Chapter 28

Magnetic Fields

A Brief History of Magnetism

13th century BC

- Chinese used a compass
  - Uses a magnetic needle
  - Probably an invention of Arabic or Indian origin

800 BC

- Greeks
  - Discovered magnetite (Fe_3O_4) attracts pieces of iron

A Brief History of Magnetism, cont.

1269

- Pierre de Maricourt found that the direction of a needle near a spherical natural magnet formed lines that encircled the sphere .
- The lines also passed through two points diametrically opposed to each other.
- He called the points poles

1600

- William Gilbert
  - Expanded experiments with magnetism to a variety of materials
  - Suggested the Earth itself was a large permanent magnet

A Brief History of Magnetism, final

1750

- Experimenters showed that magnetic poles exert attractive or repulsive forces on each other.

1819

- Found an electric current deflected a compass needle

1820's

- Faraday and Henry
  - Further connections between electricity and magnetism
  - A changing magnetic field creates an electric field.
- Maxwell
  - A changing electric field produces a magnetic field.

Hans Christian Oersted

1777 – 1851

Discovered the relationship between electricity and magnetism

An electric current in a wire deflected a nearby compass needle

The first evidence of the connection between electric and magnetic phenomena

Also the first to prepare pure aluminum

Magnetic Poles

Every magnet, regardless of its shape, has two poles.

- Called north and south poles
- Poles exert forces on one another
  - Similar to the way electric charges exert forces on each other
  - Like poles repel each other
    - N-N or S-S
  - Unlike poles attract each other
    - N-S

Magnetic Poles, cont.

The poles received their names due to the way a magnet behaves in the Earth's magnetic field.

If a bar magnet is suspended so that it can move freely, it will rotate.

- The magnetic north pole points toward the Earth's north geographic pole.
  - This means the Earth's north geographic pole is a magnetic south pole.
  - Similarly, the Earth's south geographic pole is a magnetic north pole.

Magnetic Poles, final

The force between two poles varies as the inverse square of the distance between them.

A single magnetic pole has never been isolated.

- In other words, magnetic poles are always found in pairs.
- All attempts so far to detect an isolated magnetic pole has been unsuccessful.
  - No matter how many times a permanent magnetic is cut in two, each piece always has a north and south pole.

Concept-Check Question

If you cut a bar magnet in half, how many poles does each piece have?

A) One pole each

B) Two poles each

C) No poles

D) Depends on where you cut

Magnetic Fields

Reminder: an electric field surrounds any electric charge

The region of space surrounding any *moving* electric charge also contains a magnetic field.

A magnetic field also surrounds a magnetic substance making up a permanent magnet.

Magnetic Fields, cont.

A vector quantity

Symbolized by $\vec{\mathbf{B}}$

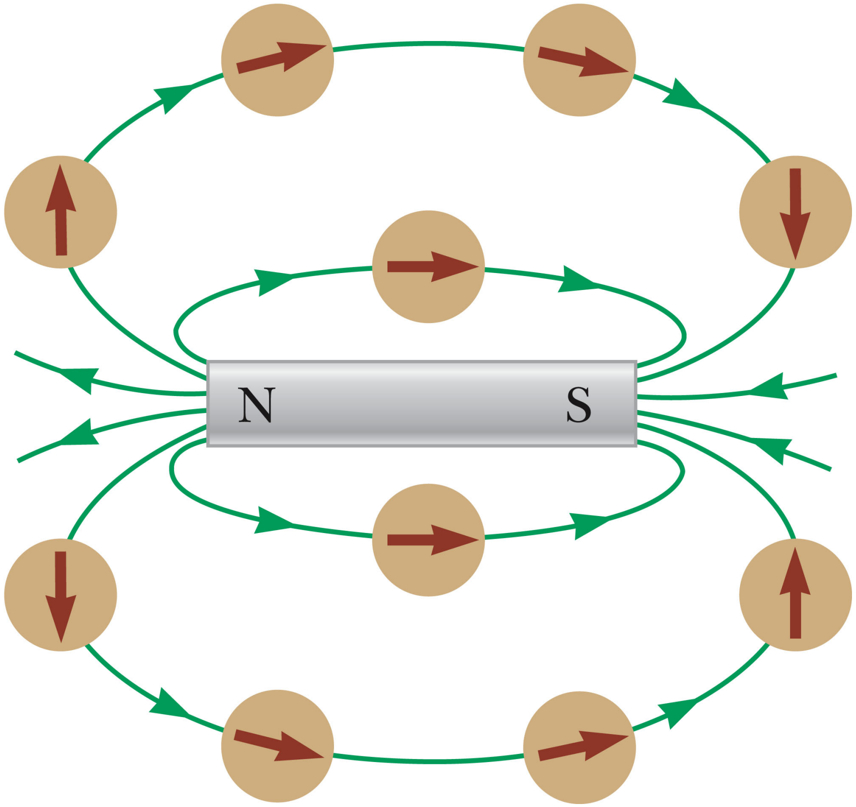
Direction is given by the direction a north pole of a compass needle points in that location

Magnetic field lines can be used to show how the field lines, as traced out by a compass, would look.

Magnetic Field Lines, Bar Magnet Example

The compass can be used to trace the field lines.

The lines outside the magnet point from the North pole to the South pole.



Concept-Check Question

Outside a bar magnet, magnetic field lines point:

A) From south to north

B) From north to south

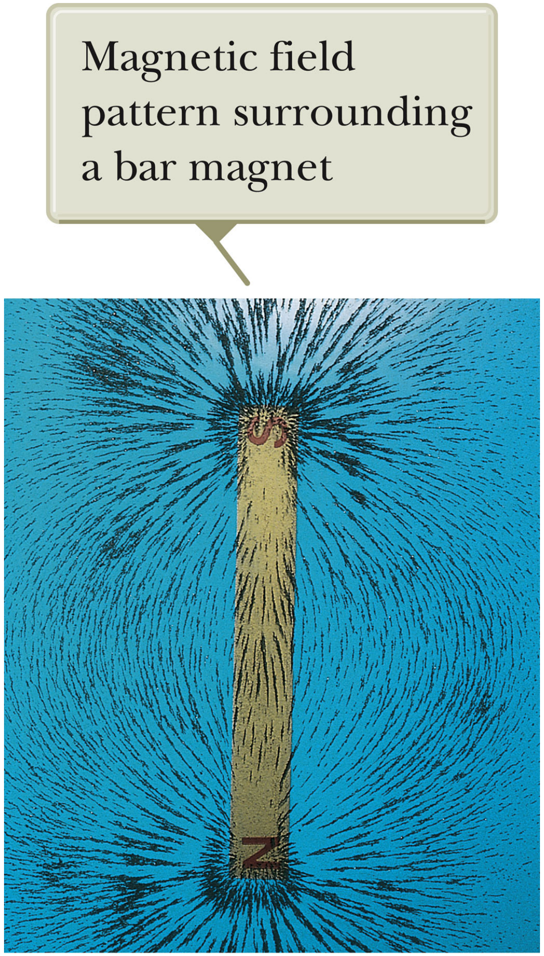
C) In circles around the magnet

D) Randomly

Magnetic Field Lines, Bar Magnet

Iron filings are used to show the pattern of the electric field lines.

The direction of the field is the direction a north pole would point.



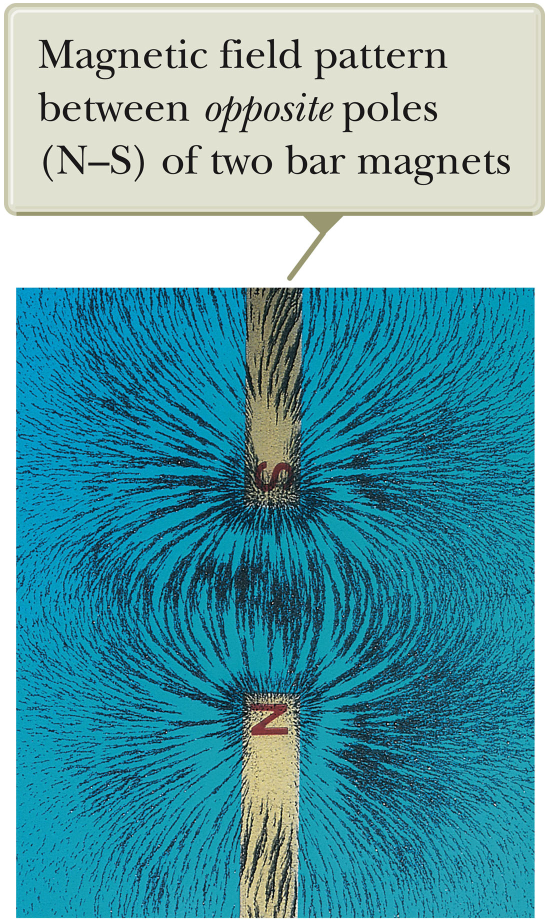
(a)

Magnetic Field Lines, Opposite Poles

Iron filings are used to show the pattern of the electric field lines.

