24 Magnetic Fields and Forces

This detailed image of the skeletal system of a dolphin wasn't made with x rays; it was made with magnetism. How is this done?

LOOKING AHEAD

The goal of Chapter 24 is to learn about magnetic fields and how magnetic fields exert forces on currents and moving charges.

Magnetic Fields

We've seen how to describe electric forces by using electric fields; now we'll look at **magnetic forces** and **magnetic fields.**

It's the magnetic force that causes a compass to line up with the earth's magnetic field.

Looking Back
20.4 The electric field

Forces on Moving Charges

Magnetic fields exert forces on moving charged particles. In a uniform field, a charged particle moves in a circular path.

The aurora is due to the motion of charged particles from the sun in the magnetic field of the earth.

Looking Back
6.3 Dynamics of circular motion

A current is simply the motion of charges, so magnetic fields exert forces on currents.

A loudspeaker works by the magnetic force acting on a current in a coil of wire at the base of the loudspeaker's cone.

Magnetic Field Sources

Iron filings work like little compasses to show magnetic field patterns. We'll see that magnetic fields are created by permanent magnets and by electric currents.

The simplest magnet is a bar magnet. It has two poles, north and south, and so creates a dipole field.

A loop of current creates a dipole field as well. You will learn how to compute magnetic fields resulting from currents in wires, loops, and coils.

Looking Back
20.5 Electric dipoles

Magnetic Materials

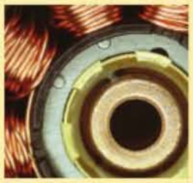
Iron and a few other elements can exhibit **permanent magnetism.** The permanent alignment of electron dipoles leads to a large, fixed magnetic field in these materials.

You will see how the atomic behavior of electrons in atoms leads to the familiar observation that magnets stick to a refrigerator.

Dipoles and Torques

A compass, a loop of wire, and electrons and protons all are **magnetic dipoles.** All dipoles experience a torque in a magnetic field that rotates them to line up with the field.

We'll explore how the alignment of atomic dipoles by the large magnetic field of an MRI solenoid can be used to create an image.



Magnetic torque on these coils causes this computer fan motor to turn.

Looking Back
7.2 Calculating torque

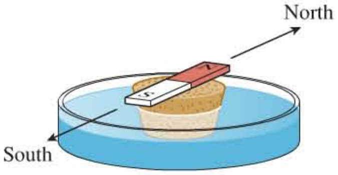
24.1 Magnetism

We began our investigation of electricity in Chapter 20 by looking at the results of simple experiments with charged rods. Let's try a similar approach with magnetism.

Exploring magnetism

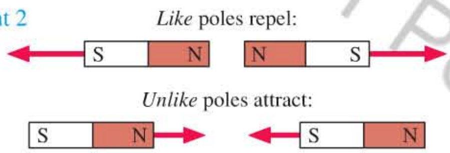
Experiment 1

If a bar magnet is taped to a piece of cork and allowed to float in a dish of water, it turns to align itself in an approximate north-south direction. The end of a magnet that points north is called the *north-seeking pole*, or simply the **north pole.** The other end is the **south pole.**



A magnet that is free to pivot like this is called a **compass.**

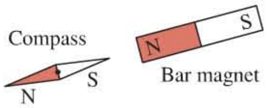
Experiment 2



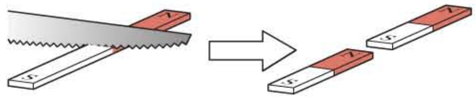
If the north pole of one magnet is brought near the north pole of another magnet, they repel each other. Two south poles also repel each other, but the north pole of one magnet exerts an attractive force on the south pole of another magnet.

Experiment 3

Since a compass needle is itself a little bar magnet, the north pole of a bar magnet attracts the south pole of a compass needle and repels the north pole.



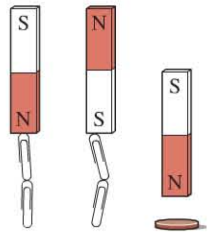
Experiment 4



Cutting a bar magnet in half produces two weaker but still complete magnets, each with a north pole and a south pole. No matter how small the magnets are cut, even down to microscopic sizes, each piece remains a complete magnet with two poles.

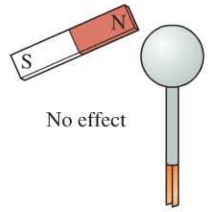
Experiment 5

Magnets can pick up some objects, such as paper clips, but not all. If an object is attracted to one pole of a magnet, it is also attracted to the other pole. Most materials, including copper, aluminum, glass, and plastic, experience no force from a magnet.



Experiment 6

When a magnet is brought near an electroscope, the leaves of the electroscope remain undeflected. If a charged rod is brought near a magnet, there is a weak *attractive* force on *both* ends of a magnet. However, the force is the same as the force on a metal bar that isn't a magnet, so it is simply a polarization force like the ones we studied in Chapter 21. Other than polarization forces, charged objects have *no effects* on magnets.



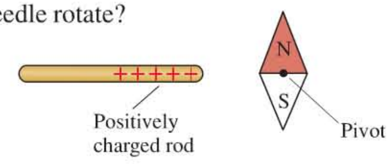
What do these experiments tell us?

1. Experiment 6 reveals that **magnetism is not the same as electricity.** Magnetic poles and electric charges share some similar behavior, but they are not the same.
2. Experiment 5 reveals that **magnetism is a long-range force.**
3. **Magnets have two types of poles,** called north and south poles. Two like poles exert repulsive forces on each other; two unlike poles exert attractive forces on each other. The behavior is *analogous* to that of electric charges, but, as noted, magnetic poles and electric charges are *not* the same. (In this text we will indicate the north pole of a magnet with reddish shading and the south pole with white.)
4. The poles of a bar magnet can be identified by using it as a compass. Other magnets aren't so easily made into a compass, but their poles can be identified by testing them against a bar magnet. **A pole that repels a known south pole and attracts a known north pole must be a south magnetic pole.**
5. Materials that are attracted to a magnet or that a magnet sticks to are called **magnetic materials.** The most common magnetic material is iron. Others include nickel and cobalt. Magnetic materials are attracted to *both* poles of a magnet. This attraction is analogous to how neutral objects are attracted to both positively and negatively charged rods by the polarization force. The difference is that *all* neutral objects are attracted to a charged rod, whereas only a few materials are attracted to a magnet.

6. Experiment 4 shows that cutting a magnet in half yields two weaker but still complete magnets, each with a north pole and a south pole. The basic unit of magnetism is thus a **magnetic dipole.** A magnetic dipole is analogous to an electric dipole, but the two charges in an electric dipole can be separated and used individually. This is *not* true for a magnetic dipole. The needle of a compass is a small, straight magnet, and so a compass needle is an especially simple magnetic dipole.

STOP TO THINK 24.1 Does the compass needle rotate?

A. Yes, clockwise.
B. Yes, counterclockwise.
C. No, not at all.

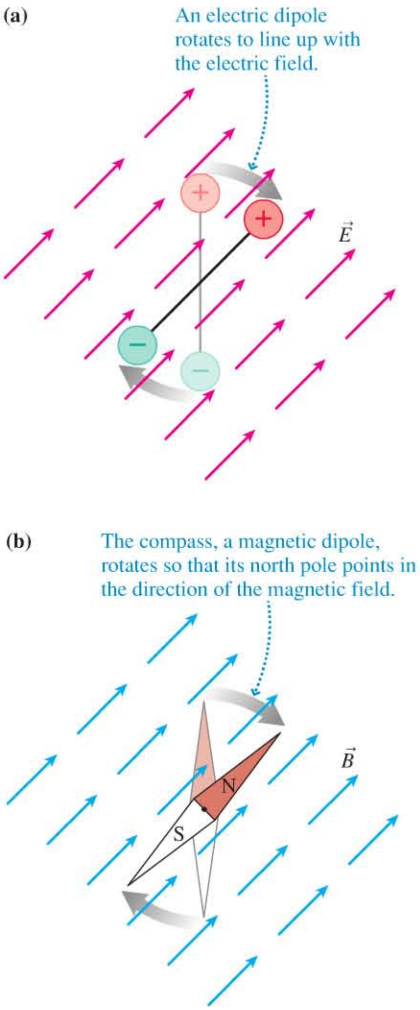


24.2 The Magnetic Field

When we studied the *electric* force between two charges in Chapter 20, we developed a new way to think about forces between charges—the *field model.* In this viewpoint, the space around a charge is not empty: The charge alters the space around it by creating an *electric field.* A second charge brought into this electric field then feels a force due to the *field.*

In Experiment 3 above, we learned that if the north pole of a bar magnet is brought near a compass, the compass needle will turn so that its south pole is toward the magnet. The concept of a field can also be used to describe the force that turns the compass: **Every magnet sets up a *magnetic* field in the space around it.** If another magnet—such as a compass needle—is then brought into this field, the second magnet will feel a force from the *field* of the first magnet. In this section, we'll see how to define the magnetic field, and then we'll study what the magnetic field looks like for some common shapes and arrangements of magnets.

FIGURE 24.1 Dipoles in electric and magnetic fields.



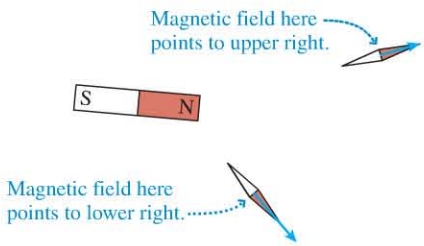
Measuring the Magnetic Field

What does the direction in which a compass needle points tell us about the magnetic field at the position of the compass? We can gain some insight by recalling how an *electric* dipole behaves when placed in an electric field, as shown in FIGURE 24.1a. In Chapter 20 we learned that an electric dipole experiences a *torque* when placed in an electric field, a torque that tends to align the axis of the dipole with the field. This means that the *direction* of the electric field is the same as the direction of the dipole's axis. Furthermore, the torque on the dipole is greater when the electric field is stronger; hence, the *magnitude* of the field, which we will often call the *strength* of the field, is proportional to the torque on the dipole.

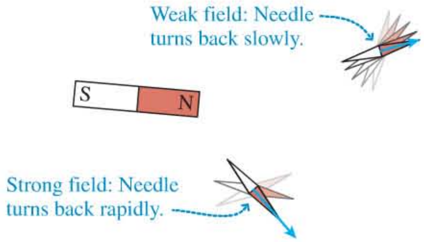
The magnetic dipole of a compass needle behaves very similarly when it is in a magnetic field. The magnetic field exerts a torque on the compass needle, causing the needle to point in the field direction, as shown in FIGURE 24.1b.

Because the magnetic field has both a direction and a magnitude, we need to represent it using a *vector.* We will use the symbol $\vec{B}$ to represent the magnetic field and B to represent the magnitude of the field. We can use compasses to determine the magnitude and direction of the magnetic field, as shown below.

- The *direction* of the magnetic field is the direction that the north pole of a compass needle points.

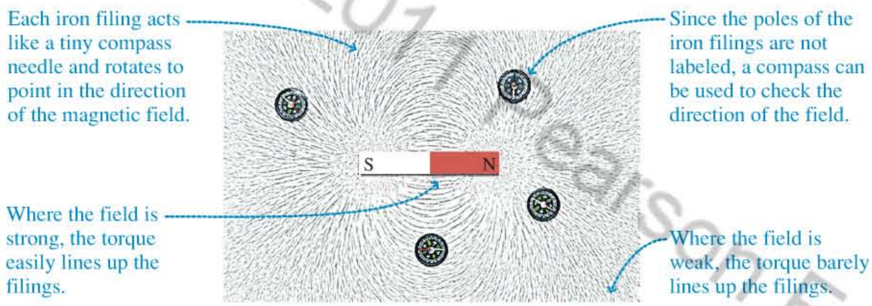


- The *strength* of the magnetic field is proportional to the torque felt by the compass needle if it is turned slightly away from the field direction.



We can produce a "picture" of the magnetic field by using *iron filings*—very small elongated grains of iron. If there are enough grains, iron filings can give a very detailed representation of the magnetic field, as shown in FIGURE 24.2. The compasses that we use to determine field direction show us that **the magnetic field of a magnet points *away* from the north pole and *toward* the south pole.**

FIGURE 24.2 Revealing the field of a bar magnet using iron filings.



Magnetic Field Vectors and Field Lines

We can draw the field of a magnet such as the one shown in Figure 24.2 in either of two ways. When we want to represent the magnetic field at one particular point, the **magnetic field vector** representation is especially useful. But if we want an overall representation of the field, **magnetic field lines** are often simpler to use. These two representations are similar to the *electric field* vectors and lines used in Chapter 20, and we'll use similar rules to draw them.

Let's start by drawing some magnetic field vectors that represent the magnetic field of our bar magnet. As shown in FIGURE 24.3, we can imagine placing a number of compasses near the magnet to measure the direction and magnitude of the magnetic field. To represent the field at the location of one of the compasses, we then draw a vector with its *tail* at that location. Figure 24.3 shows how to choose the direction and magnitude of this vector. Although we've drawn magnetic field vectors at only a few points around the magnet, it's important to remember that the magnetic field exists at *every* point around the magnet.

We can also represent the magnetic field using magnetic field lines. The rules for drawing these lines are similar to those for drawing the electric field lines of Chapter 20 and are shown for magnetic fields in FIGURE 24.4.

FIGURE 24.3 Mapping out the field of a bar magnet using compasses.

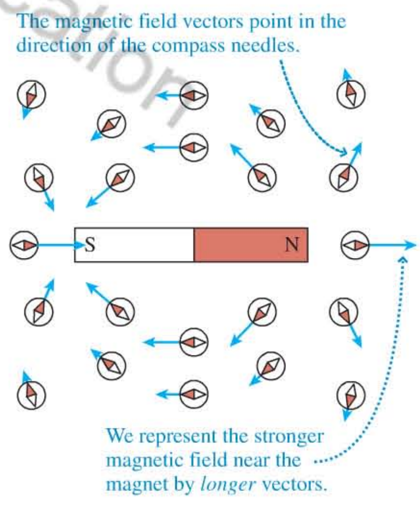
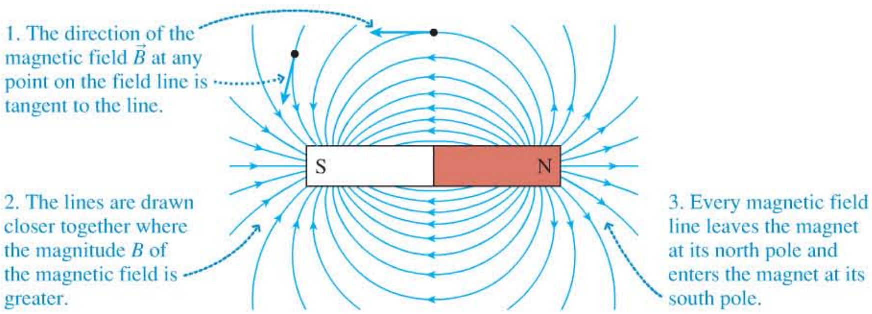
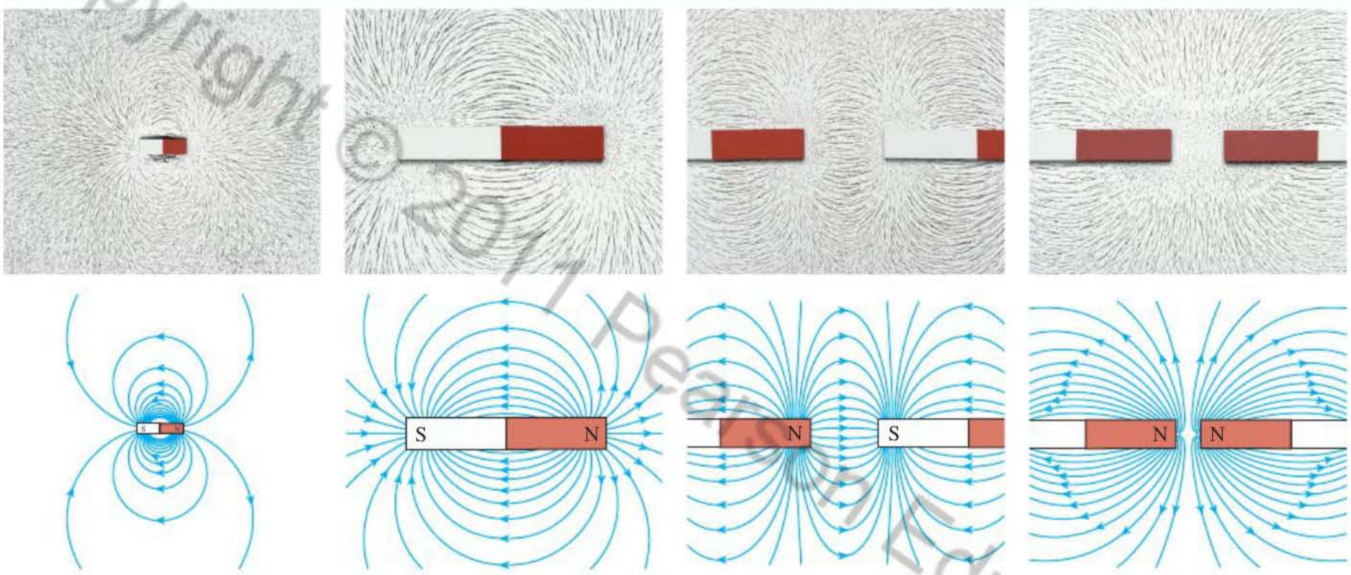


FIGURE 24.4 Drawing the magnetic field lines of a bar magnet.



Now that we know how to think about magnetic fields, let's look at magnetic fields from magnets of different arrangements. We'll use the iron filing method to show the lines from real magnets, along with a drawing of the field lines.

An atlas of magnetic fields produced by magnets



A single bar magnet: The magnetic field lines start on the north pole (red) and end on the south pole (white).

As you move away from the magnet, the field lines are farther apart, indicating a weaker field.

A single bar magnet (closeup): Closer to the magnet, we can more clearly see how the field lines always start on north poles and end on south poles.

Two bar magnets, unlike poles facing: With more than one magnet, the field lines still start on a north pole and end on a south pole. But they can start on the north pole of one magnet, and end on the south pole of another.

Two bar magnets, like poles facing: With two like poles placed nearby, the field lines starting on the north poles curve sharply toward their south poles in order to avoid the north pole of the other magnet.

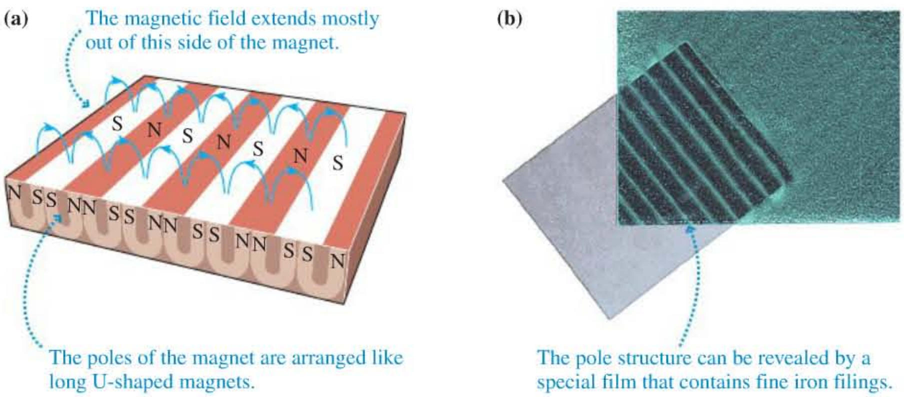
Magnetic Fields Around Us

We live in a magnetic field that is created in the earth's core, and magnetic fields are used in a wide range of technological applications. An everyday example is the flexible refrigerator magnet. As seen in FIGURE 24.5, these magnets have an unusual arrangement of long, striped poles. This arrangement forces most of the field to exit the brown side of the magnet, which is why this side sticks better to your refrigerator than the label side (see Conceptual Example 24.14).

TRY IT YOURSELF

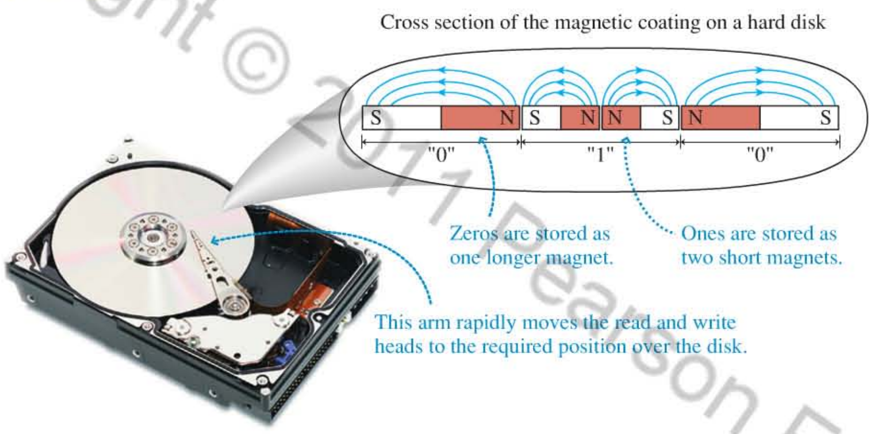
Buzzing magnets You can use two *identical* flexible refrigerator magnets for a nice demonstration of their alternating pole structure. Place the two magnets together, back to back, then quickly pull them across each other, noting the alternating attraction and repulsion from the alternating poles. If you pull them quickly enough, you will hear a buzz as the magnets are rapidly pushed apart and then pulled together.

FIGURE 24.5 The magnetic field of a refrigerator magnet.



Another application is the use of magnetic materials to store information on computer hard disk drives. As shown in **FIGURE 24.6**, a hard drive consists of a rapidly rotating disk with a thin magnetic coating on its surface. Information for computers is stored as digital zeros and ones, and on the disk these are stored as tiny magnetic dipoles. Each dipole is less than 100 nm long! The direction of the dipoles can be changed by the *write head*—a tiny switchable magnet that skims over the surface of the disk. The information can then be retrieved by the *read head*—a small probe that is sensitive to the magnetic fields of the tiny dipoles.

