The magnetic south pole of Earth's magnet is at the geographic North Pole, so the north pole of magnets is attracted to the North Pole, which is how the north pole of magnets got their name. Likewise, the south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

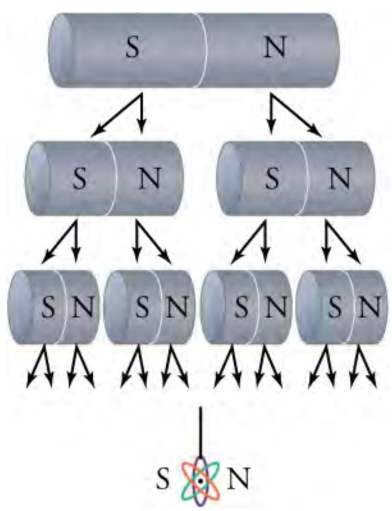


Figure 20.6 All magnets have two opposite poles, from the smallest, such as subatomic particles, to the largest, such as stars.

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.

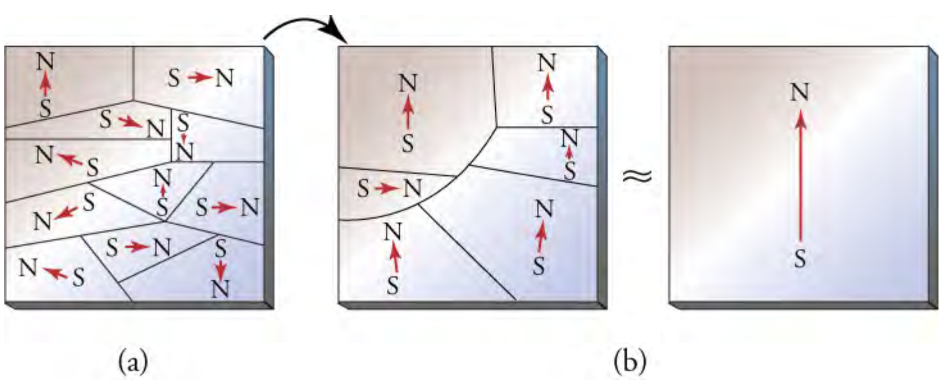


Figure 20.8 (a) An unmagnetized piece of iron—or other ferromagnetic material—has randomly oriented domains. (b) When magnetized by an external magnet, the domains show greater alignment, and some grow at the expense of others. Individual atoms are aligned within

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 $^\circ\mathrm{C}$), 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.

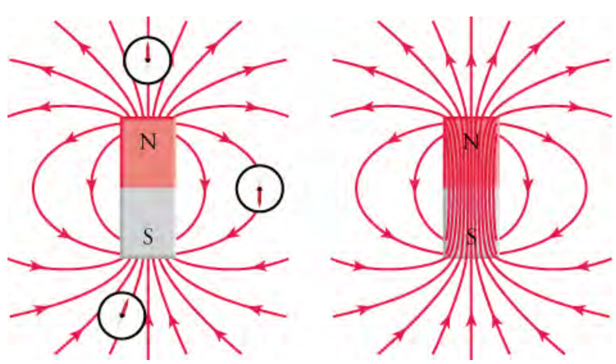


Figure 20.9 The black lines represent the magnetic field lines of a bar magnet. The field lines point in the direction that the north pole of a small compass would point, as shown at left. Magnetic field lines never stop, so the field lines actually penetrate the magnet to form complete loops, as shown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

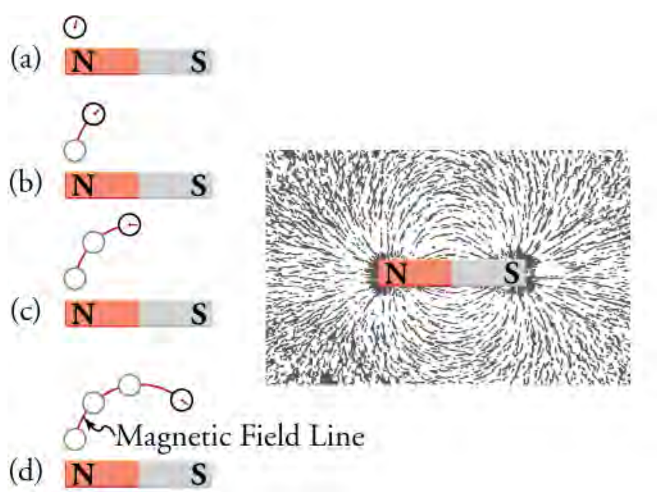


Figure 20.10 Magnetic field lines can be drawn by moving a small compass from point to point around a magnet. At each point, draw a short line in the direction of the compass needle. Joining the points together reveals the path of the magnetic field lines. Another way to visualize magnetic field lines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