The direction of the field is the direction a north pole would point.

- Compare to the electric field produced by an electric dipole



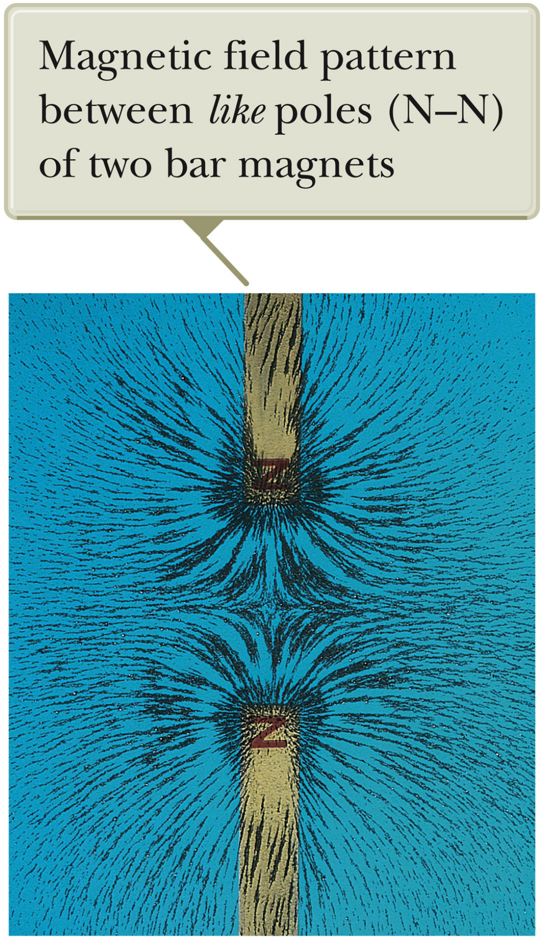
(b)

Magnetic Field Lines, Like Poles

Iron filings are used to show the pattern of the electric field lines.

The direction of the field is the direction a north pole would point.

- Compare to the electric field produced by like charges



(c)

Earth’s Magnetic Poles

More proper terminology would be that a magnet has “north-seeking” and “south-seeking” poles.

The north-seeking pole points to the north geographic pole.

- This would correspond to the Earth’s south magnetic pole.

The south-seeking pole points to the south geographic pole.

- This would correspond to the Earth’s north magnetic pole.

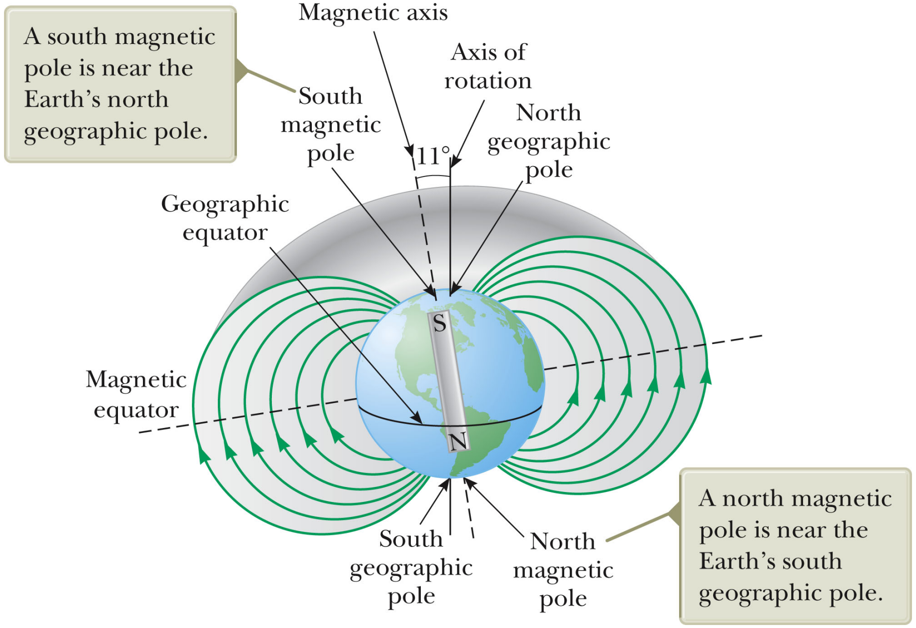
The configuration of the Earth’s magnetic field is very much like the one that would be achieved by burying a gigantic bar magnet deep in the Earth’s interior.

Earth's Magnetic Field

The source of the Earth's magnetic field is likely convection currents in the Earth's core.

There is strong evidence that the magnitude of a planet's magnetic field is related to its rate of rotation.

The direction of the Earth's magnetic field reverses periodically.



Definition of Magnetic Field

The magnetic field at some point in space can be defined in terms of the magnetic force, $\vec{\mathbf{F}}_B$.

The magnetic force will be exerted on a charged particle moving with a velocity, $\vec{\mathbf{v}}$.

- Assume (for now) there are no gravitational or electric fields present.

Concept-Check Question

A positive charge is stationary in a magnetic field. What is the magnetic force on it?

A) Depends on field strength

B) Depends on field direction

C) Zero

D) Always toward north pole

Properties of a Force on a Charge Moving in a Magnetic Field

The magnitude F_B of the magnetic force exerted on the particle is proportional to the charge, q, and to the speed, v, of the particle.

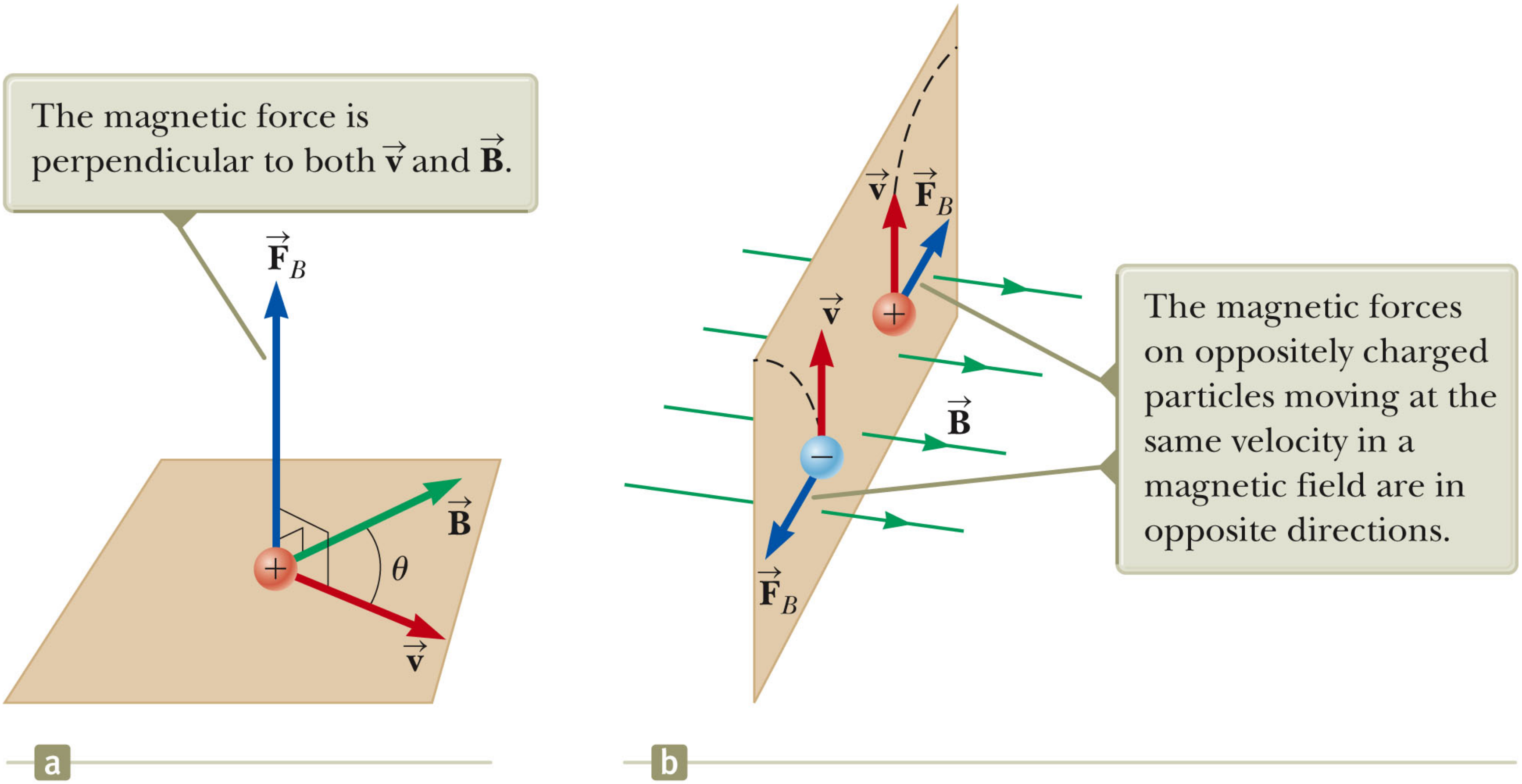
When a charged particle moves parallel to the magnetic field vector, the magnetic force acting on the particle is zero.