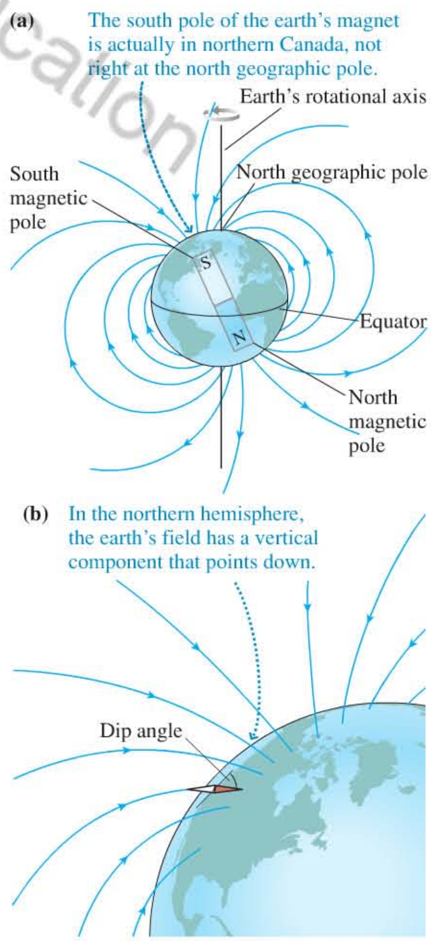
FIGURE 24.6 Computer hard disks store information using magnetic fields.



As we've seen, a bar magnet that is free to pivot—a compass—always swings so that its north pole points geographically north. But we've also seen that if a magnet is brought near a compass, the compass swings so that its north pole faces the south pole of the magnet. These observations can be reconciled if the earth itself is a large magnet, as shown in **FIGURE 24.7a**, where **the south pole of the earth's magnet is located near—but not exactly coincident with—the north geographic pole of the earth.** You can see from the figure that the north pole of a compass needle placed, for example, at the equator, will point toward the south pole of the earth's magnet—that is, to the north!

FIGURE 24.7b shows that the earth's magnetic field has components both parallel to the ground (horizontal) and perpendicular to the ground (vertical). An ordinary north-pointing compass responds only to the horizontal component, but a compass free to pivot vertically tilts downward at an angle called the **dip angle.** The dip angle varies with latitude on the earth's surface, and measuring the dip angle is one way to determine your latitude.

FIGURE 24.7 The earth's magnetic field.



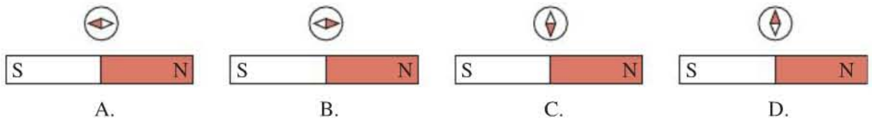
CONCEPTUAL EXAMPLE 24.1 **Balancing a compass**

Compasses made for use in northern latitudes are weighted so that the south pole of their needle is slightly heavier than the north pole. Explain why this is done.

REASON Figure 24.7b shows that, at northern latitudes, the magnetic field of the earth has a large vertical component. A compass needle that pivots to line up with the field has its north pole pointing north, but the north pole also tips down to follow the field. To keep the compass balanced, there must be an extra force on the south end of the compass. A small weight on the south pole provides a force that keeps the needle balanced.

ASSESS This strategy makes sense. Keeping the needle horizontal when the field is not horizontal requires some extra force.

STOP TO THINK 24.2 A compass is placed next to a bar magnet as shown. Which figure shows the correct alignment of the compass?



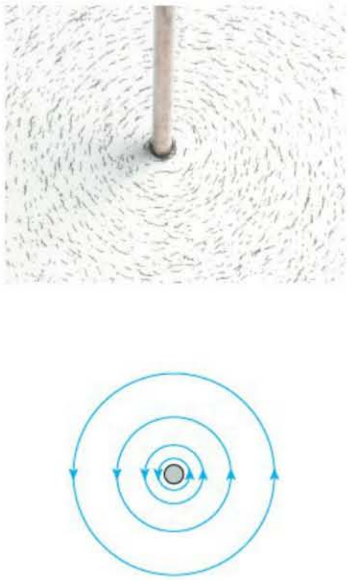
24.3 Electric Currents Also Create Magnetic Fields

As electricity began to be studied seriously in the 18th century, some scientists speculated that there might be a connection between electricity and magnetism. The link between the two was discovered in 1819 by the Danish scientist Hans Christian Oersted. Oersted was using a battery to produce a large current in a wire and he noticed that the current caused a nearby compass needle to turn. The compass responded as if a magnet had been brought near. Oersted concluded that an *electric* current produces a *magnetic* field.

Before we study these fields in detail, let's start with an overview of the fields we will see in the coming sections.

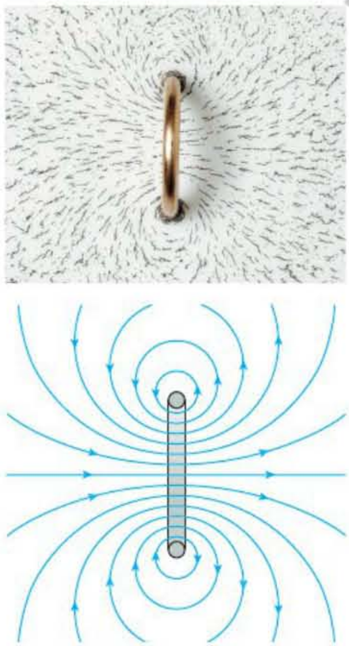
An atlas of magnetic fields produced by currents

Current in a long, straight wire



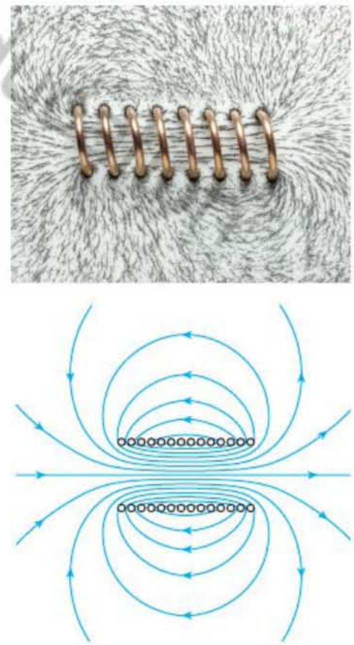
The magnetic field lines form *circles* around the wire. The iron filings are less affected by the field as the distance from the wire increases, indicating that the field is getting weaker as the distance increases.

A circular loop of current



The magnetic field lines curve through the center of the loop, around the outside, and back through the loop's center, forming complete closed curves. Notice that field lines far from the loop look like the field lines far from a bar magnet.

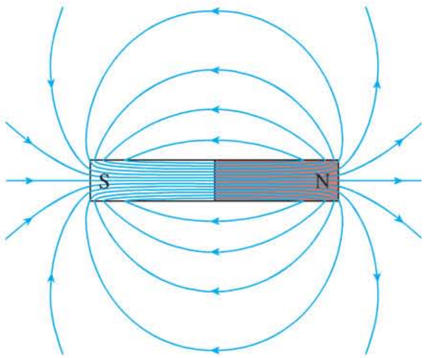
Current in a solenoid



A coil or **solenoid** is essentially a series of current loops placed along a common axis. The field outside the coil is very weak compared to the field inside. Inside the solenoid, the magnetic field lines are reasonably evenly spaced. The magnetic field inside a solenoid is nearly uniform.

There are striking similarities between the iron filing patterns created by currents in wires and those created by magnets. As we develop our understanding of magnetic fields, we'll look at the similarities and differences between fields from these two different sources.

FIGURE 24.8 Field lines form closed curves for magnets, too.



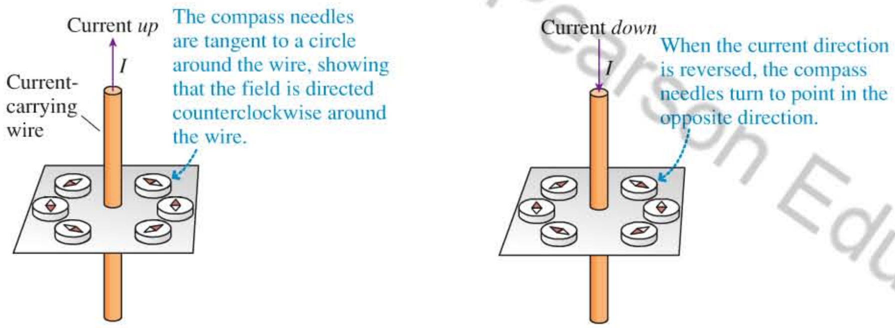
Earlier we noted that the field lines of magnets start and end on magnetic poles. However, the field lines due to currents have no start or end: They form complete closed curves. If we consider the field lines continuing *inside* a magnet, however, we find that these lines also form complete closed curves, as shown in FIGURE 24.8. In fact, *all* magnetic field lines form complete curves.

In this and the next section, we'll explore in some detail the magnetic fields created by currents; later, we'll look again at fields due to magnets. Ordinary magnets are often called **permanent magnets** to distinguish their unchanging magnetism from that caused by currents that can be switched on and off. We look at magnetism in this order because magnetism from currents is easier to understand, but keep in mind that currents and magnets are both equally important sources of magnetic fields.

The Magnetic Field of a Straight, Current-Carrying Wire

From the previous atlas picture, we see that the iron filings line up in *circles* around a straight, current-carrying wire. As FIGURE 24.9 shows, we also can use our basic instrument, the compass, to determine the direction of the magnetic field.

FIGURE 24.9 How compasses respond to a current-carrying wire.

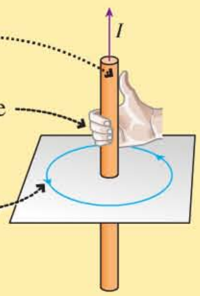


To help remember in which direction compasses will point, we use the *right-hand rule* shown in Tactics Box 24.1. We'll use this same rule later to find the direction of the magnetic field due to several other shapes of current-carrying wire, so we'll call this rule the **right-hand rule for fields.**

TACTICS BOX 24.1 Right-hand rule for fields

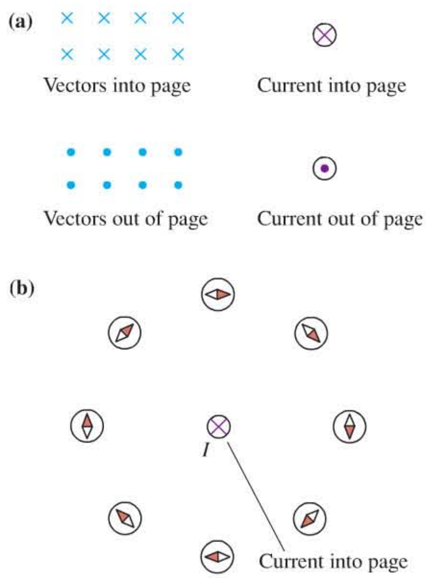
MP™

1. Point your *right* thumb in the direction of the current.
2. Wrap your fingers around the wire to indicate a circle.
3. Your fingers curl in the direction of the magnetic field lines around the wire.



Exercises 6–11

FIGURE 24.10 The notation for vectors and currents that are perpendicular to the page.



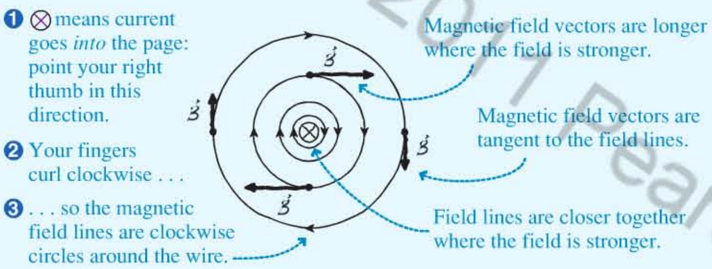
Magnetism is more demanding than electricity in often requiring a three-dimensional perspective of the sort shown in Tactics Box 24.1. But since two-dimensional figures are easier to draw, we will make as much use of them as we can. Consequently, we will often need to indicate field vectors or currents that are perpendicular to the page. FIGURE 24.10a shows the notation we will use. Then FIGURE 24.10b demonstrates this notation by showing the compasses around a current that is directed into the page. To use the right-hand rule with this drawing, point your right thumb into the page. Your fingers will curl clockwise, and that is the direction in which the north poles of the compass needles point.

CONCEPTUAL EXAMPLE 24.2 **Drawing the magnetic field of a current-carrying wire**

Sketch the magnetic field of a long, current-carrying wire, with the current going into the paper. Draw both magnetic field line and magnetic field vector representations.

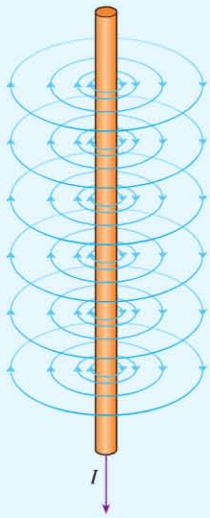
REASON From the iron filing picture in the atlas, we have seen that the field lines form circles around the wire, and the magnetic field becomes weaker as the distance from the wire is increased. **FIGURE 24.11** shows how we construct both field line and field vector representations of such a field.

FIGURE 24.11 Drawing the magnetic field of a long, straight, current-carrying wire.



ASSESS Figure 24.11 shows the key features of the field, but it's important that you understand its limitations. Although we've drawn only a few circles, the magnetic field actually exists at *all* points around the wire, out to arbitrarily great distances—although it gets quite weak as we move far from the wire. Figure 24.11 shows the field lines only in a single plane perpendicular to the wire. A more complex 3-D drawing, such as **FIGURE 24.12**, is necessary to convey the idea that the field lines also exist in *every* plane along the length of the wire.

FIGURE 24.12 Field lines exist everywhere along the wire.



The Magnetic Field of a Current Loop

We can extend our understanding of the field from a long, straight, current-carrying wire to the fields due to other shapes of current-carrying wires. Let's look at the other two configurations described in the atlas: a simple circular loop of wire (a *current loop*) and a tightly wound coil (a *solenoid*).

Let's start with the simple circular current-carrying loop, shown in three views in **FIGURE 24.13**. To see what the field due to a current loop looks like, we can imagine bending a straight wire into a loop, as shown in **FIGURE 24.14**. As we do so, the field lines near the wire will remain similar to what they looked like when the wire was still straight: circles going around the wire. Farther from the wires the field lines are no longer circles, but they still curve through the center of the loop, back around the outside, and then return through the center.

FIGURE 24.13 Three views of a current loop.

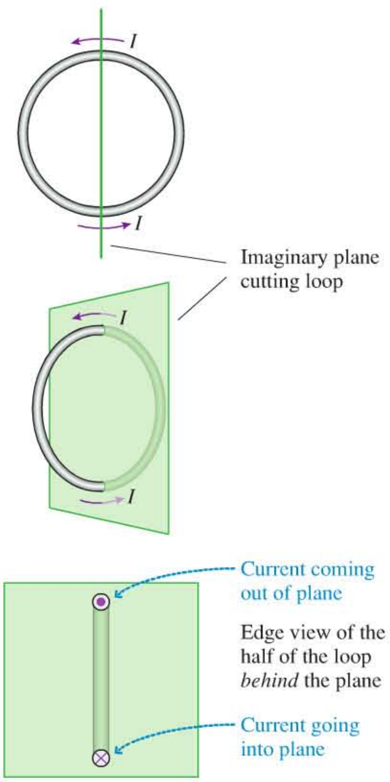
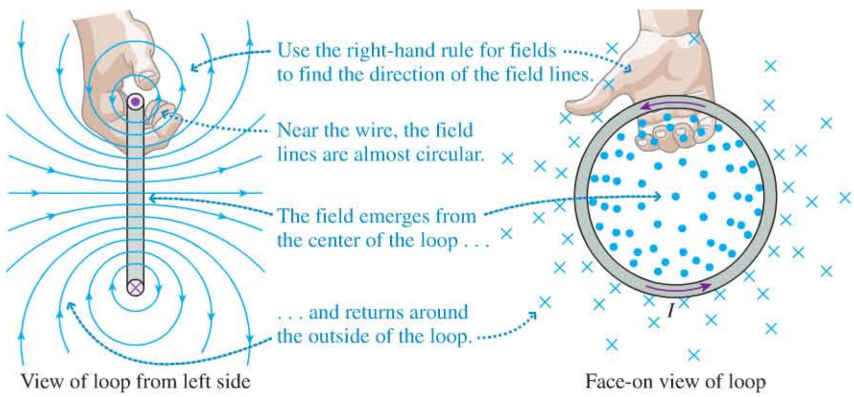
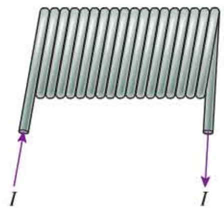


FIGURE 24.14 The magnetic field of a current loop.



If we reverse the direction of the current in the loop, all the field lines reverse direction as well. Because a current loop is essentially a straight wire bent into a circle, the same right-hand rule of Tactics Box 24.1, used to find the field direction for a long, straight wire, can also be used to find the field direction for a current loop. As shown in Figure 24.14, you again point your thumb in the direction of the current in the loop and let your fingers curl through the center of the loop. Your fingers are then pointing in the direction in which $\vec{B}$ passes through the *center* of the loop.

FIGURE 24.15 A solenoid.

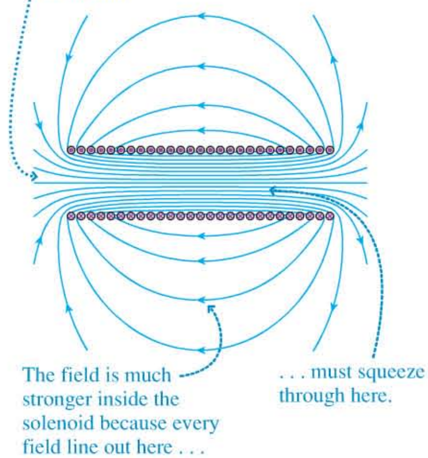


The Magnetic Field of a Solenoid

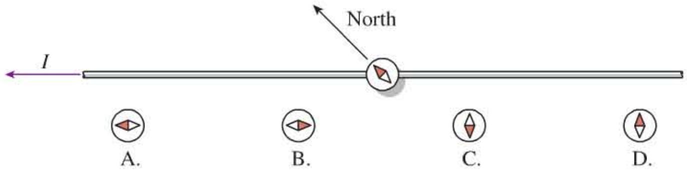
There are many applications of magnetism, such as the MRI system used to make the image at the beginning of this chapter, for which we would like to generate a **uniform magnetic field,** a field that has the same magnitude and the same direction at every point within some region of space. As we've seen, a reasonably uniform magnetic field can be generated with a **solenoid.** A solenoid, as shown in **FIGURE 24.15**, is a coil of wire with the same current I passing through each loop in the coil. Solenoids may have hundreds or thousands of coils, often called *turns,* sometimes wrapped in several layers.

The iron filing picture in the atlas on page 782 shows us that **the field within the solenoid is strong, mainly parallel to the axis, and reasonably uniform, whereas the field outside the solenoid is very weak.** **FIGURE 24.16** reviews these points and shows why the field inside is much stronger than the field outside. The field direction inside the solenoid can be determined by using the right-hand rule for any of the loops that form it.

FIGURE 24.16 The field of a solenoid.



STOP TO THINK 24.3 A compass is placed a few centimeters above a very long wire with no current. Because of the earth's field, the needle points north. When a large current is turned on in the direction shown, in which direction will the compass point?



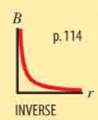
24.4 Calculating the Magnetic Field Due to a Current

ActivPhysics ONLINE 13.1

The previous section showed qualitatively how the magnetic field looks for several shapes of current-carrying wires. In this section, we'll give quantitative expressions for these magnetic fields.

Let's start with the simplest case—that of a long, straight, current-carrying wire. We've seen already that the magnetic field lines form circles around the wire and that the field gets weaker as the distance from the wire increases. Not surprisingly, the magnitude of the field also depends on the *current* through the wire, increasing in proportion to the current. The magnitude of the magnetic field a distance r from the wire carrying current I is given by the expression

$$B = \frac{\mu_0 I}{2\pi r} \tag{24.1}$$

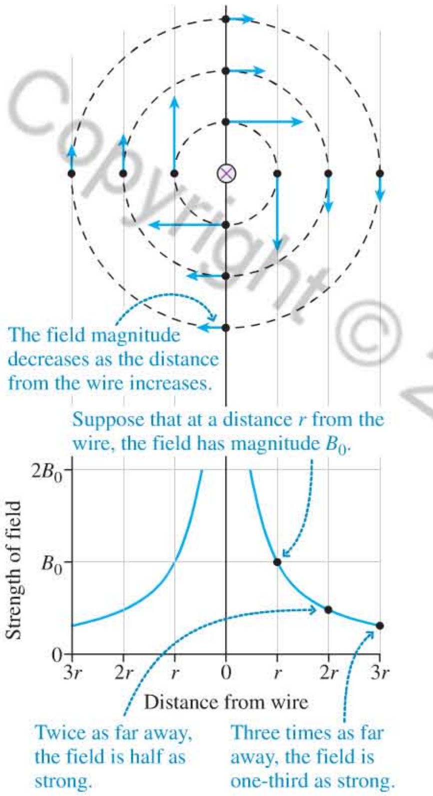


Magnetic field due to a long, straight, current-carrying wire

TABLE 24.1 Typical magnetic field strengths

Field location	Field strength (T)
Surface of the earth	5×10^{-5}
Refrigerator magnet	5×10^{-3}
Laboratory magnet	0.1 to 1
Superconducting magnet	10

FIGURE 24.17 The magnetic field due to a long, current-carrying wire.



Although this equation is exact only for an infinitely long wire, it is quite accurate whenever the length of the wire is significantly greater than the distance r from the wire. **FIGURE 24.17** shows how the field varies with distance from the wire.

The SI unit of the magnetic field is the **tesla,** abbreviated as T. One tesla is quite a large field. Table 24.1 on the previous page shows some typical magnetic field strengths. Most magnetic fields are a small fraction of a tesla. We sometimes express magnetic fields in μT (10^{-6} T) or mT (10^{-3} T). The strength of the earth's field varies from place to place, but a good average strength, which you can use for solving problems, is 50 μT.

The constant μ_0, which relates the strength of the magnetic field to the currents that produce it, in Equation 24.1 is called the **permeability constant.** Its role in magnetic field expressions is similar to the role of the permittivity constant ϵ_0 in electric field expressions. Its value is

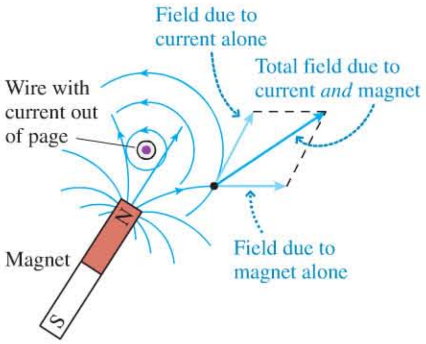
$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{T \cdot m/A} = 1.257 \times 10^{-6}\ \mathrm{T \cdot m/A}$$

Magnetic Fields from More Than One Source

When two or more sources of magnetic fields are brought near each other, how do we find the total magnetic field at any particular point in space? For electric fields, we used the principle of superposition: The total electric field at any point is the *vector* sum of the individual fields at that point. The same principle holds for magnetic fields as well. **FIGURE 24.18** illustrates the principle of superposition applied to *magnetic* fields.

