Chapter 27

Magnetic Field and Magnetic Forces

PowerPoint® Lectures for
University Physics, Thirteenth Edition
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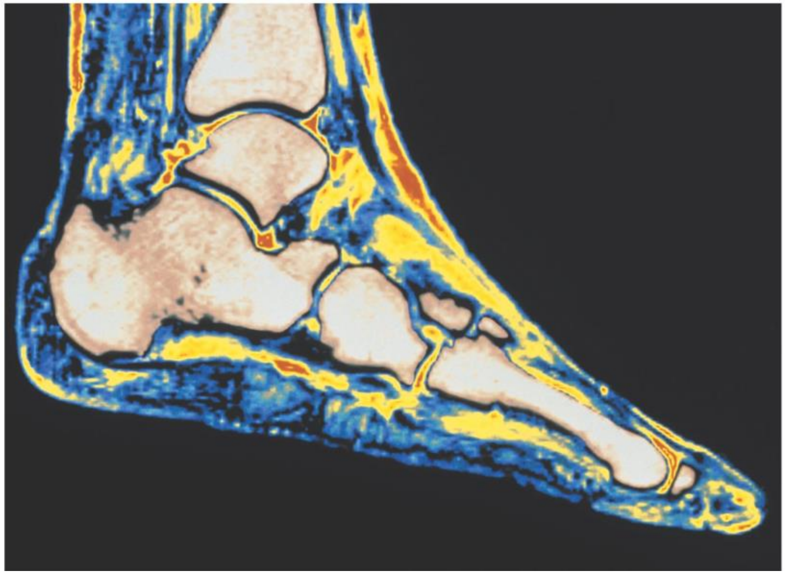
Lectures by Wayne Anderson

Goals for Chapter 27

- To study magnets and the forces they exert on each other
- To calculate the force that a magnetic field exerts on a moving charge
- To contrast magnetic field lines with electric field lines
- To analyze the motion of a charged particle in a magnetic field
- To see applications of magnetism in physics and chemistry
- To analyze magnetic forces on current-carrying conductors
- To study the behavior of current loops in a magnetic field

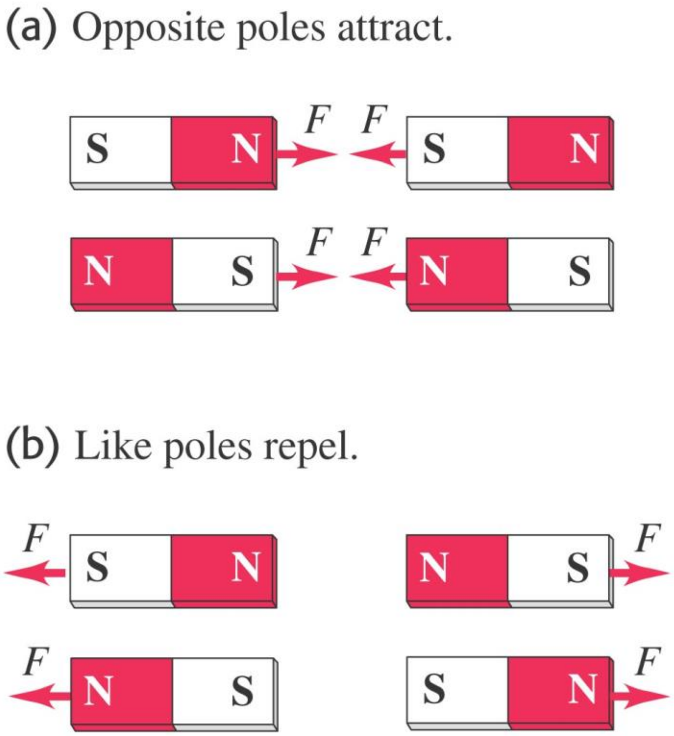
Introduction

- How does magnetic resonance imaging (MRI) allow us to see details in soft nonmagnetic tissue?
- How can magnetic forces, which act only on moving charges, explain the behavior of a compass needle?
- In this chapter, we will look at how magnetic fields affect charges.



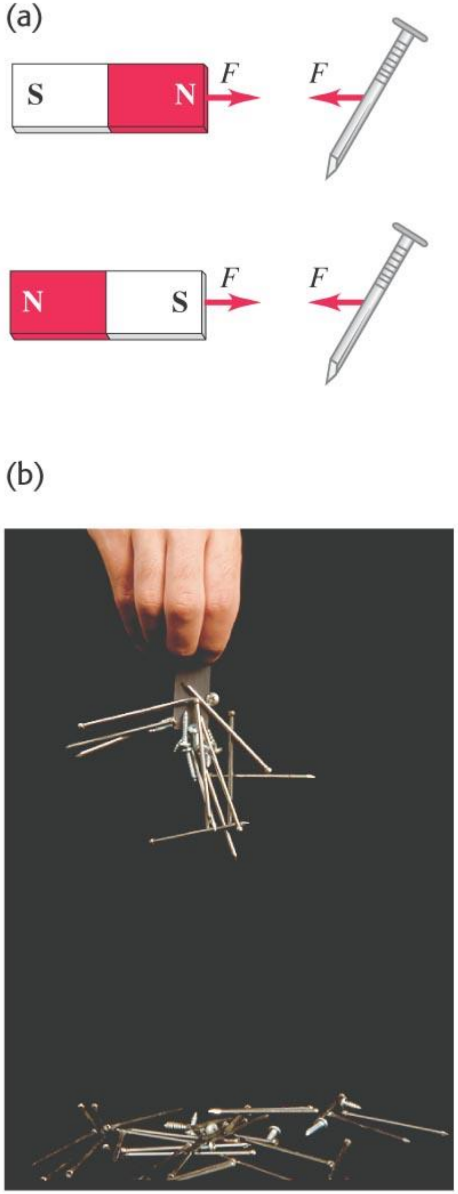
Magnetic poles

- Figure 27.1 at the right shows the forces between magnetic poles.



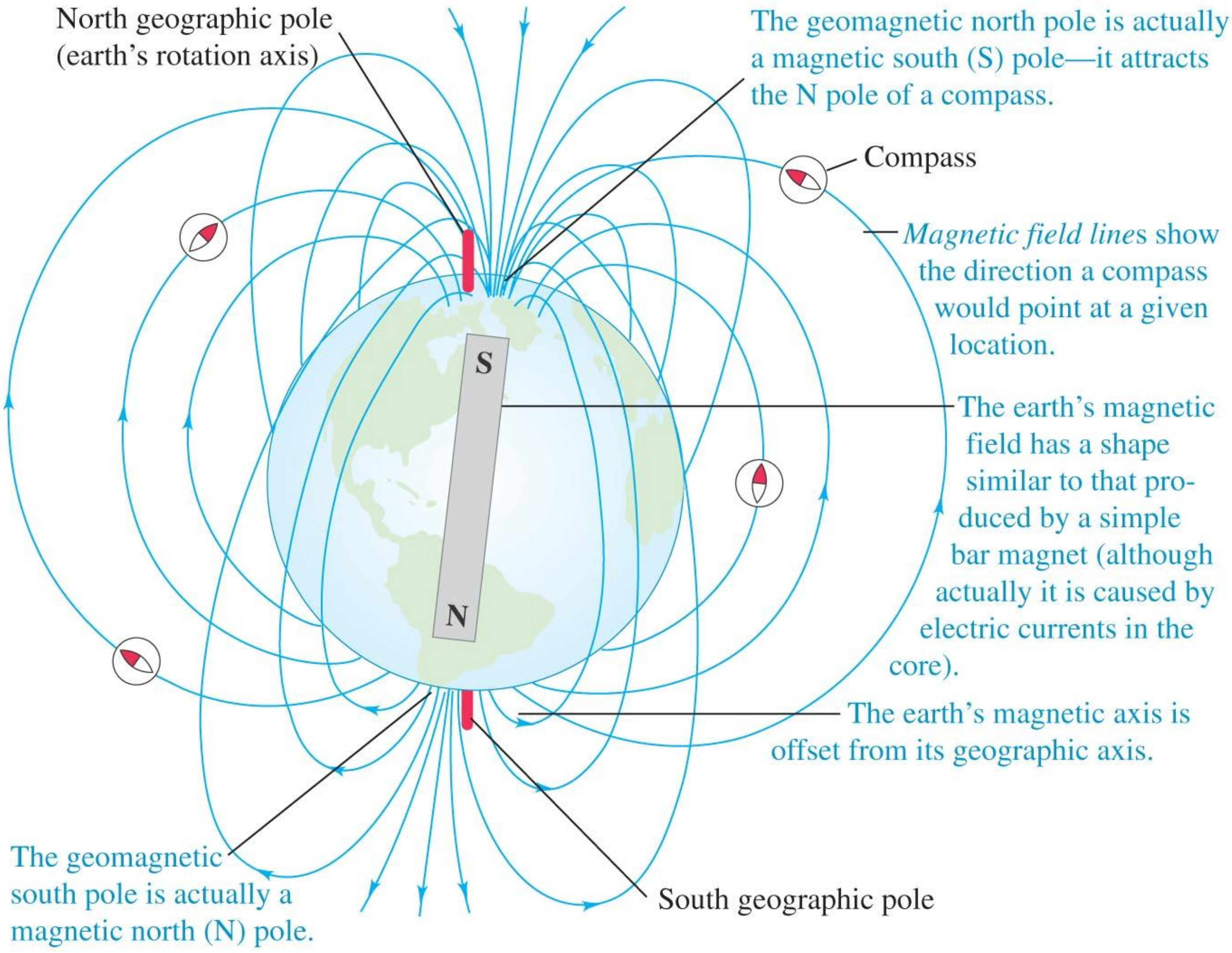
Magnetism and certain metals

- Either pole of a permanent magnet will attract a metal like iron, as shown in Figure 27.2 at the right.