When the particle's velocity vector makes any angle $\theta \neq 0$ with the field, the force acts in a direction perpendicular to the plane formed by the velocity and the field.

The magnetic force exerted on a positive charge is in the direction opposite the direction of the magnetic force exerted on a negative charge moving in the same direction.

The magnitude of the magnetic force is proportional to $\sin \theta$, where θ is the angle the particle's velocity makes with the direction of the magnetic field.

More About Direction



Force on a Charge Moving in a Magnetic Field, Formula

The properties can be summarized in a vector equation:

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$$

- $\vec{\mathbf{F}}_B$ is the magnetic force
- q is the charge
- $\vec{\mathbf{v}}$ is the velocity of the moving charge
- $\vec{\mathbf{B}}$ is the magnetic field

$$\hat{\mathbf{i}} \times \hat{\mathbf{i}} = \hat{\mathbf{j}} \times \hat{\mathbf{j}} = \hat{\mathbf{k}} \times \hat{\mathbf{k}} = 0$$

$$\hat{\mathbf{i}} \times \hat{\mathbf{j}} = \hat{\mathbf{k}} \qquad \hat{\mathbf{j}} \times \hat{\mathbf{i}} = -\hat{\mathbf{k}}$$

$$\hat{\mathbf{j}} \times \hat{\mathbf{k}} = \hat{\mathbf{i}} \qquad \hat{\mathbf{k}} \times \hat{\mathbf{j}} = -\hat{\mathbf{i}}$$

$$\hat{\mathbf{k}} \times \hat{\mathbf{i}} = \hat{\mathbf{j}} \qquad \hat{\mathbf{i}} \times \hat{\mathbf{k}} = -\hat{\mathbf{j}}$$

$$\mathbf{A} \times \mathbf{B} = \begin{vmatrix} \hat{\mathbf{i}} & \hat{\mathbf{j}} & \hat{\mathbf{k}} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix} = \begin{vmatrix} A_y & A_z \\ B_y & B_z \end{vmatrix} \hat{\mathbf{i}} - \begin{vmatrix} A_x & A_z \\ B_x & B_z \end{vmatrix} \hat{\mathbf{j}} + \begin{vmatrix} A_x & A_y \\ B_x & B_y \end{vmatrix} \hat{\mathbf{k}}$$

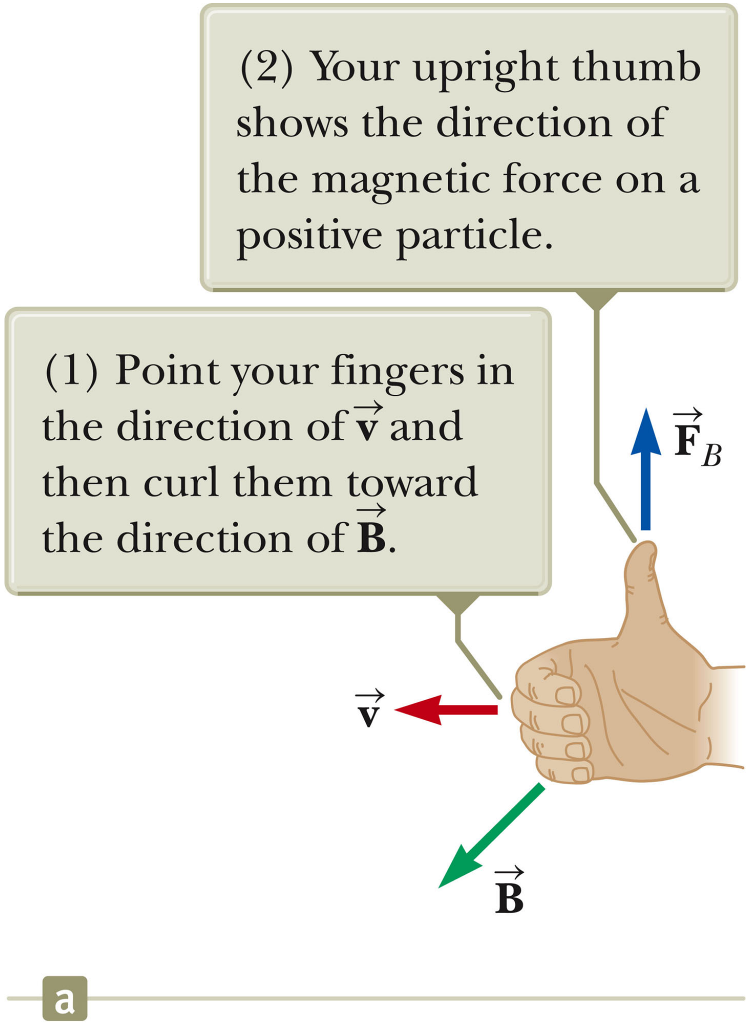
$$\mathbf{A} \times \mathbf{B} = \left(A_y B_z - A_z B_y\right) \hat{\mathbf{i}} - \left(A_x B_z - A_z B_x\right) \hat{\mathbf{j}} + \left(A_x B_y - A_y B_x\right) \hat{\mathbf{k}}$$

Direction: Right-Hand Rule #1

This rule is based on the right-hand rule for the cross product.

Your thumb is in the direction of the force if q is positive.

The force is in the opposite direction of your thumb if q is negative.



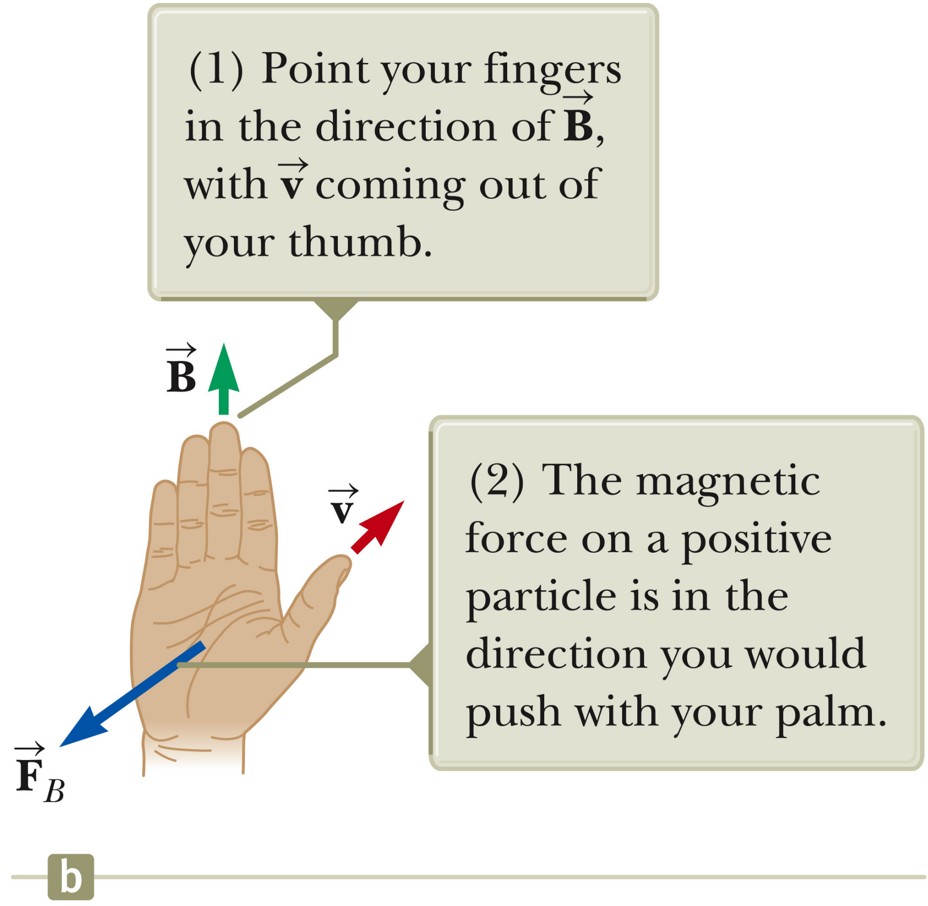
Direction: Right-Hand Rule #2

Alternative to Rule #1

The force on a positive charge extends outward from the palm.