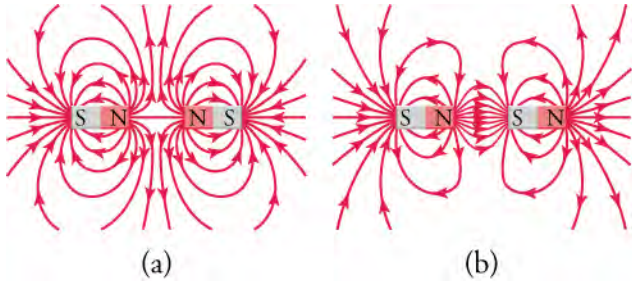


Figure 20.11 (a) When two north poles are approached together, the magnetic field lines repel each other and the two magnets experience a repulsive force. The same occurs if two south poles are approached together. (b) If opposite poles are approached together, the magnetic field lines become denser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

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

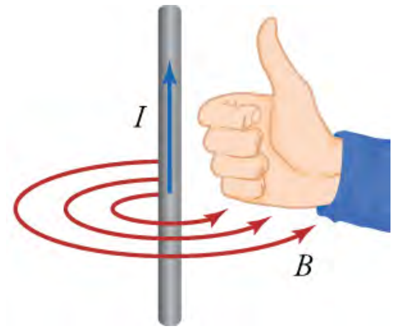


Figure 20.13 This image shows how to use the right-hand rule to determine the direction of the magnetic field created by current flowing through a straight wire. Point your right thumb in the direction of the current, and the magnetic field will be in the direction in which your fingers curl.

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.

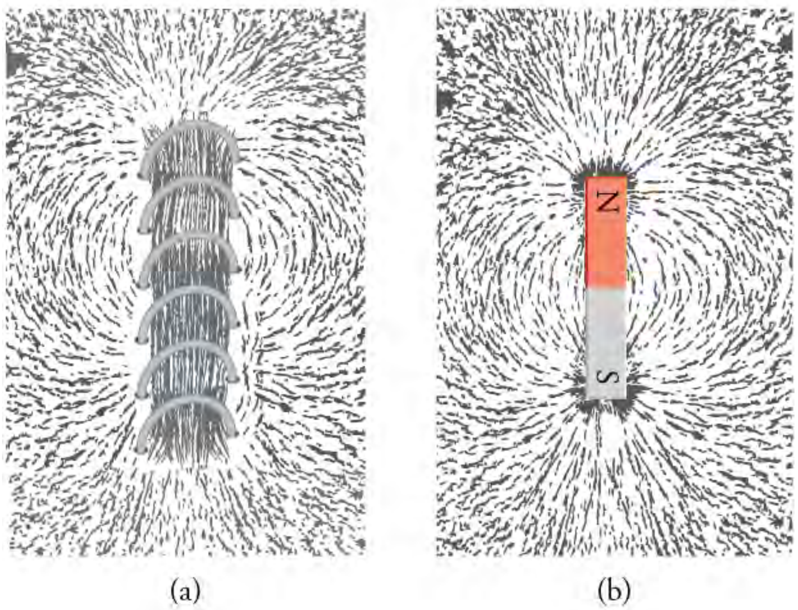


Figure 20.15 Iron filings show the magnetic field pattern around (a) a solenoid and (b) a bar magnet. The fields patterns are very similar, especially near the ends of the solenoid and bar magnet.

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 $\sin 90° = 1$.

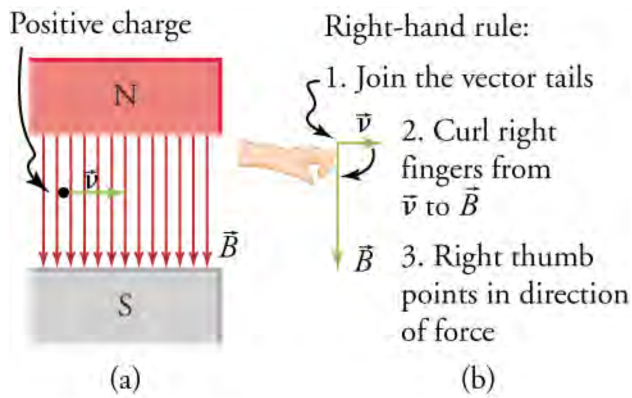


Figure 20.16 (a) An electron moves through a uniform magnetic field. (b) Using the right-hand rule, the force on the electron is found to be directed into the page.

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.

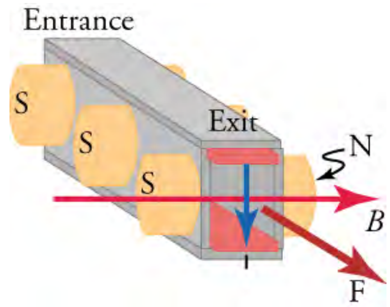


Figure 20.18 A schematic drawing of a magnetohydrodynamic drive showing the water channel, the current direction, the magnetic field direction, and the resulting force.