Magnetic field of the earth

- The earth itself is a magnet. Figure 27.3 shows its magnetic field.



North geographic pole (earth's rotation axis)

The geomagnetic north pole is actually a magnetic south (S) pole—it attracts the N pole of a compass.

Compass

Magnetic field lines show the direction a compass would point at a given location.

The earth's magnetic field has a shape similar to that produced by a simple bar magnet (although actually it is caused by electric currents in the core).

The earth's magnetic axis is offset from its geographic axis.

South geographic pole

The geomagnetic south pole is actually a magnetic north (N) pole.

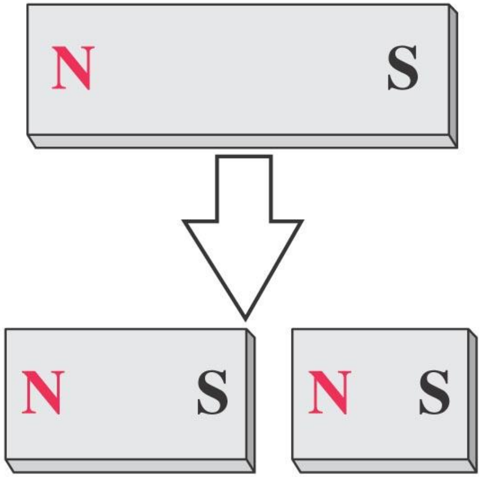
Magnetic monopoles

- Breaking a bar magnet does not separate its poles, as shown in Figure 27.4 at the right.

- There is no experimental evidence for *magnetic monopoles*.

In contrast to electric charges, magnetic poles always come in pairs and can't be isolated.

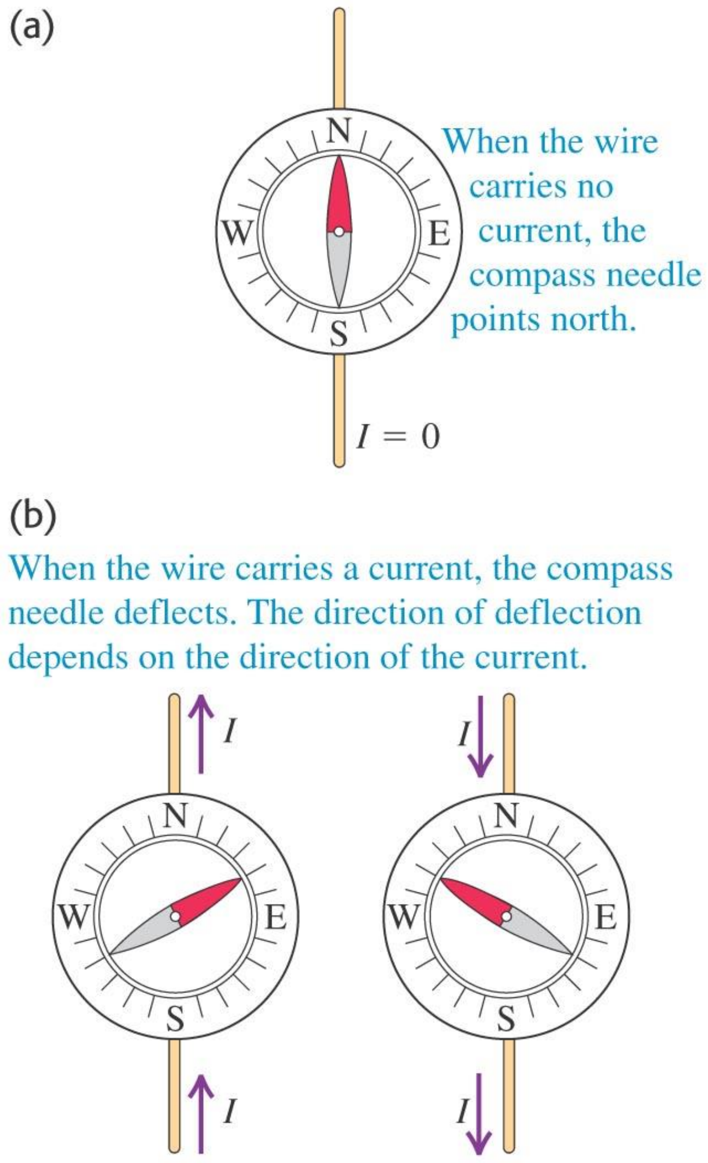
Breaking a magnet in two ...



... yields two magnets, not two isolated poles.

Electric current and magnets

- In 1820, Hans Oersted discovered that a current-carrying wire causes a compass to deflect. (See Figure 27.5 at the right.)
- This discovery revealed a connection between moving charge and magnetism.



When the wire carries no current, the compass needle points north.

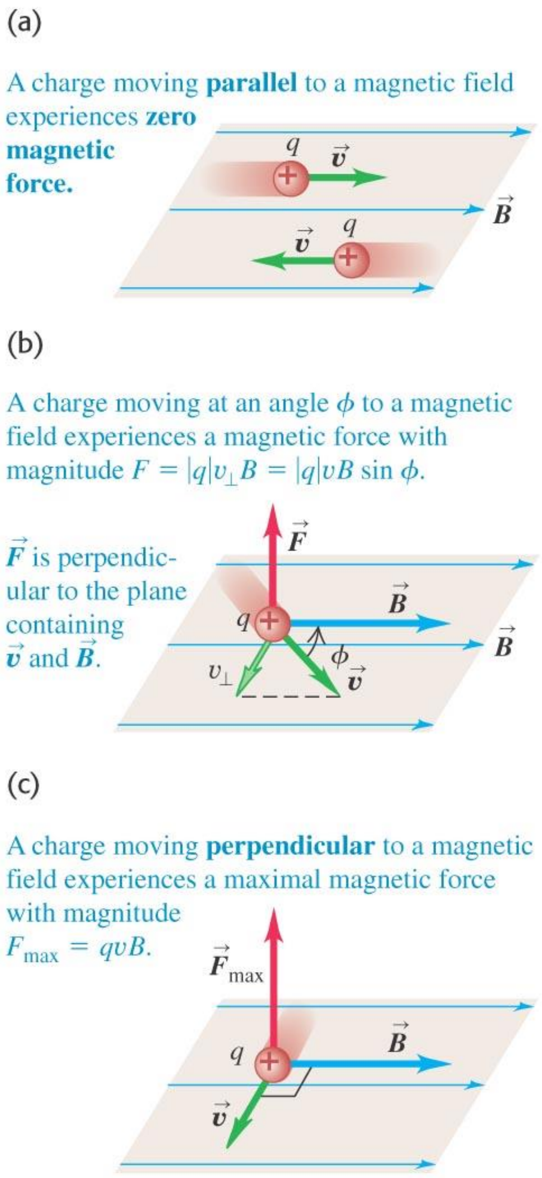
When the wire carries a current, the compass needle deflects. The direction of deflection depends on the direction of the current.

The magnetic field

- A moving charge (or current) creates a *magnetic field* in the surrounding space.
- The magnetic field exerts a force on any other moving charge (or current) that is present in the field.

The magnetic force on a moving charge

- The magnetic force on *q* is perpendicular to *both* the velocity of *q* and the magnetic field. (See Figure 27.6 at the right.)
- The magnitude of the magnetic force is $F = |q|vB \sin\phi$.