We've now learned enough to suggest the following general problem-solving strategy for finding the magnetic field at a point due to known sources of magnetic field.

FIGURE 24.18 Adding fields due to more than one source.



PROBLEM-SOLVING STRATEGY 24.1 **Magnetic field problems** MP™

PREPARE Because current-carrying wires do not lie in the same plane as the fields they produce, you'll need to prepare an especially careful drawing. Generally, you should choose the plane of your drawing so that the magnetic field vectors lie either in the plane of the paper or perpendicular to it.

- Straight wires are usually easiest to draw as seen from their ends. Then the field vectors will lie in the plane of the paper.
- Usually, it's best to draw current loops in the plane of the paper. Then the field in the loop's center is perpendicular to the paper.
- Solenoids can be drawn either end-on (field perpendicular to the plane of the paper) or as seen from the side (field in the plane of the paper).
- If the problem has more than one source of magnetic field, it's usually best that your drawing shows the field vectors in the plane of the paper. Then they can be added as vectors, using coordinate systems and components if needed.

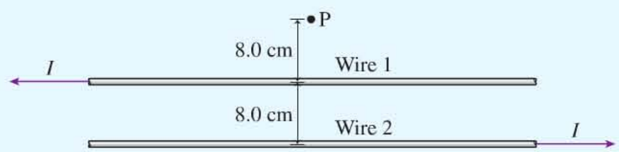
SOLVE Find the directions of the fields due to each source (wire, loop, solenoid) by using the right-hand rule for fields. Then find the magnitude of each field using the expressions given in this section for a wire, a loop, or a solenoid. Finally, add these fields together using the rules for vector addition.

ASSESS Check if the magnitude and direction of the total field seem reasonable.

Exercise 17

EXAMPLE 24.3 **Finding the magnetic field of two parallel wires**

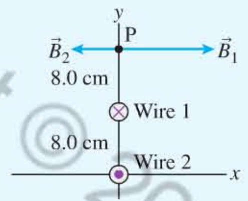
Two long, straight wires lie parallel to each other, as shown in **FIGURE 24.19**. They each carry a current of 5.0 A, but in opposite directions. What is the magnetic field at point P?



▶ **FIGURE 24.19** Two parallel current-carrying wires.

PREPARE Redraw the wires as seen from their right ends, as in **FIGURE 24.20**, and add a coordinate system. In this view, the right-hand rule for fields tells us that the magnetic field at P from wire 1 points to the right and that from wire 2 to the left. Because wire 2 is twice as far from P as wire 1, we've drawn its field $\vec{B}_2$ half as long as the field $\vec{B}_1$ from wire 1.

FIGURE 24.20 View of the wires from their right ends.



SOLVE From Figure 24.20, we can see that the total field $\vec{B}$—the vector sum of the two fields $\vec{B}_1$ and $\vec{B}_2$—points to the right. To find the magnitude of $\vec{B}$, we'll need the magnitudes of $\vec{B}_1$ and $\vec{B}_2$

We can use Equation 24.1 to find these magnitudes. From Figure 24.20, r for wire 1 is 8.0 cm (or 0.080 m), while r for wire 2 is 16 cm.

We then have

$$B_1 = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \mathrm{T \cdot m/A})(5.0\ \mathrm{A})}{2\pi(0.080\ \mathrm{m})} = 1.25 \times 10^{-5}\ \mathrm{T}$$

and

$$B_2 = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \mathrm{T \cdot m/A})(5.0\ \mathrm{A})}{2\pi(0.16\ \mathrm{m})} = 0.63 \times 10^{-5}\ \mathrm{T}$$

Because $\vec{B}_2$ points to the left, its x-component is negative. Thus, the x-component of the total field $\vec{B}$ is

$$\begin{aligned} B_x &= (B_1)_x + (B_2)_x \\ &= 1.25 \times 10^{-5}\ \mathrm{T} - 0.63 \times 10^{-5}\ \mathrm{T} = 0.62 \times 10^{-5}\ \mathrm{T} \\ &= 6.2\ \mu\mathrm{T} \end{aligned}$$

In terms of the original view of the problem in Figure 24.19, we can write

$$\vec{B} = (6.2\ \mu\mathrm{T},\ \text{into the page})$$

ASSESS That B_x is positive tells us that the total field points to the right, in the same direction as the field due to wire 1. This makes sense, because wire 1 is closer to P than is wire 2.

Current Loops

ActivPhysics Online 13.2

The magnetic field due to a current loop is more complex than that of a straight wire, as we can see from **FIGURE 24.21**, but there is a simple expression for the field at an important place: the *center* of the loop. Because the loop can be thought of as a wire bent into a circle (of radius R), the expression for the field at the center is very similar to that of a wire. The field at the center is given by

$$B = \frac{\mu_0 I}{2R} \tag{24.2}$$

Magnetic field at the center of a current loop of radius R

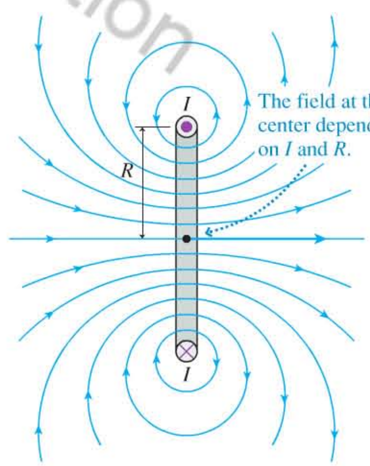
where I is the current in the loop. We have already seen how to find the *direction* of the field in the center, using our right-hand rule for fields.

If N loops of wire carrying the same current I are all tightly wound into a single thin coil, then the field at the center is just N times bigger (since we're superimposing N individual current loops):

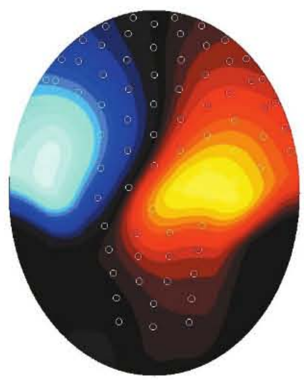
$$B = \frac{\mu_0 N I}{2R} \tag{24.3}$$

Magnetic field at the center of a thin coil with N turns

FIGURE 24.21 The magnetic field at the center of a current loop.



▶ **The magnetocardiogram** BIO When the heart muscle contracts, action potentials create a dipole electric field that can be measured to create an electrocardiogram. These action potentials also cause charges to circulate around the heart, creating a current loop. This current loop creates a small, but measurable, magnetic field. A record of the heart's magnetic field, a *magnetocardiogram,* can provide useful information about the heart in cases where an electrocardiogram is not possible. This image shows the magnetic field of a fetal heartbeat measured at the surface of the mother's abdomen. Here, blue represents a field pointing into the body and red a field out of the body. This is just the field expected from a current loop whose plane lies along the black line between the two colored areas.

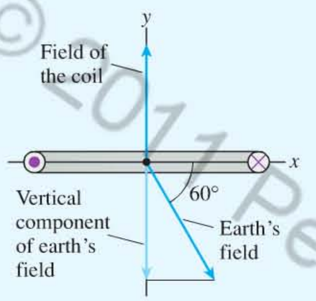


EXAMPLE 24.4 **Canceling the earth's field**

Green turtles are thought to navigate by using the dip angle of the earth's magnetic field. To test this hypothesis, green turtle hatchlings were placed in a 72-cm-diameter tank with a 50-turn coil of wire wrapped around the outside. A current in the coil created a magnetic field at the center of the tank that exactly canceled the vertical component of earth's 50 μT field. At the location of the test, the earth's field was directed 60° below the horizontal. What was the current in the coil?

PREPARE FIGURE 24.22 shows the earth's field passing downward through the coil. To cancel the vertical component of this field, the current in the coil must generate an upward field of equal magnitude. We can use the right-hand rule (see Figure 24.14) to find that the current must circulate around the coil as shown. Viewed from above, the current will be counterclockwise.

FIGURE 24.22 The coil field needed to cancel the earth's field.



SOLVE The vertical component of the earth's field is

$$(B_{\text{earth}})_y = -(50 \times 10^{-6}\ \text{T})\sin(60°) = -43 \times 10^{-6}\ \text{T}$$

The field of the coil, given by Equation 24.3, must have the same magnitude at the center. The $2R$ in the equation is just the diameter of the coil, 72 cm or 0.72 m. Thus

$$B_{\text{coil}} = \frac{\mu_0 NI}{2R} = 43 \times 10^{-6}\ \text{T}$$

$$I = \frac{(43 \times 10^{-6}\ \text{T})(2R)}{(\mu_0 N)}$$

$$= \frac{(43 \times 10^{-6}\ \text{T})(0.72\ \text{m})}{(4\pi \times 10^{-7}\ \text{T/m} \cdot \text{A})(50)} = 0.49\ \text{A}$$

As noted, this current is counterclockwise as viewed from above.

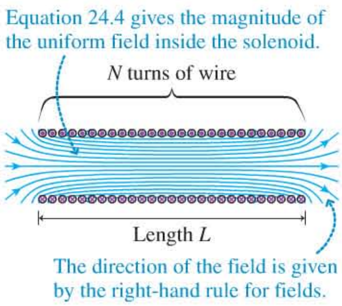
ASSESS This seems like a reasonable current. The earth's field isn't very strong, so the coil need not carry a large current to cancel it.

Solenoids

13.3 ActivPhysics ONLINE

As we've seen, the field inside a solenoid is fairly uniform, while the field outside is quite small; the greater a solenoid's length in comparison to its diameter, the better these statements hold. Measurements that need a uniform magnetic field are often conducted inside a solenoid, which can be built quite large. The cylinder that surrounds a patient undergoing magnetic resonance imaging (MRI), such as the one shown on the next page, contains a large solenoid made of superconducting wire, allowing it to carry the very large currents needed to generate a strong uniform magnetic field. Consider a solenoid of length L having N turns of wire, as in FIGURE 24.23. We expect that the more turns we can pack into a solenoid of a given length—that is, the greater the ratio N/L—the stronger the field inside will be. We further expect that the strength of the field will be proportional to the current I in the turns. Somewhat surprisingly, the field inside a solenoid does *not* depend on its radius. For this reason, the radius R doesn't appear in the equation for the field inside a solenoid:

FIGURE 24.23 The magnetic field inside a solenoid.



$$B = \mu_0 I \frac{N}{L} \tag{24.4}$$

Magnetic field inside a solenoid of length L with N turns

EXAMPLE 24.5 **Generating an MRI magnetic field**

A typical MRI solenoid has a length of about 1 m and a diameter of about 1 m. A typical field inside such a solenoid is about 1 T. How many turns of wire must the solenoid have to produce this field if the largest current the wire can carry is 100 A?

PREPARE This solenoid is not very long compared to its diameter, so using Equation 24.4 will give only an approximate result. This is acceptable, since we have only rough estimates of the field B and the length L.

Equation 24.4 gives the magnetic field B of a solenoid in terms of the current I, the number of turns N, and the length L. Here, however, we want to find the number of turns in terms of the other variables. We'll need $B = 1$ T, $I = 100$ A, and $L = 1$ m.

SOLVE We can solve Equation 24.4 for N to get

$$N = \frac{LB}{\mu_0 I} = \frac{(1\ \text{m})(1\ \text{T})}{(4\pi \times 10^{-7}\ \text{T} \cdot \text{m/A})(100\ \text{A})} = 8000\ \text{turns}$$

to one significant figure.

ASSESS The number of turns required is quite large, but the field is quite large, so this makes sense.

The amount of wire in an MRI solenoid is surprisingly large. In the above example, the diameter of the solenoid was about 1 m. The length of wire in each turn is thus $\pi \times 1$ m, or about 3 m. The total length of wire is then about 8000 turns $\times$ 3 m/turn $=$ 24,000 m $=$ 24 km $\approx$ 15 miles! If this magnet used ordinary copper wire large enough to carry 100 A, the total resistance R would be about 35 Ω. We learned in Chapter 23 that the power dissipated by a resistor is equal to I^2R, so the total power would be about $(100\text{ A})^2(35\ \Omega) = 350{,}000$ W, a huge and impractical value. MRI magnets must use *superconducting* wire, which when cooled near absolute zero has *zero* resistance. This allows 24 km of wire to carry 100 A with no power dissipation at all.

A patient's head in the solenoid of an MRI scanner.

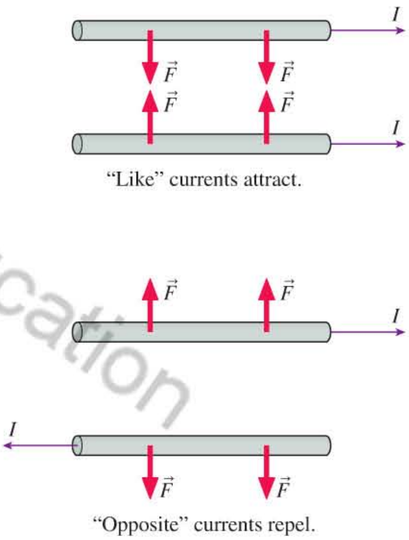
24.5 Magnetic Fields Exert Forces on Moving Charges

It's time to switch our attention from what magnetic fields look like and how they are generated to what they actually *do:* exert forces and torques on moving charges and currents. As we saw earlier in the chapter, Oersted discovered that a current passing through a wire deflects a nearby compass. Upon hearing of Oersted's discovery, the French scientist André Marie Ampère reasoned that the current was acting like a magnet and that two current-carrying wires should exert magnetic forces on each other, just as two magnets do.

Ampère set up two parallel wires that could carry large currents in either the same direction or in opposite directions. **FIGURE 24.24** shows the outcome of his experiment: For currents, "likes" attract and "opposites" repel. This is the opposite of what would have happened had the wires been charged and thus exerting electric forces on each other.

Ampère's experiment showed that **a magnetic field exerts a force on a current.** Since currents consist of moving charges, Ampère's experiment therefore also implies that **a magnetic field exerts a force on a moving charged particle.** Let's explore the nature of this force.

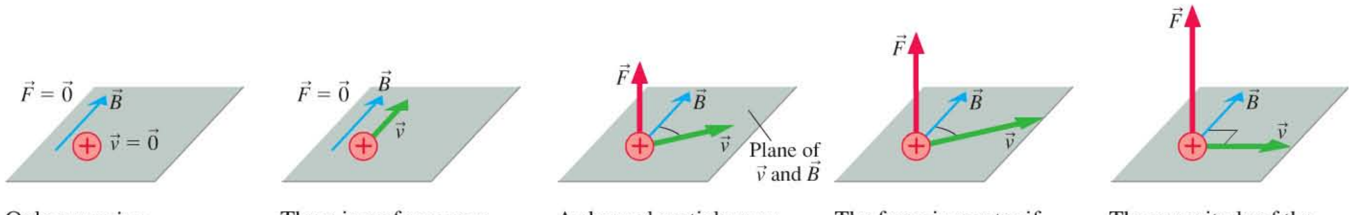
FIGURE 24.24 The forces between parallel current-carrying wires.



The Magnetic Force on a Moving Charged Particle

The following series of experiments illustrates the nature of the magnetic force on a moving charged particle.

The force on a charged particle moving in a magnetic field



Only a *moving* charged particle experiences a magnetic force. There is no magnetic force on a charge at rest ($v = 0$) in a magnetic field.

There is no force on a charged particle moving *parallel* to a magnetic field. There is a force only if the charged particle is moving at an angle to the field.

A charged particle moving at an angle to the field *does* experience a force. This force is perpendicular to *both* $\vec{v}$ and $\vec{B}$. That is, the force is at right angles to the plane containing $\vec{v}$ and $\vec{B}$.

The force is greater if the particle moves faster or if the magnitude of the charge is increased.

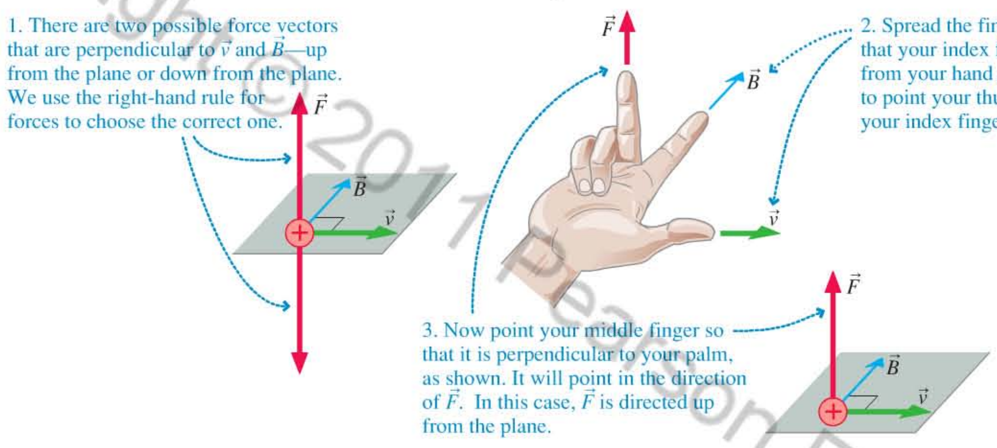
The magnitude of the force depends on the angle between $\vec{v}$ and $\vec{B}$. For given values of v and B, the force is greatest when the angle between $\vec{v}$ and $\vec{B}$ is 90°.

The magnetic force is quite different from the electric force: A charged particle in an electric field feels a force that is *parallel* to the field, but a charged particle moving in a magnetic field feels a force that is *perpendicular* to the field.

The magnetic force on a moving charged particle is perpendicular to the field and the velocity, but this is not sufficient to uniquely determine the direction of the force. We also need the **right-hand rule for forces,** as shown in FIGURE 24.25.

NOTE ► The right-hand rule for forces is different from the right-hand rule for fields. ◄

FIGURE 24.25 The right-hand rule for forces.



NOTE ► The right-hand rule for forces gives the direction of the force on a *positive* charge. For a negative charge, the force is in the opposite direction. ◄

13.4 ActivPhysics ONLINE

We can organize all of the experimental information about the magnetic force on a moving charged particle into a single equation. If a particle of charge q moves with a velocity $\vec{v}$ at an angle α to a magnetic field $\vec{B}$, the force is

$$\vec{F} = (|q|vB\sin\alpha, \text{ direction given by the right-hand rule for forces}) \qquad (24.5)$$

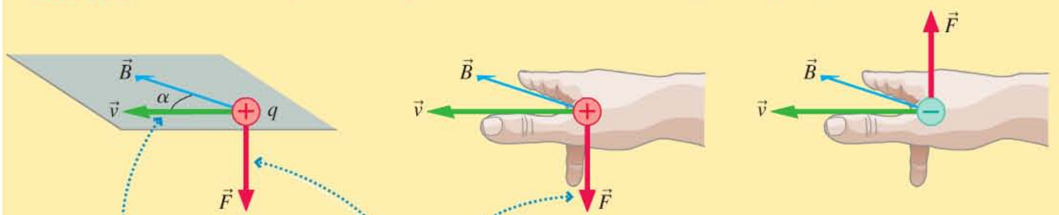
Force on a charged particle moving in a magnetic field

The velocity and the magnetic field are perpendicular in many practical situations. In this case α is 90°, and we can simplify Equation 24.5 to

$$\vec{F} = (|q|vB, \text{ direction given by the right-hand rule for forces}) \qquad (24.6)$$

The following Tactics Box summarizes and shows how to use the above information.

TACTICS BOX 24.2 Determining the magnetic force on a moving charged particle



$F = |q|vB\sin\alpha$

❶ Note the direction of $\vec{v}$ and $\vec{B}$, and find the angle α between them.

❷ The force is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$. The direction of $\vec{F}$ is given by the right-hand rule.

❸ For a negative charge, the force is in the direction opposite that predicted by the right-hand rule.

❹ The magnitude of the force is given by Equation 24.5.

Exercises 18, 19

CONCEPTUAL EXAMPLE 24.6 Determining the force on a moving electron

An electron is moving to the right in a magnetic field that points upward, as in **FIGURE 24.26**. What is the direction of the magnetic force?

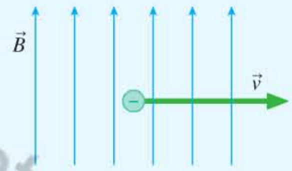


FIGURE 24.26 An electron moving in a magnetic field.

REASON **FIGURE 24.27** shows how the right-hand rule for forces is applied to this situation:

- Point your right thumb in the direction of the electron's velocity and your index finger in the direction of the magnetic field.
- Bend your middle finger to be perpendicular to your index finger. Your middle finger, which now points out of the page, is the direction of the force on a positive charge. But the electron is negative, so the force on the electron is *into* the page.

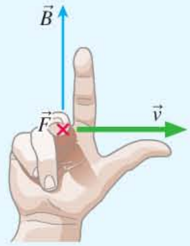


FIGURE 24.27 Using the right-hand rule.

ASSESS The force is perpendicular to both the velocity and the magnetic field, as it must be. The force on an electron is into the page; the force on a proton would be out of the page.

CONCEPTUAL EXAMPLE 24.7 Determining the force on a charged particle moving near a current-carrying wire

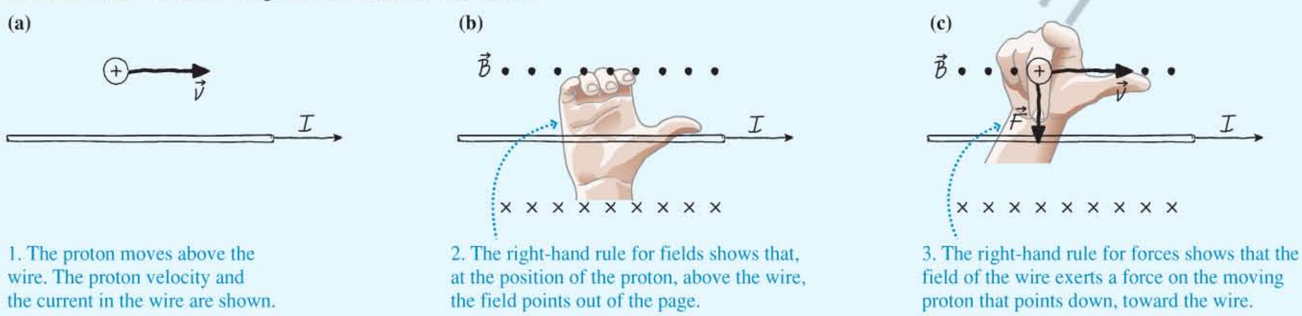
A proton is moving to the right above a horizontial wire that carries a current to the right. What is the direction of the magnetic force on the proton?

