Magnetism

The 1st - Mathematics

Course professor

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Magnetic Forces and Fields

19.1 MAGNETIC FIELDS

Permanent Magnets

Permanent magnets have been known at least since the time of the ancient Greeks, about 2500 years ago. A naturally occurring iron ore called lodestone (now called magnetite) was mined in various places, including the region of modern-day Turkey called Magnesia. Some of the chunks of lodestone were permanent magnets; they exerted magnetic forces on each other and on iron and could be used to turn a piece of iron into a permanent magnet. In China, the magnetic compass was used as a navigational aid at least a thousand years ago—possibly much earlier. Not until 1820 was a connection between electricity and magnetism established, when Danish scientist Hans Christian Oersted (1777–1851) discovered that a compass needle is deflected by a nearby electric current.

Figure 19.1a shows a plate of glass lying on top of a bar magnet. Iron filings have been sprinkled on the glass and then the glass has been tapped to shake the filings a bit and allow them to move around. The filings have lined up with the **magnetic field** (symbol:$\vec{B}$) due to the bar magnet. Figure 19.1b shows a sketch of the magnetic field lines representing this magnetic field. As is true for electric field lines, the magnetic field lines represent both the magnitude and direction of the magnetic field vector. The magnetic field vector at any point is tangent to the field line and the magnitude of the field is proportional to the number of lines per unit area perpendicular to the lines.

Figure 19.1b may strike you as being similar to a sketch of the electric field lines for an electric dipole. The similarity is not a coincidence; the bar magnet is one instance of a **magnetic dipole**. By *dipole* we mean *two opposite poles*. In an electric dipole, the electric poles are positive and negative

CONNECTION:

Electric dipole: one positive charge and one negative charge. Magnetic dipole: one north pole and one south pole.

electric charges. A magnetic dipole consists of two opposite magnetic poles. The end of the bar magnet where the field lines emerge is called the **North Pole** and the end where the lines go back in is called the **South Pole**. If two magnets are near one another, opposite poles (the north pole of one magnet and the south pole of the other) exert attractive forces on one another; like poles (two north poles or two south poles) repel one another.

The names *North Pole* and *South Pole* are derived from magnetic compasses. A compass is simply a small bar magnet that is free to rotate. Any magnetic dipole, including a compass needle, feels a torque that tends to line it up with an external magnetic field (Fig. 19.2). The north pole of the compass needle is the end that points in the direction of the magnetic field. In a compass, the bar magnet needle is mounted to minimize frictional and other torques so it can swing freely in response to a magnetic field.

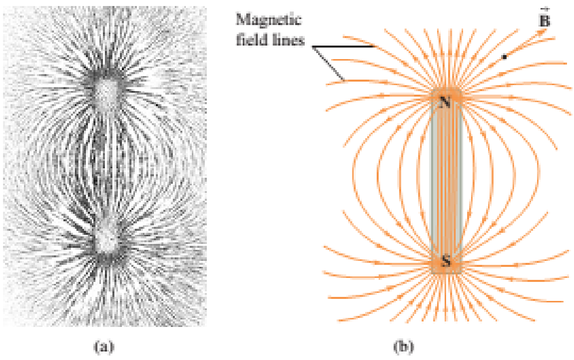


Figure 19.1 *(a) Photo of a bar magnet. Nearby iron filings line up with the magnetic field. (b) Sketch of the magnetic field lines due to the bar magnet. The magnetic field vectors are tangent to the field lines.*

Figure 19.2 Each compass needle is aligned with the magnetic field due to the bar magnet. The "north" (red) end of each needle points in the direction of the magnetic field.

Permanent magnets come in many shapes other than the bar magnet. Figure 19.3 shows some others, with the magnetic field lines sketched. Notice in Fig. 19.3a that if the pole faces are parallel and close together, the magnetic field between them is nearly uniform. A magnet need not have only two poles; it must have *at least* one North Pole and *at least* one South Pole. Some magnets are designed to have a large number of north and south poles. The flexible magnetic card (Fig. 19.3b), commonly found on refrigerator doors, is designed to have many poles, both north and south, on one side and no poles on the other. The magnetic field is strong near the side with the poles and weak near the other side; the card sticks to an iron surface (such as a refrigerator door) on one side but not on the other.

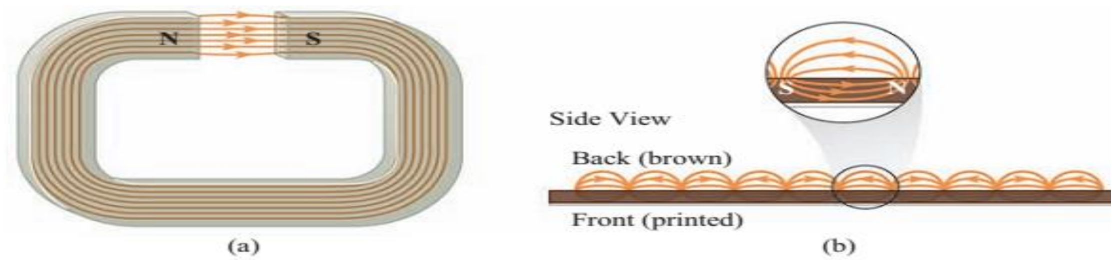


*Figure 19.3 Two permanent magnets with their magnetic field lines. In **(a)**, the magnetic field between the pole faces is nearly uniform. **(b)** A refrigerator magnet (shown here in a side view) has many poles.*

No Magnetic Monopoles Coulomb's law for *electric* forces gives the force acting between two point charges-two electric *monopoles*. However, as far as we know, there are no *magnetic* monopoles-that is, there is no such thing as an isolated north pole or an isolated south pole. If you take a bar magnet and cut it in half, you do not obtain one piece with a north pole and another piece with a south pole. Both pieces are magnetic dipoles (Fig. 19.4). There have been theoretical predictions of the existence of magnetic monopoles, but years of experiments have yet to turn up a single one. If magnetic monopoles do exist in our universe, they must be extremely rare.

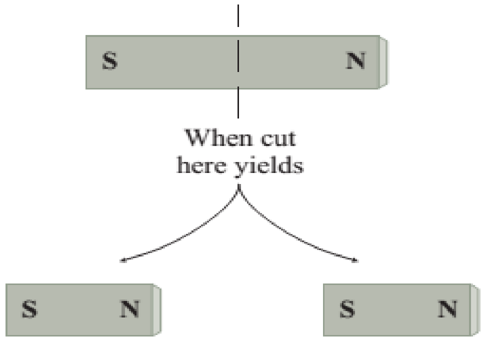


Figure 19.4 *Sketch of a bar magnet that is subsequently cut in half. Each piece has both a north and a south pole.*

Magnetic Field Lines

Figure 19.1 shows that magnetic field lines do not begin on north poles and end on south poles: magnetic field lines are always closed loops. If there are no magnetic monopoles, there is no place for the field lines to begin or end, so they must be closed loops. Contrast Fig. 19.1b with Fig. 16.29—the field lines for an electric dipole. The field line patterns are similar away from the dipole, but nearby and between the poles they are quite different. The electric field lines are not closed loops; they start on the positive charge and end on the negative charge.

> *Magnetic field lines are always closed loops.*

Despite these differences between electric and magnetic field lines, the *interpretation* of magnetic field lines is exactly the same as for electric field lines:

1. The direction of the magnetic field vector at any point is *tangent to the field line* passing through that point and is in the direction indicated by arrows on the field line (as in Fig. 19.1b).
2. The magnetic field is strong where field lines are close together and weak where they are far apart. More specifically, if you imagine a small surface perpendicular to the field lines, the

CONNECTION:

Magnetic field lines help us visualize the magnitude and direction of the magnetic field vectors, just as electric field lines do for the magnitude and direction of $\vec{\mathbf{E}}$.

magnitude of the magnetic field is proportional to the number of lines that cross the surface, divided by the area.

The Earth's Magnetic Field

Figure 19.5 shows field lines for Earth's magnetic field. Near Earth's surface, the magnetic field is approximately that of a dipole, as if a bar magnet was buried at the center of the Earth. Farther away from Earth's surface, the dipole field is distorted by the solar wind—charged particles streaming from the Sun toward Earth. As discussed in Section 19.8, moving charged particles create their own magnetic fields, so the solar wind has a magnetic field associated with it.

In most places on the surface, Earth's magnetic field is not horizontal; it has a significant vertical component. The vertical component can be measured directly using a *dip meter*, which is just a compass, mounted so that it can rotate in a vertical plane. In the northern hemisphere, the vertical component is downward, while in the southern hemisphere it is upward. In other words, magnetic field lines emerge from Earth's surface in the southern hemisphere and reenter in the northern hemisphere. A magnetic dipole that is free to rotate aligns itself with the magnetic field such that the north end of the dipole points in the direction of the field. Figure 19.2 shows a bar magnet with several compasses in the vicinity. Each compass needle points in the direction of the local magnetic field, which in this case is due to the magnet. A compass is normally used to detect Earth's magnetic field. In a horizontally mounted compass, the needle is free to rotate only in a horizontal plane, so its north end points in the direction of the *horizontal component* of Earth's field.

Note the orientation of the fictitious bar magnet in Fig. 19.5: the south pole of the magnet faces roughly toward geographic north and the north pole of the magnet faces roughly toward geographic south. The field lines emerge from Earth's surface in the southern hemisphere and return in the northern hemisphere.

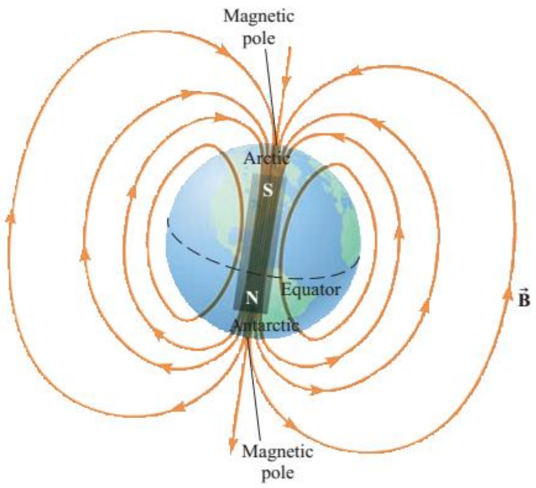


Figure 19.5 *Earth's magnetic field. The diagram shows the magnetic field lines in one plane. In general, the magnetic field at the surface has both horizontal and vertical components. The magnetic poles are the points where the magnetic field at the surface is purely vertical. The magnetic poles do not coincide with the geographic poles, which are the points at which the axis of rotation intersects the surface. Near the surface, the field is approximately that of a dipole, like that of the fictitious bar magnet shown. Note that the south pole of this bar magnet points toward the Arctic and the north pole points toward the Antarctic.*

19.2 MAGNETIC FORCE ON A POINT CHARGE

Before we go into more detail on the magnetic forces and torques on a magnetic dipole, we need to start with the simpler case of the magnetic force on a moving point charge. Recall that, we defined the electric field as the electric force per unit charge. The electric force is either in the same direction as $\vec{E}$ or in the opposite direction, depending on the sign of the point charge.