A charge moving **parallel** to a magnetic field experiences **zero magnetic force.**

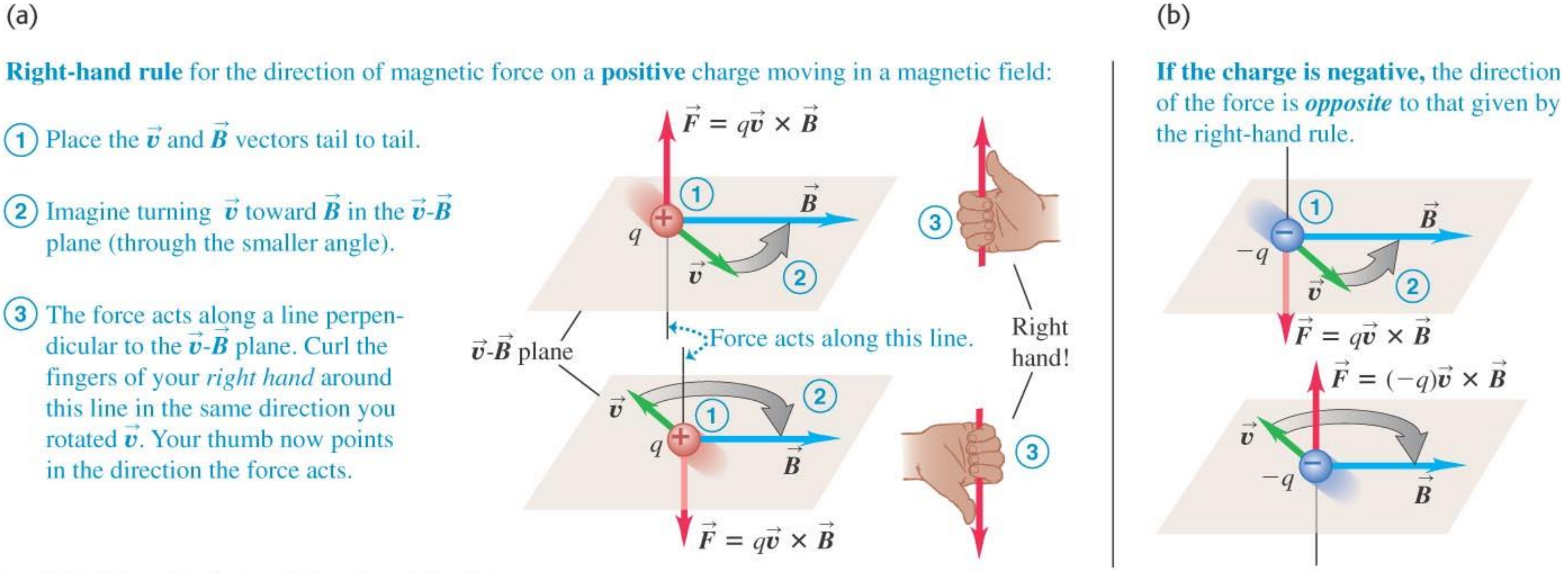
A charge moving at an angle ϕ to a magnetic field experiences a magnetic force with magnitude $F = |q|v_\perp B = |q|vB \sin\phi$.

$\vec{F}$ is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$.

A charge moving **perpendicular** to a magnetic field experiences a maximal magnetic force with magnitude $F_{max} = qvB$.

Magnetic force as a vector product

- We can write the magnetic force as a vector product (see Figure 27.7 below).
- The right-hand rule gives the direction of the force on a *positive* charge.



(a)

Right-hand rule for the direction of magnetic force on a **positive** charge moving in a magnetic field:

① Place the $\vec{v}$ and $\vec{B}$ vectors tail to tail.

② Imagine turning $\vec{v}$ toward $\vec{B}$ in the $\vec{v}$-$\vec{B}$ plane (through the smaller angle).

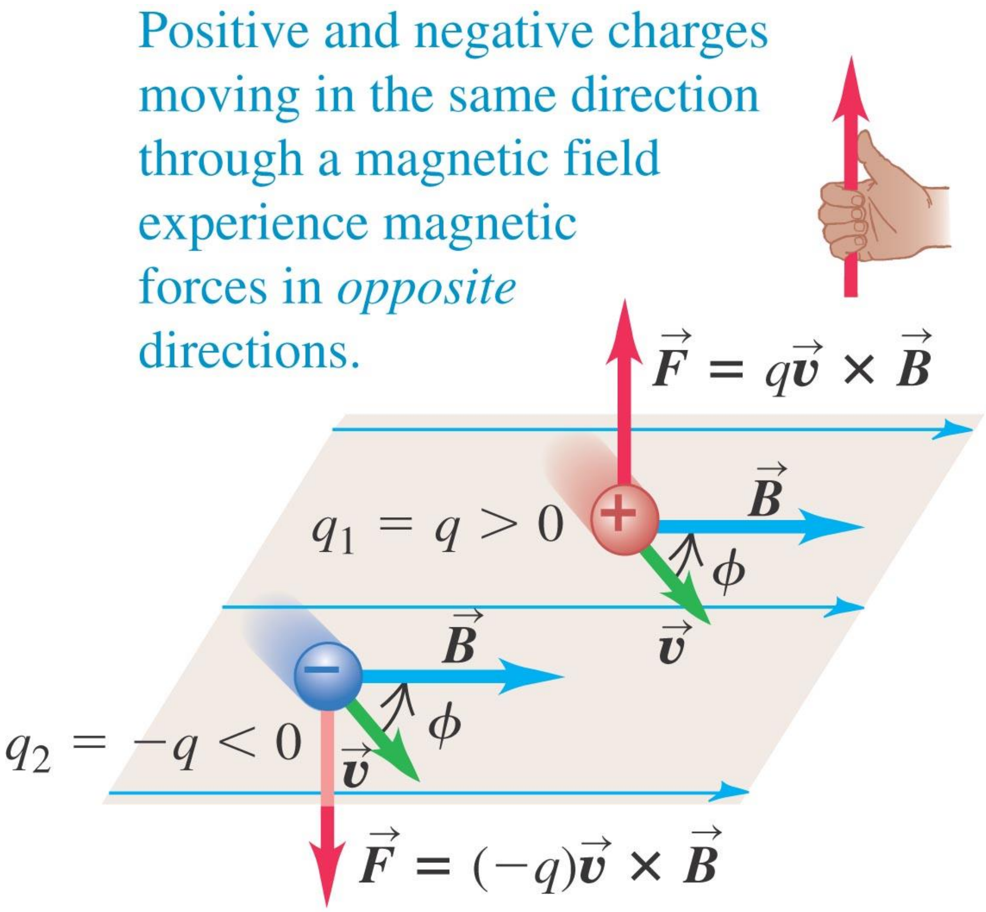
③ The force acts along a line perpendicular to the $\vec{v}$-$\vec{B}$ plane. Curl the fingers of your *right hand* around this line in the same direction you rotated $\vec{v}$. Your thumb now points in the direction the force acts.

(b)

If the charge is negative, the direction of the force is ***opposite*** to that given by the right-hand rule.