REASON The current in the wire creates a magnetic field; this magnetic field exerts a force on the moving proton. We follow three steps to solve the problem:

1. Sketch the situation, as shown in **FIGURE 24.28a**.
2. Determine the direction of the field at the position of the proton due to the current in the wire (**FIGURE 24.28b**).
3. Determine the direction of the force that this field exerts on the proton (**FIGURE 24.28c**). In this case, the force is down.

ASSESS At the start of this section, where we looked at the forces between currents, we saw that "like" currents attract each other. So we'd expect that a proton moving to the right, which is essentially a small current in the same direction as the current in the wire, will feel a force toward the wire.

FIGURE 24.28 Determining the direction of the force.



EXAMPLE 24.8 Force on a charged particle in the earth's field

The sun emits streams of charged particles (in what is called the *solar wind*) that move toward the earth at very high speeds. A proton is moving toward the equator of the earth at a speed of 500 km/s. At this point, the earth's field is 5.0×10^{-5} T directed parallel to the earth's surface. What are the direction and the magnitude of the force on the proton?

PREPARE Our first step is, as usual, to draw a picture. As we saw in Figure 24.7a, the field lines of the earth go from the earth's south pole to the earth's north pole. **FIGURE 24.29** shows the proton entering the field, which is directed north.

We also need to convert the proton's velocity to m/s:

$$500 \text{ km/s} = 5.0 \times 10^2 \text{ km/s} \times \frac{1 \times 10^3 \text{ m}}{1 \text{ km}} = 5.0 \times 10^5 \text{ m/s}$$

SOLVE We use the steps of Tactics Box 24.2 to determine the force.

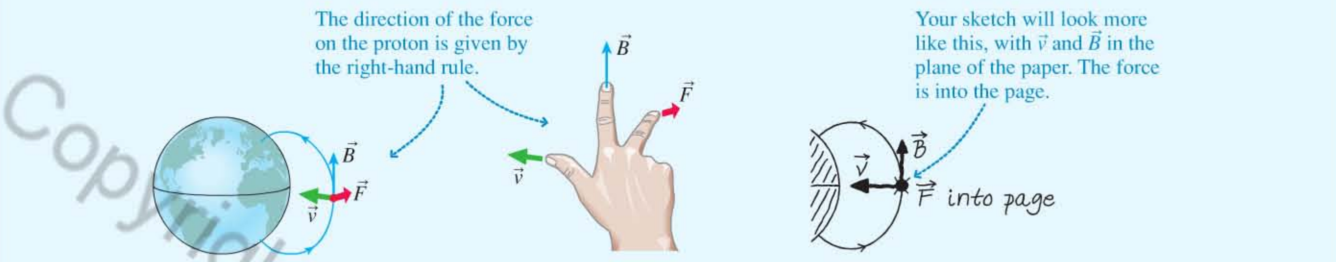
❶ $\vec{v}$ and $\vec{B}$ are perpendicular, so $\alpha = 90°$.
❷ The right-hand rule for forces tells us that the force will be into the page in Figure 24.29. That is, the force is toward the east.
❹ We compute the magnitude of the force using Equation 24.6:

$$F = |q|vB = (1.6 \times 10^{-19} \text{ C})(5.0 \times 10^5 \text{ m/s})(5.0 \times 10^{-5} \text{ T})$$
$$= 4.0 \times 10^{-18} \text{ N}$$

ASSESS This is a small force, but the proton has an extremely small mass of 1.67×10^{-27} kg. Consequently, this force produces a very large acceleration: 200 million times the acceleration due to gravity!

Continued

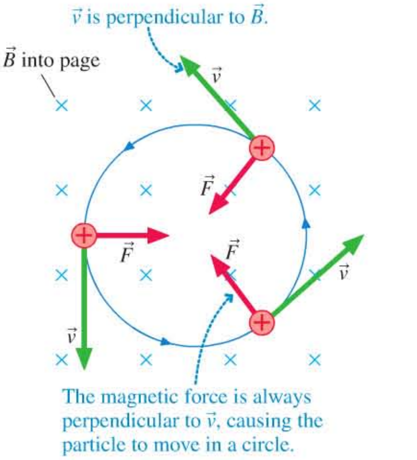
FIGURE 24.29 A proton in the field of the earth.



Example 24.8 looked at the force on a proton from the sun as it reaches the magnetic field of the earth. How does this force affect the motion of the proton? Let's consider the general question of how charged particles move in magnetic fields.

Paths of Charged Particles in Magnetic Fields

FIGURE 24.30 A charged particle moving perpendicular to a uniform magnetic field.



We know that the magnetic force on a moving charged particle is always perpendicular to its velocity. This means that the force changes the *direction* of the velocity but not the *magnitude*. The particle's path will bend, but the particle will not speed up or slow down. Suppose a positively charged particle is moving perpendicular to a uniform magnetic field $\vec{B}$, as shown in FIGURE 24.30. In Chapter 6, we looked at the motion of objects subject to a force that was always perpendicular to the velocity. The net result was *circular motion at a constant speed*. For a mass moving in a circle at the end of a string, the tension force is always perpendicular to $\vec{v}$. For a satellite moving in a circular orbit, the gravitational force is always perpendicular to $\vec{v}$. Now, for a charged particle moving in a magnetic field, it is the magnetic force that is always perpendicular to $\vec{v}$ and so causes the particle to move in a circle. Thus, **a particle moving perpendicular to a uniform magnetic field undergoes uniform circular motion at constant speed.**

NOTE ► The direction of the force on a negative charge is opposite to that on a positive charge, so a particle with a negative charge will orbit in the opposite sense from that shown in Figure 24.30 for a positive charge. ◄

FIGURE 24.31 A particle in circular motion.

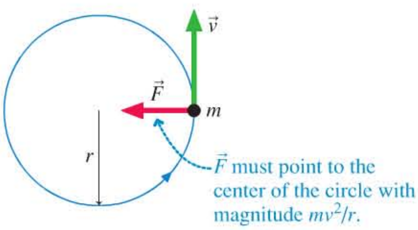


FIGURE 24.31 shows a particle of mass m moving at a speed v in a circle of radius r. We found in Chapter 6 that this motion requires a force directed toward the center of the circle with magnitude

$$F = \frac{mv^2}{r} \tag{24.7}$$

For a charged particle moving in a magnetic field, this force is provided by the magnetic force. In Figure 24.30 we assumed that the velocity was perpendicular to the magnetic field, so the magnitude of the force on the charged particle due to the magnetic field is given by Equation 24.6. This is the force that produces the circular motion, so we can equate it to the force in Equation 24.7:

$$F = |q|vB = \frac{mv^2}{r}$$

Solving for the radius of the orbit, we get

$$r = \frac{mv}{|q|B} \tag{24.8}$$

The radius depends on the ratio of the mass of the particle to its charge, a fact we will use later. The radius also depends on the particle's speed and the magnetic field strength: Increasing the speed will increase the radius of the circular motion, while increasing the field will decrease the radius.

A particle moving *perpendicular* to a magnetic field moves in a circle. In the table at the start of this section, we saw that a particle moving *parallel* to a magnetic field experiences no magnetic force, and so continues in a straight line. A more general situation in which a charged particle's velocity $\vec{v}$ is neither parallel to nor perpendicular to the field $\vec{B}$ is shown in FIGURE 24.32. The net result is a circular motion due to the perpendicular component of the velocity coupled with a constant velocity parallel to the field: The charged particle spirals around the magnetic field lines in a helical trajectory.

High-energy particles stream out from the sun in the solar wind. Some of the charged particles of the solar wind become trapped in the earth's magnetic field. As FIGURE 24.33 shows, the particles spiral in helical trajectories along the earth's magnetic field lines. Some of these particles enter the atmosphere near the north and south poles, ionizing gas and creating the ghostly glow of the **aurora.**

FIGURE 24.32 A charged particle in a magnetic field follows a helical trajectory.

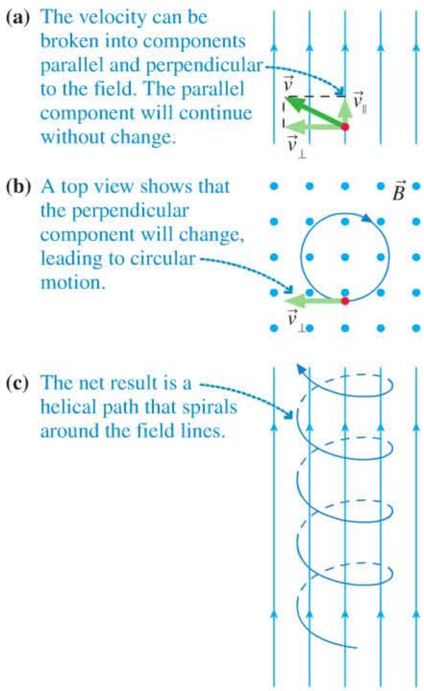


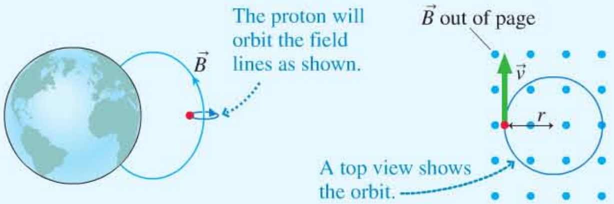
FIGURE 24.33 Charged particles in the earth's magnetic field create the aurora.

EXAMPLE 24.9 Force on a charged particle in the earth's field, revisited

In Example 24.8, we considered a proton in the solar wind moving toward the equator of the earth, where the earth's field is 5.0×10^{-5} T, at a speed of 500 km/s (5.0×10^5 m/s). We now know that the proton will move in a circular orbit around the earth's field lines. What are the radius and the period of the orbit?

PREPARE We begin with a sketch of the situation, noting the proton's orbit, as shown in FIGURE 24.34.

FIGURE 24.34 A proton orbits the earth's field lines.



SOLVE Before we use any numbers, we will do some work with symbols. The radius r of the orbit of the proton is given by Equation 24.8. The period T for one orbit is just the distance of one orbit (the circumference $2\pi r$) divided by the speed:

$$T = \frac{2\pi r}{v}$$

We substitute Equation 24.8 for the radius of the orbit of a charged particle moving in a magnetic field to get

$$T = \frac{2\pi}{v} r = \frac{2\pi}{\cancel{v}}\left(\frac{m\cancel{v}}{qB}\right) = \frac{2\pi m}{qB}$$

The speed cancels, and doesn't appear in the final expression. All protons in the earth's field orbit with the same period, regardless of their speed. A higher speed just means a larger circle, completed in the same time. Using values for mass, charge, and field, we compute the radius and the period of the orbit:

$$r = \frac{(1.67 \times 10^{-27}\ \text{kg})(5.0 \times 10^5\ \text{m/s})}{(1.60 \times 10^{-19}\ \text{C})(5.0 \times 10^{-5}\ \text{T})} = 100\ \text{m}$$

$$T = \frac{2\pi(1.67 \times 10^{-27}\ \text{kg})}{(1.60 \times 10^{-19}\ \text{C})(5.0 \times 10^{-5}\ \text{T})} = 0.0013\ \text{s}$$

ASSESS We can do a quick check on our math. We've found the radius of the orbit and the period, so we can compute the speed:

$$v = \frac{2\pi r}{T} = \frac{2\pi(100\ \text{m})}{0.0013\ \text{s}} = 5 \times 10^5\ \text{m/s}$$

This is the speed that we were given in the problem statement, which is a good check on our work.

13.7 ActivPhysics

FIGURE 24.35 Mass spectrum of the atmosphere of Jupiter.

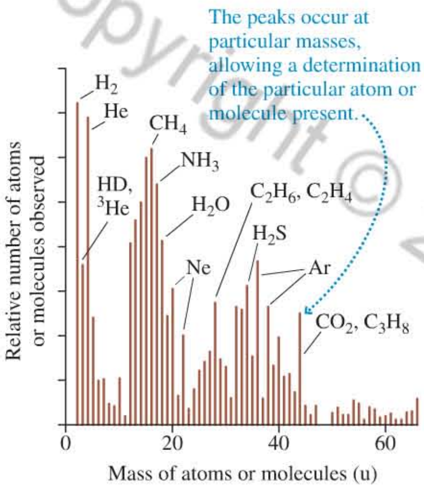
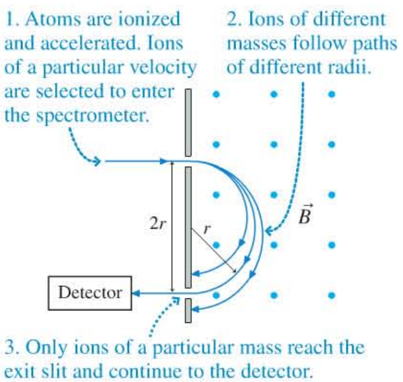


FIGURE 24.36 A mass spectrometer.



The Mass Spectrometer

In 1995, the Galileo spacecraft dropped a probe into Jupiter's atmosphere. One instrument on board, called a **mass spectrometer,** was used to determine the composition of the atmosphere. The data, shown in FIGURE 24.35, are called a **mass spectrum,** a record of the masses of atoms and molecules that were encountered.

It's possible to determine the mass of a charged atom or molecule by observing its circular path in a uniform magnetic field. As we've seen, the radius of the orbit depends on the magnetic field, the velocity of the particle, the charge of the particle, and, most important, the mass of the particle.

The operation of such a mass spectrometer is illustrated in FIGURE 24.36. A sample to be analyzed is collected and, if necessary, vaporized to form a gas. The atoms and molecules in this sample are then ionized: An electron is removed from each atom or molecule, leaving a positive ion. The ions are accelerated through an electric field, and ions of a particular velocity selected. These ions travel into a region of a uniform magnetic field, where they follow circular paths. An exit slit allows ions that have followed a particular path to be counted by a detector.

For a fixed field strength, only ions of a certain mass follow the necessary path to reach the detector. A rearrangement of Equation 24.8 gives the mass of the particles that reach the detector as

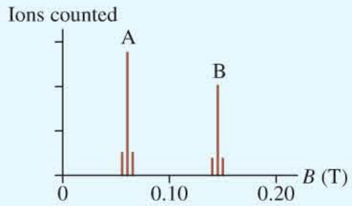
$$m = \frac{qBr}{v} \tag{24.9}$$

Varying the magnetic field scans, one by one, all the different ions in the sample across the exit slit where they can be detected. A plot of the number of ions recorded versus mass is a mass spectrum like the one in Figure 24.35. Mass spectrometers find wide application in chemistry and biology, from the detection of trace pollutants in groundwater to the identification of proteins in biological systems.

CONCEPTUAL EXAMPLE 24.10 Using a mass spectrometer

A mass spectrometer is measuring singly ionized atoms that enter the detector at the same speed. The detector is at a fixed position, and the field is varied to measure different ions. There are two clear peaks in the spectrum, as shown in FIGURE 24.37. Which one corresponds to a greater mass?

FIGURE 24.37 Mass spectrum for singly ionized atoms.



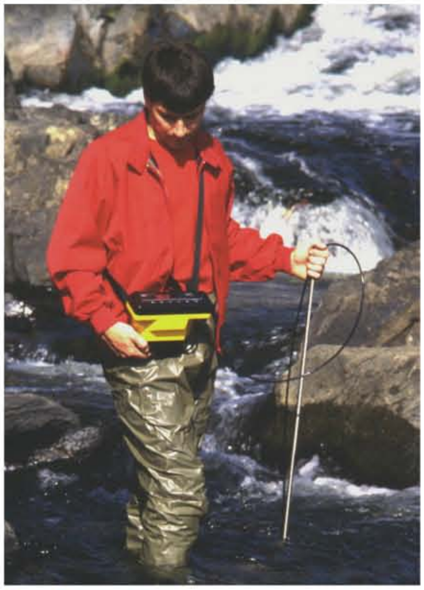
REASON The atoms all have the same charge and the same speed, and they follow the same path. Equation 24.9 indicates that a particle with greater mass m will require a stronger field B to send it to the detector. Peak B thus corresponds to a greater mass.

ASSESS Our result makes sense. The particles move through the same circular path at the same speed, so they have the same acceleration. The more massive particles will require a larger force—and thus a stronger field.

Electromagnetic Flowmeters

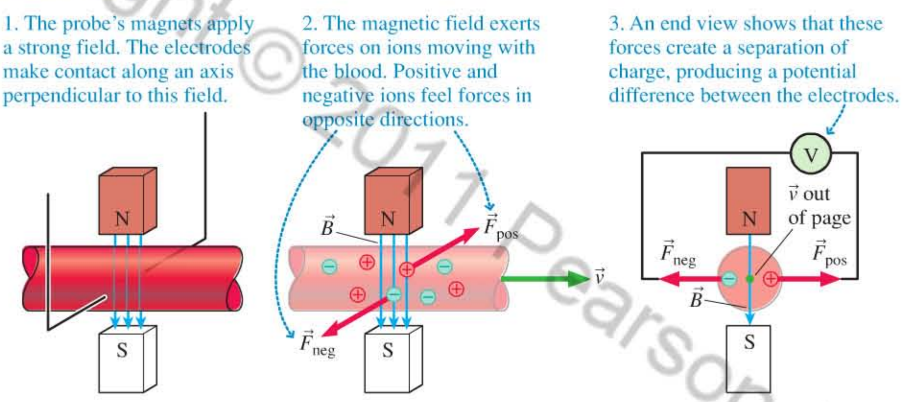
Blood contains many kinds of ions, such as Na^+ and Cl^-. When blood flows through a vessel, these ions move with the blood. An applied magnetic field will produce a force on these moving charges. We can use this principle to make a completely noninvasive device for measuring the blood flow in an artery: an *electromagnetic flowmeter.*

A flowmeter probe clamped to an artery has two active elements: magnets that apply a strong field across the artery and electrodes that contact the artery on opposite sides, as shown in FIGURE 24.38. The blood flowing in an artery carries a mix of positive and negative ions. Because these ions are in motion, the magnetic field exerts a force on them that produces a measurable voltage. We know from Equation 24.5 that the faster the blood's ions are moving, the greater the forces separating the positive and negative ions. The greater the forces, the greater the degree of separation and the larger the voltage. The measured voltage is therefore directly proportional to the velocity of the blood.

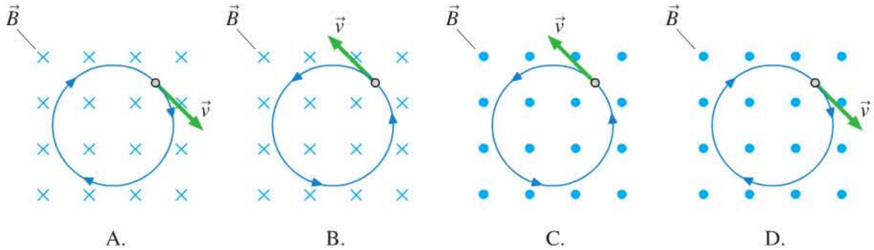


Go with the flow Many scientists and resource managers rely on accurate measurements of stream flows. The easiest way to get a quick measurement of the speed of a river or creek is to use an electromagnetic flowmeter similar to the one used for measuring flow in blood vessels. Water flows between the poles of a strong magnet. Two electrodes measure the resulting potential difference, which is proportional to the flow speed.

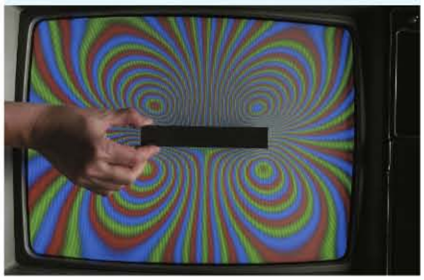
FIGURE 24.38 The operation of an electromagnetic flowmeter.



STOP TO THINK 24.4 These charged particles are traveling in circular orbits with velocities and field directions as noted. Which particles have a negative charge?



DON'T TRY IT YOURSELF



▶ **Magnets and television screens** The image on a cathode-ray tube television screen is drawn by an electron beam that is steered by magnetic fields from coils of wire. Other magnetic fields can also exert forces on the moving electrons. If you place a strong magnet near the TV screen, the electrons will be forced along altered trajectories and will strike different places on the screen than they are supposed to, producing an array of bright colors. *(The magnet can magnetize internal components and permanently alter the image, so do not do this to your television!)*

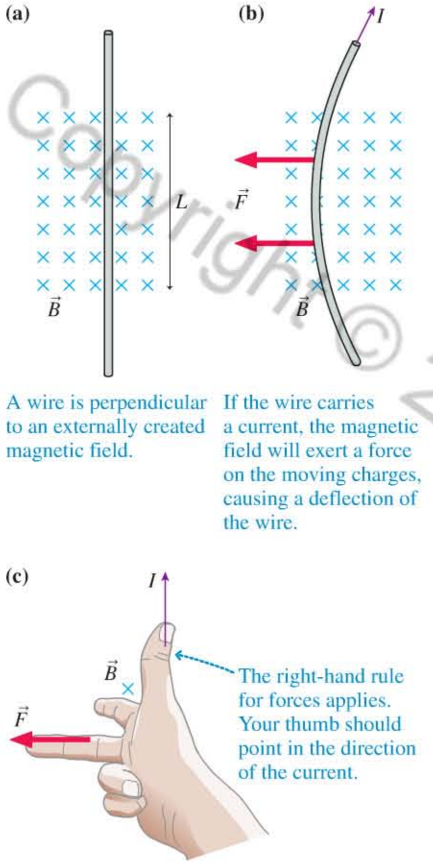
24.6 Magnetic Fields Exert Forces on Currents

We have seen that a magnetic field exerts a force on a current. This force is responsible for the operation of loudspeakers, electric motors, and many other devices.

The Form of the Magnetic Force on a Current

In the table at the start of Section 24.5, we saw that a magnetic field exerts no force on a charged particle moving parallel to a magnetic field. If a current-carrying wire is *parallel* to a magnetic field, we also find that the force on it is zero.

FIGURE 24.39 Magnetic force on a current-carrying wire.



However, there is a force on a current-carrying wire that is *perpendicular* to a magnetic field, as shown in **FIGURE 24.39**.

NOTE ► The magnetic field is an external field, created by a permanent magnet or by other currents; it is *not* the field of the current I in the wire. ◄

The direction of the force on the current is found by considering the force on each charge in the current. We model current as the flow of positive charge, so **the right-hand rule for forces applies to currents in the same way it does for moving charges.** With your fingers aligned as usual, point your right thumb in the direction of the current (the direction of the motion of positive charges) and your index finger in the direction of $\vec{B}$. Your middle finger is then pointing in the direction of the force $\vec{F}$ on the wire, as in **FIGURE 24.39c**. Consequently, the entire length of wire within the magnetic field experiences a force perpendicular to both the current direction and the field direction, as shown in **FIGURE 24.39b**.