The magnetic force on a point charge is more complicated—it is not the charge times the magnetic field. The magnetic force depends on the point charge's velocity as well as on the magnetic field. If the point charge is at rest, there is no magnetic force. The magnitude and direction of the magnetic force depend on the direction and speed of the charge's motion. We have learned about other velocity-dependent forces, such as the drag force on an object moving through a fluid. Like drag forces, the magnetic force increases in magnitude with increasing velocity. However, the direction of the drag force is always opposite to the object's velocity, while the direction of the magnetic force on a charged particle is *perpendicular* to the velocity of the particle.

> *The magnetic force is velocity-dependent.*

Imagine that a positive point charge q moves at velocity $\vec{\mathbf{v}}$ at a point where the magnetic field is $\vec{B}$. The angle between $\vec{V}$ and $\vec{B}$ is θ (Fig. 19.6a). The magnitude of the magnetic force acting on the point charge is the product of

- The magnitude of the charge $|q|$,
- The magnitude of the field $\vec{B}$, and
- The component of the velocity perpendicular to the field (Fig. 19.6b).

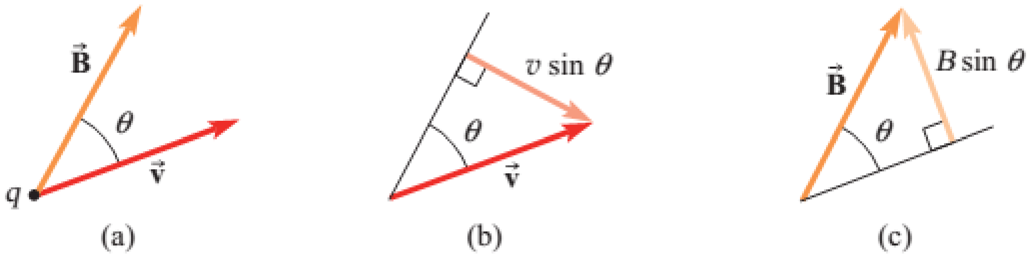


Figure 19.6 A positive charge moving in a magnetic field. (a) The particle's velocity vector $\vec{V}$ and the magnetic field vector $\vec{B}$ are drawn starting at the same point. θ is the angle between them. (b) The component of $\vec{V}$ perpendicular to $\vec{B}$ is $v \sin\theta$. (c) The component of $\vec{B}$ perpendicular to $\vec{V}$ is $B \sin\theta$.

Magnitude of the magnetic force on a moving point charge:

$$F_B = |q|v_\perp B = |q|v(\sin\theta)B$$

Since $$v_\perp = v \sin\theta \quad \text{(19-1a)}$$

Note that if the point charge is at rest $(v = 0)$ or if its motion is along the same line as the magnetic field $(v_\perp = 0)$, then the magnetic force is zero.

In some cases it is convenient to look at the factor $\sin\theta$ from a different point of view. If we associate the factor $\sin\theta$ with the magnetic field instead of with the velocity, then $B \sin\theta$ is the component of the magnetic field perpendicular to the velocity of the charged particle (Fig. 19.6c):

$$F_B = |q|v(B \sin\theta) = |q|vB_\perp \quad \text{(19-1b)}$$

SI Unit of Magnetic Field

From Eq. (19-1), the SI unit of magnetic field is

$$\frac{force}{\text{charge} \times \text{velocity}} = \frac{N}{C \times m/sec} = \frac{N}{A.m}$$

This combination of units is given the name tesla (symbol T) after Nikola Tesla (1856–1943), an American engineer who was born in Croatia.

$$1\,T = 1\,\frac{N}{A \cdot m} \quad \text{(19-2)}$$

Cross Product of Two Vectors

The direction and magnitude of the magnetic force depend on the vectors $\vec{V}$ and $\vec{B}$ in a special way that occurs often in physics and mathematics. The magnetic force can be written in terms of the **cross product** (or *vector product*) of $\vec{V}$ and $\vec{B}$. The cross product of two vectors $\vec{a}$ and $\vec{b}$ is written $\vec{a} \times \vec{b}$. The magnitude of the cross product is the magnitude of one vector times the perpendicular component of the other; it doesn't matter which is which.

CONNECTION:

The cross product of two vectors is a vector quantity. The cross product is a different mathematical operation than the dot product of two vectors, which is a *scalar* .
The cross product has its maximum magnitude when the two vectors are perpendicular; the dot product is maximum when the two vectors are parallel.

$$\left|\vec{a} \times \vec{b}\right| = \left|\vec{a} \times \vec{b}\right| = a_{\perp} b = a b_{\perp} = ab \sin\theta \qquad (19\text{-}3)$$

However, the order of the vectors *does* matter in determining the *direction* of the result. Switching the order reverses the direction of the product:

$$\vec{b} \times \vec{a} = -\vec{a} \times \vec{b} \qquad (19\text{-}4)$$

Since magnetism is inherently three-dimensional, we often need to draw vectors that are perpendicular to the page. The symbol • (or ⊙) represents a vector arrow pointing out of the page; think of the tip of an arrow coming toward you. The symbol × (or ⊗) represents a vector pointing into the page; it suggests the tail feathers of an arrow moving away from you.

The cross product of two vectors $\vec{a}$ *and* $\vec{b}$ *is a vector that is perpendicular to both* $\vec{a}$ *and* $\vec{b}$ *. Note that* $\vec{a}$ *and* $\vec{b}$ *do not have to be perpendicular to one another. For any two vectors that are neither in the same direction nor in opposite directions, there are two directions perpendicular to both vectors. To choose between the two, we use a* ***right hand rule****.*

Using Right-Hand Rule 1 to Find the Direction of a Cross Product $\vec{a}$ X $\vec{b}$

1. Draw the vectors $\vec{a}$ and $\vec{b}$ starting from the same origin (Fig. 19.7a).
2. The cross product is in one of the two directions that are perpendicular to both $\vec{a}$ and $\vec{b}$. Determine these two directions.
3. Choose one of these two perpendicular directions to test. Place your right hand in a "karate chop" position with your palm at the origin, your fingertips pointing in the direction of $\vec{a}$, and your thumb in the direction you are testing (Fig. 19.7b).
4. Keeping the thumb and palm stationary, curl your fingers inward toward your palm until your fingertips point in the direction of $\vec{b}$ (Fig. 19.7c). If you can do it, sweeping your fingers through an angle less than 180°, then your thumb points in the direction of the cross product $\vec{a} \times \vec{b}$. If you can't do it because your fingers would have to sweep through an angle greater than 180°, then your thumb points in the direction *opposite* to $\vec{a} \times \vec{b}$.

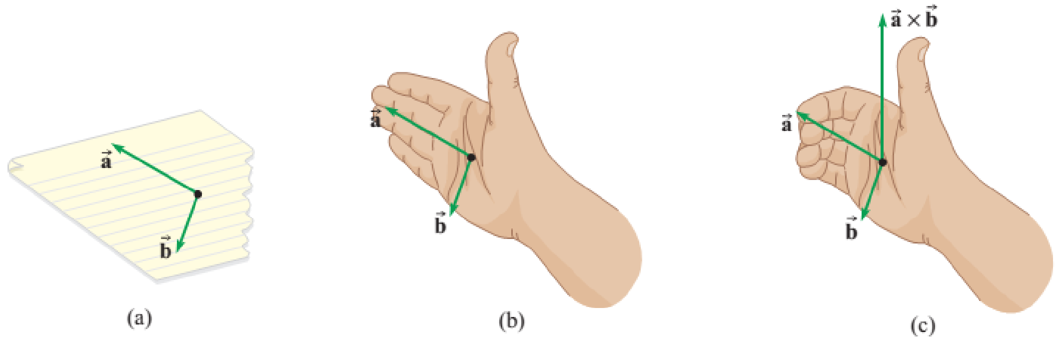


Figure 19.7 *Using the righthand rule to find the direction of a cross product.* **(a)** *First we draw the two vectors,* $\vec{a}$ *and* $\vec{b}$*, starting at the same point.* **(b)** *Initial hand position to test whether* $\vec{a} \times \vec{b}$ *is up. The thumb points up and the fingers point along* $\vec{a}$*.* **(c)** *The fingers are curled in through an angle* $< 180°$ *until they point along* $\vec{b}$*. Therefore,* $\vec{a} \times \vec{b}$ *is up.*

Direction of the Magnetic Force

> *Vector symbols: • or ⊙ = out of the page; × or ⊗ = into the page The magnetic force on a point charge is perpendicular to the magnetic field and perpendicular to the velocity*

The magnetic force on a charged particle can be written as the charge times the cross product of $\vec{V}$ and $\vec{B}$:

Magnetic force on a moving point charge:

$$\overrightarrow{F_B} = q\vec{V} \times \vec{B} \qquad (19\text{-}5)$$

Magnitude: $F_B = qvB \sin\theta$

Direction: perpendicular to both $\vec{V}$ and $\vec{B}$; use the right-hand rule to find $\vec{V} \times \vec{B}$, then reverse it if q is negative.

The magnetic force on a point charge is perpendicular to the magnetic field and perpendicular to the velocity.

The direction of the magnetic force is not along the same line as the field (as is the case for the electric field); instead it is *perpendicular*. The force is also perpendicular to the charged particle's velocity. Therefore, if $\vec{V}$ and $\vec{B}$ lie in a plane, the magnetic force is always perpendicular to that plane; magnetism is inherently three dimensional. A negatively charged particle feels a magnetic force in the direction *opposite* to $\vec{V} \times \vec{B}$; multiplying a *negative* scalar (q) by $\vec{V} \times \vec{B}$ reverses the direction of the magnetic force.