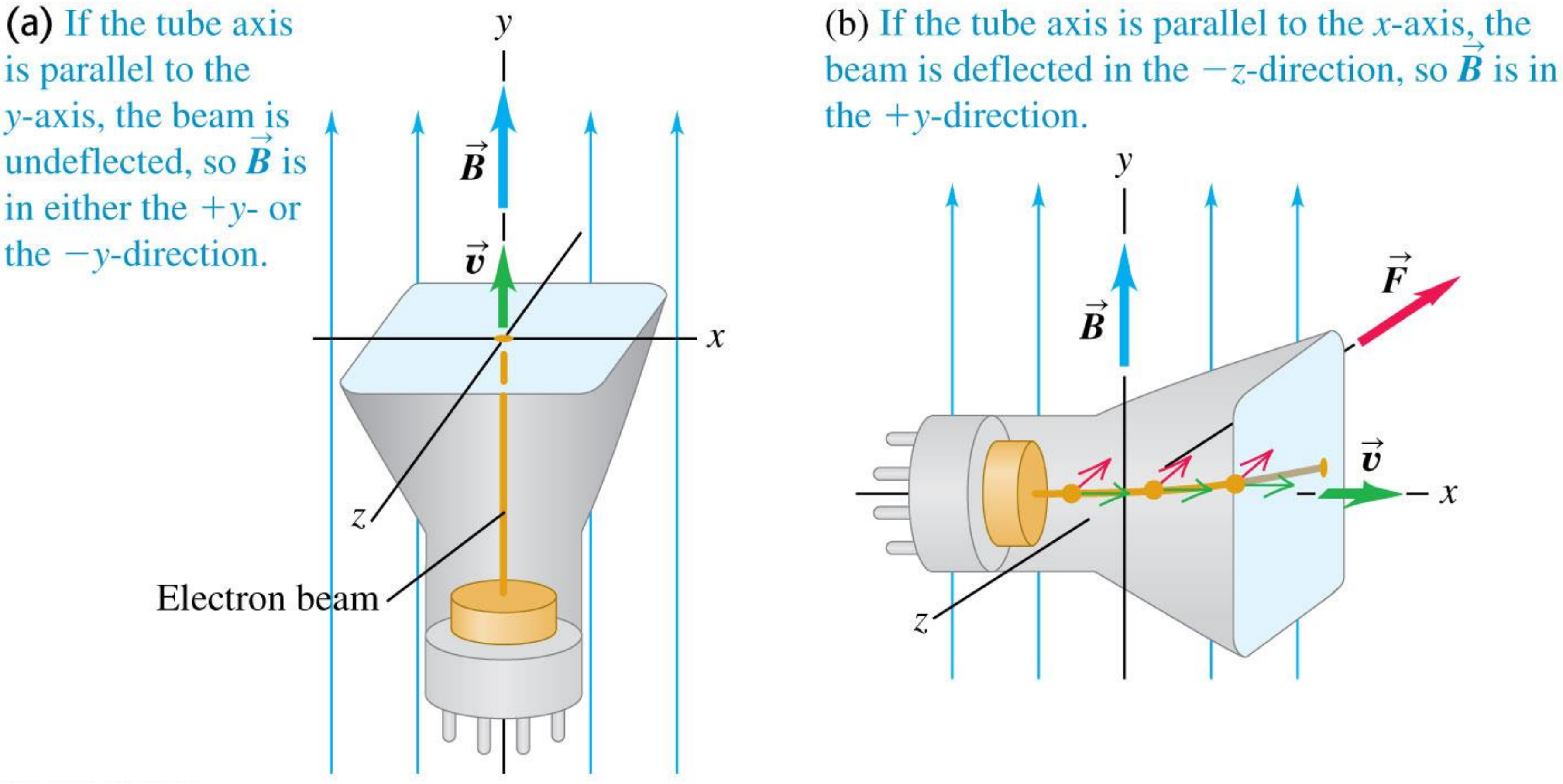
Equal velocities but opposite signs

- Two charges of equal magnitude but opposite signs moving in the same direction in the same field will experience magnetic forces in opposite directions. (See Figure 27.8 below.)


Positive and negative charges moving in the same direction through a magnetic field experience magnetic forces in *opposite* directions.

Determining the direction of a magnetic field

- A cathode-ray tube can be used to determine the direction of a magnetic field, as shown in Figure 27.9 below.

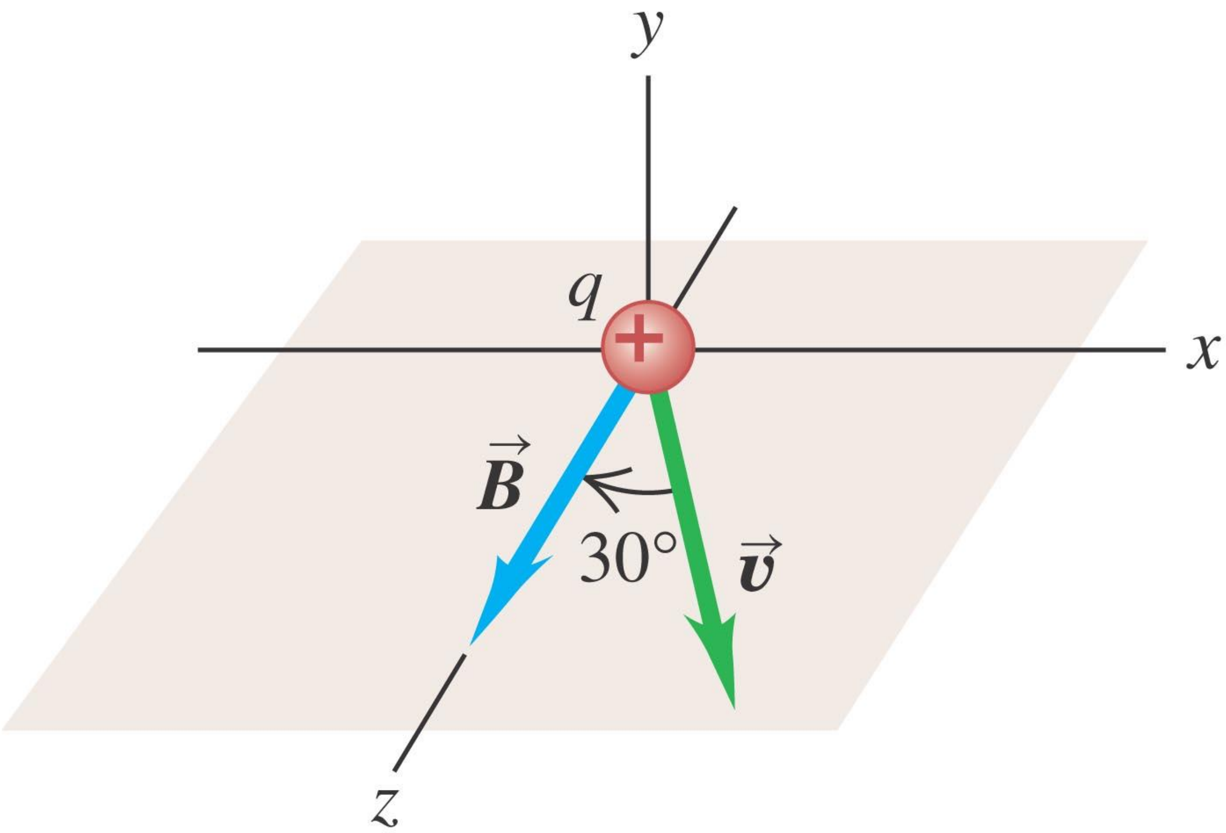


(a) If the tube axis is parallel to the y-axis, the beam is undeflected, so $\vec{B}$ is in either the $+y$- or the $-y$-direction.

(b) If the tube axis is parallel to the x-axis, the beam is deflected in the $-z$-direction, so $\vec{B}$ is in the $+y$-direction.

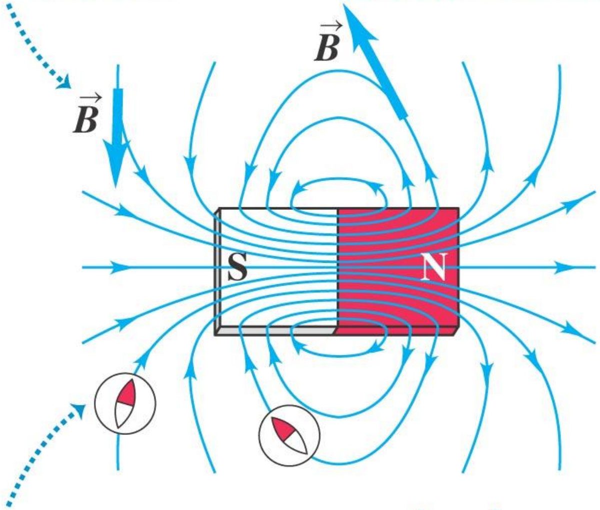
Magnetic force on a proton

- Refer to Problem-Solving Strategy 27.1.
- Follow Example 27.1 using Figure 27.10 below.



Magnetic field lines

- Figure 27.11 below shows the *magnetic field lines* of a permanent magnet.



At each point, the field line is tangent to the magnetic field vector $\vec{B}$.

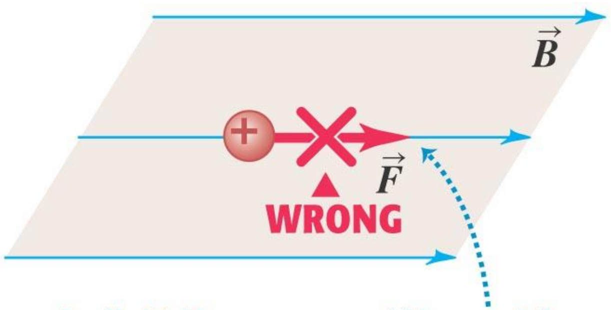
The more densely the field lines are packed, the stronger the field is at that point.

At each point, the field lines point in the same direction a compass would . . .

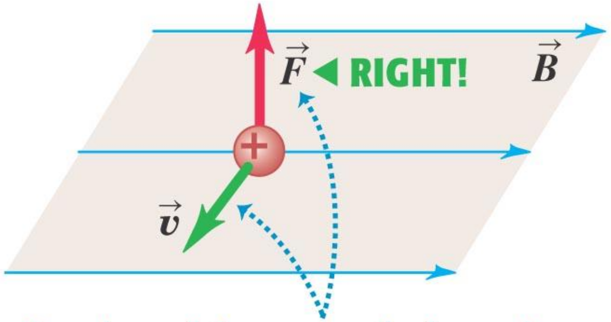
. . . therefore, magnetic field lines point *away from* N poles and *toward* S poles.

Magnetic field lines are *not* lines of force

- It is important to remember that magnetic field lines are *not* lines of magnetic force. (See Figure 27.12 below.)