The advantage of this rule is that the force on the charge is in the direction you would push on something with your hand.

The force on a negative charge is in the opposite direction.



More About Magnitude of F

The magnitude of the magnetic force on a charged particle is $F_B = |q| vB \sin\theta$.

- θ is the smaller angle between v and B
- F_B is zero when the field and velocity are parallel or antiparallel
  - $\theta = 0$ or $180°$
- F_B is a maximum when the field and velocity are perpendicular
  - $\theta = 90°$

Concept-Check Question

A proton moves east in a magnetic field pointing north. The magnetic force on the proton points:

A) North

B) East

C) Upward

D) Downward

Differences Between Electric and Magnetic Fields

Direction of force

- The electric force acts along the direction of the electric field.
- The magnetic force acts perpendicular to the magnetic field.

Motion

- The electric force acts on a charged particle regardless of whether the particle is moving.
- The magnetic force acts on a charged particle only when the particle is in motion.

Work

- The electric force does work in displacing a charged particle.
- The magnetic force associated with a steady magnetic field does no work when a particle is displaced.
  - This is because the force is perpendicular to the displacement of its point of application.

Work in Fields, cont.

The kinetic energy of a charged particle moving through a magnetic field cannot be altered by the magnetic field alone.

When a charged particle moves with a given velocity through a magnetic field, the field can alter the direction of the velocity, but not the speed or the kinetic energy.

Concept-Check Question

A magnetic field can change a charged particle's:

A) Speed

B) Kinetic energy

C) Direction of motion

D) Charge

Units of Magnetic Field

The SI unit of magnetic field is the tesla (T).

$$\mathrm{T} = \frac{\mathrm{Wb}}{\mathrm{m}^2} = \frac{\mathrm{N}}{\mathrm{C} \cdot \mathrm{m/s}} = \frac{\mathrm{N}}{\mathrm{A} \cdot \mathrm{m}}$$

- Wb is a weber

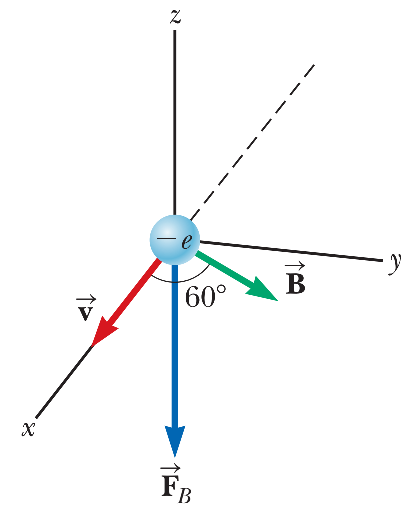
A non-SI commonly used unit is a gauss (G).

- $1\ \mathrm{T} = 10^4\ \mathrm{G}$

Example 28.01: An Electron Moving in a Magnetic Field

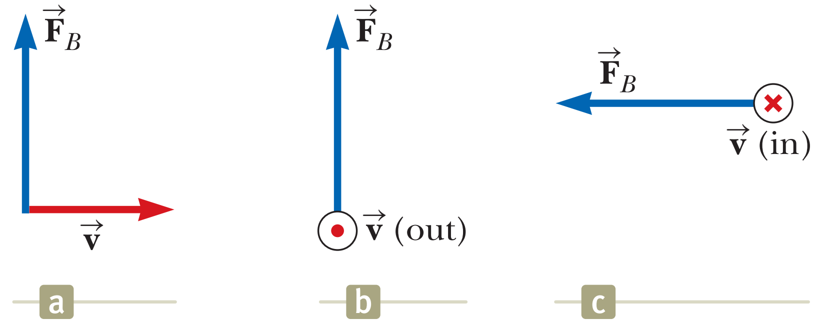
An electron moves through space as a cosmic ray with a speed of $8.0 \times 10^6\ \mathrm{m/s}$ along the x axis. At its location, the magnetic field of the Earth has a magnitude of $0.050\,\mathrm{mT}$, and is directed at an angle of $60°$ to the x axis, lying in the xy plane. Calculate the magnetic force on the electron.

$$
\begin{aligned}
F_B &= |q| vB \sin\theta \\
&= \left(1.6 \times 10^{-19}\mathrm{C}\right)\left(8.0 \times 10^6\ \mathrm{m/s}\right)\left(5.0 \times 10^{-5}\ \mathrm{T}\right)\left(\sin 60°\right) \\
&= 5.5 \times 10^{-17}\ \mathrm{N}
\end{aligned}
$$



Problem 28.03:

Find the direction of the magnetic field acting on a positively charged particle moving in the various situations shown in the figure if the direction of the magnetic force acting on it is as indicated.



(a) into the page
(b) toward the right
(c) toward the bottom of the page

Problem 28.04:

A proton moving at $4.00 \times 10^6 \ \mathrm{m/s}$ through a magnetic field of magnitude $1.70\,\mathrm{T}$ experiences a magnetic force of magnitude $8.20 \times 10^{-13} \ \mathrm{N}$. What is the angle between the proton's velocity and the field?

The magnitude of the force on a moving charge in a magnetic field

$F_B = qvB\sin\theta$, So

$$\theta = \sin^{-1}\left[\frac{F_B}{qvB}\right]$$

$$\theta = \sin^{-1}\left[\frac{8.20 \times 10^{-13}\ \mathrm{N}}{\left(1.60 \times 10^{-19}\mathrm{C}\right)\left(4.00 \times 10^{6}\ \mathrm{m/s}\right)(1.70\ \mathrm{T})}\right]$$

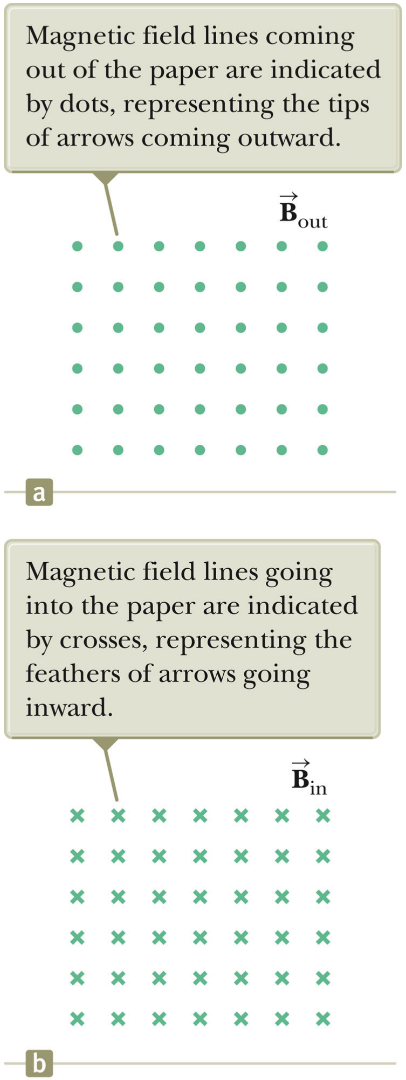
$= 48.9^\circ$ or 131°

Notation Notes

When vectors are perpendicular to the page, dots and crosses are used.

- The dots represent the arrows coming out of the page.
- The crosses represent the arrows going into the page.

The same notation applies to other vectors.