Example 1

Electron in a Magnetic Field

An electron moves with speed 2.0×10^6 m/sec in a uniform magnetic field of 1.4 T directed due north. At one instant, the electron experiences an upward agnetic force of 1.6×10^{-13} N. In what direction is the electron moving at that instant? [*Hint:* If there is more than one possible answer, find all the possibilities.]

Strategy This example is more complicated. We need to apply the magnetic force law again, but this time we must deduce the direction of the velocity from the directions of the force and field.

Solution The magnetic force is always perpendicular to both the magnetic field and the particle's velocity. The force is upward, therefore the velocity must lie in a horizontal plane.

Figure 19.12 shows the magnetic field pointing north and a variety of possibilities for the velocity (all in the horizontal plane). The direction of the magnetic force is up, so the direction of $\vec{V} \times \vec{B}$ must be down since the charge is negative.

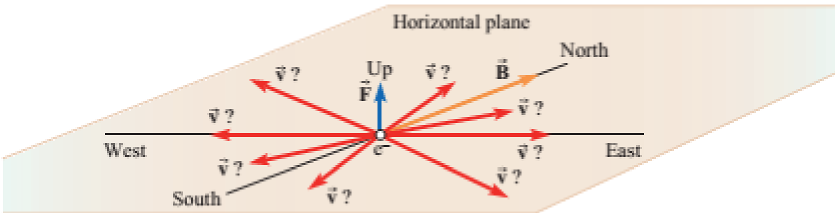


Figure 19.12 *The velocity must be perpendicular to the force and thus in the plane shown. Various possibilities for the direction of* $\vec{V}$ *are considered. Only those in the west half of the plane give the correct direction for* $\vec{V} \times \vec{B}$.

Pointing the thumb of the right hand downward, the fingers curl in the clockwise sense. Since we curl from $\vec{V}$ to $\vec{B}$, the velocity must be somewhere in the left half of the plane; in other words, it must have a west component in addition to a north or south component.

The westward component is the component of $\vec{V}$ that is perpendicular to the field. Using the magnitude of the force, we can find the perpendicular component of the velocity:

$$F_B = |q| v_\perp B$$

$$v_\perp = \frac{F_B}{|q|B} = \frac{1.6 \times 10^{-13} N}{1.6 \times 10^{-19} C \times 1.4 T} = 7.14 \times 10^5 \, m/sec$$

The velocity also has a component in the direction of the field that can be found using the Pythagorean Theorem:

$$v^2 = v_\perp^2 + v_\parallel^2$$

$$v_{\parallel} = \pm\sqrt{v^2 - v_{\perp}^2}$$

$$= \pm 1.87 \times 10^6 \; m/sec$$

The $\pm$ sign would seem to imply that $v_{\parallel}$ could either be a north or a south component. The two possibilities are shown in Fig. 19.13. Use of the right-hand rule confirms that *either* gives $\vec{V} \times \vec{B}$ in the correct direction. Now we need to find the direction of $\vec{V}$ given its components. From Fig. 19.13,

$$\sin\theta = \frac{v_{\perp}}{v} = \frac{7.14 \times 10^5 \; m/sec}{2.0 \times 10^6 \; m/sec}$$

$$\theta = 21° W \; of \; N \; or 159° W \; of \; N$$

Since 159° W of N is the same as 21° W of S, the direction of the velocity is either 21° W of N or 21° W of S.

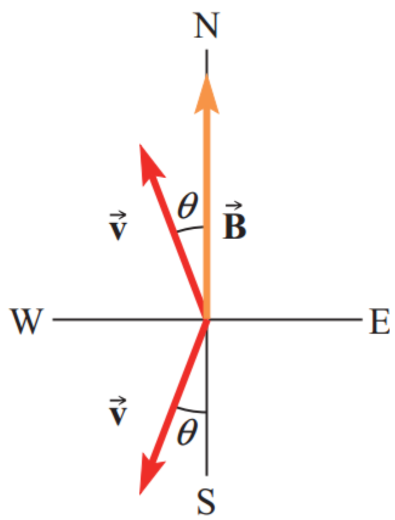


Figure 19.13 *Two possibilities for the direction of* $\vec{V}$.

Discussion *We cannot assume that* $\vec{V}$ *is perpendicular to* $\vec{B}$. *The magnetic force is always perpendicular to both* $\vec{V}$ *and* $\vec{B}$, *but there can be any angle between* $\vec{V}$ *and* $\vec{B}$.

19.3 CHARGED PARTICLE MOVING PERPENDICUL-ARLY TO A UNIFORM MAGNETIC FIELD

Using the magnetic force law and Newton's second law of motion, we can deduce the trajectory of a charged particle moving in a uniform magnetic field with no other forces acting. In this section, we discuss a case of particular interest: when the particle is initially moving perpendicularly to the magnetic field.

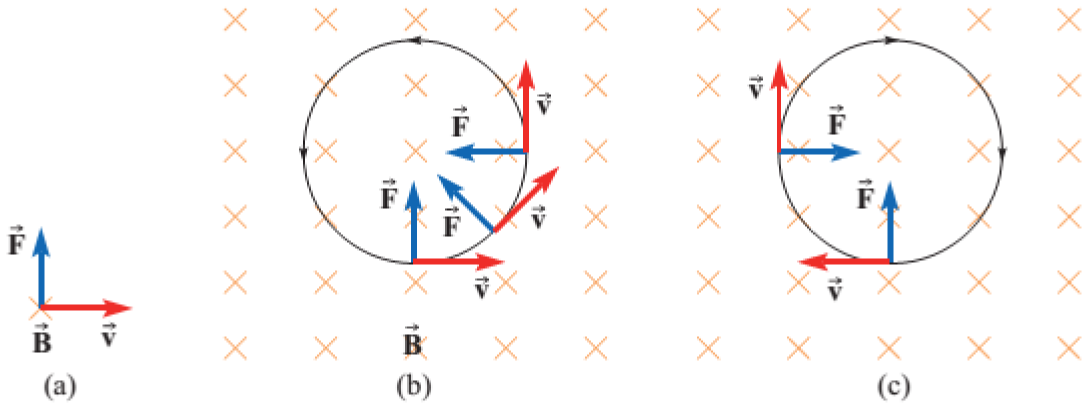


Figure 19.14 *(a) Force on a positive charge moving to the right in a magnetic field that is into the page. (b) As the velocity changes direction, the magnetic force changes direction to stay perpendicular to both* $\vec{V}$ *and* $\vec{B}$*. The force is constant in magnitude, so the particle moves along the arc of a circle. (c) Motion of a negative charge in the same magnetic field.*

Figure 19.14a shows the magnetic force on a positively charged particle moving perpendicularly to a magnetic field. Since $v_\perp = v$, the magnitude of the force is

$$F = |q|vB \quad (19\text{-}6)$$

Since the force is perpendicular to the velocity, the particle changes direction but not speed. The force is also perpendicular to the field, so there is no acceleration component in the direction of $\vec{B}$. Thus, the particle's velocity remains perpendic-ular to $\vec{B}$. As the velocity changes direction, the magnetic force changes direction to stay perpendicular to both $\vec{V}$ and $\vec{B}$. The magnetic force acts as a steering force, curving the

CONNECTION:

The expression for the radially inward acceleration of a particle in uniform circular motion, $a_r = v^2/r$, is the same one used for other kinds of circular motion.

particle around in a trajectory of radius r at constant speed. The particle undergoes uniform circular motion, so its acceleration is directed radially inward and has magnitudev^2/r. From Newton's second law,

$$a^r = \frac{v^2}{r} = \sum \frac{F}{m} = \frac{|q|vB}{m} \qquad \textbf{(19-7)}$$

where m is the mass of the particle. Since the radius of the trajectory is constant — r depends only on q, V, B, and m, which are all constant— the particle moves in a circle at constant speed (Fig. 19.14b). Negative charges move in the opposite sense from positive charges in the same field (Fig. 19.14c).

Magnetic fields can cause charges to move along circular paths.

19.4 MOTION OF A CHARGED PARTICLE IN A UNIFORM MAGNETIC FIELD: GENERAL

What is the trajectory of a charged particle moving in a uniform magnetic field with no other forces acting? In Section 19.3, we saw that the trajectory is a circle *if* the velocity is perpendicular to the magnetic field. If $\vec{\mathbf{v}}$ has no perpendicular component, the magnetic force is zero and the particle moves at constant velocity.

In general, the velocity may have components both perpendicular to and parallel to the magnetic field. The component parallel to the field is constant, since the magnetic force is always perpendicular to the field. The particle therefore moves along a *helical* path (Text website interactive: magnetic fields). The helix is formed by circular motion of the charge in a plane perpendicular to the field superimposed onto motion of the charge at constant speed along a field line (Fig. 19.19a).

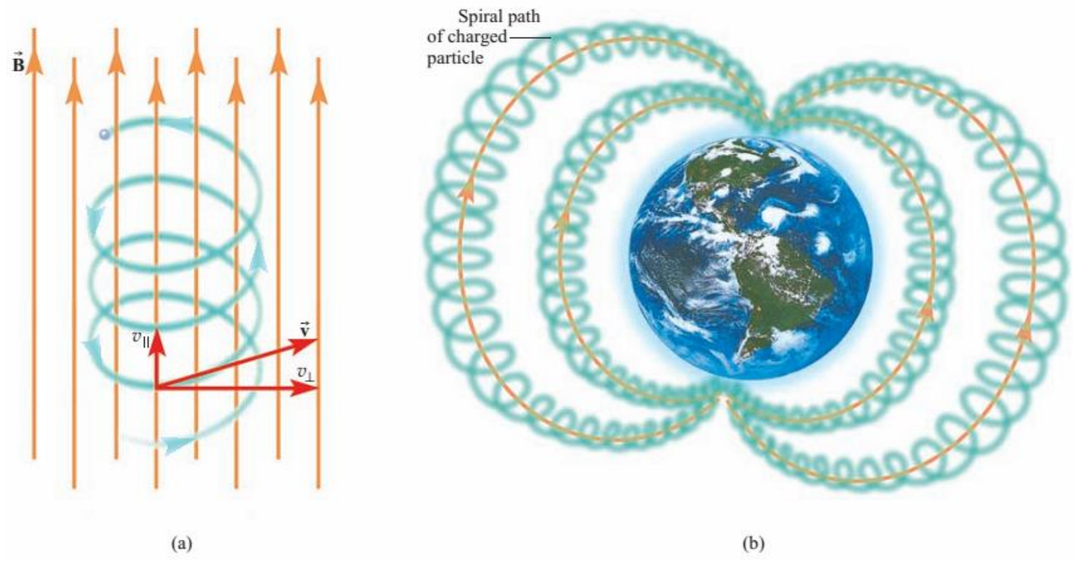


Figure 19.19 *(a) Helical motion of a charged particle in a uniform magnetic field. (b) Charged particles spiral back and forth along field lines high above the atmosphere.*

Even in nonuniform fields, charged particles tend to spiral around magnetic field lines. Above Earth's surface, charged particles from cosmic rays and the solar wind (charged particles streaming toward Earth from the Sun) are trapped by Earth's magnetic field. The particles spiral back and forth along magnetic field lines (Fig. 19.19b). Near the poles, the field lines are closer together, so the field is stronger. As the field strength increases, the radius of a spiraling particle's path gets smaller and smaller. As a result, there is a concentration of these particles near the poles. The particles collide with and ionize air molecules. When the ions recombine with electrons to form neutral atoms, visible light is emitted—the *aurora borealis* in the northern hemisphere and the *aurora australis* in the southern hemisphere. Aurorae also occur on Jupiter and Saturn, which have much stronger magnetic fields than does Earth.