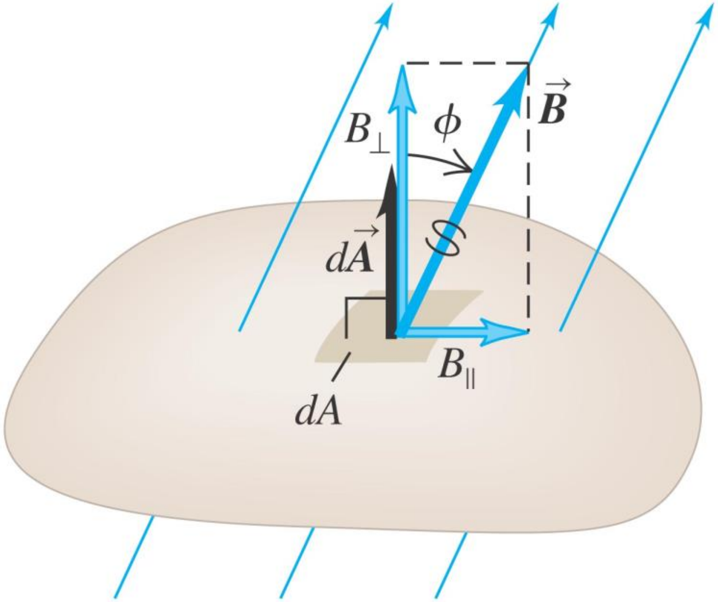
Magnetic field lines are *not* “lines of force.” The force on a charged particle is not along the direction of a field line.



The direction of the magnetic force depends on the velocity $\vec{v}$, as expressed by the magnetic force law $\vec{F} = q\vec{v} \times \vec{B}$.

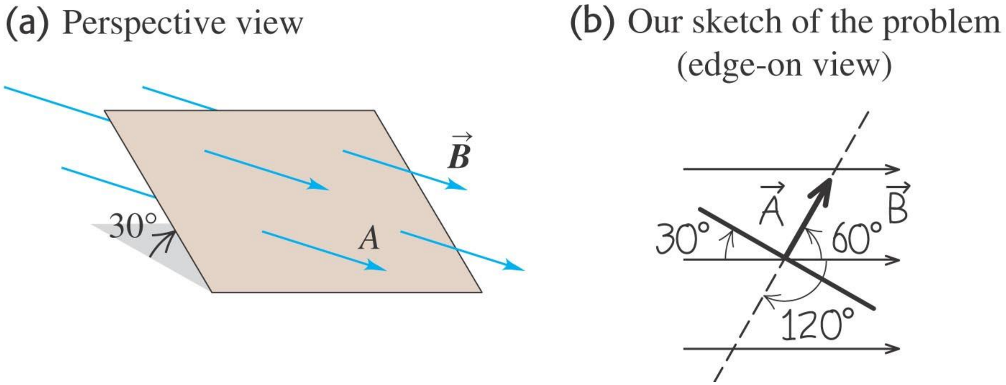
Magnetic flux

- We define the *magnetic flux* through a surface just as we defined electric flux. See Figure 27.15 below.
- Follow the discussion in the text of magnetic flux and Gauss’s law for magnetism.
- The magnetic flux through any closed surface is zero.



Magnetic flux calculations

- Follow Example 27.2 using Figure 27.16 below.

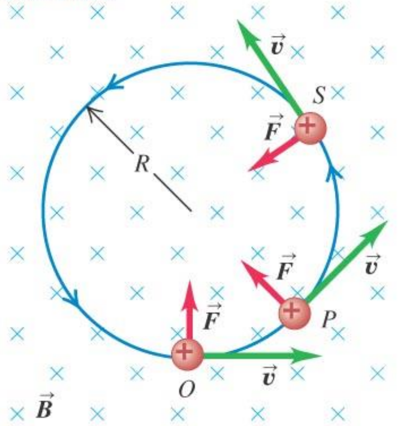


Motion of charged particles in a magnetic field

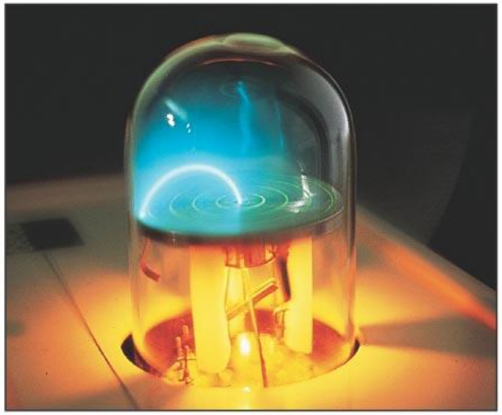
- A charged particle in a magnetic field always moves with constant speed.
- Figure 27.17 at the right illustrates the forces and shows an experimental example.
- If the velocity of the particle is perpendicular to the magnetic field, the particle moves in a circle of radius $R = mv/|q|B$.
- The number of revolutions of the particle per unit time is the *cyclotron frequency*.

(a) The orbit of a charged particle in a uniform magnetic field

A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.

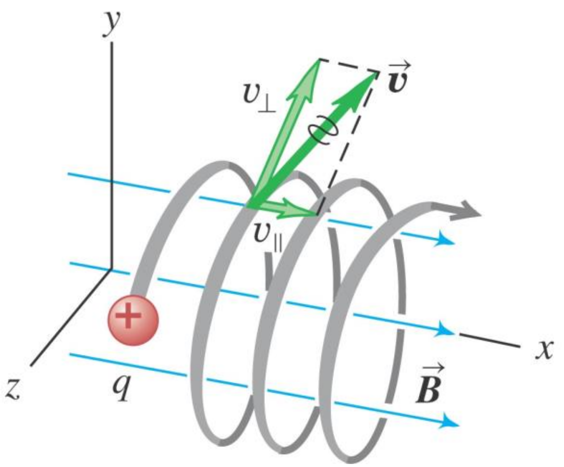


(b) An electron beam (seen as a blue arc) curving in a magnetic field



Helical motion

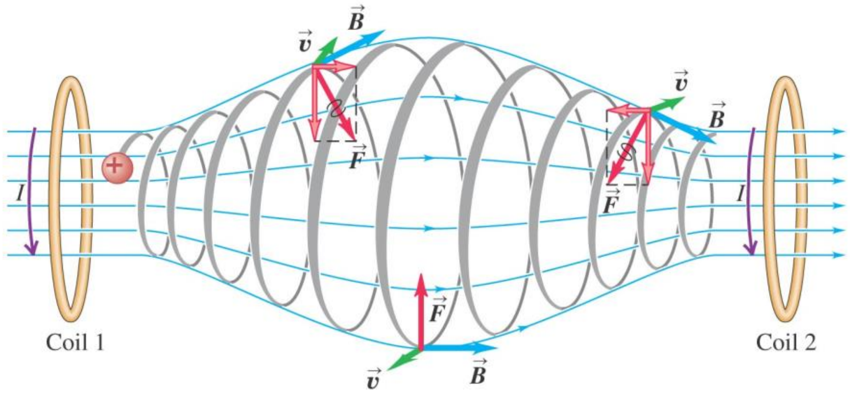
- If the particle has velocity components parallel to and perpendicular to the field, its path is a *helix*. (See Figure 27.18 at the right.)
- The speed and kinetic energy of the particle remain constant.



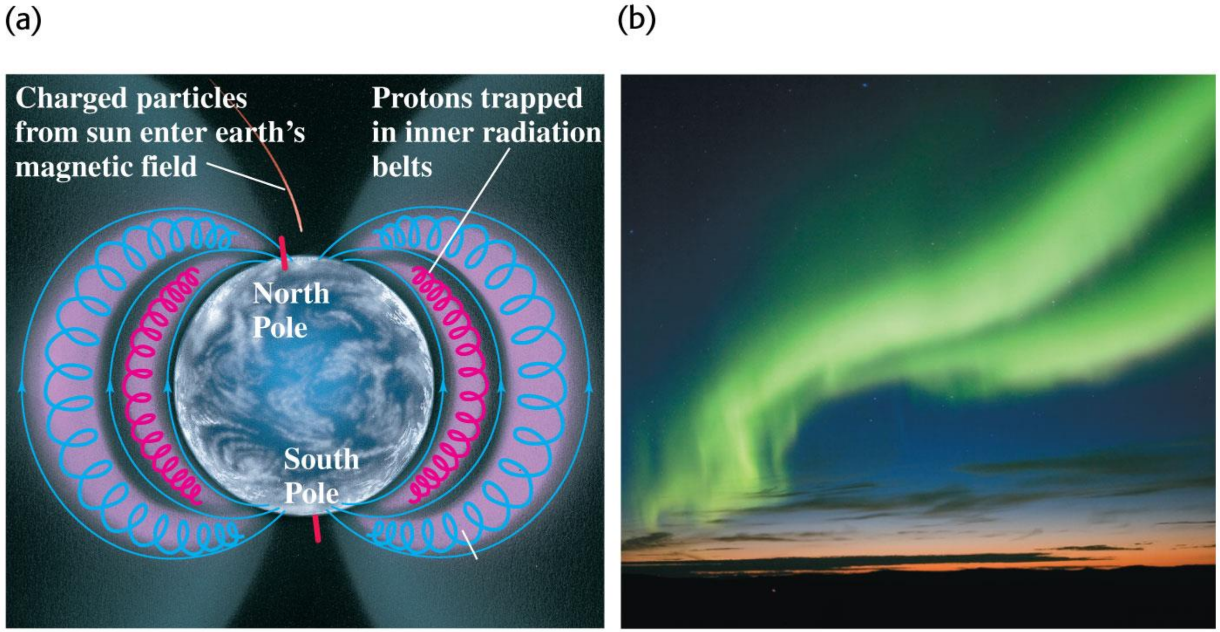
This particle's motion has components both parallel ($v_{\|}$) and perpendicular ($v_{\perp}$) to the magnetic field, so it moves in a helical path.