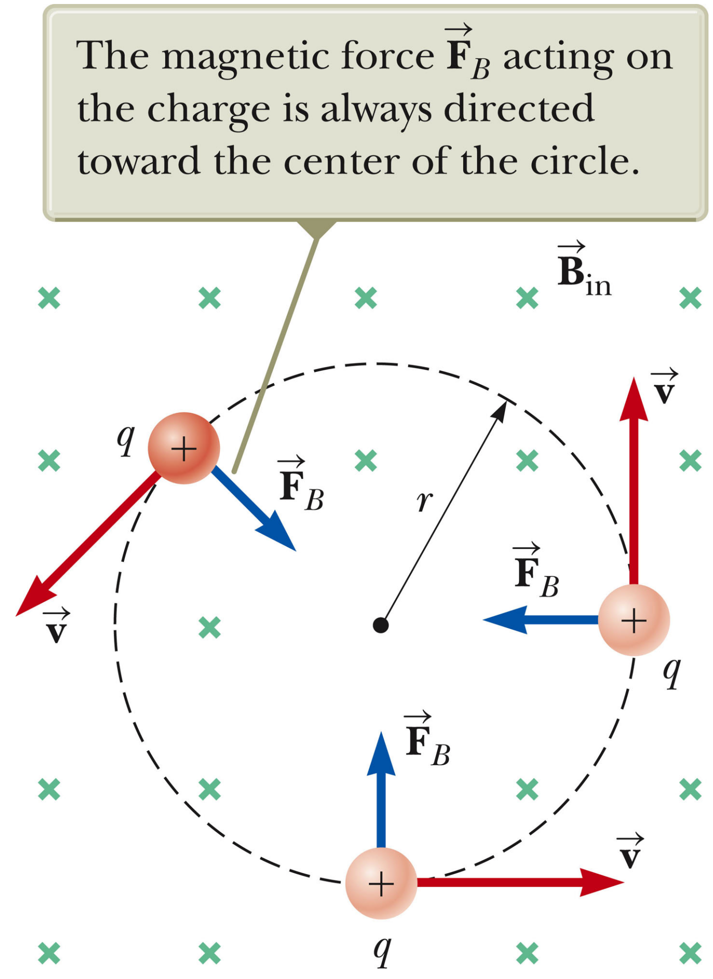


Charged Particle in a Magnetic Field

Consider a particle moving in an external magnetic field with its velocity perpendicular to the field.

The force is always directed toward the center of the circular path.

The magnetic force causes a centripetal acceleration, changing the direction of the velocity of the particle.



Force on a Charged Particle

Use the particle under a net force and a particle in uniform circular motion models.

Equating the magnetic and centripetal forces:

$$F_B = qvB = \frac{mv^2}{r}$$

Solving for r:

$$r = \frac{mv}{qB}$$

- r is proportional to the linear momentum of the particle and inversely proportional to the magnetic field.

More About Motion of Charged Particle

The angular speed of the particle is

$$\omega = \frac{v}{r} = \frac{qB}{m}$$

- The angular speed, ω, is also referred to as the **cyclotron frequency.**

The period of the motion is

$$T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}$$

Concept-Check Question

If you double the speed of a proton moving perpendicular to a magnetic field, the radius of its circular path:

A) Stays the same

B) Doubles

C) Quadruples

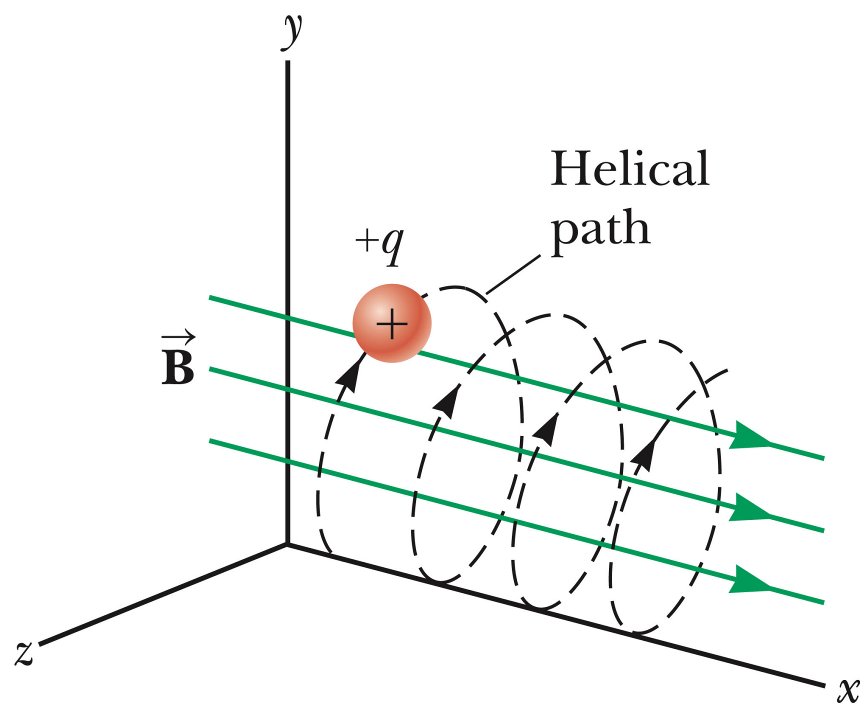
D) Halves

Motion of a Particle, General

If a charged particle moves in a magnetic field at some arbitrary angle with respect to the field, its path is a helix.

Same equations apply, with v replaced by

$$v_{\perp} = \sqrt{v_y^2 + v_z^2}$$



Concept-Check Question

A charged particle enters a magnetic field at an angle (not perpendicular). Its path will be:

A) A straight line

B) A circle

C) A helix

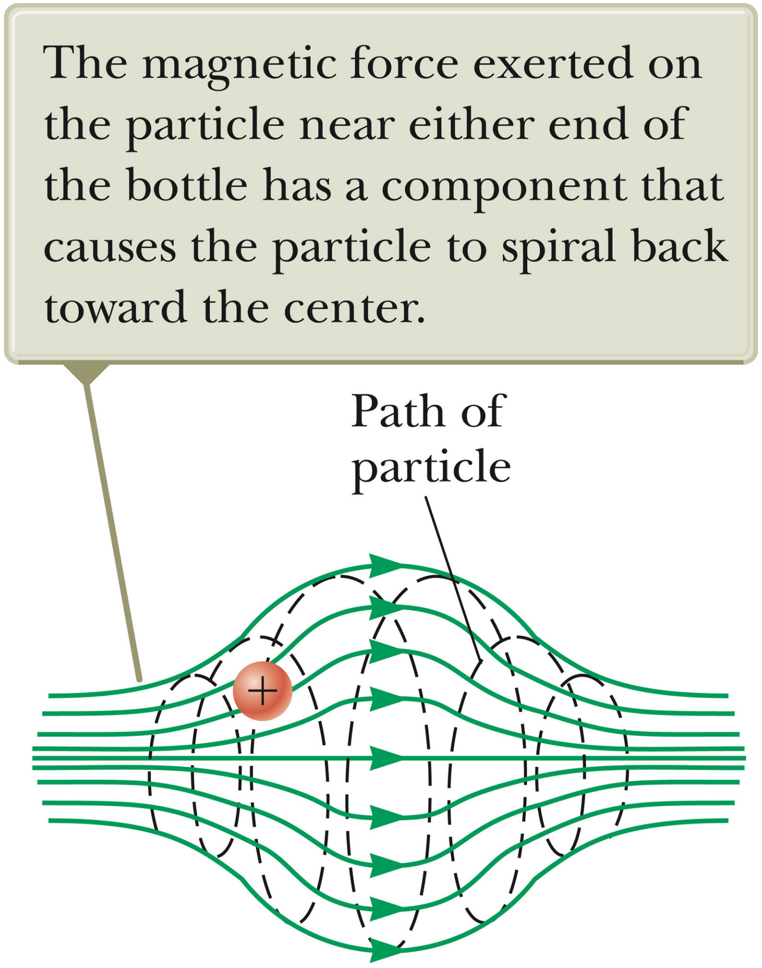
D) A parabola

Particle in a Nonuniform Magnetic Field

The motion is complex.

For example, the particles can oscillate back and forth between two positions.

This configuration is known as a *magnetic bottle.*



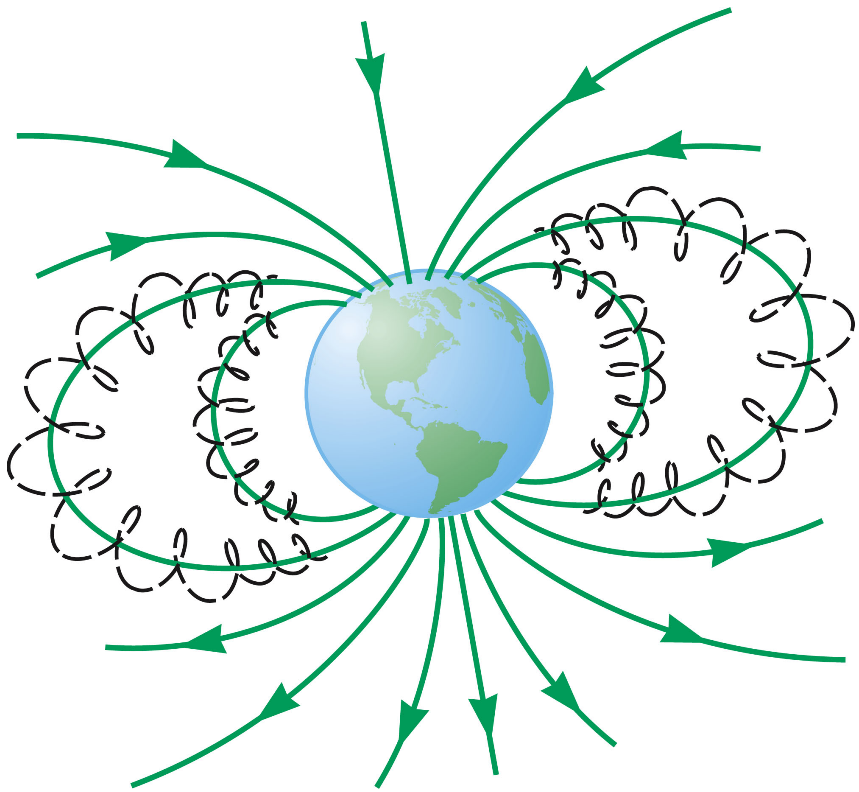
Van Allen Radiation Belts

The Van Allen radiation belts consist of charged particles surrounding the Earth in doughnut-shaped regions.