19.5 A CHARGED PARTICLE IN CROSSED $\vec{E}$ AND $\vec{B}$ FIELDS

If a charged particle moves in a region of space where both electric and magnetic fields are present, then the electromagnetic force on the particle is the vector sum of the electric and magnetic forces:

$$\vec{F} = \vec{F}_E + \vec{F}_B \qquad (19-8)$$

A particularly important and useful case is when the electric and magnetic fields are perpendicular to one another and the velocity of a charged particle is perpendicular to both fields. Since the magnetic force is always perpendicular to both $\vec{V}$ and $\vec{B}$, it must be either in the same direction as the electric force or in the opposite direction. If the magnitudes of the two forces are the same and the directions are opposite, then there is zero net force on the charged particle (Fig. 19.20). For any particular combination of electric and magnetic fields, this balance of forces occurs only for one particular particle speed, since the magnetic force is velocity-dependent, but the electric force is not. The velocity that gives zero net force can be found from

$$\vec{F} = \vec{F}_E + \vec{F}_B = 0$$

$$q\vec{E} + q\vec{V} \times \vec{B} = 0$$

Dividing out the common factor of q,

$$\vec{E} + \vec{V} \times \vec{B} = 0 \qquad (19-9)$$

There is zero net force on the particle only if

$$v = \frac{E}{B} \qquad (19-10)$$

and if the direction of $\vec{V}$ is correct. Since $\vec{E} = -\vec{V} \times \vec{B}$, it can be shown (see Conceptual Question 7) that the correct direction of $\vec{V}$ is the direction of $\vec{E} \times \vec{B}$.

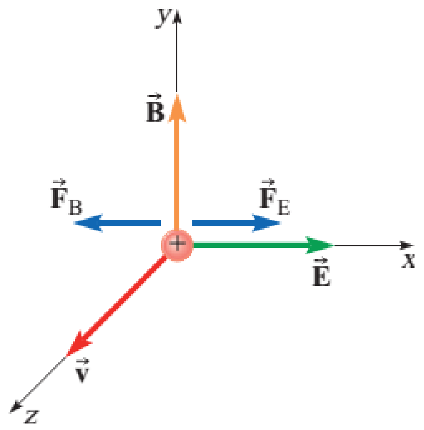


Figure 19.20 Positive point charge moving in crossed $\vec{E}$ and $\vec{B}$ fields. For the velocity direction shown, $F_E + F_B = 0$ if $v = E/B$.

19.6 MAGNETIC FORCE ON A CURRENT-CARRYING WIRE

A wire carrying electric current has many moving charges in it. For a current-carrying wire in a magnetic field, the magnetic forces on the individual moving charges add up to produce a net magnetic force on the wire. Although the average force on one of the charges may be small, there are so many charges that the net magnetic force on the wire can be appreciable.

Say a straight wire segment of length L in a uniform magnetic field $\vec{B}$ carries a current I. The mobile carriers have charge q. The magnetic force on any one charge is

$$\vec{F} = q\vec{V} \times \vec{B}$$

where $\vec{V}$ is the instantaneous velocity of that charge. The net magnetic force on the wire is the vector sum of these forces. The sum isn't easy to carry out, since we don't know the instantaneous velocity of each of the charges. The charges move about in random directions at high speeds; their velocities suffer large changes when they collide with other particles.

> **CONNECTION:**
>
> The magnetic force on a current-carrying wire is the sum of the magnetic forces on the charge carriers in the wire.

Instead of summing the instantaneous magnetic force on each charge, we can instead multiply the *average* magnetic force on each charge by the number of charges. Since each charge has the same average velocity—the drift velocity—each experiences the same average magnetic force $\vec{F}_{av}$.

$$\vec{F}_{av} = q\vec{V}_D \times \vec{B}$$

Then, if N is the total number of carriers in the wire, the total magnetic force on the wire is

$$\vec{F} = Nq\vec{V}_D \times \vec{B} \qquad (19-11)$$

Equation (19-11) can be rewritten in a more convenient way. Instead of having to figure out the number of carriers and the drift velocity, it is more convenient to have an expression that gives the magnetic force in terms of the current *I*. The current *I* is related to the drift velocity:

$$I = nqAv_D \qquad (18-3)$$

Here n is the number of carriers *per unit volume*. If the length of the wire is L and the cross-sectional area is *A*, then

$$N = number\ per\ unit\ volume \times volume = nLA$$

By substitution, the magnetic force on the wire can be written

$$F = Nq\vec{V}_D \times \vec{B} = nqAL\vec{V}_D \times \vec{B}$$

Almost there! Since current is not a vector, we cannot substitute $\vec{I} = nqA\vec{V}_D$. Therefore, we define a *length vector* $\vec{L}$ to be a vector in the direction of the current with magnitude equal to the length of the wire (Fig. 19.27). Then $nqAL\vec{V}_D = I\vec{L}$ and Magnetic force on a straight segment of current-carrying wire:

$$\vec{F} = I\,\vec{L} \times \vec{B} \qquad (19-12a)$$

The current I times the cross product $\vec{L} \times \vec{B}$ gives the magnitude and direction of the force. The magnitude of the force is

$$F = IL_{\perp}B = ILB_{\perp} = ILB\ \sin\theta \qquad (19-12b)$$

The direction of the force is perpendicular to both $\vec{L}$ and $\vec{B}$. The same right-hand rule used for any cross product is used to choose between the two possibilities.

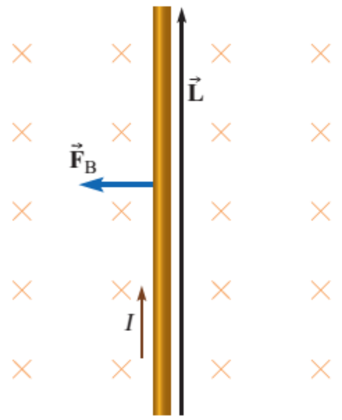


Figure 19.27 A current carrying wire in an externally applied magnetic field experiences a magnetic force.

19.8 MAGNETIC FIELD DUE TO AN ELECTRIC CURRENT

So far we have explored the magnetic forces acting on charged particles and currentcarrying wires. We have not yet looked at *sources* of magnetic fields other than permanent magnets. It turns out that *any moving charged particle* creates a magnetic field. There is a certain symmetry about the situation:

- Moving charges experience magnetic forces and moving charges create magnetic fields;
- Charges at rest feel no magnetic forces and create no magnetic fields;
- Charges feel electric forces and create electric fields, whether moving or not.

Today we know that electricity and magnetism are closely intertwined. It may be surprising to learn that they were not known to be related until the nineteenth century. Hans Christian Oersted discovered in 1820 by happy accident that electric currents flowing in wires made nearby compass needles swing around. Oersted's discovery was the first evidence of a connection between electricity and magnetism.

The magnetic field due to a single moving charged particle is negligibly small in most situations. However, when an electric current flows in a wire, there are enormous numbers of moving charges. The magnetic field due to the wire is the sum of the magnetic fields due to each charge; the principle of superposition applies to magnetic fields just as it does to electric fields.

Magnetic Field due to a Long Straight Wire

Let us first consider the magnetic field due to a long, straight wire carrying a current I. What is the magnetic field at a distance *r* from the wire and far from its ends? Figure 19.34a is a photo of such a wire, passing through a glass plate on which iron filings have been sprinkled. The iron bits line up with the magnetic field due to the current in the wire. The photo suggests that the magnetic field lines are circles centered on the wire. Circular field lines are indeed the only possibility, given the symmetry of the situation. If the lines were any other shape, they would be farther from the wire in some directions than in others.

The iron filings do not tell us the direction of the field. By using compasses instead of iron filings (Fig. 19.34b), the direction of the field is revealed—it is the direction indicated by the north end of each compass. The field lines due to the wire are shown in Fig. 19.34c , where the current in the wire flows upward.