A nonuniform magnetic field

- Figure 27.19 at the right shows charges trapped in a *magnetic bottle*, which results from a nonuniform magnetic field.

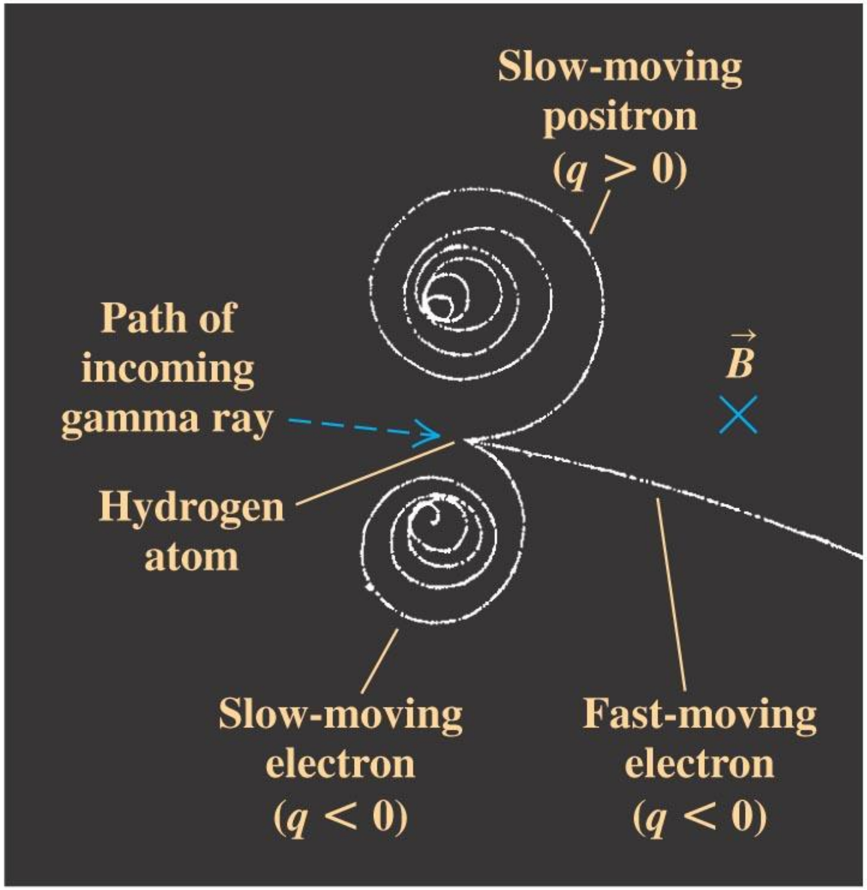


- Figure 27.20 below shows the Van Allen radiation belts and the resulting aurora. These belts are due to the earth’s nonuniform field.



Bubble chamber

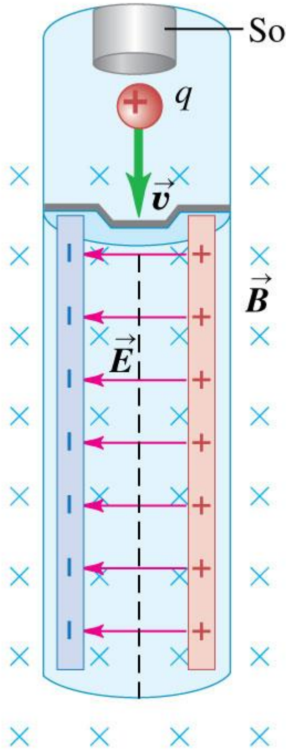
- Figure 27.21 at the right shows the tracks of charged particles in a bubble chamber experiment.
- Follow Problem-Solving Strategy 27.2.
- Follow Example 27.3.
- Follow Example 27.4.



Velocity selector

- A *velocity selector* uses perpendicular electric and magnetic fields to select particles of a specific speed from a beam. (See Figure 27.22 at the right.)
- Only particles having speed *v* = *E*/*B* pass through undeflected.

(a) Schematic diagram of velocity selector

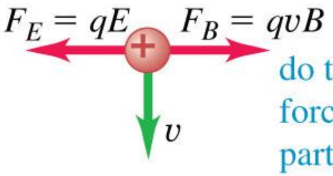


By the right-hand rule, the force of the $\vec{B}$ field on the charge points to the right.

The force of the $\vec{E}$ field on the charge points to the left.

For a negative charge, the directions of *both* forces are reversed.

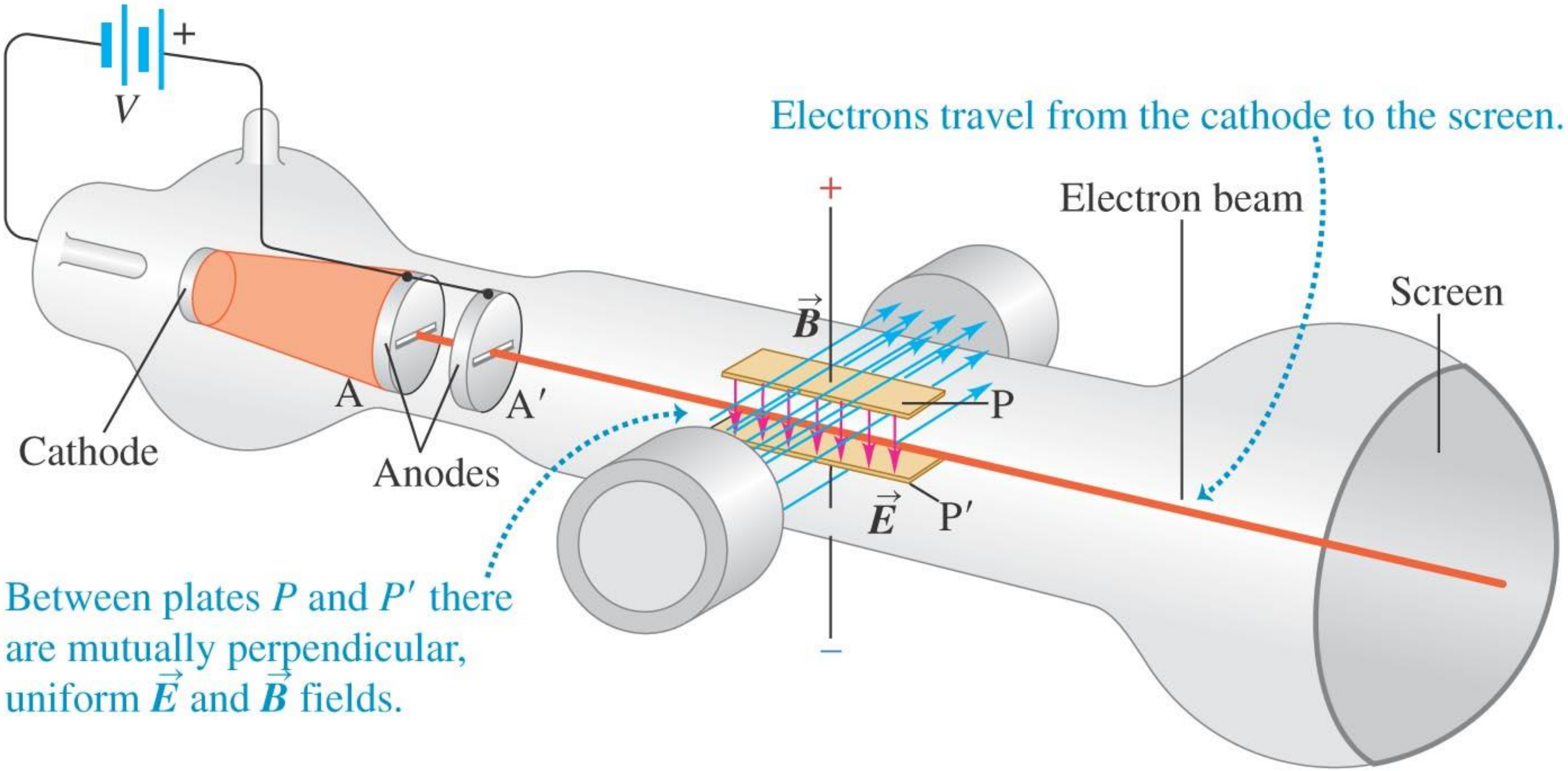
(b) Free-body diagram for a positive particle



Only if a charged particle has $v = E/B$ do the electric and magnetic forces cancel. All other particles are deflected.