The particles are trapped by the Earth's nonuniform magnetic field.

The particles spiral from pole to pole.

- May result in auroras



Example 28.02: A Proton Moving Perpendicular to a Uniform Magnetic Field

A proton is moving in a circular orbit of radius $14\ \mathrm{cm}$ in a uniform $0.35-\mathrm{T}$ magnetic field perpendicular to the velocity of the proton. Find the speed of the proton.

$$v = \frac{qBr}{m_p}$$

$$v = \frac{\left(1.60 \times 10^{-19}\mathrm{C}\right)(0.35\ \mathrm{T})(0.14\ \mathrm{m})}{1.67 \times 10^{-27}\ \mathrm{kg}}$$

$$= 4.7 \times 10^{6}\ \mathrm{m/s}$$

Example 28.03: Bending an Electron Beam

In an experiment designed to measure the magnitude of a uniform magnetic field, electrons are accelerated from rest through a potential difference of 350 V and then enter a uniform magnetic field that is perpendicular to the velocity vector of the electrons. The electrons travel along a curved path because of the magnetic force exerted on them, and the radius of the path is measured to be 7.5 cm .

(A) What is the magnitude of the magnetic field?

(B) What is the angular speed of the electrons?

$$\Delta K + \Delta U_E = 0$$

$$\left(\frac{1}{2}m_e v^2 - 0\right) + (q\Delta V) = 0$$

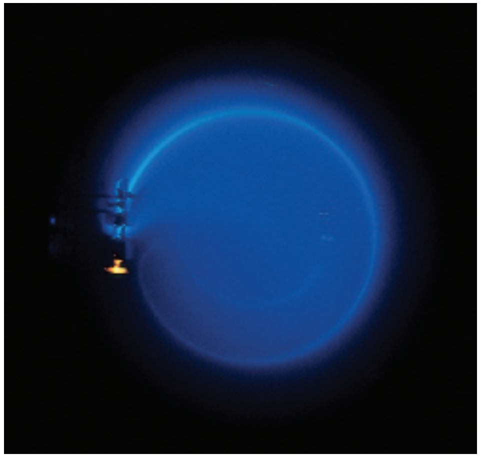
$$v = \sqrt{\frac{-2q\Delta V}{m_e}}$$

(A)

$$v = \sqrt{\frac{-2\left(-1.60\times10^{-19}\text{C}\right)(350\ \text{V})}{9.11\times10^{-31}\ \text{kg}}} = 1.11\times10^{7}\ \text{m/s}$$

$$B = \frac{m_e v}{er}$$

$$B = \frac{\left(9.11\times10^{-31}\ \text{kg}\right)\left(1.11\times10^{7}\ \text{m/s}\right)}{\left(1.60\times10^{-19}\text{C}\right)(0.075\ \text{m})} = 8.4\times10^{-4}\ \text{T}$$



Courtesy of Henry Leap and Jim Lehman

(B) $\omega = \frac{v}{r} = \frac{1.11\times10^{7}\ \text{m/s}}{0.075\ \text{m}} = 1.5\times10^{8}\text{rad/s}$

Problem 28.09:

A proton (charge $+e$, mass m_p), a deuteron (charge $+e$, mass $2m_p$), and an alpha particle (charge $+2e$, mass $4m_p$) are accelerated from rest through a common potential difference ΔV. Each of the particles enters a uniform magnetic field $\vec{\mathbf{B}}$, with its velocity in a direction perpendicular to $\vec{\mathbf{B}}$. The proton moves in a circular path of radius r_p. In terms of r_p, determine (a) the radius r_d of the circular orbit for the deuteron and (b) the radius r_α for the alpha particle.

$$q\Delta V = \frac{1}{2}mv^2 \text{ thus } v = \sqrt{\frac{2q\Delta V}{m}}$$

$$r = \frac{mv}{qB} = \frac{m}{qB}\sqrt{\frac{2q\Delta V}{m}} = \frac{1}{B}\sqrt{\frac{2m\Delta V}{q}}$$

For the protons, $r_p = \frac{1}{B}\sqrt{\frac{2m_p\Delta V}{e}}$

(a) For the deuterons,

$$r_d = \frac{1}{B}\sqrt{\frac{2\left(2m_p\right)\Delta V}{e}} = \sqrt{2}r_p$$

(b) For the alpha particles,

$$r_\alpha = \frac{1}{B}\sqrt{\frac{2\left(4m_p\right)\Delta V}{2e}} = \sqrt{2}r_p$$

Applications Involving Charged Particles Moving in a Magnetic Field

In many applications, charged particles will move in the presence of both magnetic and electric fields.

In that case, the total force is the sum of the forces due to the individual fields.

- The total force is called the Lorentz force.

In general:

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} + q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$$

Velocity Selector

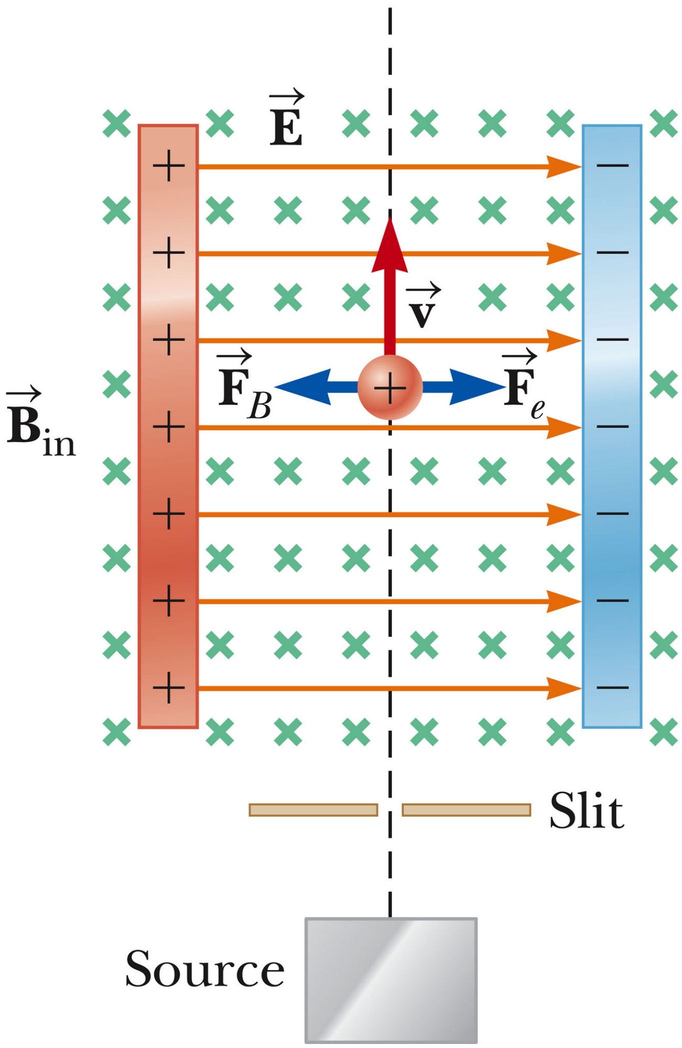
Used when all the particles need to move with the same velocity.

A uniform electric field is perpendicular to a uniform magnetic field.

When the force due to the electric field is equal but opposite to the force due to the magnetic field, the particle moves in a straight line.

This occurs for velocities of value.

$$v = E/B$$



Velocity Selector, cont.

Only those particles with the given speed will pass through the two fields undeflected.

The magnetic force exerted on particles moving at a speed greater than this is stronger than the electric field and the particles will be deflected to the left.

Those moving more slowly will be deflected to the right.