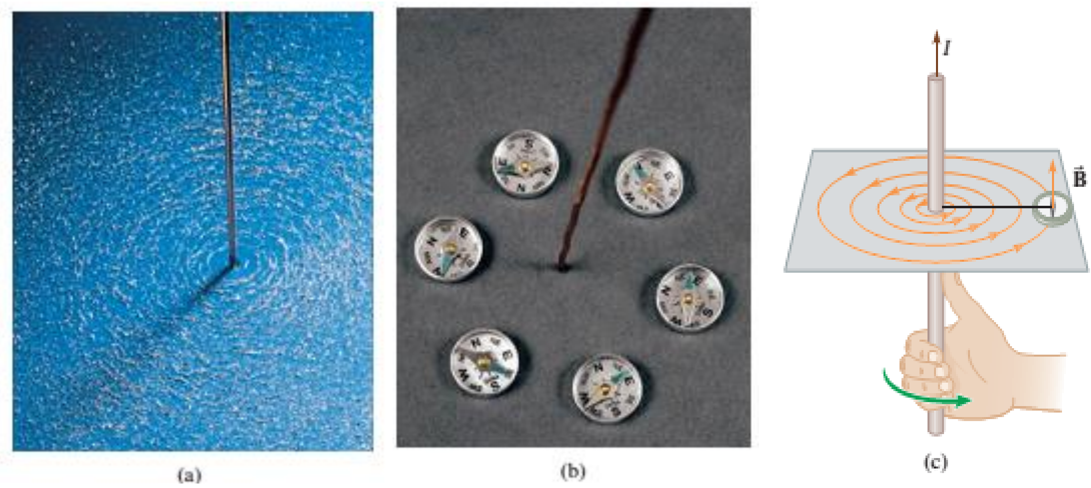


Figure 19.34 Magnetic field due to a long straight wire. (a) Photo of a long wire, with iron filings lining up with the magnetic field. (b) Compasses show the direction of the field. (c) Sketch illustrating how to use the right-hand rule to determine the

direction of the field lines. At any point, the magnetic field is tangent to one of the circular field lines and, therefore, perpendicular to a radial line from the wire.

Using Right-Hand Rule 2 to Find the Direction of the Magnetic Field due to a Long Straight Wire

1. Point the thumb of the right hand in the direction of the current in the wire.
2. Curl the fingers inward toward the palm; the direction that the fingers curl is the direction of the magnetic field lines around the wire (Fig. 19.34c).
3. As always, the magnetic field at any point is tangent to a field line through that point. For a long straight wire, the magnetic field is tangent to a circular field line and, therefore, perpendicular to a radial line from the wire.

A right-hand rule relates the current direction in the wire to the direction of the field around the wire:

The magnitude of the magnetic field at a distance *r* from the wire can be found using Ampère's law:

Magnetic field due to a long straight wire:

$$B = \frac{\mu_o I}{2\pi r} \qquad \mathbf{(19-14)}$$

where I is the current in the wire and μ_o is a universal constant known as the **permeability of free space**. The permeability plays a role in magnetism similar to the role of the permittivity (ϵ_o) in electricity. In SI units, the value of μ_o is

$$\mu_o = 4\pi \times 10^{-7}\ \frac{T \cdot m}{A} \quad (exact, by\ definition) \qquad \mathbf{(19-15)}$$

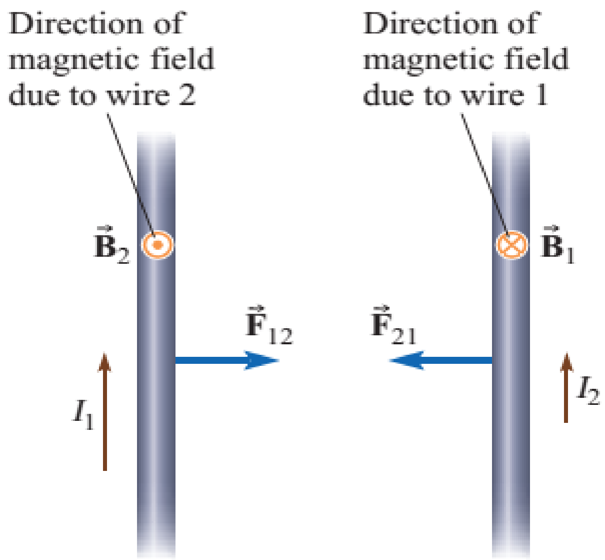


Figure 19.35 Two parallel wires exert magnetic forces on one another. The force on wire 1 due to wire 2's magnetic field is $\vec{F}_{12} = I_1\vec{L}_1 \times \vec{B}_2$. Even if the currents are unequal, $\vec{F}_{21} = -\vec{F}_{12}$ (Newton's third law).

Two parallel current-carrying wires that are close together exert magnetic forces on one another. The magnetic field of wire 1 causes a magnetic force on wire 2; the magnetic field of wire 2 causes a magnetic force on wire 1 (Fig. 19.35). From Newton's third law, we expect the forces on the wires to be equal and opposite. If the currents flow in the same direction, the force is attractive; if they flow in opposite directions, the force is repulsive (see Problem 72).

Note that for current-carrying wires, "likes" (currents in the same direction) attract one another and "unlikes" (currents in opposite directions) repel one another.

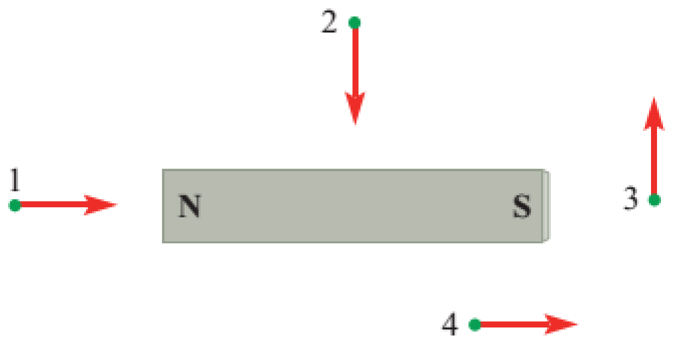
The constant μ_o can be assigned an exact value because the magnetic forces on two parallel wires are used to *define* the ampere, which is an SI base unit. One ampere is the current in each of two long parallel wires 1 m apart such that each exerts a magnetic force on the other of exactly $2 \times 10^{-7}\ N$ per meter of length. The ampere, not the coulomb, is chosen to be an SI base unit because it can be defined in terms of forces and lengths that can be measured accurately. The coulomb is then defined as 1 ampere-second.

Multiple-Choice Questions

Multiple-Choice Questions 1–4. In the figure, four point charges move in the directions indicated in the vicinity of a bar magnet. The magnet, charge positions, and velocity vectors all lie in the plane of this page. Answer choices:

(a) ↑ **(b)** ↓ **(c)** ← **(d)** →

(e) × (into page) **(f)** • (out of page) **(g)** the force is zero



Multiple-Choice Questions 1– 4

1. What is the direction of the magnetic force on charge 1 if $q_1 < 0$?

2. What is the direction of the magnetic force on charge 2 if $q_2 < 0$?

3. What is the direction of the magnetic force on charge 3 if $q_3 < 0$?

4. What is the direction of the magnetic force on charge 4 if $q_4 < 0$?

5. The magnetic force on a point charge in a magnetic field $\vec{B}$ is largest, for a given speed, when it

   (a) moves in the direction of the magnetic field.

   (b) moves in the direction opposite to the magnetic field.

   (c) moves perpendicular to the magnetic field.

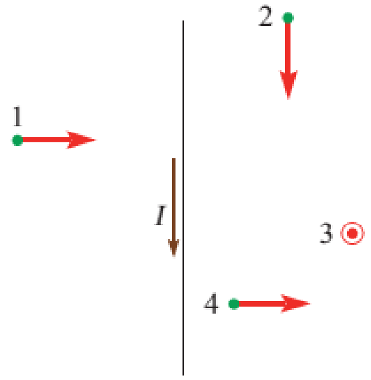
   (d) has velocity components both parallel to and perpendicular to the field.

Multiple-Choice Questions 6–9.

A wire carries current as shown in the figure. Charged particles 1, 2, 3, and 4 move in the directions indicated. Answer choices for Questions 6–8:

(a) ↑ **(b)** ↓ **(c)** ← **(d)** →

(e) × (into page) **(f)** ⊙ (out of page) **(g)** the force is zero



6. What is the direction of the magnetic force on charge 1 if $q_1 < 0$?

7. What is the direction of the magnetic force on charge 2 if $q_2 > 0$?

8. What is the direction of the magnetic force on charge 3 if $q_3 < 0$?

9. If the magnetic forces on charges 1 and 4 are equal and their velocities are equal,

(a) the charges have the same sign and $|q_1| > |q_4|$.

(b) the charges have opposite signs and $|q_1| > |q_4|$.

(c) the charges have the same sign and $|q_1| < |q_4|$.

(d) the charges have opposite signs and $|q_1| < |q_4|$.

(e) $q_1 = q_4$.

(f) $q_1 = -q_4$

10. The magnetic field lines *inside* a bar magnet run in what direction?

(a) from north pole to south pole

(b) from south pole to north pole

(c) from side to side

(d) None of the above—there are no magnetic field lines *inside* a bar magnet.

11. The magnetic forces that two parallel wires with unequal currents flowing in opposite directions exert on each other are

(a) attractive and unequal in magnitude.

(b) repulsive and unequal in magnitude.

(c) attractive and equal in magnitude.

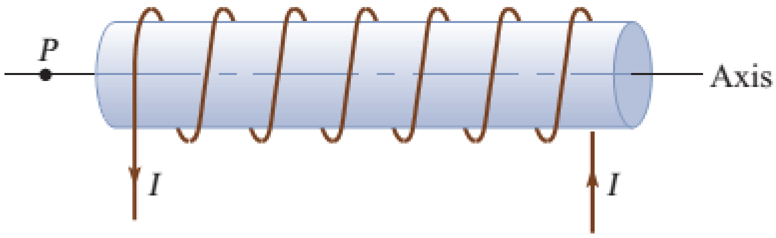
(d) repulsive and equal in magnitude.

(e) both zero.

(f) in the same direction and unequal in magnitude.

(g) in the same direction and equal in magnitude.

12. What is the direction of the magnetic field at point *P* in the figure? (*P* is on the axis of the coil.)

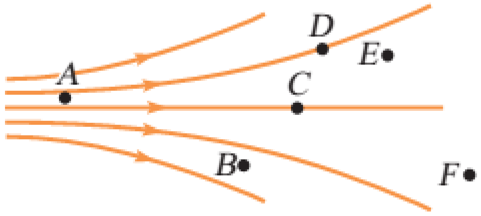


(a) ↑ **(b)** ↓ **(c)** ← **(d)** →

(e) × (into page) **(f)** • (out of page

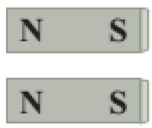
Problems

1. At which point in the diagram is the magnetic field strength (a) the smallest and (b) the largest? Explain.
2. Draw vector arrows to indicate the direction and relative magnitude of the magnetic field at each of the points *A*–*F*.