If the length of the wire L, the current I, or the magnetic field B is increased, then the magnitude of the force on the wire will also increase. We can show that the force on the wire is given by

$$F_{\text{wire}} = ILB \tag{24.10}$$

Magnitude of the force on a current-carrying wire of length L perpendicular to a magnetic field B

If the wire is at an angle α to the field, the force will depend on this angle:

$$F_{\text{wire}} = ILB \sin \alpha \tag{24.11}$$

It is sometimes useful to rewrite Equation 24.10 as

$$B = \frac{F_{\text{wire}}}{IL} \tag{24.12}$$

Given this expression, we can see that the unit for magnetic field, the tesla, can be defined in terms of other units:

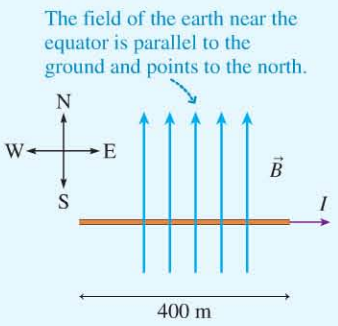
$$1\ \text{T} = 1\ \frac{\text{N}}{\text{A} \cdot \text{m}}$$

EXAMPLE 24.11 Magnetic force on a power line

A DC power line near the equator runs east-west. At this location, the earth's magnetic field is parallel to the ground, points north, and has magnitude 50 μT. A 400 m length of the heavy cable that spans the distance between two towers has a mass of 1000 kg. What direction and magnitude of current would be necessary to offset the force of gravity and "levitate" the wire? (The power line will actually carry a current that is much less than this; 850 A is a typical value.)

PREPARE First, we sketch a top view of the situation, as in **FIGURE 24.40**. The magnetic force on the wire must be opposite that of gravity. An application of the right-hand rule for forces shows that a current to the east will result in an upward force—out of the page.

FIGURE 24.40 Top view of a power line near the equator.



SOLVE The magnetic field is perpendicular to the current, so the magnitude of the magnetic force is given by Equation 24.10. To levitate the wire, this force must be opposite to the weight force but equal in magnitude, so we can write

$$mg = ILB$$

where m and L are the mass and length of the wire and B is the magnitude of the earth's field. Solving for the current, we find

$$I = \frac{mg}{LB} = \frac{(1000\ \text{kg})(9.8\ \text{m/s}^2)}{(400\ \text{m})(50 \times 10^{-6}\ \text{T})} = 4.9 \times 10^5\ \text{A}$$

directed to the east.

ASSESS The current is much larger than a typical current, as we expected.

Forces Between Currents

ActivPhysics 13.5

Because a current produces a magnetic field, and a magnetic field exerts a force on a current, it follows that two current-carrying wires will exert forces on each other, as Ampère discovered. It will be a good check on our results to this point to show that the experimental results we saw earlier are consistent with our rules for determining magnetic fields from currents and determining forces on currents due to magnetic fields.

Suppose we have two parallel wires of length L a distance d apart, each carrying a current. **FIGURE 24.41a** shows the currents I_1 and I_2 in the same direction and **FIGURE 24.41b** in opposite directions. We will assume that the wires are sufficiently long to allow us to use the earlier result, Equation 24.1, for the magnetic field of a long, straight wire: $B = \mu_0 I/2\pi r$.

Let's look at the situation of Figure 24.41a. There are three steps in our analysis:

1. The current I_2 in the lower wire creates a magnetic field $\vec{B}_2$ at the position of the upper wire. This field $\vec{B}_2$ points out of the page, perpendicular to the current I_1. **It is this field $\vec{B}_2$, due to the lower wire, that exerts a magnetic force on the upper wire.** At the position of the upper wire, which is a constant distance $r = d$ from the lower wire, the field has the same value at all points along the wire. The field is

$$\vec{B}_2 = \left(\frac{\mu_0 I_2}{2\pi d}, \text{ out of the page}\right) \tag{24.13}$$

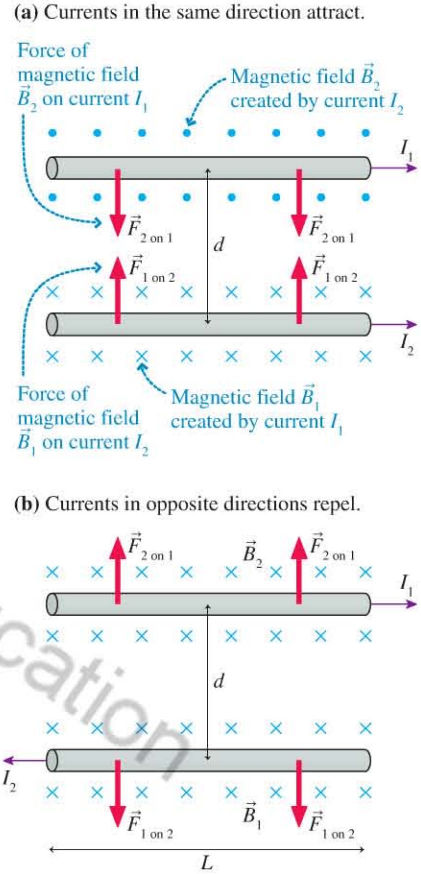
2. For the upper wire, the current is to the right and the field $\vec{B}_2$ from the lower wire points out of the page. Using the right-hand rule for forces, you can see that the force on the upper wire is downward, attracting it toward the lower wire.
3. The magnitude of the force on the upper wire is given by Equation 24.10. Using the field from Equation 24.13, we compute

$$F_{\text{parallel wires}} = I_1 L B_2 = I_1 L \frac{\mu_0 I_2}{2\pi d}$$

$$F_{\text{parallel wires}} = \frac{\mu_0 L I_1 I_2}{2\pi d} \tag{24.14}$$

Magnetic force between two parallel current-carrying wires

FIGURE 24.41 Forces between currents.

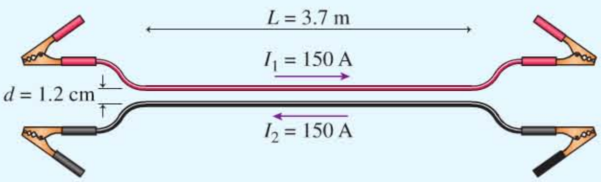


The current in the upper wire exerts an upward-directed magnetic force on the lower wire with exactly the same magnitude. (You know that this must be the case: The two forces form a Newton's third law pair.) You should convince yourself, using the right-hand rule, that the forces are repulsive and tend to push the wires apart if the two currents are in opposite directions, as shown in Figure 24.41b. Our rules predict exactly what the experimental results showed: Parallel wires carrying currents in the same direction attract each other; parallel wires carrying currents in opposite directions repel each other.

EXAMPLE 24.12 Finding the force between wires in jumper cables

You may have used a set of jumper cables connected to a running vehicle to start a car with a dead battery. Jumper cables are a matched pair of wires, red and black, joined together along their length. Suppose we have a set of jumper cables in which the two wires are separated by 1.2 cm along their 3.7 m (12 ft) length. While starting a car, the wires each carry a current of 150 A, in opposite directions. What is the force between the two wires?

FIGURE 24.42 Jumper cables carrying opposite currents.



PREPARE Our first step is to sketch the situation, noting distances and currents, as shown in **FIGURE 24.42**. Because the currents in the two wires are in opposite directions, the force between the two wires is repulsive.

Continued

SOLVE The currents are parallel all along the length of the wires, so we can use Equation 24.14 to compute the force between the wires. The current in each is 150 A, so

$$F = \frac{\mu_0 L I_1 I_2}{2\pi d}$$
$$= \frac{(1.26 \times 10^{-6}\ \mathrm{T \cdot m/A})(3.7\ \mathrm{m})(150\ \mathrm{A})(150\ \mathrm{A})}{2(\pi)(0.012\ \mathrm{m})}$$
$$= 1.4\ \mathrm{N}$$

ASSESS These wires are long, close together, and carry very large currents. But the force between them is quite small—much less than the weight of the wires. In practice, the forces between currents are not an important consideration unless there are many coils of wire, leading to a large total force. This is the case in an MRI solenoid, as we will discuss on page 801.

Crushed by currents The forces between currents are quite small for ordinary currents, even the large currents in the jumper cables of the previous example. But for a current of tens of thousands of amps, it's a different story. This lightning rod is hollow. When struck by lightning, it carried an enormous current for a very short time. The currents in all parts of the rod were parallel, so they attracted each other. The tremendous size of the currents led to attractive forces strong enough to crush the rod.

We're now able to summarize the steps in finding the magnetic force on a charge or current due to known magnetic fields:

PROBLEM-SOLVING STRATEGY 24.2 **Magnetic force problems** MP™

PREPARE There are two key factors to identify in magnetic force problems:

- The source of the magnetic field.
- The charges or currents that feel a force due to this magnetic field.

SOLVE First, determine the magnitude and direction of the magnetic field at the position of the charges or currents that are of interest.

- In some problems the magnetic field is given.
- If the field is due to a current, use the right-hand rule for fields to determine the field direction and the appropriate equation to determine its magnitude (see Problem-Solving Strategy 24.1).

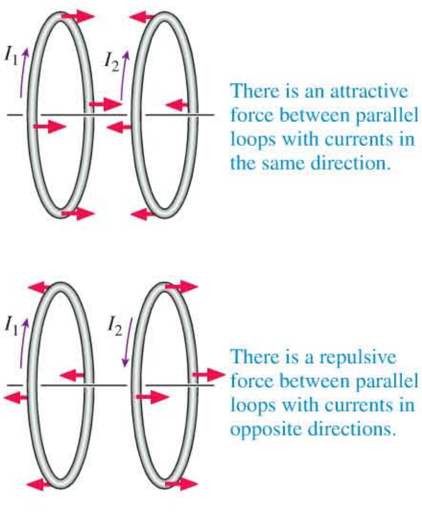
Next, determine the force this field produces. Working with the charges or currents you identified previously,

- Use the right-hand rule for forces to determine the direction of the force on any moving charge or current.
- Use the appropriate equation to determine the magnitude of the force on any moving charge or current.

ASSESS Are the forces you determine perpendicular to velocities of moving charges and to currents? Are the forces perpendicular to the fields? Do the magnitudes of the forces seem reasonable?

Exercise 34

FIGURE 24.43 Forces between parallel current loops.



Forces Between Current Loops

We will now consider the forces between two current loops. Doing so will allow us to begin to make connections with some of the basic phenomena of magnetism that we saw earlier in the chapter.

We've seen that there is an attractive force between two parallel wires that have their currents in the same direction. If these two wires are bent into loops, as in FIGURE 24.43, then the force between the two loops will also be attractive. The forces will be repulsive if the currents are in opposite directions.

Early in the chapter, we examined the fields from various permanent magnets and current arrangements. FIGURE 24.44a on the next page reminds us that a bar magnet is a magnetic dipole, with a north and a south pole. Field lines come out of its north pole, loop back around, and go into the south pole. FIGURE 24.44b shows that the field of a current loop is very similar to that of a bar magnet. This leads us to the conclusion that **a current loop, like a bar magnet, is a magnetic dipole,** with a north and a south pole, as indicated in Figure 24.44b. We can use this conclusion to understand the forces between current loops. In FIGURE 24.45, we show how the poles of each current loop can be represented by a magnet. This model helps us understand the forces between current loops; in the next section, we'll use this model to understand torques on current loops as well.

FIGURE 24.44 We can picture the loop as a small bar magnet.

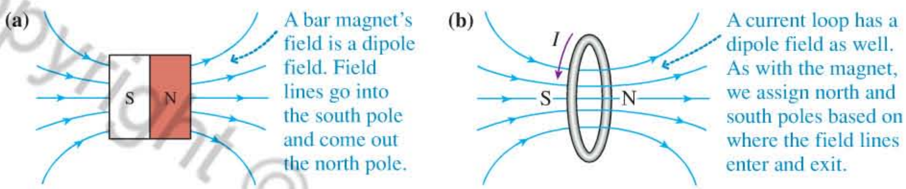
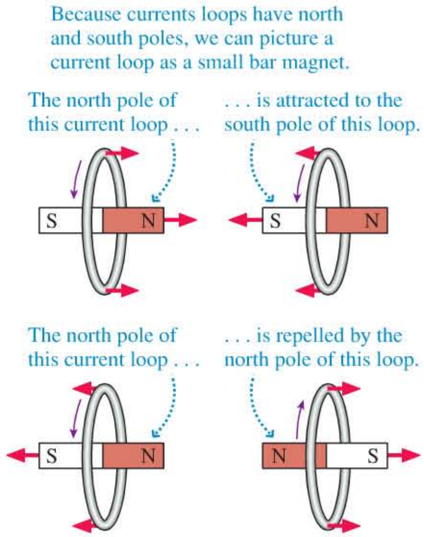
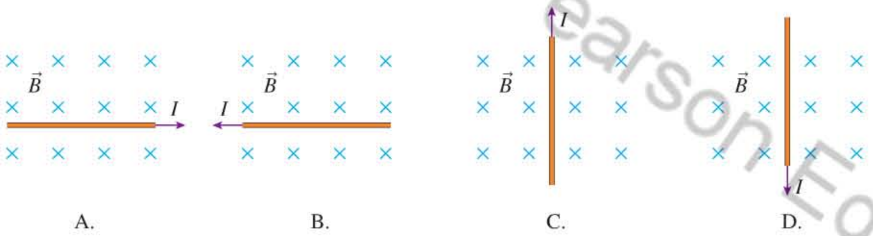


FIGURE 24.45 Forces between current loops can be understood in terms of their magnetic poles.



STOP TO THINK 24.5 Four wires carry currents in the directions shown. A uniform magnetic field is directed into the paper as shown. Which wire experiences a force to the left?



24.7 Magnetic Fields Exert Torques on Dipoles

One of our first observations at the beginning of the chapter was that a compass needle is a small magnet. The fact that it pivots to line up with an external magnetic field means that it experiences a *torque*. In this section, we'll use what we've learned about magnetic forces to understand the torque on a magnetic dipole. We will consider only the case of a current loop (which you'll recall is a magnetic dipole), but the results will be equally applicable to permanent magnets and magnetic dipoles such as compass needles.

A Current Loop in a Uniform Field

FIGURE 24.46 shows a current loop—a magnetic dipole—in a *uniform* magnetic field. To make our analysis more straightforward, we consider a square current loop, but any shape would do. The current in each of the four sides of the loop experiences a magnetic force due to the external field $\vec{B}$. Because the field is uniform, the forces on opposite sides of the loop are of equal magnitude. The direction of each force is determined by the right-hand rule for forces. The forces $\vec{F}_{\text{front}}$ and $\vec{F}_{\text{back}}$ produce no net force or torque. The forces $\vec{F}_{\text{top}}$ and $\vec{F}_{\text{bottom}}$ also add to give no net force, but because $\vec{F}_{\text{top}}$ and $\vec{F}_{\text{bottom}}$ don't act along the same line, they will rotate the loop by exerting a torque on it.

Although we've shown a current loop, the conclusion is true for any magnetic dipole: **In a uniform field, a dipole experiences a torque but no net force.** For example, a compass needle is not attracted to the earth's poles; it merely feels a torque that lines it up with the earth's field.

FIGURE 24.46 A loop in a uniform magnetic field experiences a torque.

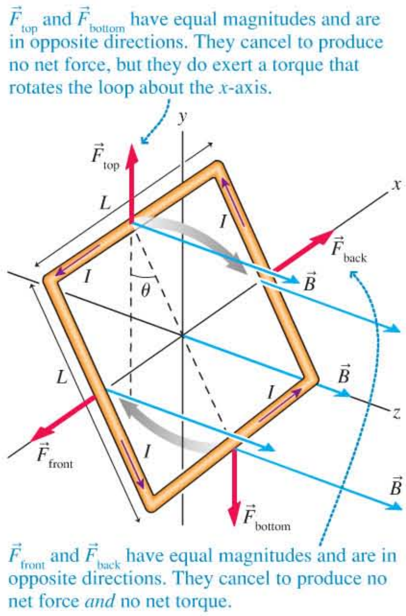
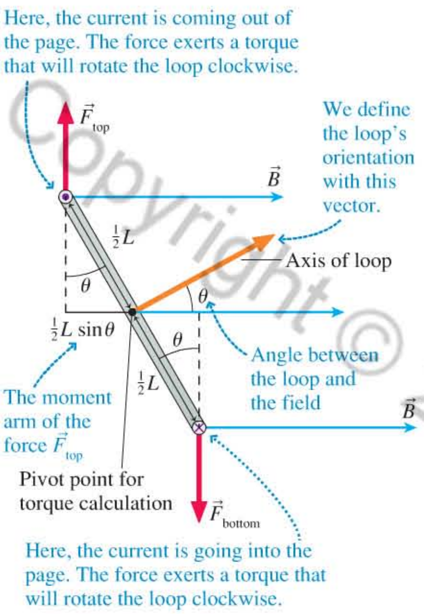


FIGURE 24.47 Calculating the torque on a current loop in a uniform magnetic field.



We can calculate the torque by looking at a side view of the current loop of Figure 24.46. This is shown in FIGURE 24.47. The angle between the loop and the field will be important. We've drawn a vector from the center of the loop that we'll use to define this angle. We also use this angle to compute the torques on segments of the loop. In Chapter 7, we calculated the torque by multiplying the force by the moment arm. The loop will rotate about a pivot point through the center, and we will compute our moment arms from this point. As you can see, the moment arm of $\vec{F}_{top}$ is $\frac{1}{2}L \sin\theta$. $\vec{F}_{top}$ and $\vec{F}_{bottom}$ each produce a torque that tends to rotate the loop. The torque τ_{top} on the top segment of the loop rotates the loop clockwise, as does the torque τ_{bottom} on the bottom segment. The net torque is

$$
\begin{aligned}
\tau = \tau_{top} + \tau_{bottom} &= F_{top}(\tfrac{1}{2}L \sin\theta) + F_{bottom}(\tfrac{1}{2}L \sin\theta) \\
&= (ILB)(\tfrac{1}{2}L \sin\theta) + (ILB)(\tfrac{1}{2}L \sin\theta) \\
&= (IL^2)B \sin\theta
\end{aligned}
$$

L^2 is the area A of the square loop. Using this, we can generalize the result to any loop of area A:

$$\tau = (IA)B \sin\theta \tag{24.15}$$

There are two things to note about this torque:

13.6 ActivPhysics Online

1. **The torque depends on properties of the current loop:** its area (A) and the current (I). The quantity IA, known as the **magnetic dipole moment** (or simply *magnetic moment*), is a measure of how much torque a dipole will feel in a magnetic field. A permanent magnet can be assigned a magnetic dipole moment as well. We'll represent the magnetic moment as an arrow pointing in the direction of the dipole's magnetic field, as in FIGURE 24.48. This figure shows the magnetic dipole moment for a current loop and a bar magnet. You can now see that the vector defining the axis of the loop in Figure 24.47 is simply the magnetic dipole moment.
2. **The torque depends on the angle between the magnetic dipole moment and the magnetic field.** The torque is maximum when θ is 90°, when the magnetic moment is perpendicular to the field. The torque is zero when θ is 0° (or 180°), when the magnetic moment is parallel to the field. As we see in FIGURE 24.49, a magnetic dipole free to rotate in a field will do so until θ is zero, at which point it will be stable. **A magnetic dipole will rotate to line up with a magnetic field** just as an electric dipole will rotate to line up with an electric field.

FIGURE 24.48 The dipole moment vector.

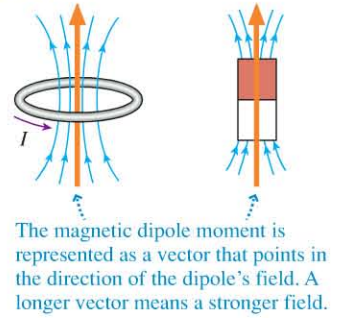
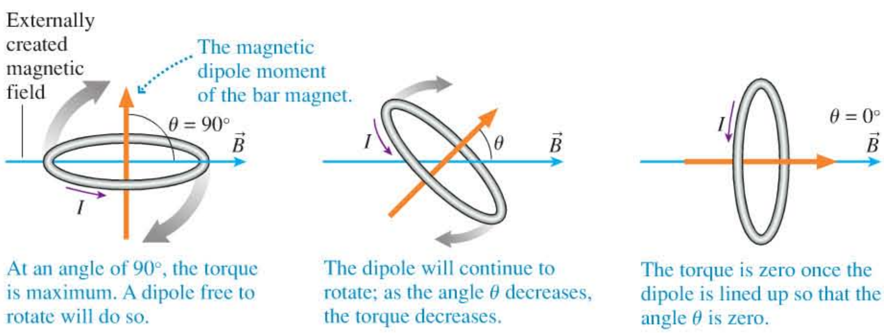


FIGURE 24.49 Torque on a dipole in an externally created magnetic field.

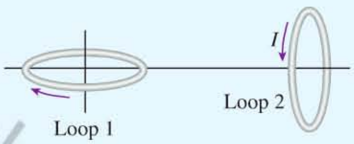


A compass needle, which is a dipole, also rotates until its north pole is in the direction of the magnetic field, as we noted at the very start of the chapter.

CONCEPTUAL EXAMPLE 24.13 **Does the loop rotate?**

Two nearby current loops are oriented as shown in **FIGURE 24.50**. Loop 1 is fixed in place; loop 2 is free to rotate. Will it do so?

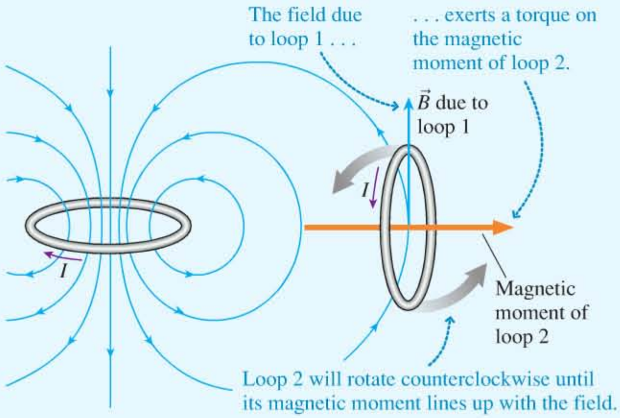
FIGURE 24.50 Will loop 2 rotate?



REASON The current in loop 1 generates a magnetic field. As **FIGURE 24.51** shows, the field of loop 1 is upward as it passes loop 2. Because the field is perpendicular to the magnetic moment of loop 2, the field exerts a torque on loop 2 and causes loop 2 to rotate until its magnetic moment lines up with the field from loop 1.