Concept-Check Question

In a velocity selector, a particle travels straight through when:

A) The electric force is zero

B) The magnetic force is zero

C) Electric and magnetic forces are equal and opposite

D) The particle has no charge

Problem 28.16:

Singly charged uranium-238 ions are accelerated through a potential difference of $2.00\,\mathrm{kV}$ and enter a uniform magnetic field of magnitude $1.20\,\mathrm{T}$ directed perpendicular to their velocities. (a) Determine the radius of their circular path. (b) Repeat this calculation for uranium-235 ions. (c) What If? How does the ratio of these path radii depend on the accelerating voltage? (d) On the magnitude of the magnetic field?

$$q\Delta V = \frac{1}{2}mv^2 \text{ thus } v = \sqrt{\frac{2q\Delta V}{m}}$$

$$r = \frac{mv}{qB} = \frac{m}{qB}\sqrt{\frac{2q\Delta V}{m}} = \frac{1}{B}\sqrt{\frac{2m\Delta V}{q}}$$

(a) Substituting numerical values for uranium-238,

$$r_{238} = \left(\frac{1}{1.20\ \mathrm{T}}\right)\sqrt{\frac{2\left[238\left(1.66\times10^{-27}\ \mathrm{kg}\right)\right](2000\ \mathrm{V})}{1.60\times10^{-19}\mathrm{C}}}$$

$$= 8.28\times10^{-2}\ \mathrm{m} = 8.28\ \mathrm{cm}$$

(b) For uranium-235 ions,

$$r_{235} = \left(\frac{1}{1.20\ \mathrm{T}}\right)\sqrt{\frac{2\left[235\left(1.66\times10^{-27}\ \mathrm{kg}\right)\right](2000\ \mathrm{V})}{1.60\times10^{-19}\mathrm{C}}}$$

$$= 8.23\times10^{-2}\ \mathrm{m} = 8.23\ \mathrm{cm}$$

(c) From $r = \frac{1}{B}\sqrt{\frac{2m(\Delta V)}{q}}$, we see for two different masses m_{A} and m_{B} of the same charge q, the ratio of the path radii is $\frac{r_B}{r_A} = \sqrt{\frac{m_B}{m_A}}$.

(d) The ratio of the path radii is independent of ΔV.

(e) The ratio of the path radii is independent of B.

Magnetic Force on a Current Carrying Conductor

A force is exerted on a current-carrying wire placed in a magnetic field.

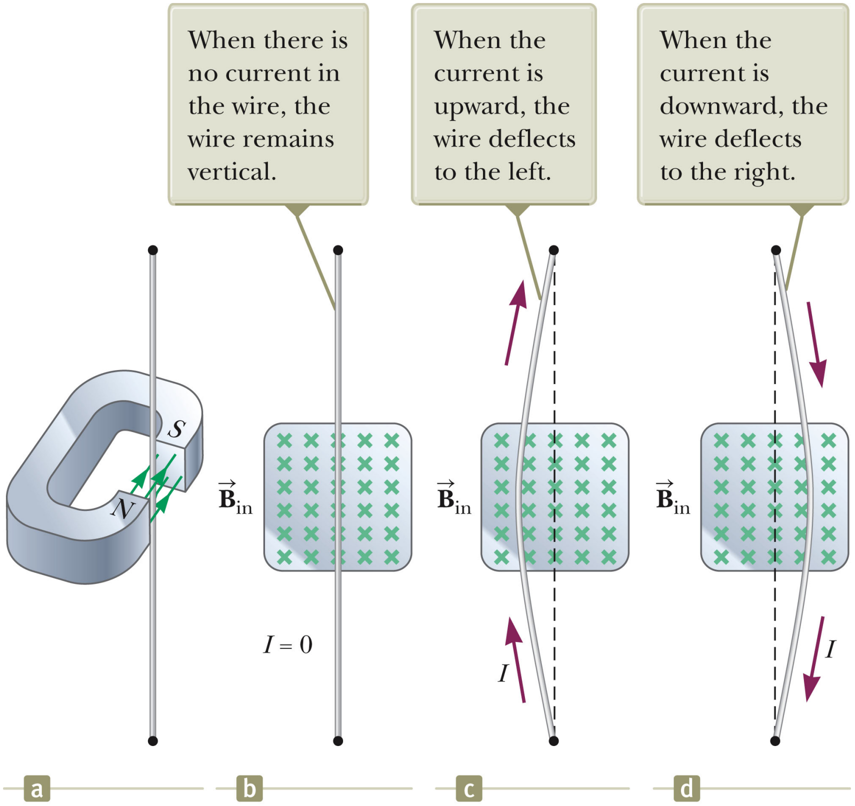
- The current is a collection of many charged particles in motion.

The direction of the force is given by the right-hand rule.

Force on a Wire

In this case, there is no current, so there is no force.

Therefore, the wire remains vertical.