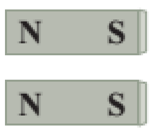


Problems 1 and 2

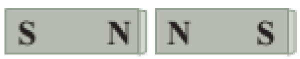
3. Two identical bar magnets lie next to one another on a table. Sketch the magnetic field lines if the north poles are at the same end



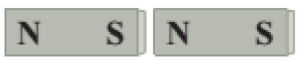
4. Two identical bar magnets lie next to one another on a table. Sketch the magnetic field lines if the north poles are at opposite ends.



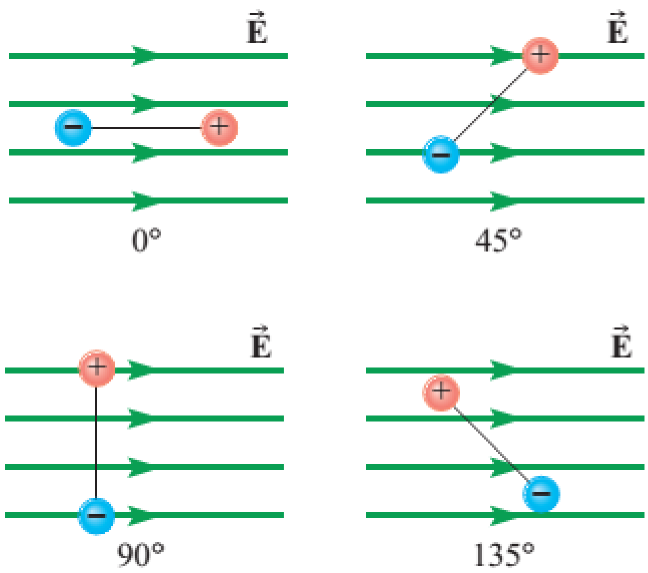
5. Two identical bar magnets lie on a table along a straight line with their north poles facing each other. Sketch the magnetic field lines.



6. Two identical bar magnets lie on a table along a straight line with opposite poles facing each other. Sketch the magnetic field lines.



7. The magnetic forces on a magnetic dipole result in a torque that tends to make the dipole line up with the magnetic field. In this problem we show that the electric forces on an electric dipole result in a torque that tends to make the electric dipole line up with the electric field.(a) For each orientation of the dipole shown in the diagram, sketch the electric forces and determine the direction of the torque—clockwise or counterclockwise—about an axis perpendicular to the page through the center of the dipole. (b) The torque always tends to make the dipole rotate toward what orientation?



19.2 Magnetic Force on a Point Charge

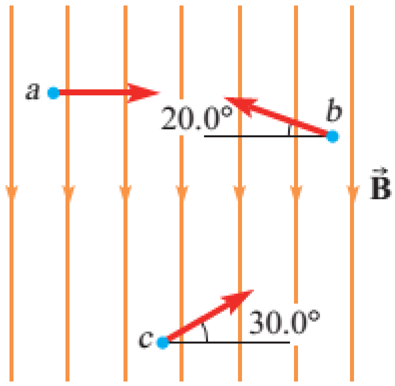
8. Find the magnetic force exerted on an electron moving vertically upward at a speed of 2.0 × 107 m/s by a horizontal magnetic field of 0.50 T directed north. (tutorial: magnetic deflection of electron)

9. Find the magnetic force exerted on a proton moving east at a speed of 6.0 × 106 m/s by a horizontal magnetic field of 2.50 T directed north.

10. A uniform magnetic field points north; its magnitude is 1.5 T. A proton with kinetic energy 8.0×10^{-13} J is moving vertically downward in this field. What is the magnetic force acting on it?

11. A uniform magnetic field points vertically upward; its magnitude is 0.800 T. An electron with kinetic energy 7.2 × 10−18 J is moving horizontally eastward in this field. What is the magnetic force acting on it?

Problems 12–14. Several electrons move at speed 8.0 ×105 m/s in a uniform magnetic field with magnitude *B* = 0.40 T directed downward.



Problems 12–14

12. Find the magnetic force on the electron at point a.

13. Find the magnetic force on the electron at point *b*.

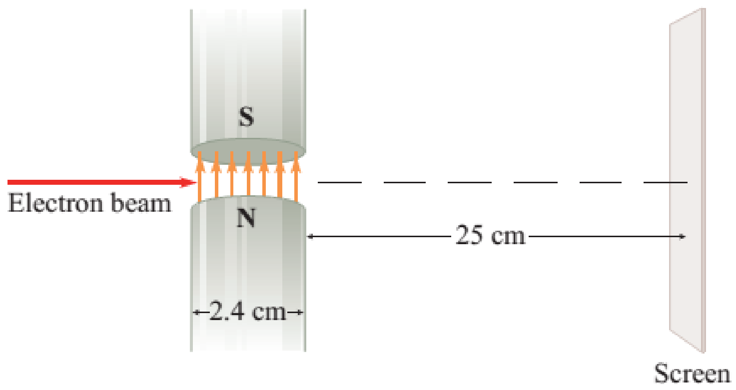
14. Find the magnetic force on the electron at point *c*.

15. Electrons in a television's CRT are accelerated from rest by an electric field through a potential difference of 2.5 kV. In contrast to an oscilloscope, where the electron beam is deflected by an electric field, the beam is deflected by a magnetic field. (a) What is the speed of the electrons? (b) The beam is deflected by a perpendicular magnetic field of magnitude 0.80 T. What is the magnitude of the acceleration of the electrons while in the field? (c) What is the speed of the electrons after they travel 4.0 mm through the magnetic field? (d) What strength electric field would give the electrons the same magnitude acceleration as in (b)? (e) Why do we have to use an electric field in the first place to get the electrons up to speed? Why not use the large acceleration due to a magnetic field for that purpose?

16. A magnet produces a 0.30-T field between its poles, directed to the east. A dust particle with charge $q = -8.0 \times 10-18$ C is moving straight down at 0.30 cm/s in this field. What is the magnitude and direction of the magnetic force on the dust particle?

17. At a certain point on Earth's surface in the southern hemisphere, the magnetic field has a magnitude of $5.0 \times 10-5$ T and points upward and toward the north at an angle of 55° above the horizontal. A cosmic ray muon with the same charge as an electron and a mass of $1.9 \times 10-28$ kg is moving directly down toward Earth's surface with a speed of 4.5×107 m/s. What is the magnitude and direction of the force on the muon?

18. An electron beam in vacuum moving at 1.8×107 m/s passes between the poles of an electromagnet. The diameter of the magnet pole faces is 2.4 cm and the field between them is $0.20 \times 10-2$ T. How far and in what direction is the beam deflected when it hits the screen, which is 25 cm past the magnet? [*Hint:* The electron velocity changes relatively little, so approximate the magnetic force as a constant force acting during a 2.4-cm displacement to the right.]



19. A positron ($q = +e$) moves at 5.0×107 m/s in a magnetic field of magnitude 0.47 T. The magnetic force on the positron has magnitude $2.3 \times 10-12$ N. (a) What is the component of the positron's velocity perpendicular to the magnetic field? (b) What is the component of the positron's velocity parallel

to the magnetic field? (c) What is the angle between the velocity and the field?

20. An electron moves with speed 2.0 × 105 m/s in a 1.2-T uniform magnetic field. At one instant, the electron is moving due west and experiences an upward magnetic force of 3.2 × 10−14 N. What is the direction of the magnetic field? Be specific: give the angle(s) with respect to N, S, E, W, up, down. (If there is more than one possible answer, find all the possibilities.)
21. An electron moves with speed 2.0 × 105 m/s in a uniform magnetic field of 1.4 T, pointing south. At one instant, the electron experiences an upward magnetic force of 1.6 × 10−14 N. In what direction is the electron moving at that instant? Be specific: give the angle(s) with respect to N, S, E, W, up, down. (If there is more than one possible answer, find all the possibilities.)

19.3 Charged Particle Moving Perpendicularly to a Uniform Magnetic Field

22. The magnetic field in a cyclotron is 0.50 T. Find the magnitude of the magnetic force on a proton with speed 1.0 × 107 m/s moving in a plane perpendicular to the field.
23. An electron moves at speed 8.0 × 105 m/s in a plane perpendicular to a cyclotron's magnetic field. The magnitude of the magnetic force on the electron is 1.0 × 10−13 N. What is the magnitude of the magnetic field?
24. When two particles travel through a region of uniform magnetic field pointing out of the plane of the paper, they follow the trajectories shown. What are the signs of the charges of each particle?
25. The magnetic field in a cyclotron is 0.360 T. The dees have radius 82.0 cm. What maximum speed can a proton achieve in this cyclotron?
26. The magnetic field in a cyclotron is 0.50 T. What must be the minimum radius of the dees if the maximum proton speed desired is 1.0 × 107 m/s?

27. A singly charged ion of unknown mass moves in a circle of radius 12.5 cm in a magnetic field of 1.2 T. The ion was accelerated through a potential difference of 7.0 kV before it entered the magnetic field. What is the mass of the ion?

Problems 28–32. The conversion between atomic mass units and kilograms is 1 u $= 1.66 \times 10^{-27}$ kg

28. Natural carbon consists of two different isotopes (excluding 14C, which is present in only trace amounts). The isotopes have different masses, which is due to different numbers of neutrons in the nucleus; however, the number of protons is the same, and subsequently the chemical properties are the same. The most abundant isotope has an atomic mass of 12.00 u. When natural carbon is placed in a mass spectrometer, two lines are formed on the photographic plate. The lines show that the more abundant isotope moved in a circle of radius 15.0 cm, while the rarer isotope moved in a circle of radius 15.6 cm. What is the atomic mass of the rarer isotope? (The ions have the same charge and are accelerated through the same potential difference before entering the magnetic field.)

29. After being accelerated through a potential difference of 5.0 kV, a singly charged carbon ion (12C+) moves in a circle of radius 21 cm in the magnetic field of a mass spectrometer. What is the magnitude of the field?

30. A sample containing carbon (atomic mass 12 u), oxygen (16 u), and an unknown element is placed in a mass spectrometer. The ions all have the same charge and are accelerated through the same potential difference before entering the magnetic field. The carbon and oxygen lines are separated by 2.250 cm on the photographic plate, and the unknown element makes a line between them that is 1.160 cm from the carbon line. (a) What is the mass of the unknown element? (b) Identify the element.

31. A sample containing sulfur (atomic mass 32 u), manganese (55 u), and an unknown element is placed in a mass spectrometer. The ions have the same

charge and ✦ are accelerated through the same potential difference before entering the magnetic field. The sulfur and manganese lines are separated by 3.20 cm, and the unknown element makes a line between them that is 1.07 cm from the sulfur line. (a) What is the mass of the unknown element? (b) Identify the element.