ASSESS These two loops align so that their magnetic moments point in opposite directions. We can think of this in terms of their poles: When aligned this way, the north pole of loop 1 is closest to the south pole of loop 2. This makes sense, because these opposite poles attract each other.

FIGURE 24.51 How the field of loop 1 affects loop 2.

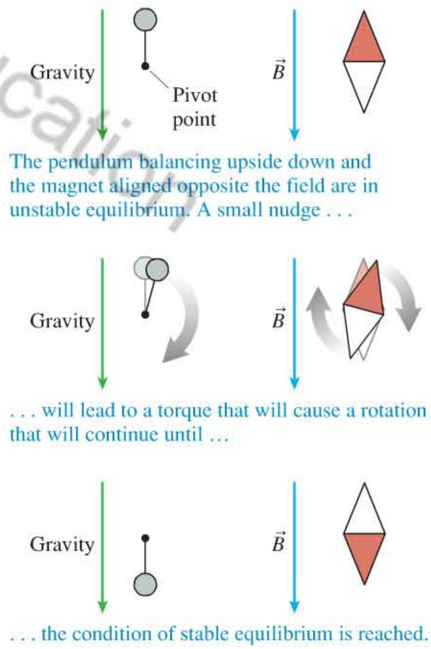


For any dipole in a field, there are actually two angles for which the torque is zero, $\theta = 0°$ and $\theta = 180°$, but there is a difference between these two cases. The $\theta = 0°$ case is *stable:* Once the dipole is in this configuration, it will stay there. The $\theta = 180°$ case is *unstable*. There is no torque if the alignment is perfect, but the slightest rotation will result in a torque that rotates the dipole until it reaches $\theta = 0°$.

We can make a gravitational analogy with this situation in **FIGURE 24.52**. For an upside-down pendulum, there will be no torque if the mass is directly above the pivot point. But, as we saw in Chapter 8, this is a position of unstable equilibrium. If displaced even slightly, the mass will rotate until it is below the pivot point. This is the point of lowest potential energy.

We can see, by analogy with the upside-down pendulum, that the unstable alignment of a magnetic dipole has a higher energy. Given a chance, the magnet will rotate "downhill" to the position of lower energy and stable equilibrium. This difference in energy is the key to understanding how the magnetic properties of atoms can be used to image tissues in the body in MRI.

FIGURE 24.52 Going from unstable to stable equilibrium.



Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging is a modern diagnostic tool that provides detailed images of tissues and structures in the body with no radiation exposure. The key to this imaging technique is the magnetic nature of atoms. **The nuclei of individual atoms have magnetic moments and behave like magnetic dipoles.** Atoms of different elements have different magnetic moments; therefore, a magnetic field exerts different torques on different kinds of atoms.

A person receiving an MRI scan is placed in a large solenoid that has a strong magnetic field along its length. Think about one hydrogen atom in this person's body. The nucleus of the hydrogen atom is a single proton. The proton has a magnetic moment, but the proton is a bit different from a simple bar magnet: It is subject to the rules of quantum mechanics, which we will learn about in Chapter 28. A bar magnet can have any angle with the field, but the proton can only line up either *with the field* (the low-energy state) or *opposed to the field* (the high-energy state), as we see in **FIGURE 24.53** on the next page.

The energy difference ΔE between these two orientations of the proton depends on two key parameters: the magnetic moment of the proton and the strength of the magnetic field.

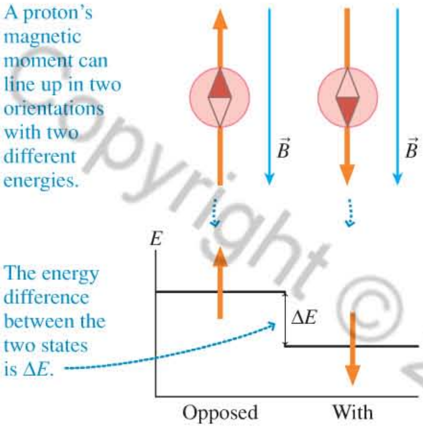
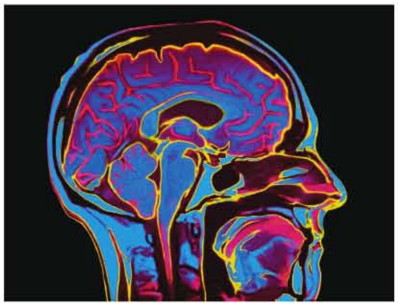


FIGURE 24.53 The energy difference between the two possible orientations of a proton's magnetic moment during MRI.

A tissue sample will have many hydrogen atoms with many protons. Some of the protons will be in the high-energy state and some in the low-energy state. A second magnetic field, called a *probe field,* can be applied to "flip" the dipoles from the low-energy state to the high-energy state. The probe field must be precisely tuned to the energy difference ΔE for this to occur. The probe field is selected to correspond to the magnetic moment of a particular nucleus, in this case hydrogen. If the tuning is correct, dipoles will change state and a signal is measured. A strong signal means that many atoms of this kind are present.

How is this measurement turned into an image? The magnetic field strengths of the solenoid and the probe field are varied so that the correct tuning occurs at only one point in the patient's body. The position of the point of correct tuning is swept across a "slice" of tissue. Combining atoms into molecules slightly changes the energy levels. Different tissues in the body have different concentrations of atoms in different chemical states, so the strength of the signal at a point will vary depending on the nature of the tissue at that point. As the point of correct tuning is moved, the intensity of the signal is measured at each point; a record of the intensity versus position gives an image of the structure of the interior of the body, as in **FIGURE 24.54**.

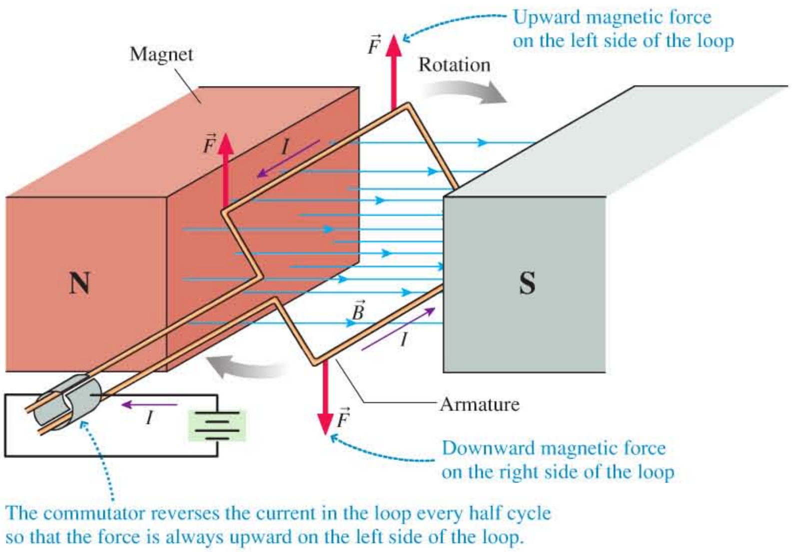
FIGURE 24.54 Cross-sectional image from an MRI scan.



Electric Motors

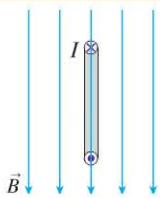
The torque on a current loop in a magnetic field is the basis for how an electric motor works. The *armature* of a motor is a loop of wire wound on an axle that is free to rotate. This loop is in a strong magnetic field. A current in the loop causes the wires of the loop to feel forces due to this field, as **FIGURE 24.55** shows. The loop becomes a magnetic dipole that will rotate to align itself with the external field. If the current were steady, the armature would simply rotate until its magnetic moment was in its stable position. To keep the motor turning, a device called a *commutator* reverses the current direction in the loop every 180°. As the loop reaches its stable configuration, the direction of current in the loop switches, putting the loop back into the unstable configuration, so it will keep rotating to line up in the other direction. This process continues: Each time the loop nears a stable point, the current switches. The loop will keep rotating as long as the current continues.

▶ FIGURE 24.55 The operation of a simple motor depends on the torque on a current loop in a magnetic field.



STOP TO THINK 24.6 Which way will this current loop rotate?

A. Clockwise.
B. Counterclockwise.
C. The loop will not rotate.



24.8 Magnets and Magnetic Materials

We started the chapter by looking at permanent magnets. We know that permanent magnets produce a magnetic field, but what is the source of this field? There are no electric currents in these magnets. Why can you make a magnet out of certain materials but not others? Why does a magnet stick to the refrigerator? The goal of this section is to answer these questions by developing an atomic-level view of the magnetic properties of matter.

Ferromagnetism

Iron, nickel, and cobalt are elements that have very strong magnetic behavior: A chunk of iron (or steel, which is mostly iron) will stick to a magnet, and the chunk can be magnetized so that it is itself a magnet. Other metals—such as aluminum and copper—do not exhibit this property. We call materials that are strongly attracted to magnets and that can be magnetized **ferromagnetic** (from the Latin for iron, *ferrum*).

The key to understanding magnetism at the atomic level was the 1922 discovery that electrons, just like protons and nuclei, have an *inherent magnetic moment*, as we see in FIGURE 24.56. Magnetism, at an atomic level, is due to the inherent magnetic moment of electrons.

If the magnetic moments of all the electrons in an atom pointed in the same direction, the atom would have a very strong magnetic moment. But this doesn't happen. In atoms with many electrons, the electrons usually occur in pairs with magnetic moments in opposite directions, as we'll see in Chapter 29. Only the electrons that are unpaired are able to give the atom a net magnetic moment.

Even so, atoms with magnetic moments don't necessarily form a solid with magnetic properties. For most elements whose atoms have magnetic moments, the magnetic moments of the atoms are randomly arranged when the atoms join together to form a solid. As FIGURE 24.57 shows, this random arrangement produces a solid whose net magnetic moment is very close to zero. Ferromagnetic materials have atoms with net magnetic moments that tend to line up and reinforce each other as in FIGURE 24.58. This alignment of moments occurs in only a few elements and alloys, and this is why a small piece of iron has such a strong overall magnetic moment. Such a piece has a north and a south magnetic pole, generates a magnetic field, and aligns parallel to an external magnetic field. In other words, it is a magnet—and a very strong one at that.

In a large sample of iron, the magnetic moments will be lined up in local regions called **domains,** each looking like the ordered situation of Figure 24.58, but there will be no long-range ordering. Inside a domain, the atomic magnetic moments will be aligned, but the magnetic moments of individual domains will be randomly oriented. The individual domains are quite small—on the order of 0.1 mm or so—so a piece of iron the size of a nail has thousands of domains. The random orientation of the magnetic moments of the domains, as shown in FIGURE 24.59, means that there is no overall magnetic moment. So, how can you magnetize a nail?

Induced Magnetic Moments

When you bring a magnet near a piece of iron, as in FIGURE 24.60 on the next page, the magnetic field of the magnet penetrates the iron and creates torques on the atomic magnetic moments. The atoms will stay organized in domains, but certain domains will now have more favorable alignments. Domain boundaries move: Domains aligned with the external field become larger at the expense of domains opposed to the field. After this shift in domain boundaries, the magnetic moments of the domains no longer cancel out. The iron will have a net magnetic moment that is aligned with the external field. The iron will have developed an *induced magnetic moment*.

FIGURE 24.56 Magnetic moment of the electron.

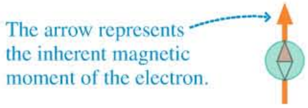


FIGURE 24.57 The random magnetic moments of the atoms in a typical solid.

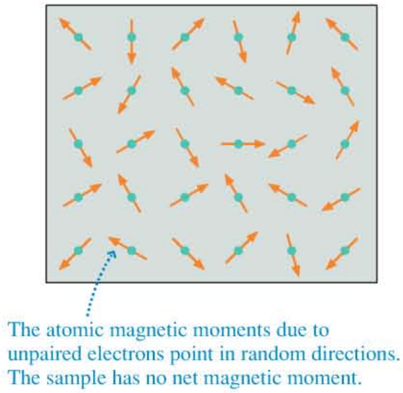


FIGURE 24.58 In a ferromagnetic solid, the atomic magnetic moments align.

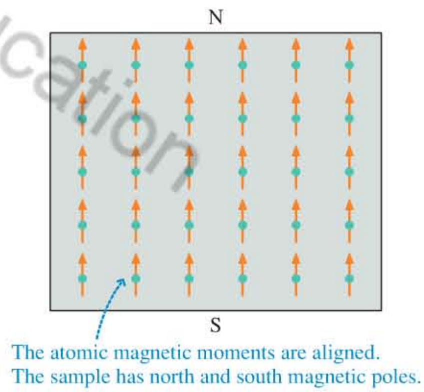


FIGURE 24.59 Magnetic domains in a ferromagnetic material.

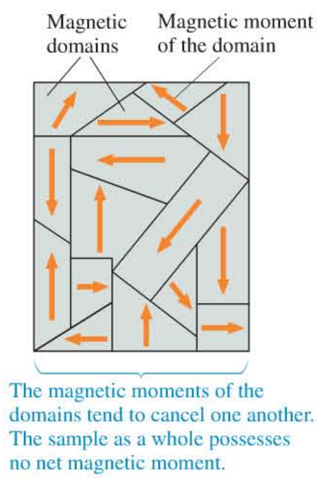
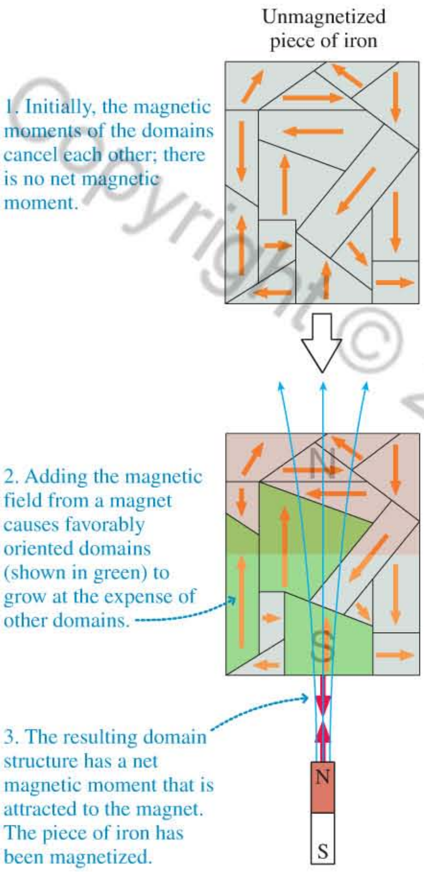


FIGURE 24.60 Inducing a magnetic moment in a piece of iron.



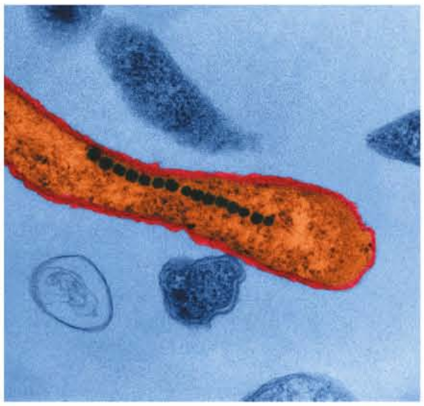
NOTE ▶ Inducing a magnetic moment with a magnetic field is analogous to inducing an electric dipole with an electric field, which we saw in Chapter 21. ◀

Looking at the pole structure of the induced magnetic moment in the iron, we can see that the iron will now be attracted to the magnet. The fact that a magnet attracts and picks up ferromagnetic objects was one of the basic observations about magnetism with which we started the chapter. Now we have an explanation of how this works, based on three facts:

1. Electrons are microscopic magnets due to their inherent magnetic moment.
2. A ferromagnetic material in which the magnetic moments are aligned is organized into magnetic domains.
3. The individual domains shift in response to an external magnetic field to produce an induced magnetic moment for the entire object. This induced magnetic moment will be attracted by a magnet that produced the orientation.

When a piece of iron is near a magnet, the iron becomes a magnet as well. But when the applied field is taken away, the domain structure will (generally) return to where it began: The induced magnetic moment will disappear. In the presence of a *very* strong field, however, a piece of iron can undergo more significant changes to its domain structure, and some domains may permanently change orientation. When the field is removed, the iron may retain some of this magnetic character: The iron will have become permanently magnetized. But pure iron is a rather poor permanent magnetic material; it is very easy to disrupt the ordering of the domains that has created the magnetic moment of the iron. For instance, if you heat (or even just drop!) a piece of magnetized iron, the resulting random atomic motions tend to destroy the alignment of the domains, destroying the magnetic character in the process.

Alloys of ferromagnetic materials often possess more robust magnetic characters. Alloys of iron and other ferromagnetic elements with rare earth elements can make permanent magnets of incredible strength.



Magnetotactic bacteria BIO Several organisms use the earth's magnetic field to navigate. The clearest example of this is *magnetotactic bacteria*. The dark dots in this image are small pieces of iron; each piece is a single domain and hence a very strong magnet. Such a bacterium possesses a very strong magnetic moment: The bacterium itself acts like a bar magnet, and lines up with the earth's magnetic field. In the temperate regions where such bacteria live, the earth's field has a large vertical component. The bacteria use their alignment with this vertical field component to navigate up and down.

CONCEPTUAL EXAMPLE 24.14 Sticking things to the refrigerator

Everyone has used a magnet to stick papers to the fridge. Why does the magnet stick to the fridge through a layer of paper?

REASON When you bring a magnet near the steel door of the refrigerator, the magnetic field of the magnet induces a magnetic moment in the steel. The direction of this induced moment will be such that it is attracted to the magnet—thus the magnet will stick to the fridge. Magnetic fields go through nonmagnetic materials such as paper, so the magnet will hold the paper to the fridge.

ASSESS This result helps makes sense of another observation you've no doubt made: You can't stick a thick stack of papers to the fridge. This is because the magnetic field of the magnet decreases rapidly with distance. Because the field is weaker, the induced magnetic moment is smaller.

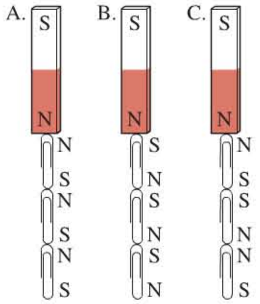
Electromagnets

The magnetic domains in a ferromagnetic material have a strong tendency to line up with an applied magnetic field. This means that it is possible to use a piece of iron or other ferromagnetic material to increase the strength of the field from a current-carrying wire. For example, suppose a solenoid is wound around a piece of iron. When current is passed through the wire, the solenoid's magnetic field lines up the domains in the iron, thus magnetizing it. The resulting **electromagnet** may produce a field that is hundreds of times stronger than the field due to the solenoid itself.

In the past few sections, we've begun to see examples of the deep connection between electricity and magnetism. This connection was one of the most important scientific discoveries of the 1800s, and is something we will explore in more detail in the next chapter.

An electric current in the wire produces a magnetic field that magnetizes the nail around which the wire is wound.

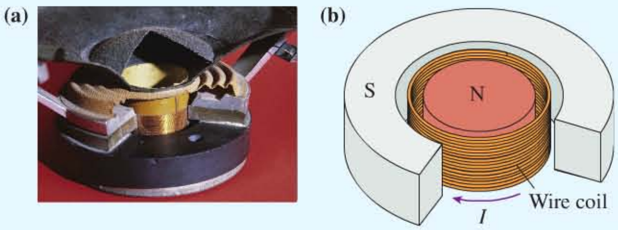
STOP TO THINK 24.7 A chain of paper clips is hung from a permanent magnet. Which diagram shows the correct induced pole structure of the paper clips?



INTEGRATED EXAMPLE 24.15 Making music with magnetism

A loudspeaker creates sound by pushing air back and forth with a paper cone that is driven by a magnetic force on a wire coil at the base of the cone. FIGURE 24.61 shows the details. The bottom of the cone is wrapped with several turns of fine wire. This coil of wire sits in the gap between the poles of a circular magnet, the black disk in the photo. The magnetic field exerts a force on a current in the wire, pushing the cone and thus pushing the air.

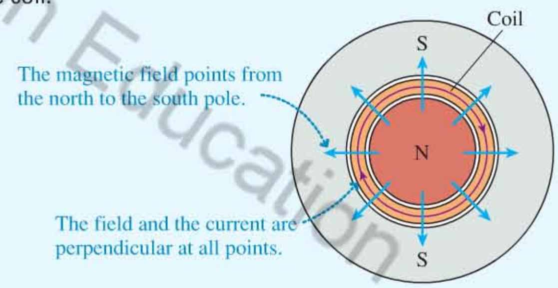
FIGURE 24.61 The arrangement of the coil and magnet poles in a loudspeaker.



There is a 0.18 T field in the gap between the poles. The coil of wire that sits in this gap has a diameter of 5.0 cm, contains 20 turns of wire, and has a resistance of 8.0 Ω. The speaker is connected to an amplifier whose instantaneous output voltage of 6.0 V creates a clockwise current in the coil as seen from above. What is the magnetic force on the coil at this instant?

PREPARE The current in the coil experiences a force due to the magnetic field between the poles. Let's start with a sketch of the field to determine the direction of this force. Magnetic field lines go from the north pole to the south pole of a magnet, so the field lines for the loudspeaker magnet appear as in FIGURE 24.62. The field is at all points perpendicular to the current, and the right-hand rule shows us that, for a clockwise current, the force at each point of the wire is out of the page.

FIGURE 24.62 The magnetic field in the gap and the current in the coil.



SOLVE The current in the wire is produced by the amplifier. The current is related to the potential difference and the resistance of the wire by Ohm's law:

$$I = \frac{\Delta V}{R} = \frac{6.0\text{ V}}{8.0\ \Omega} = 0.75\text{ A}$$

Because the current is perpendicular to the field, we can use Equation 24.10 to determine the force on this current. We know the field and the current, but we need to know the length of the wire in the field region. The coil has diameter 5.0 cm and thus circumference $\pi(0.050\text{ m})$. The coil has 20 turns, so the total length of the wire in the field is

$$L = 20\pi(0.050\text{ m}) = 3.1\text{ m}$$

The magnitude of the force is then given by Equation 24.10 as

$$F = ILB = (0.75\text{ A})(3.1\text{ m})(0.18\text{ T}) = 0.42\text{ N}$$

This force is directed out of the page, as already noted.

ASSESS The force is small, but this is reasonable. A loudspeaker cone is quite light, so only a small force is needed for a large acceleration. The force for a clockwise current is out of the page, but when the current switches direction to counterclockwise, the force will switch directions as well. A current that alternates direction will cause the cone to oscillate in and out—just what is needed for making music.

SUMMARY

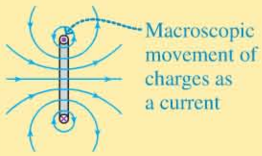
The goal of Chapter 24 has been to learn about magnetic fields and how magnetic fields exert forces on currents and moving charges.