Thomson's *e/m* experiment

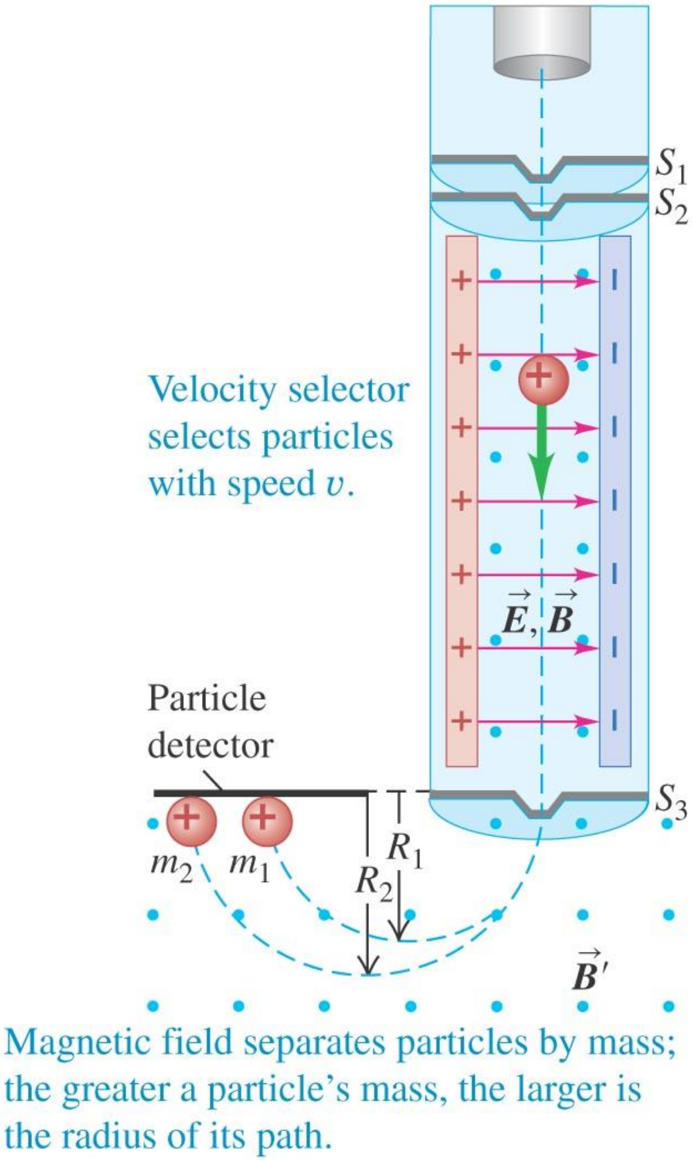
- Thomson's experiment measured the ratio *e/m* for the electron. His apparatus is shown in Figure 27.23 below.



Between plates P and P' there are mutually perpendicular, uniform $\vec{E}$ and $\vec{B}$ fields.

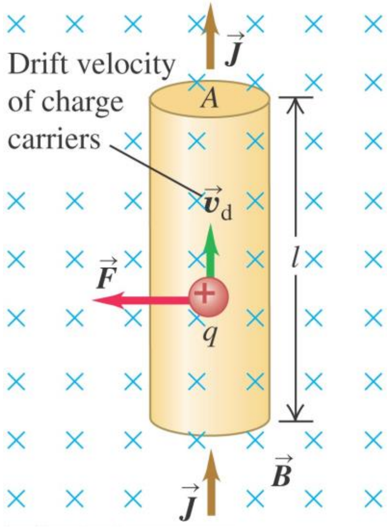
Mass spectrometer

- A *mass spectrometer* measures the masses of ions.
- The Bainbridge mass spectrometer (see Figure 27.24 at the right) first uses a velocity selector. Then the magnetic field separates the particles by mass.
- Follow Example 27.5.
- Follow Example 27.6.



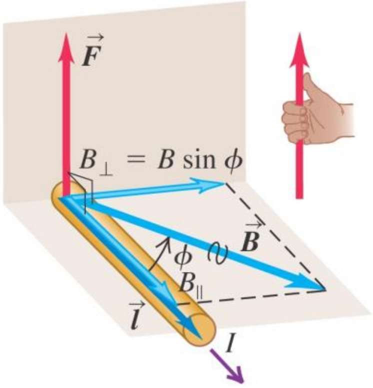
The magnetic force on a current-carrying conductor

- Figure 27.25 (top) shows the magnetic force on a moving positive charge in a conductor.
- Figure 27.26 (bottom) shows that the magnetic force is perpendicular to the wire segment and the magnetic field.
- Follow the discussion of the magnetic force on a conductor in the text.



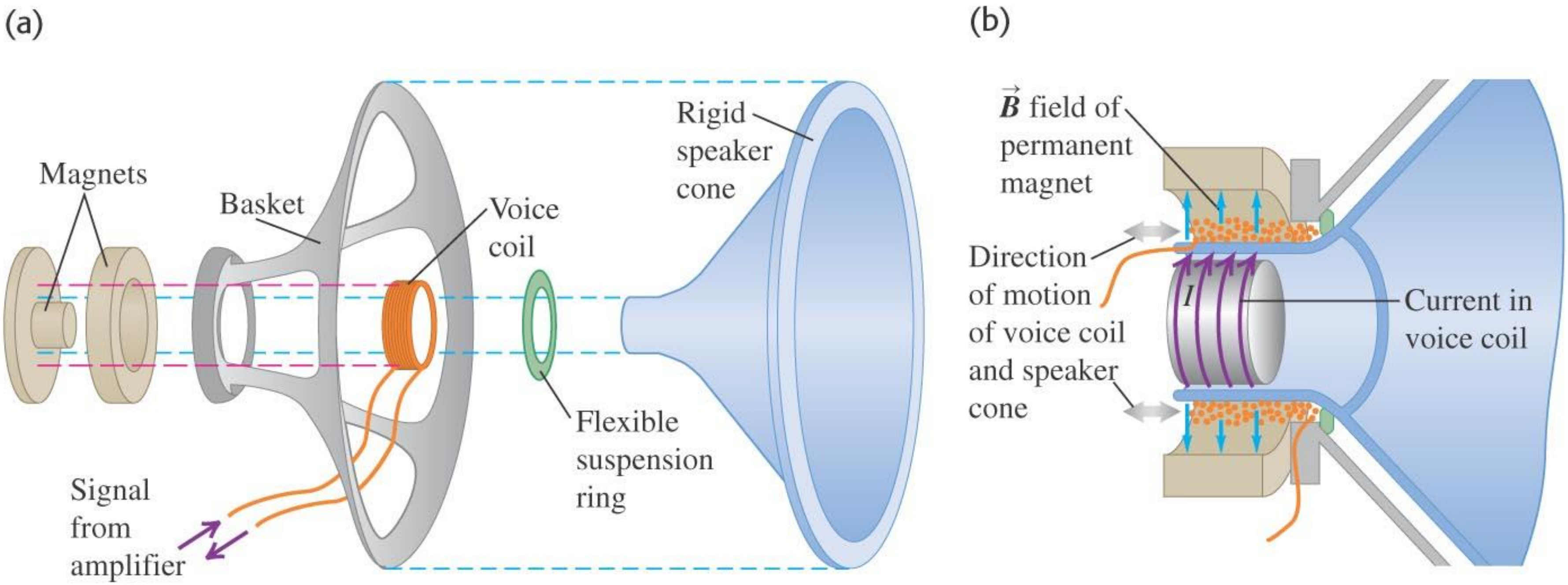
Force $\vec{F}$ on a straight wire carrying a positive current and oriented at an angle ϕ to a magnetic field $\vec{B}$:

- Magnitude is $F = IlB_{\perp} = IlB \sin \phi$.
- Direction of $\vec{F}$ is given by the right-hand rule.



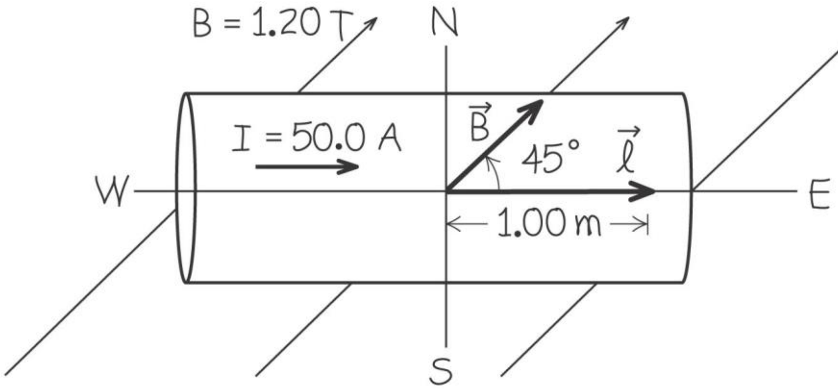
Loudspeaker

- Figure 27.28 shows a loudspeaker design. If the current in the voice coil oscillates, the speaker cone oscillates at the same frequency.