32. In one type of mass spectrometer, ions having the *same velocity* move through a uniform magnetic field. The spectrometer is being used to distinguish 12C+ and 14C+ ions that have the same charge. The 12C+ ions move in a circle of diameter 25 cm. (a) What is the diameter of the orbit of 14C+ ions? (b) What is the ratio of the frequencies of revolution for the two types of ion?

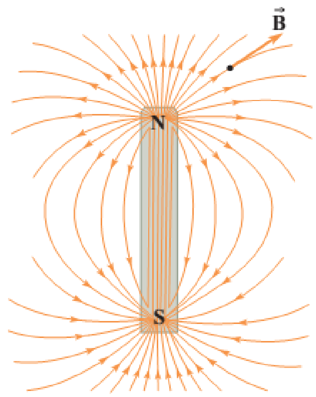
33. Prove that the time for one revolution of a charged particle moving perpendicular to a uniform magnetic field is independent of its speed. (This is the principle on which the cyclotron operates.) In doing so, write an expression that gives the period T (the time for one revolution) in terms of the mass of the particle, the charge of the particle, and the magnetic field strength.

Master the Concepts

✓ Magnetic field lines are interpreted just like electric field lines. The magnetic field at any point is tangent to the field line; the magnitude of the field is proportional to the number of lines per unit area perpendicular to the lines.

✓ Magnetic field lines are always closed loops because there are no magnetic monopoles.

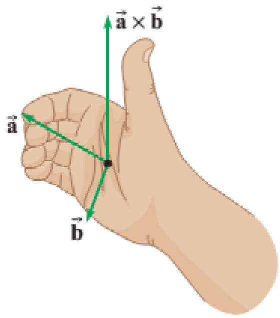
✓ The smallest unit of magnetism is the magnetic dipole. Field lines emerge from the North Pole and reenter at the South Pole. A magnet can have more than two poles, but it must have at least one North Pole and at least one South Pole.



✓ The magnitude of the cross product of two vectors is the magnitude of one vector times the perpendicular component of the other:

$$|\vec{a} \times \vec{b}| = |\vec{a} \times \vec{b}| = a_{\perp} b = a b_{\perp} = ab \sin\theta \qquad (19\text{-}3)$$

✓ The direction of the cross product is the direction perpendicular to both vectors that is chosen using righthand rule 1.



✓ The magnetic force on a charged particle is $\vec{F_B} = q\vec{V} \times \vec{B}$ (19-5)

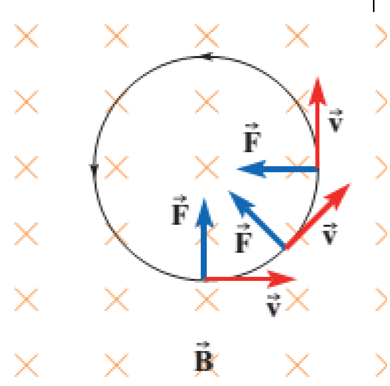
If the charge is at rest ($v = 0$) or if its velocity has no component perpendicular to the magnetic field ($v_{\perp} = 0$), then the magnetic force is zero. The force is always perpendicular to the magnetic field and to the velocity of the particle.

$$\text{Magnitude: } F_B = qvB\sin\theta$$

Direction: use the right-hand rule to find $\vec{V} \times \vec{B}$, then reverse it if q is negative.

✓ The SI unit of magnetic field is the tesla: $1\,T = 1\,\frac{N}{A \cdot m}$ **(19-2)**

✓ If a charged particle moves at right angles to a uniform magnetic field, then its trajectory is a circle. If the velocity has a component parallel to the field as well as a component perpendicular to the field, then its trajectory is a helix.



✓ The magnetic force on a straight wire carrying current I is

$$\vec{F} = I\vec{L} \times \vec{B} \qquad \textbf{(19-12a)}$$

where $\vec{L}$ is a vector whose magnitude is the length of the wire and whose direction is along the wire in the direction of the current.

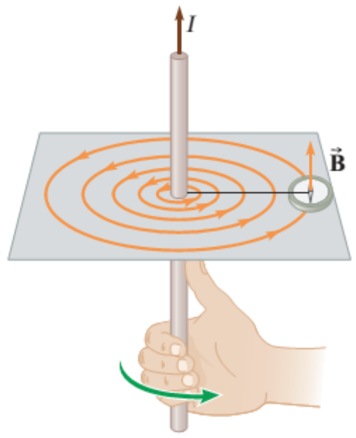
✓ The magnetic torque on a planar current loop is $\tau = NIAB\sin\theta$ **(19-13b)** where θ is the angle between the magnetic field and the dipole moment vector of the loop. The direction of the dipole moment is perpendicular to the loop as chosen using right-hand rule 1 (take the cross product of $\vec{L}$ for any side with $\vec{L}$ for the *next* side, going around in the same direction as the current).

- ✓ The magnetic field at a distance *r* from a long straight wire has magnitude

  $B = \_\_\_\_\_ m_0 I$

  $2pr$ **(19-14)**

- ✓ The field lines are circles around the wire with the direction given by right-hand rule 2.



The permeability of free space is

$m_0 = 4p \times 10^{-7}$ ____ T·m

A **(19-15)**

The magnetic field inside a long tightly wound solenoid is uniform:

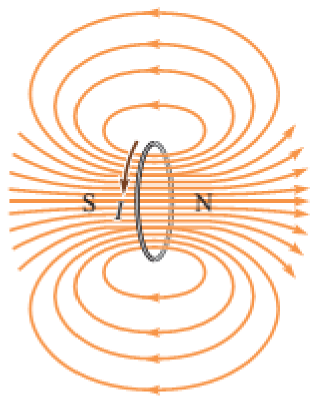
$B = \_\_\_\_\_ m_0 NI$

$L = m_0 nI$ **(19-17)**

Its direction is along the axis of the solenoid, as given by right-hand rule 3.

- ✓ Ampère’s law relates the circulation of the magnetic field around a closed path to the *net* current *I* that crosses the interior of the path.

  $\sum B_{\parallel} \Delta l = m_0 I$ **(19-19)**



The magnetic properties of ferromagnetic materials are due to an interaction that keeps the magnetic dipoles aligned within regions called domains, even in the *absence* of an external magnetic field.

Answers
to Selected Questions and Problems

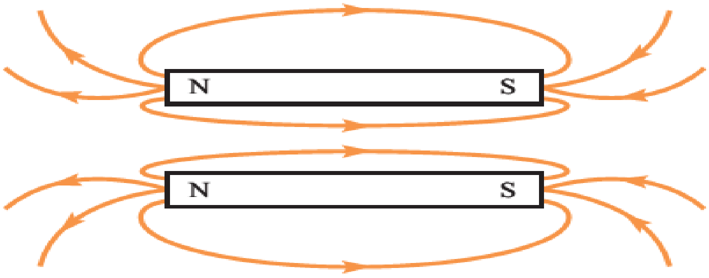
Multiple-Choice Questions

1. (g) **2.** (f) **3.** (e) **4.** (e) **5.** (c) **6.** (b) **7.** (c) **8.** (g) **9.** (b) **10.** (b) **11.** (d) **12.** (d)

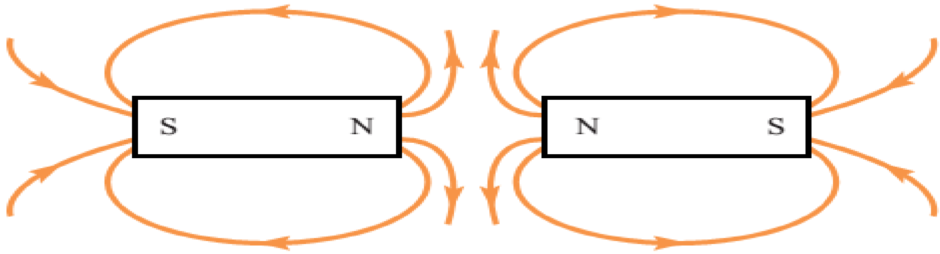
Problems

1. (a) *F* (b) *A*; highest density of field lines at point *A* and lowest density at point *F*

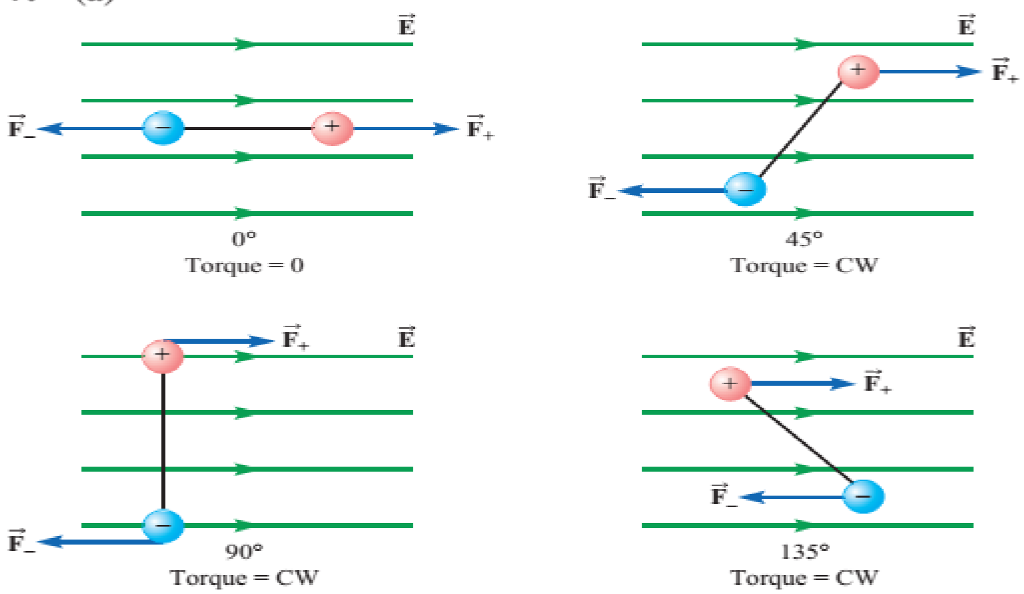
3.



5.