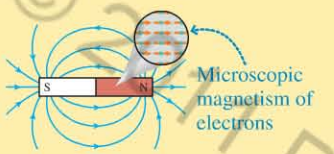
GENERAL PRINCIPLES

Sources of Magnetism

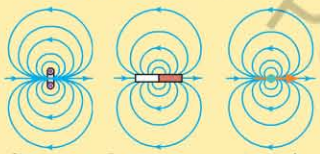
At its most fundamental level, magnetism is an interaction between moving charges. Magnetic fields can be created by either:

- Electric currents or
- Permanent magnets





The most basic unit of magnetism is the **magnetic dipole,** which consists of a north and a south pole.



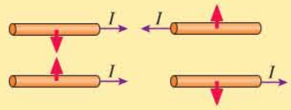
Three basic kinds of dipoles are: Current loop, Permanent magnet, Atomic magnet

Consequences of Magnetism

Magnetic fields exert long-range forces on magnetic materials and on moving charges (or currents).

- Unlike poles of magnets attract each other; like poles repel each other.

- Parallel wires with currents in the same direction attract each other; when the currents are in opposite directions, the wires repel each other.



Magnetic fields exert torques on magnetic dipoles, lining them up with the field.

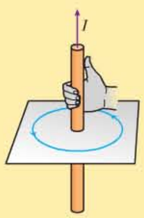
If two or more sources of magnetic field are present, the **principle of superposition** applies.

IMPORTANT CONCEPTS

Magnetic Fields

The **direction of the magnetic field**

- is the direction in which the north pole of a compass needle points.
- due to a current can be found from the **right-hand rule for fields.**



The **strength of the magnetic field** is

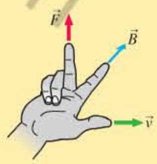
- proportional to the torque on a compass needle when turned slightly from the field direction.
- measured in tesla (T)

Magnetic Forces and Torques

The magnitude of the magnetic force on a *moving* charge depends on its charge q, its speed v, and the angle α between the velocity and the field:

$$F = |q|vB\sin\alpha$$

The direction of this force on a positive charge is given by the **right-hand rule for forces.**



The magnitude of the force on a *current-carrying wire* perpendicular to the magnetic field depends on the current and the length of the wire: $F = ILB$.

The torque on a *current loop* in a magnetic field depends on the current, the loop's area, and how the loop is oriented in the field: $\tau = (IA)B\sin\theta$.

APPLICATIONS

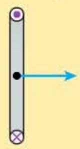
Fields due to common currents

Long straight wire

$$B = \frac{\mu_0 I}{2\pi r}$$

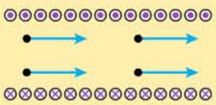
Current loop

$$B = \frac{\mu_0 I}{2R}$$



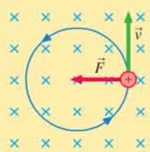
Solenoid

$$B = \mu_0 I \frac{N}{L}$$



Charged-particle motion

No force if $\vec{v}$ is parallel to $\vec{B}$.



If $\vec{v}$ is perpendicular to $\vec{B}$, the particle undergoes uniform circular motion with radius $r = mv/|q|B$.

Stability of magnetic dipoles

A magnetic dipole is stable (in a lower energy state) when aligned with the external magnetic field. It is unstable (in a higher energy state) when aligned opposite to the field.

The probe field of an MRI scanner measures the flipping of magnetic dipoles between these two orientations.

For homework assigned on MasteringPhysics, go to www.masteringphysics.com

Problem difficulty is labeled as | (straightforward) to |||| (challenging).

Problems labeled INT integrate significant material from earlier chapters; BIO are of biological or medical interest.

QUESTIONS

Conceptual Questions

1. The north pole of a bar magnet is brought near the *center* of another bar magnet, as shown in Figure Q24.1. Will the force between the magnets be attractive, repulsive, or zero? Why?

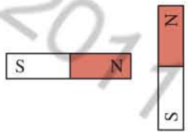


FIGURE Q24.1

2. You have a bar magnet whose poles are not marked. How can you find which pole is north and which is south by using only a piece of string?
3. When you are in the southern hemisphere, does a compass point north or south?
4. BIO Green turtles use the earth's magnetic field to navigate. They seem to use the field to tell them their latitude—how far north or south of the equator they are. Explain how knowing the direction of the earth's field could give this information.
5. A *horseshoe* magnet consists of a bar magnet bent into a U-shape, as shown in Figure Q24.5. Sketch the magnetic field lines for a horseshoe magnet.

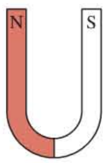


FIGURE Q24.5

6. What is the current direction in the wire of Figure Q24.6? Explain.

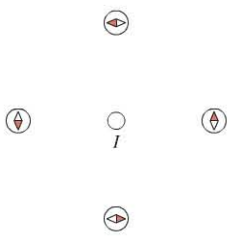


FIGURE Q24.6

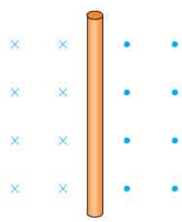


FIGURE Q24.7

7. What is the current direction in the wire of Figure Q24.7?
8. Since the wires in the walls of your house carry current, you might expect that you could use a compass to detect the positions of the wires. In fact, a compass will experience no deflection when brought near a current-carrying wire because the current is AC (meaning "alternating current"—the current switches direction 120 times each second). Explain why a compass doesn't react to an AC current.
9. Two wires carry currents in opposite directions, as in Figure Q24.9. The field is 2.0 mT at a point below the lower wire. What are the strength and direction of the field at point 1 (midway between the two wires) and at point 2 (the same distance above the upper wire as the 2.0 mT point is below the lower wire)?

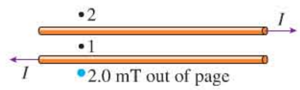


FIGURE Q24.9

10. As shown in Figure Q24.10, a uniform magnetic field points upward, in the plane of the paper. A long wire perpendicular to the paper initially carries no current. When a current is turned on in the wire in the direction shown, the magnetic field at point 1 is found to be zero. Draw the magnetic field vector at point 2 when the current is on.

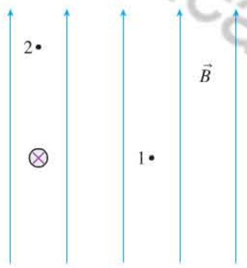


FIGURE Q24.10

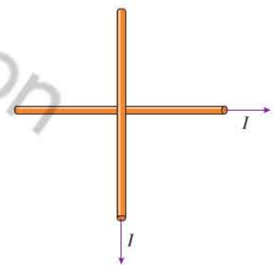


FIGURE Q24.11

11. Two long wires carry currents in the directions shown in Figure Q24.11. One wire is 10 cm above the other. In which direction is the magnetic field at a point halfway between them?
12. If an electron is not moving, is it possible to set it in motion using a magnetic field? Explain.
13. Figure Q24.13 shows a solenoid as seen in cross section. Compasses are placed at points 1 and 2. In which direction will each compass point when there is a large current in the direction shown? Explain.

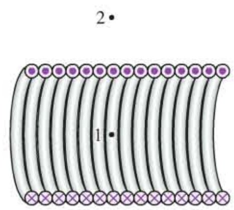


FIGURE Q24.13

14. One long solenoid is placed inside another solenoid with twice the diameter but the same length. Each solenoid carries the same current but in opposite directions, as shown in Figure Q24.14. If they also have the same number of turns, in which direction does the magnetic field in the center point? Explain.

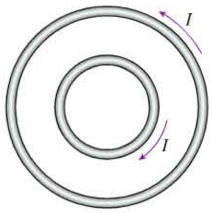


FIGURE Q24.14

15. What is the *initial* direction of deflection for the charged particles entering the magnetic fields shown in Figure Q24.15?

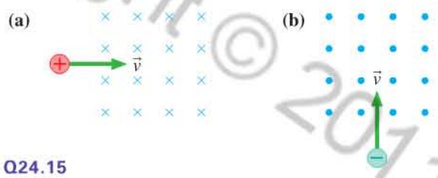


FIGURE Q24.15

16. What is the *initial* direction of deflection for the charged particles entering the magnetic fields shown in Figure Q24.16?

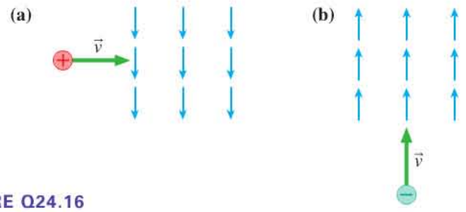


FIGURE Q24.16

17. Determine the magnetic field direction that causes the charged particles shown in Figure Q24.17 to experience the indicated magnetic forces.

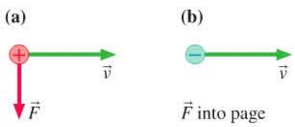


FIGURE Q24.17

18. Determine the magnetic field direction that causes the charged particles shown in Figure Q24.18 to experience the indicated magnetic forces.

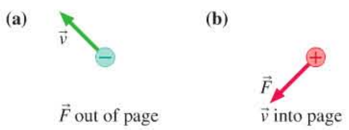


FIGURE Q24.18

19. An electron is moving near a long, current-carrying wire, as shown in Figure Q24.19. What is the direction of the magnetic force on the electron?

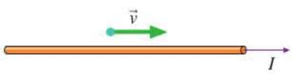


FIGURE Q24.19

20. Two positive charges are moving in a uniform magnetic field with velocities, as shown in Figure Q24.20. The magnetic force on each charge is also shown. In which direction does the magnetic field point?

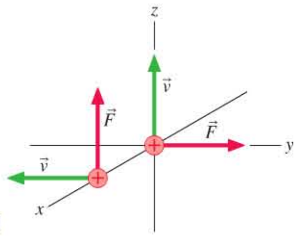


FIGURE Q24.20

21. An electron is moving in a circular orbit in the earth's magnetic field directly above the north magnetic pole. Viewed from above, is the rotation clockwise or counterclockwise?

22. A proton moves in a region of uniform magnetic field, as shown in Figure Q24.22. The velocity at one instant is shown. Will the subsequent motion be a clockwise or counterclockwise orbit?

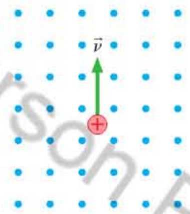


FIGURE Q24.22

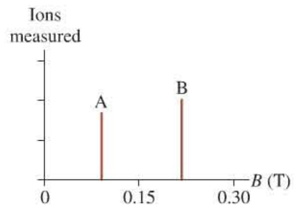


FIGURE Q24.23

23. The detector in a mass spectrometer records the number of ions measured at a fixed position as the field is varied. For a sample consisting of a single atomic species, two peaks were found where one was expected, as shown in Figure Q24.23. The most likely explanation is that the atoms received different charges when ionized. If the two peaks correspond to ions with charges $+e$ and $+2e$, which peak is which? Explain.

24. A proton is moving near a long, current-carrying wire. When the proton is at the point shown in Figure Q24.24, in which direction is the force on it?

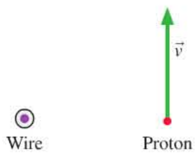


FIGURE Q24.24

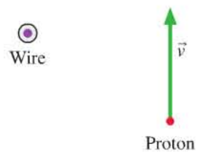


FIGURE Q24.25

25. A proton is moving near a long, current-carrying wire. When the proton is at the point shown in Figure Q24.25, in which direction is the force on it?

26. A long wire and a square loop lie in the plane of the paper. Both carry a current in the direction shown in Figure Q24.26. In which direction is the net force on the loop? Explain.

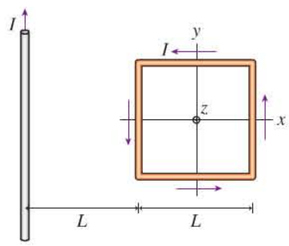


FIGURE Q24.26

27. The computers that control MRI machines cannot have CRT monitors. Explain why this is so.

28. A Slinky is a child's toy that is a long coil spring. Suppose you take a Slinky and let it hang down and stretch out so that the coils do not touch each other, as in Figure Q24.28. Now you connect the Slinky to a power supply and pass a large DC current through it. Think about the current in the coils. Will the Slinky expand or contract?

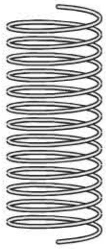


FIGURE Q24.28

29. A solenoid carries a current that produces a field inside it. A wire carrying a current lies inside the solenoid, at the center, carrying a current along the solenoid's axis. Is there a force on this wire due to the field of the solenoid? Explain.
30. You want to make an electromagnet by wrapping wire around a nail. Should you use bare copper wire or wire coated with insulating plastic? Explain.
31. The moon does not have a molten iron core like the earth, but the moon does have a small magnetic field. What might be the source of this field?
32. Archaeologists can use instruments that measure small variations in magnetic field to locate buried walls made of fired brick, as shown in Figure Q24.32. When fired, the magnetic moments in the clay become randomly aligned; as the clay cools, the magnetic moments line up with the earth's field and retain this alignment even if the bricks are subsequently moved. Explain how this leads to a measurable magnetic field variation over a buried wall.


FIGURE Q24.32

Multiple-Choice Questions

33. | | An unmagnetized metal sphere hangs by a thread. When the north pole of a bar magnet is brought near, the sphere is strongly attracted to the magnet, as shown in Figure Q24.33. Then the magnet is reversed and its south pole is brought near the sphere. How does the sphere respond?

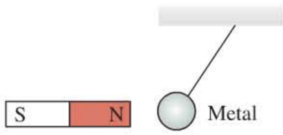


FIGURE Q24.33

A. It is strongly attracted to the magnet.
B. It is weakly attracted to the magnet.
C. It does not respond.
D. It is weakly repelled by the magnet.
E. It is strongly repelled by the magnet.

34. | | If a compass is placed above a current-carrying wire, as in Figure Q24.34, the needle will line up with the field of the wire. Which of the views shows the correct orientation of the needle for the noted current direction?

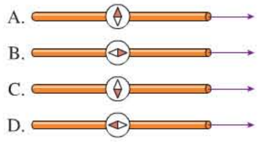


FIGURE Q24.34

35. | Two wires carry equal and opposite currents, as shown in Figure Q24.35. At a point directly between the two wires, the field is


FIGURE Q24.35

A. Directed up, toward the top of the page.
B. Directed down, toward the bottom of the page.
C. Directed to the left.
D. Directed to the right.
E. Zero.

36. | Figure Q24.36 shows four particles moving to the right as they enter a region of uniform magnetic field, directed into the paper as noted. All particles move at the same speed and have the same charge. Which particle has the largest mass?

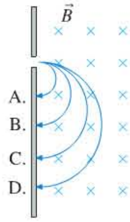


FIGURE Q24.36

37. | Four particles of identical charge and mass enter a region of uniform magnetic field and follow the trajectories shown in Figure Q24.37. Which particle has the highest velocity?

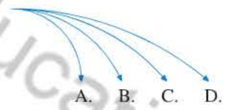


FIGURE Q24.37

38. | If all of the particles shown in Figure Q24.37 are electrons, what is the direction of the magnetic field that produced the indicated deflection?
A. Up (toward the top of the page).
B. Down (toward the bottom of the page).
C. Out of the plane of the paper.
D. Into the plane of the paper.

39. | If two compasses are brought near enough to each other, the magnetic fields of the compasses themselves will be larger than the field of the earth, and the needles will line up with each other. Which of the arrangements of two compasses shown in Figure Q24.39 is a possible stable arrangement?

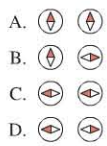


FIGURE Q24.39

PROBLEMS

Section 24.1 Magnetism

Section 24.2 The Magnetic Field

Section 24.3 Electric Currents Also Create Magnetic Fields

Section 24.4 Calculating the Magnetic Field Due to a Current

1. | What currents are needed to generate the magnetic field strengths of Table 24.1 at a point 1.0 cm from a long, straight wire?
2. | At what distances from a very thin, straight wire carrying a 10 A current would the magnetic field strengths of Table 24.1 be generated?
3. | | The magnetic field at the center of a 1.0-cm-diameter loop is 2.5 mT.
   a. What is the current in the loop?
   b. A long, straight wire carries the same current you found in part a. At what distance from the wire is the magnetic field 2.5 mT?

4. For a particular scientific experiment, it is important to be completely isolated from any magnetic field, including the earth's field. A 1.00-m-diameter current loop with 200 turns of wire is set up so that the field at the center is exactly equal to the earth's field in magnitude but opposite in direction. What is the current in the current loop?

5. What are the magnetic field strength and direction at points 1 to 3 in Figure P24.5?

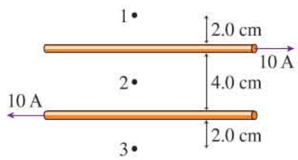


FIGURE P24.5

6. BIO Although the evidence is weak, there has been concern in recent years over possible health effects from the magnetic fields generated by transmission lines. A typical high-voltage transmission line is 20 m off the ground and carries a current of 200 A. Estimate the magnetic field strength on the ground underneath such a line. What percentage of the earth's magnetic field does this represent?

7. BIO Some consumer groups urge pregnant women not to use electric blankets, in case there is a health risk from the magnetic fields from the approximately 1 A current in the heater wires.
   a. Estimate, stating any assumptions you make, the magnetic field strength a fetus might experience. What percentage of the earth's magnetic field is this?
   b. It is becoming standard practice to make electric blankets with minimal external magnetic field. Each wire is paired with another wire that carries current in the opposite direction. How does this reduce the external magnetic field?

8. A long wire carrying a 5.0 A current perpendicular to the xy-plane intersects the x-axis at $x = -2.0$ cm. A second, parallel wire carrying a 3.0 A current intersects the x-axis at $x = +2.0$ cm. At what point or points on the x-axis is the magnetic field zero if (a) the two currents are in the same direction and (b) the two currents are in opposite directions?

9. The element niobium, which is a metal, is a superconductor (i.e., no electrical resistance) at temperatures below 9 K. However, the superconductivity is destroyed if the magnetic field at the surface of the wire of the metal reaches or exceeds 0.10 T. What is the maximum current in a straight, 3.0-mm-diameter superconducting niobium wire?
   Hint: You can assume that all the current flows in the center of the wire.

10. BIO The small currents in axons corresponding to nerve impulses produce measurable magnetic fields. A typical axon carries a peak current of 0.040 μA. What is the strength of the field at a distance of 1.0 mm?

11. A solenoid used to produce magnetic fields for research purposes is 2.0 m long, with an inner radius of 30 cm and 1000 turns of wire. When running, the solenoid produces a field of 1.0 T in the center. Given this, how large a current does it carry?

12. Two concentric current loops lie in the same plane. The smaller loop has a radius of 3.0 cm and a current of 12 A. The bigger loop has a current of 20 A. The magnetic field at the center of the loops is found to be zero. What is the radius of the bigger loop?

13. BIO The magnetic field of the brain has been measured to be approximately 3.0×10^{-12} T. Although the currents that cause this field are quite complicated, we can get a rough estimate of their size by modeling them as a single circular current loop 16 cm (the width of a typical head) in diameter. What current is needed to produce such a field at the center of the loop?

14. A researcher would like to perform an experiment in zero magnetic field, which means that the field of the earth must be cancelled. Suppose the experiment is done inside a solenoid of diameter 1.0 m, length 4.0 m, with a total of 5000 turns of wire. The solenoid is oriented to produce a field that opposes and exactly cancels the field of the earth. What current is needed in the solenoid's wire?

15. What is the magnetic field at the center of the loop in Figure P24.15?

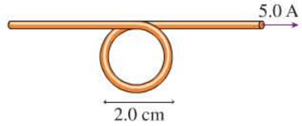


FIGURE P24.15

16. BIO Experimental tests have shown that hammerhead sharks can detect magnetic fields. In one such test, 100 turns of wire were wrapped around a 7.0-m-diameter cylindrical shark tank. A magnetic field was created inside the tank when this coil of wire carried a current of 1.5 A. Sharks trained by getting a food reward when the field was present would later unambiguously respond when the field was turned on.
   a. What was the magnetic field strength in the center of the tank due to the current in the coil?
   b. Is the strength of the coil's field at the center of the tank larger or smaller than that of the earth?

17. BIO We have seen that the heart produces a magnetic field that can be used to diagnose problems with the heart. The magnetic field of the heart is a dipole field produced by a loop current in the outer layers of the heart. Suppose the field at the center of the heart is 90 pT (a pT is 10^{-12} T) and that the heart has a diameter of approximately 12 cm. What current circulates around the heart to produce this field?

18. You have a 1.0-m-long copper wire. You want to make an N-turn current loop that generates a 1.0 mT magnetic field at the center when the current is 1.0 A. You must use the entire wire. What will be the diameter of your coil?

19. In the Bohr model of the hydrogen atom, the electron moves in a circular orbit of radius 5.3×10^{-11} m with speed 2.2×10^6 m/s. According to this model, what is the magnetic field at the center of a hydrogen atom due to the motion of the electron?
   Hint: Determine the *average* current of the orbiting electron.

Section 24.5 Magnetic Fields Exert Forces on Moving Charges

20. A proton moves with a speed of 1.0×10^7 m/s in the directions shown in Figure P24.20. A 0.50 T magnetic field points in the positive x-direction. For each, what is magnetic force on the proton? Give your answers as a magnitude and a direction.

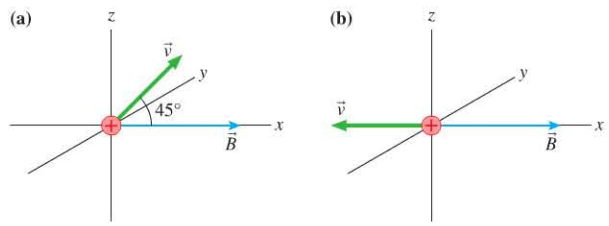


FIGURE P24.20

21. An electron moves with a speed of $1..0 \times 10^7$ m/s in the directions shown in Figure P24.21. A 0.50 T magnetic field points in the positive x-direction. For each, what is magnetic force $\vec{F}$ on the electron? Give your answers as a magnitude and a direction.

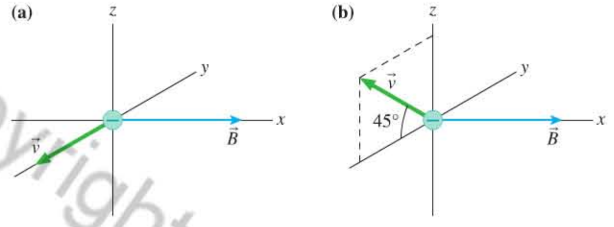


FIGURE P24.21

22. An electromagnetic flowmeter applies a magnetic field of 0.20 T
BIO to blood flowing through a coronary artery at a speed of 15 cm/s. What force is felt by a chlorine ion with a single negative charge?