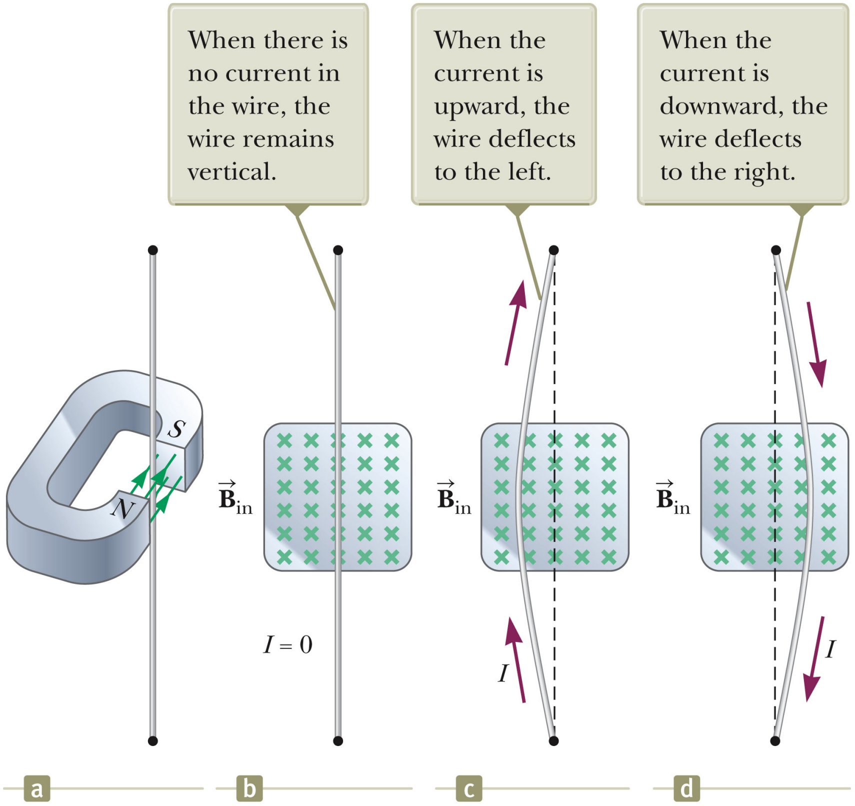
Force on a Wire, 2

The magnetic field is into the page

The current is up the page

The force is to the left

The wire deflects to the left



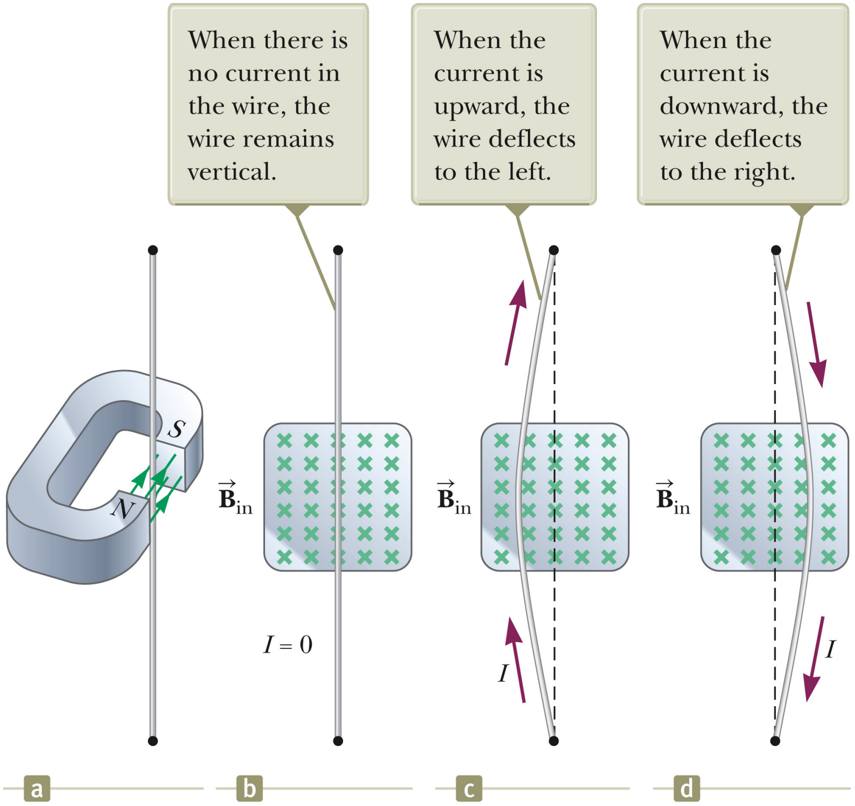
Force on a Wire, 3

The magnetic field is into the page

The current is down the page

The force is to the right

The wire deflects to the right



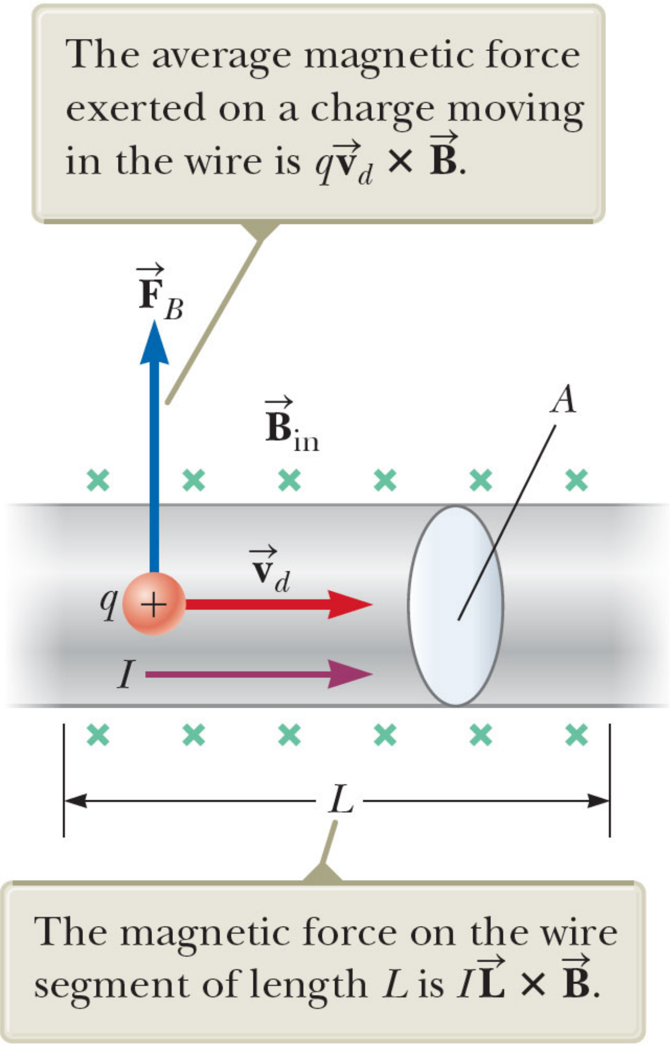
Force on a Wire, equation

The magnetic force is exerted on each moving charge in the wire.

- $\vec{\mathbf{F}} = q\vec{\mathbf{v}}_d \times \vec{\mathbf{B}}$

The total force is the product of the force on one charge and the number of charges.

- $\vec{\mathbf{F}} = \left(q\vec{\mathbf{v}}_d \times \vec{\mathbf{B}}\right) nAL$



Force on a Wire, Equation cont.

In terms of the current, this becomes

$$\vec{\mathbf{F}}_B = I\vec{\mathbf{L}} \times \vec{\mathbf{B}}$$

- I is the current.
- $\vec{\mathbf{L}}$ is a vector that points in the direction of the current.
  - Its magnitude is the length L of the segment.
- $\vec{\mathbf{B}}$ is the magnetic field.

Force on a Wire, Arbitrary Shape

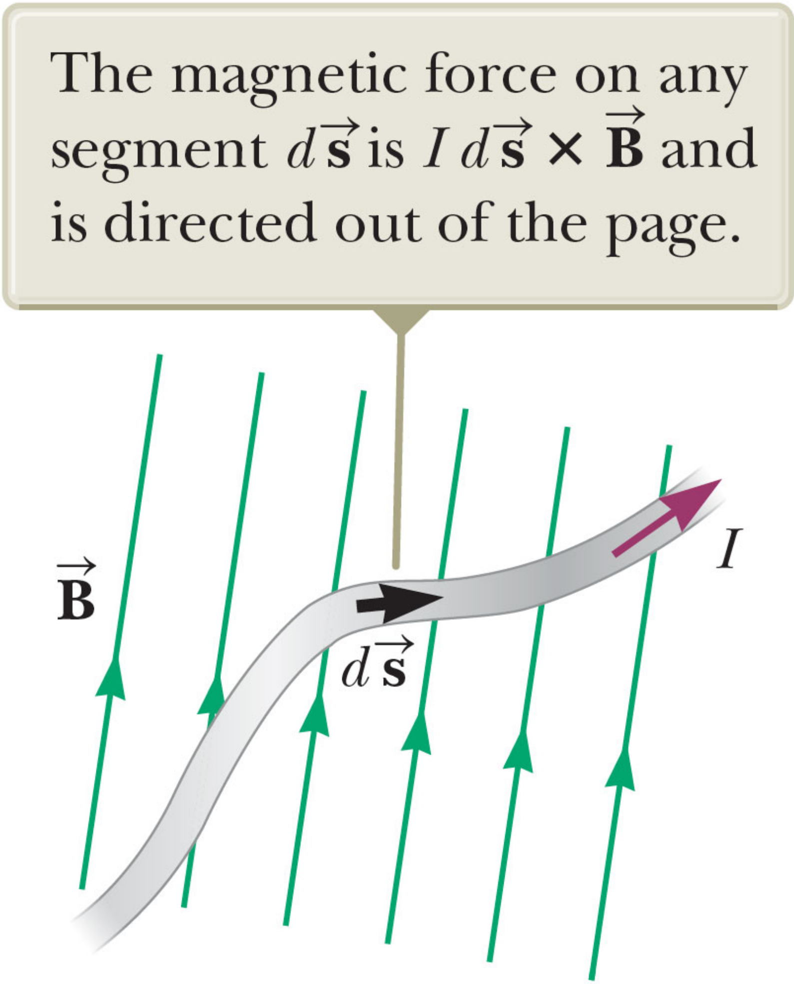
Consider a small segment of the wire, $d\vec{\mathbf{s}}$

The force exerted on this segment is

$$d\vec{\mathbf{F}}_B = I d\vec{\mathbf{s}} \times \vec{\mathbf{B}}$$

The total force is

$$\vec{\mathbf{F}}_B = I \int_{\mathbf{a}}^{b} d\vec{\mathbf{s}} \times \vec{\mathbf{B}}$$



Concept-Check Question

A horizontal wire carries current to the right. A magnetic field points into the page. The force on the wire is:

A) To the right

B) Into the page

C) Upward

D) Downward

Problem 28.21:

A wire carries a steady current of $2.40\ \mathrm{A}$. A straight section of the wire is $0.750\ \mathrm{m}$ long and lies along the x axis within a uniform magnetic field, $\vec{\mathbf{B}} = 1.60\hat{\mathbf{k}}\ \mathrm{T}$. If the current is in the positive x direction, what is the magnetic force on the section of wire?

The vector magnetic force on the wire is

$$\vec{\mathbf{F}}_B = I\vec{\ell} \times \vec{\mathbf{B}} = (2.40\ \mathrm{A})(0.750\ \mathrm{m})\hat{\mathbf{i}} \times (1.60\ \mathrm{T})\hat{\mathbf{k}} = (-2.88\hat{\mathbf{j}})\mathrm{N}$$

Problem 28.25:

A wire having a mass per unit length of $0.500\ \text{g/cm}$ carries a $2.00-\text{A}$ current horizontally to the south. What are (a) the direction and (b) the magnitude of the minimum magnetic field needed to lift this wire vertically upward?

(a) The magnetic force must be upward to lift of the wire. For current in the south direction, the magnetic field must be east to produce an upward force, as shown by the right-hand rule in the figure.

(b)

$$F_B = ILB\sin\theta \quad \text{with} \quad F_B = F_g = mg$$

$$mg = ILB\sin\theta \quad \text{so} \quad \frac{m}{L}g = IB\sin\theta \quad \rightarrow \quad B = \frac{m}{L}\frac{g}{I\sin\theta}$$

$$B = \frac{m}{L}\frac{g}{I\sin\theta} = \left(\frac{0.500\times 10^{-3}\ \text{kg}}{1.00\times 10^{-2}\ \text{m}}\right)\left(\frac{9.80\ \text{m/s}^2}{(2.00\ \text{A})\sin 90.0^\circ}\right) = 0.245\ \text{T}$$