7. (a)



(b) parallel to the electric field lines

9. 2.4 × 10−12 N up

11. 5.1 × 10−13 N north

13. 4.8 × 10−14 N into the page

15. (a) 3.0 × 107 m/s (b) 4.2 × 1018 m/s2 (c) 3.0 × 107 m/s

(d) 2.4 × 107 V/m (e) Since the force due to the magnetic field is always perpendicular to the velocity of the electrons, it does not increase the electrons' speed but only changes their direction.

17. 2.1 × 10−16 N to the west

19. (a) 3.1 × 107 m/s (b) 4.0 × 107 m/s (c) 38°

21. There are two possibilities: 21°E of N and 21°E of S. **23.** 0.78 T **25.** 2.83 ×

10^7 m/s

27. 2.6 × 10−25 kg

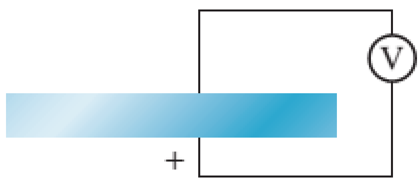
29. 0.17 T

31. (a) 39 u (b) potassium

33. _____ *2pm*

qB **35.** (a),

(b)



37. 8.4 × 1028 m−3

39. (a) upward (b) 0.20 mm/s

41. (a) 0.35 m/s (b) 4.4 × 10−6 m3/s (c) the east lead

43. ________ *E*2

2*B*2 Δ*V* **45.** (a) 0.50 T (b) We do not know the directions of the current and the field; therefore, we set sin *q* = 1 and get

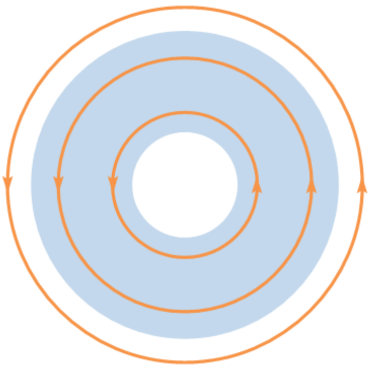
the minimum field strength. **47.** (a) north (b) 15.5 m/s

49. (a) **F** $\vec{}$top = 0.75 N in the −*y*-direction; **F** $\vec{}$bottom = 0.75 N in the

+*y*-direction; **F** $\vec{}$left = 0.50 N in the +*x*-direction; **F** $\vec{}$right = 0.50 N in the −*x*-direction (b) 0 **51.** (a) 18° below the horizontal with the horizontal component due south (b) 42 A **53.** (a) 0.21 T (b) clockwise **55.** (a) 0.0014 N·m (b) 0 **59.** 4.9°

61. 9 × 10−8 T out of the page **63.** 0 **65.** 3.2 × 10−16 N parallel to the current **67.** *B*, *D*, *C*, *A* **69.** **B** $\vec{}$*A* = 0; **B** $\vec{}$*B* = 3.38 × 10−7 T out of the page **71.** 750 A into the page **73.** 6.03 A, CCW **75.** 80 µT to the right **77.** 0.11 mT to the right **79.** (a) 4.9 cm (b) opposite

81. (a)



(b) _____ *m*0*I*

2*pr* CCW as seen from above **83.** *n* depends upon *r*; *B* = ______ *m* 20*p NI r* ;

the field is not uniform since *B* ∝ ___ 1

r. **85.** 9.3 × 10−24 N·m

87. (a) graph a (b) graph c **89.** south **91.** 1.25 × 10−17 N in the +*x*-direction **93.** (a) 10 A (b) farther apart

95. (a) 1.2 × 107 Hz (b) 2.2 × 1010 Hz **97.** 20.1 cm/s

99. 2.00 × 10−7 T up **101.** into the page **103.** tan−1 ______ *m* 0*NI*

2*rB*

H

105. (a)

Side Current direction Field direction Force direction

top right out of the page attracted to

long wire

bottom left out of the page repelled by

long wire

left up out of the page right

right down out of the page left

(b) 1.0×10^{-8} N away from the long wire **107.** (a) $\vec{F}_{top} = 0.65$ N into the page; $\vec{F}_{bottom} = 0.65$ N out of the page; $\vec{F}_{right} = 0.25$ N out of the page; $\vec{F}_{left} = 0.25$ N into the page (b) 0 **109.** 6.4×10^{-14} N at 86° below west **111.** (a) 8.6×10^{-15} N at 68° below west

(b) No; since $\vec{F}_E$ and $\vec{F}_B$ are perpendicular **113.** (a) 180 km

(b) 2.4×10^{6} m

Multiple-Choice Questions

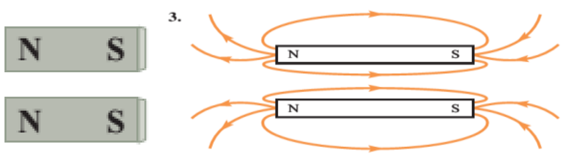
5. The magnetic force on a point charge in a magnetic field $\vec{B}$ is largest, for a given speed, when it
   (a) moves in the direction of the magnetic field.
   (b) moves in the direction opposite to the magnetic field.
   (c) moves perpendicular to the magnetic field.
   (d) has velocity components both parallel to and perpendicular to the field.

10. The magnetic field lines *inside* a bar magnet run in what direction?
   (a) from north pole to south pole
   (b) from south pole to north pole
   (c) from side to side
   (d) None of the above—there are no magnetic field lines inside a bar magnet.

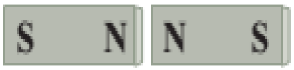
11. The magnetic forces that two parallel wires with unequal currents flowing in opposite directions exert on each other are
   (a) attractive and unequal in magnitude.
   (b) repulsive and unequal in magnitude.
   (c) attractive and equal in magnitude.
   (d) repulsive and equal in magnitude.

Problems

3. Two identical bar magnets lie next to one another on a table. Sketch the magnetic field lines if the north poles are at the same end



5. Two identical bar magnets lie on a table along a straight line with their north poles facing each other. Sketch the magnetic field lines.



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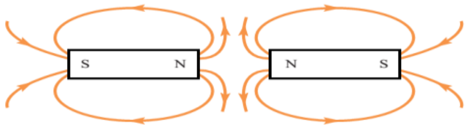

9.2 Magnetic Force on a Point Charge

9. Find the magnetic force exerted on a proton moving east at a speed of 6.0×10^6 m/s by a horizontal magnetic field of 2.50 T directed north. **9.** 2.4×10^{-12} N up

11. A uniform magnetic field points vertically upward; its magnitude is 0.800 T. An electron with kinetic energy 7.2×10^{-18} J is moving horizontally eastward in this field. What is the magnetic force acting on it? **11.** 5.1×10^{-13} N north

17. At a certain point on Earth's surface in the southern hemisphere, the magnetic field has a magnitude of 5.0×10^{-5} T and points upward and toward the north at an angle of 55° above the horizontal. A cosmic ray muon with the same charge as an electron and a mass of 1.9×10^{-28} kg is moving directly down toward Earth's surface with a speed of 4.5×10^7 m/s. What is the magnitude and direction of the force on the muon? **17.** 2.1 × 10−16 N to the west

19. A positron ($q = +e$) moves at 5.0×10^7 m/s in a magnetic field of magnitude 0.47 T. The magnetic force on the positron has magnitude 2.3×10^{-12} N. (a) What is the component of the positron's velocity perpendicular to the magnetic field? (b) What is the component of the positron's velocity parallel to the magnetic field? (c) What is the angle between the velocity and the field? **19.** (a) 3.1 × 107 m/s (b) 4.0 × 107 m/s (c) 38°

Quiz

Refer to the text in this chapter if necessary. A good score is eight correct.

1. **What's the different between**
   - → Permanent magnet and ferromagnetic materials
   - → Magnetic dipole and monopoles
   - → The Tesla and the Gauss

2. **What is the flux density in teslas and in in gauss at a distance of 200 mm from a straight, thin wire carrying 400 mA of direct current?**

3. **Suppose that a metal rod is surrounded by a coil and that the magnetic flux density can be made as great as 0.500 T; further increases in current cause no further increase in the flux density inside the core. Then the current is removed; the flux density drops to 500 G. What is the retentivity of this core material?**

4. **Consider a DC electromagnet that carries a certain current. It measures 20 cm long and has 100 turns of wire. The flux density in the core, which is known not to be in a state of saturation, is 20 G. The permeability of the core material is 100. What is the current in the wire?**

5. **The geomagnetic field**
   (a) makes the Earth like a huge horseshoe magnet.
   (b) runs exactly through the geographic poles.
   (c) makes a compass work.
   (d) makes an electromagnet work.

6. **A material that can be permanently magnetized is generally said to be**
(a) magnetic.
(b) electromagnetic.
(c) permanently magnetic.
(d) ferromagnetic.

7. **The magnetic flux around a straight current-carrying wire**
(a) gets stronger with increasing distance from the wire.
(b) is strongest near the wire.
(c) does not vary in strength with distance from the wire.
(d) consists of straight lines parallel to the wire.

8. **The gauss is a unit of**
(a) overall magnetic field strength.
(b) ampere-turns.
(c) magnetic flux density.
(d) magnetic power.

9. **If a wire coil has 10 turns and carries 500 mA of current, what is the** magnetomotive force in ampere-turns?
(a) 5,000
(b) 50
(c) 5.0
(d) 0.02

10. **Which of the following is not generally observed in a geomagnetic storm?**
(a) Charged particles streaming out from the Sun
(b) Fluctuations in the Earth's magnetic field
(c) Disruption of electrical power transmission
(d) Disruption of microwave propagation

11. **An ac electromagnet**
(a) will attract only other magnetized objects.
(b) will attract iron filings.
(c) will repel other magnetized objects.

(d) will either attract or repel permanent magnets depending on the polarity.

12. **A substance with high retentivity is best suited for making**
(a) an ac electromagnet.
(b) a dc electromagnet.
(c) an electrostatic shield.
(d) a permanent magnet.

13. **A device that reverses magnetic field polarity to keep a dc motor rotating is**
(a) a solenoid.
(b) an armature coil.
(c) a commutator.
(d) a field coil.

14. **An advantage of a magnetic disk, as compared with magnetic tape, for data**
storage and retrieval is that
(a) a disk lasts longer.
(b) data can be stored and retrieved more quickly with disks than with tapes.
(c) disks look better.
(d) disks are less susceptible to magnetic fields.