23. The aurora is caused when electrons and protons, moving in the earth's magnetic field of $\approx 5.0 \times 10^{-5}$ T, collide with molecules of the atmosphere and cause them to glow. What is the radius of the circular orbit for

a. An electron with speed 1.0×10^6 m/s?
b. A proton with speed 5.0×10^4 m/s?

24. Problem 24.23 describes two particles that orbit the earth's magnetic field lines. What is the *frequency* of the circular orbit for

a. An electron with speed 1.0×10^6 m/s?
b. A proton with speed 5.0×10^4 m/s?

25. The microwaves in a microwave oven are produced in a special tube called a *magnetron*. The electrons orbit in a magnetic field at a frequency of 2.4 GHz, and as they do so they emit 2.4 GHz electromagnetic waves. What is the strength of the magnetic field?

26. A mass spectrometer similar to the one in Figure 24.36 is designed to separate protein fragments. The fragments are ionized by the removal of a single electron, then they enter a 0.80 T uniform magnetic field at a speed of 2.3×10^5 m/s. If a fragment has a mass 85 times the mass of the proton, what will be the distance between the points where the ion enters and exits the magnetic field?

27. In a certain mass spectrometer, particles with a charge of $+e$ are sent into the spectrometer with a velocity of 2.5×10^5 m/s. They are found to move in a circular path with a radius of 0.21 m. If the magnetic field of the spectrometer is 0.050 T, what kind of particles are these likely to be?

28. At $t = 0$ s, a proton is moving with a speed of 5.5×10^5 m/s at an angle of 30° from the x-axis, as shown in Figure P24.28. A uniform magnetic field of magnitude 1.50 T is pointing in the positive y-direction. What will be the y-coordinate of the proton 10 μs later?

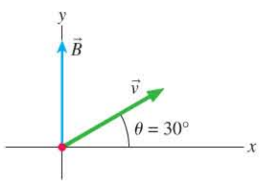


FIGURE P24.28

29. Early black-and-white television sets used an electron beam
INT to draw a picture on the screen. The electrons in the beam were accelerated by a voltage of 3.0 kV; the beam was then steered to different points on the screen by coils of wire that produced a magnetic field of up to 0.65 T.

a. What is the speed of electrons in the beam?
b. What acceleration do they experience due to the magnetic field, assuming that it is perpendicular to their path? What is this acceleration in units of g?
c. If the electrons were to complete a full circular orbit, what would be the radius?
d. A magnetic field can be used to redirect the beam, but the electrons are brought to high speed by an electric field. Why can't we use a magnetic field for this task?

Section 24.6 Magnetic Fields Exert Forces on Currents

30. What magnetic field strength and direction will levitate the 2.0 g wire in Figure P24.30?

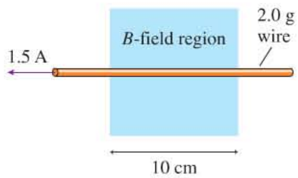


FIGURE P24.30

31. What is the net force (magnitude and direction) on each wire in Figure P24.31?

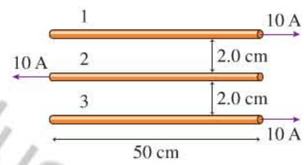


FIGURE P24.31

32. The unit of current, the ampere, is defined in terms of the force between currents. If two 1.0-meter-long sections of very long wires a distance 1.0 m apart each carry a current of 1.0 A, what is the force between them? (If the force between two actual wires has this value, the current is defined to be exactly 1 A.)

33. A uniform 2.5 T magnetic field points to the right. A 3.0-m-long wire, carrying 15 A, is placed at an angle of 30° to the field, as shown in Figure 24.33. What is the force (magnitude and direction) on the wire?

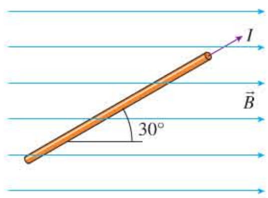


FIGURE P24.33

34. The four wires in Figure P24.34 are tilted at 20° with respect to a uniform 0.35 T field. If each carries 4.5 A and is 0.35 m long, what is the force (direction and magnitude) on each?

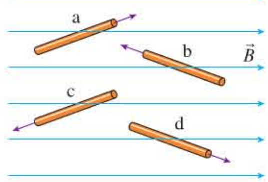


FIGURE P24.34

35. Magnetic information on hard drives is accessed by a read head that must move rapidly back and forth across the disk. The force to move the head is generally created with a *voice coil actuator*, a flat coil of fine wire that moves between the poles of a strong magnet, as in Figure P24.35. Assume that the coil is a square 1.0 cm on a side made of 200 turns of fine wire with total resistance 1.5 Ω. The field between the poles of the magnet is 0.30 T; assume that the field does not extend beyond the edge of the magnet. The coil and the mount that it rides on have a total mass of 12 g.
   a. If a voltage of 5.0 V is applied to the coil, what is the current?
   b. If the current is clockwise viewed from above, what are the magnitude and direction of the net force on the coil?
   c. What is the magnitude of the acceleration of the coil?

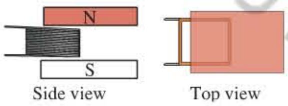


FIGURE P24.35

Section 24.7 Magnetic Fields Exert Torques on Dipoles

36. A current loop in a motor has an area of 0.85 cm^2. It carries a 240 mA current in a uniform field of 0.62 T. What is the magnitude of the maximum torque on the current loop?

37. A square current loop 5.0 cm on each side carries a 500 mA current. The loop is in a 1.2 T uniform magnetic field. The axis of the loop, perpendicular to the plane of the loop, is 30° away from the field direction. What is the magnitude of the torque on the current loop?

38. Figure P24.38 shows two square current loops. The loops are far apart and do not interact with each other.
   a. Use force diagrams to show that both loops are in equilibrium, having a net force of zero and no torque.
   b. One of the loop positions is stable. That is, the forces will return it to equilibrium if it is rotated slightly. The other position is unstable, like an upside-down pendulum: If rotated slightly, it will not return to the position shown. Which is which? Explain.

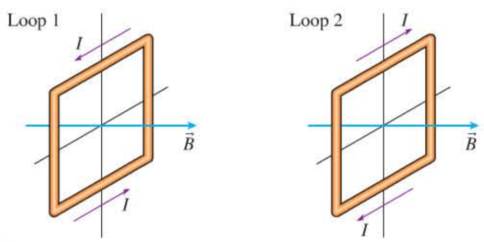


FIGURE P24.38

39. The earth's magnetic dipole moment of 8.0×10^{22} A · m^2 is generated by currents within the molten iron of the earth's outer core. (The inner core is solid iron.) As a simple model, consider the outer core to be a 3000-km-diameter current loop. What is the current in the current loop?

40. a. What is the magnitude of the torque on the circular current loop in Figure P24.40?
   b. What is the loop's equilibrium position?

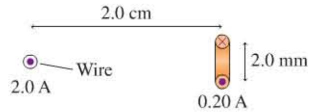


FIGURE P24.40

Section 24.8 Magnets and Magnetic Materials

41. A computer diskette is a plastic disk with a ferromagnetic coating. A single magnetic domain can have its magnetic moment oriented to point either up or down, and these two orientations can be interpreted as a binary 0 (up) or 1 (down). Each 0 or 1 is called a *bit* of information. A diskette stores roughly 500,000 *bytes* of data on one side, and each byte contains eight bits. Estimate the width of a magnetic domain, and compare your answer to the typical domain size given in the text. List any assumptions you use in your estimate.

42. All ferromagnetic materials have a *Curie temperature,* a temperature above which they will cease to be magnetic. Explain in some detail why you might expect this to be so.

General Problems

43. In Figure P24.43, a compass sits 1.0 cm above a wire in a circuit containing a 1.0 F capacitor charged to 5.0 V, a 1.0 Ω resistor, and an open switch. The compass is lined up with the earth's magnetic field. The switch is then closed, so there is a current in the circuit, and the switch remains closed until the capacitor has completely discharged.
   a. At the position of the compass, what is the magnitude of the magnetic field due to the current in the wire right after the switch is closed? How does this compare with the magnitude of the field of the earth?
   b. Describe how the compass orientation changes right after the switch is closed, and how the compass orientation changes as time goes on.

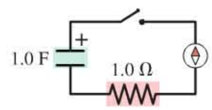


FIGURE P24.43

44. The right edge of the circuit in Figure P24.44 extends into a 50 mT uniform magnetic field. What are the magnitude and direction of the net force on the circuit?

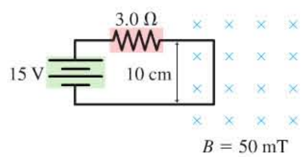


FIGURE P24.44

45. The two 10-cm-long parallel wires in Figure P24.45 are separated by 5.0 mm. For what value of the resistor R will the force between the two wires be 5.4×10^{-5} N?

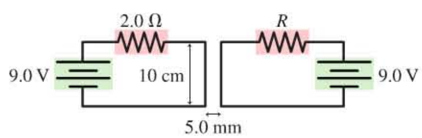


FIGURE P24.45

46. ||| The capacitor in Figure P24.46 is charged to 50 V. The switch
INT closes at $t = 0$ s. Draw a graph showing the magnetic field strength as a function of time at the position of the dot. On your graph indicate the maximum field strength and provide an appropriate numerical scale on the horizontal axis.

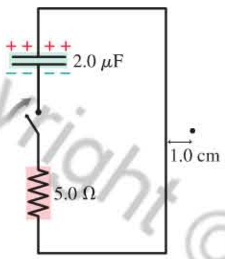


FIGURE P24.46

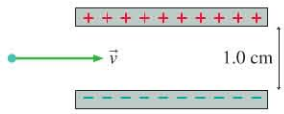


FIGURE P24.47

47. || An electron travels with speed 1.0×10^7 m/s between the
INT two parallel charged plates shown in Figure P24.47. The plates are separated by 1.0 cm and are charged by a 200 V battery. What magnetic field strength and direction will allow the electron to pass between the plates without being deflected?

48. || The two springs in Figure P24.48 each have a spring constant
INT of 10 N/m. They are stretched by 1.0 cm when a current passes through the wire. How big is the current?

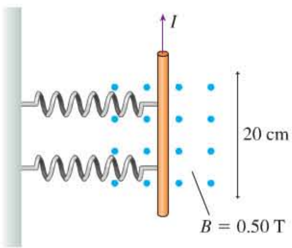


FIGURE P24.48

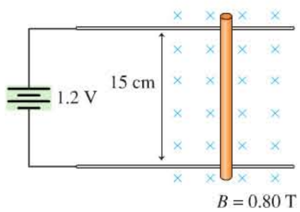


FIGURE P24.49

49. || A device called a *railgun* uses the magnetic force on currents
INT to launch projectiles at very high speeds. An idealized model of a railgun is illustrated in Figure 24.49. A 1.2 V power supply is connected to two conducting rails. A segment of copper wire, in a region of uniform magnetic field, slides freely on the rails. The wire has a 0.85 mΩ resistance and a mass of 5.0 g. Ignore the resistance of the rails. When the power supply is switched on,
   a. What is the current?
   b. What are the magnitude and direction of the force on the wire?
   c. What will be the wire's speed after it has slid a distance of 6.0 cm?

50. || An antiproton (which has
INT the same properties as a proton except that its charge is $-e$) is moving in the combined electric and magnetic fields of Figure P24.50.
   a. What are the magnitude and direction of the antiproton's acceleration at this instant?
   b. What would be the magnitude and direction of the acceleration if $\vec{v}$ were reversed?

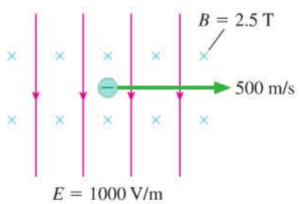


FIGURE P24.50

51. | Typical blood velocities in the coronary arteries range from
INT 10 to 30 cm/s. An electromagnetic flowmeter applies a magnetic
BIO field of 0.25 T to a coronary artery with a blood velocity of 15 cm/s. As we saw in Figure 24.38, this field exerts a force on ions in the blood, which will separate. The ions will separate until they make an electric field that exactly balances the magnetic force. This electric field produces a voltage that can be measured.
   a. What force is felt by a singly ionized (positive) sodium ion?
   b. Charges in the blood will separate until they produce an electric field that cancels this magnetic force. What will be the resulting electric field?
   c. What voltage will this electric field produce across an artery with a diameter of 3.0 mm?

52. | A power line consists of two wires, each carrying a current of 400 A in the same direction. The lines are perpendicular to the earth's magnetic field, and are separated by a distance of 5.0 m. Which is larger: the force of the earth's magnetic field on each wire or the magnetic force between the wires?

53. ||| Bats are capable of navigating using the earth's field—a plus
BIO for an animal that may fly great distances from its roost at night. If, while sleeping during the day, bats are exposed to a field of a similar magnitude but different direction than the earth's field, they are more likely to lose their way during their next lengthy night flight. Suppose you are a researcher doing such an experiment in a location where the earth's field is 50 μT at a 60° angle below horizontal. You make a 50-cm-diameter, 100-turn coil around a roosting box; the sleeping bats are at the center of the coil. You wish to pass a current through the coil to produce a field that, when combined with the earth's field, creates a net field with the same strength and dip angle (60° below horizontal) as the earth's field but with a horizontal component that points south rather than north. What are the proper orientation of the coil and the necessary current?

54. ||| At the equator, the earth's field is essentially horizontal; near
BIO the north pole, it is nearly vertical. In between, the angle varies. As you move farther north, the dip angle, the angle of the earth's field below horizontal, steadily increases. Green turtles seem to use this dip angle to determine their latitude. Suppose you are a researcher wanting to test this idea. You have gathered green turtle hatchlings from a beach where the magnetic field strength is 50 μT and the dip angle is 56°. You then put the turtles in a 1.2-m-diameter circular tank and monitor the direction in which they swim as you vary the magnetic field in the tank. You change the field by passing a current through a 100-turn horizontal coil wrapped around the tank. This creates a field that adds to that of the earth. What current should you pass through the coil, and in what direction, to produce a net field in the center of the tank that has a dip angle of 62°?

55. || Internal components of cathode-ray-tube televisions and computer monitors can become magnetized; the resulting magnetic field can deflect the electron beam and distort the colors on the screen. Demagnetization can be accomplished with a coil of wire whose current switches direction rapidly and gradually decreases in amplitude. Explain what effect this will have on the magnetic moments of the magnetic materials in the device, and how this might eliminate any magnetic ordering.

56. ||| A 1.0-m-long, 1.0-mm-diameter copper wire carries a current
INT of 50.0 A to the east. Suppose we create a magnetic field that produces an upward force on the wire exactly equal in magnitude to the wire's weight, causing the wire to "levitate." What are the field's direction and magnitude?

57. | An insulated copper wire is wrapped around an iron nail. The resulting coil of wire consists of 240 turns of wire that cover 1.8 cm of the nail, as shown in Figure P24.57. A current of 0.60 A passes through the wire. If the ferromagnetic properties of the nail increase the field by a factor of 100, what is the magnetic field strength inside the nail?

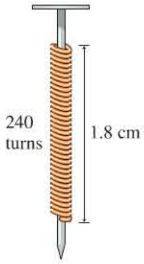


FIGURE P24.57

58. |||| Figure P24.58 is a cross section through three long wires with linear mass density 50 g/m. They each carry equal currents in the directions shown. The lower two wires are 4.0 cm apart and are attached to a table. What current I will allow the upper wire to "float" so as to form an equilateral triangle with the lower wires?
INT

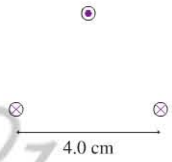


FIGURE P24.58

59. ||| A long, straight wire with a linear mass density of 50 g/m is suspended by threads, as shown in Figure P24.59. There is a uniform magnetic field pointing vertically downward. A 10 A current in the wire experiences a horizontal magnetic force that deflects it to an equilibrium angle of 10°. What is the strength of the magnetic field $\vec{B}$?
INT

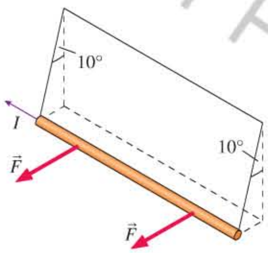


FIGURE P24.59

60. || A mass spectrometer is designed to separate atoms of carbon to determine the fraction of different isotopes. (Isotopes of an element, as we will see in Chapter 30, have the same atomic number but different atomic mass, due to different numbers of neutrons.) There are three main isotopes of carbon, with the following atomic masses:

Atomic masses

^{12}C	1.99×10^{-26} kg
^{13}C	2.16×10^{-26} kg
^{14}C	2.33×10^{-26} kg

The atoms of carbon are singly ionized and enter a mass spectrometer with magnetic field strength $B = 0.200$ T at a speed of 1.50×10^5 m/s. The ions move along a semicircular path and exit through an exit slit. How far from the entrance will the beams of the different isotope ions end up?

61. | A solenoid is near a piece of iron, as shown in Figure P24.61. When a current is present in the solenoid, a magnetic field is created. This magnetic field will magnetize the iron, and there will be a net force between the solenoid and the iron.

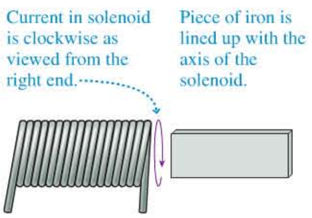


FIGURE P24.61

a. Make a sketch showing the direction of the magnetic field from the solenoid. On your sketch, label the induced north magnetic pole and the induced south magnetic pole in the iron.
b. Will the force on the iron be attractive or repulsive?
c. Suppose this force moves the iron. Which way will the iron move?

Passage Problems

The Velocity Selector INT ActivPhysics 13.8

In experiments where all the charged particles in a beam are required to have the same velocity (for example, when entering a mass spectrometer), scientists use a *velocity selector*. A velocity selector has a region of uniform electric and magnetic fields that are perpendicular to each other and perpendicular to the motion of the charged particles. Both the electric and magnetic fields exert a force on the charged particles. If a particle has precisely the right velocity, the two forces exactly cancel and the particle is not deflected. Equating the forces due to the electric field and the magnetic field gives the following equation:

$$qE = qvB$$

Solving for the velocity, we get:

$$v = \frac{E}{B}$$

A particle moving at this velocity will pass through the region of uniform fields with no deflection, as shown in Figure P24.62. For higher or lower velocities than this, the particles will feel a net force and will be deflected. A slit at the end of the region allows only the particles with the correct velocity to pass.

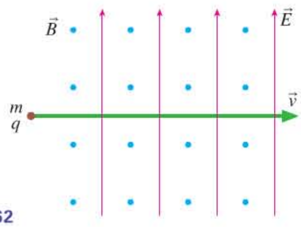


FIGURE P24.62

62. | Assuming the particle in Figure P24.62 is positively charged, what are the directions of the forces due to the electric field and to the magnetic field?
A. The force due to the electric field is directed up (toward the top of the page); the force due to the magnetic field is directed down (toward the bottom of the page).
B. The force due to the electric field is directed down (toward the bottom of the page); the force due to the magnetic field is directed up (toward the top of the page).
C. The force due to the electric field is directed out of the plane of the paper; the force due to the magnetic field is directed into the plane of the paper.
D. The force due to the electric field is directed into the plane of the paper; the force due to the magnetic field is directed out of the plane of the paper.

63. | How does the kinetic energy of the particle in Figure P24.62 change as it traverses the velocity selector?
   A. The kinetic energy increases.
   B. The kinetic energy does not change.
   C. The kinetic energy decreases.
64. | Suppose a particle with twice the velocity of the particle in Figure P24.62 enters the velocity selector. The path of this particle will curve
   A. Upward (toward the top of the page).
   B. Downward (toward the bottom of the page).
   C. Out of the plane of the paper.
   D. Into the plane of the paper.
65. | Next, a particle with the same mass and velocity as the particle in Figure P24.62 enters the velocity selector. This particle has a charge of $2q$—twice the charge of the particle in Figure P24.62. In this case, we can say that
   A. The force of the electric field on the particle is greater than the force of the magnetic field.
   B. The force of the magnetic field on the particle is greater than the force of the electric field.
   C. The forces of the electric and magnetic fields on the particle are still equal.

Ocean Potentials INT

The ocean is salty because it contains many dissolved ions. As these charged particles move with the water in strong ocean currents, they feel a force from the earth's magnetic field. Positive and negative charges are separated until an electric field develops that balances this magnetic force. This field produces measurable potential differences that can be monitored by ocean researchers.

The Gulf Stream moves northward off the east coast of the United States at a speed of up to 3.5 m/s. Assume that the current flows at this maximum speed and that the earth's field is 50 μT tipped 60° below horizontal.

66. | What is the direction of the magnetic force on a singly ionized negative chlorine ion moving in this ocean current?
   A. East
   B. West
   C. Up
   D. Down
67. | What is the magnitude of the force on this ion?
   A. 2.8×10^{-23} N
   B. 2.4×10^{-23} N
   C. 1.6×10^{-23} N
   D. 1.4×10^{-23} N
68. | What magnitude electric field is necessary to exactly balance this magnetic force?
   A. 1.8×10^{-4} N/C
   B. 1.5×10^{-4} N/C
   C. 1.0×10^{-4} N/C
   D. 0.9×10^{-4} N/C
69. | The electric field produces a potential difference. If you place one electrode 10 m below the surface of the water, you will measure the greatest potential difference if you place the second electrode
   A. At the surface.
   B. At a depth of 20 m.
   C. At the same depth 10 m to the north.
   D. At the same depth 10 m to the east.

STOP TO THINK ANSWERS

Stop to Think 24.1: C. The compass needle will not rotate since there is no force between the stationary charges on the rod and the magnetic poles of the compass needle.

Stop to Think 24.2: A. The compass needle will rotate to line up with the field of the magnet, which goes from the north to the south pole.

Stop to Think 24.3: D. The compass needle will rotate to line up with the field circling the wire. The right-hand rule for fields shows this to be toward the top of the paper in the figure.

Stop to Think 24.4: A, C. The force to produce these circular orbits is directed toward the center of the circle. Using the right-hand rule for forces, we see that this will be true for the situations in A and C if the particles are negatively charged.

Stop to Think 24.5: C. The right-hand rule for forces gives the direction of the force. With the field into the paper, the force is to the left if the current is toward the top of the paper.

Stop to Think 24.6: B. Looking at the forces on the top and the bottom of the loop, we can see that the loop will rotate counterclockwise. Alternatively, we can look at the dipole structure of the loop: With a north pole on the left and a south pole on the right, the loop will rotate counterclockwise.

Stop to Think 24.7: B. All of the induced dipoles will be aligned with the field of the bar magnet.