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

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

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

$$F = I\ell B\sin\theta(1.4). \quad (20.6)$$

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.

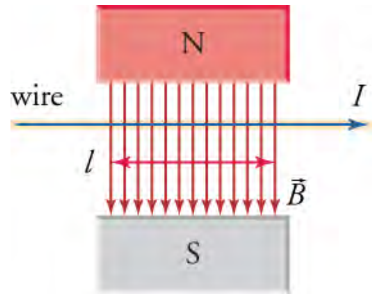


Figure 20.19 A straight wire carrying current I in a magnetic field B. The force exerted on the wire is directed into the page. The length ℓ is the length of the wire that is *in* the magnetic field.

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?

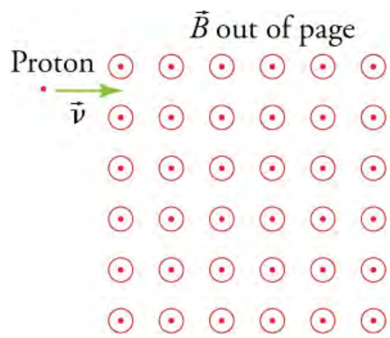


Figure 20.20 A proton enters a region of uniform magnetic field. The magnetic field is coming out of the page—the circles with dots represent vector arrow heads coming out of the page.

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

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

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.

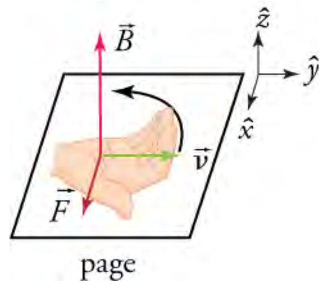


Figure 20.21 The velocity vector and a magnetic field vector from Figure 20.20 are placed end to end. A right hand is shown with the fingers curling up from the velocity vector toward the magnetic field vector. The thumb points in the direction of the resulting force, which is the $\hat{z}$ -direction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

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

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.

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

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

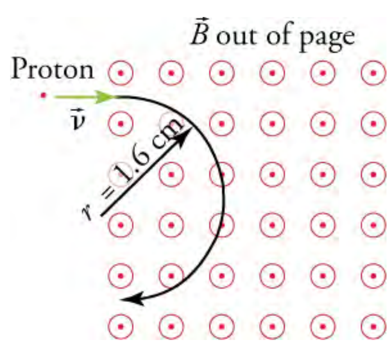
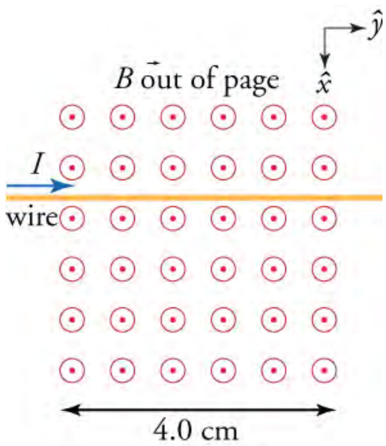


Figure 20.22 When traveling perpendicular to a constant magnetic field, a charged particle will execute circular motion, as shown here for a proton.

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

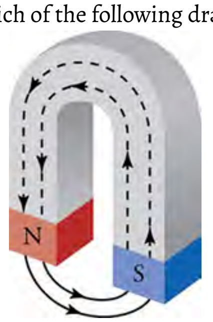
3. If two magnets repel each other, what can you conclude about their relative orientation?
   a. Either the south pole of magnet 1 is closer to the north pole of magnet 2 or the north pole of magnet 1 is closer to the south pole of magnet 2.
   b. Either the south poles of both the magnet 1 and magnet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

and magnet 2 are closer to each other.

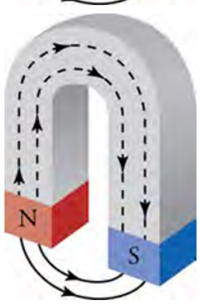
4. Describe methods to demagnetize a ferromagnet.
   a. by cooling, heating, or submerging in water
   b. by heating, hammering, and spinning it in external magnetic field
   c. by hammering, heating, and rubbing with cloth
   d. by cooling, submerging in water, or rubbing with cloth

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.

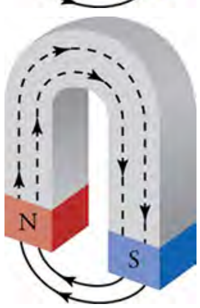
6. Which of the following drawings is correct?



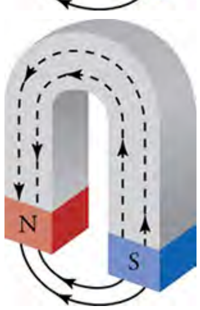
a.



b.



c.



d.