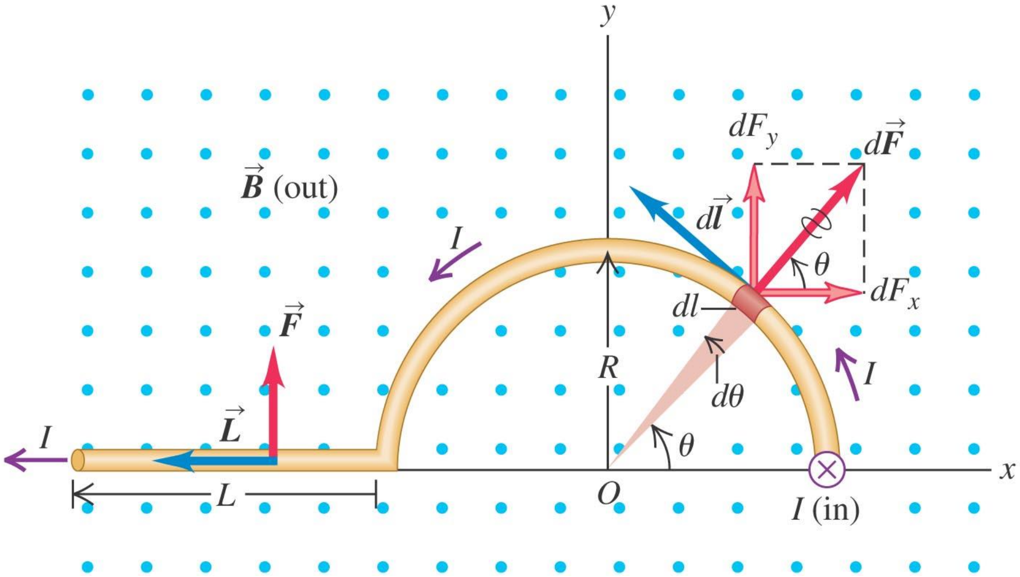
Magnetic force on a straight conductor

- Follow Example 27.7 using Figure 27.29 below.



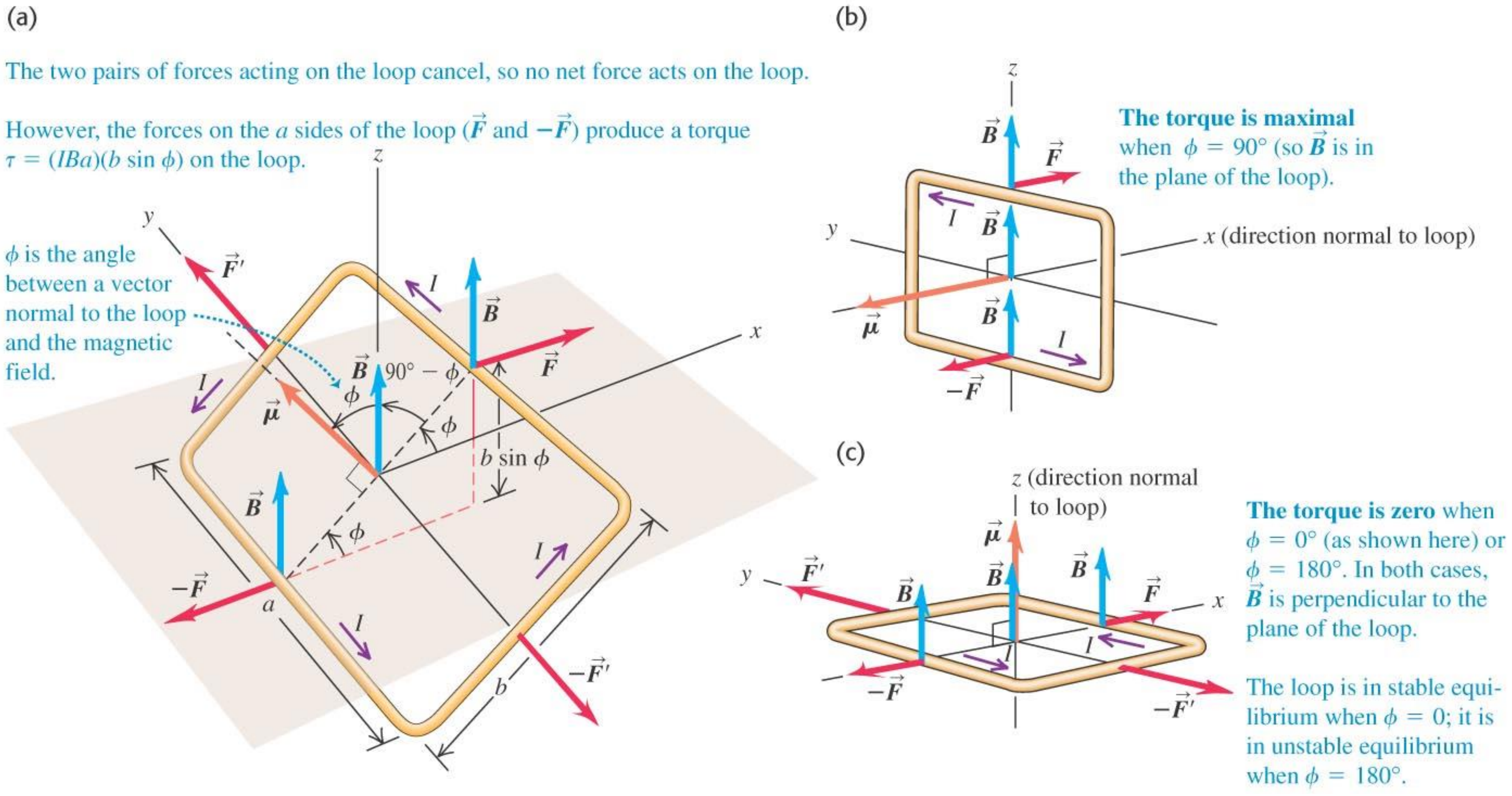
Magnetic force on a curved conductor

- Follow Example 27.8 using Figure 27.30 below.



Force and torque on a current loop

- The net force on a current loop in a uniform magnetic field is zero. But the net torque is not, in general, equal to zero.
- Figure 27.31 below shows the forces and how to calculate the torque.



(a)

The two pairs of forces acting on the loop cancel, so no net force acts on the loop.

However, the forces on the a sides of the loop ($\vec{F}$ and $-\vec{F}$) produce a torque $\tau = (IBa)(b \sin\phi)$ on the loop.

ϕ is the angle between a vector normal to the loop and the magnetic field.

(b)

The torque is maximal when $\phi = 90°$ (so $\vec{B}$ is in the plane of the loop).

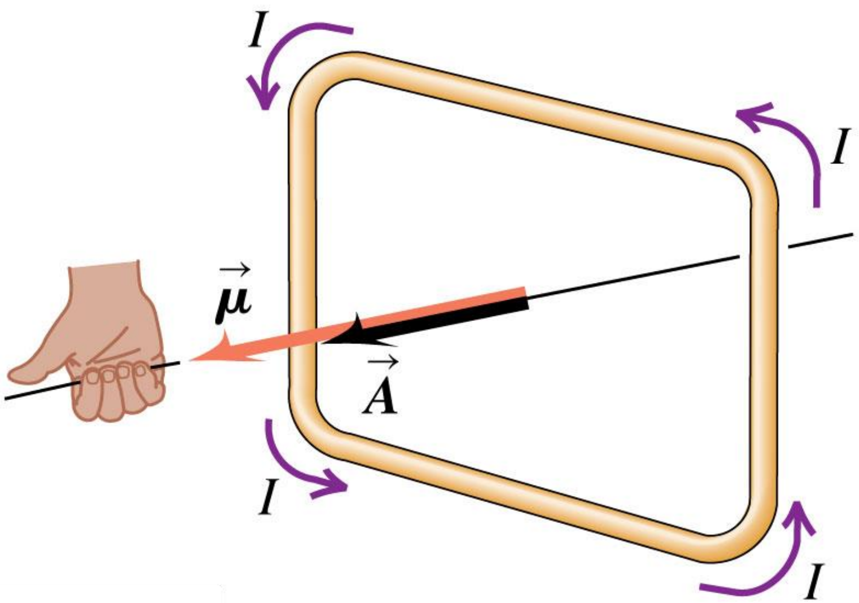
(c)

The torque is zero when $\phi = 0°$ (as shown here) or $\phi = 180°$. In both cases, $\vec{B}$ is perpendicular to the plane of the loop.

The loop is in stable equilibrium when $\phi = 0$; it is in unstable equilibrium when $\phi = 180°$.

Magnetic moment

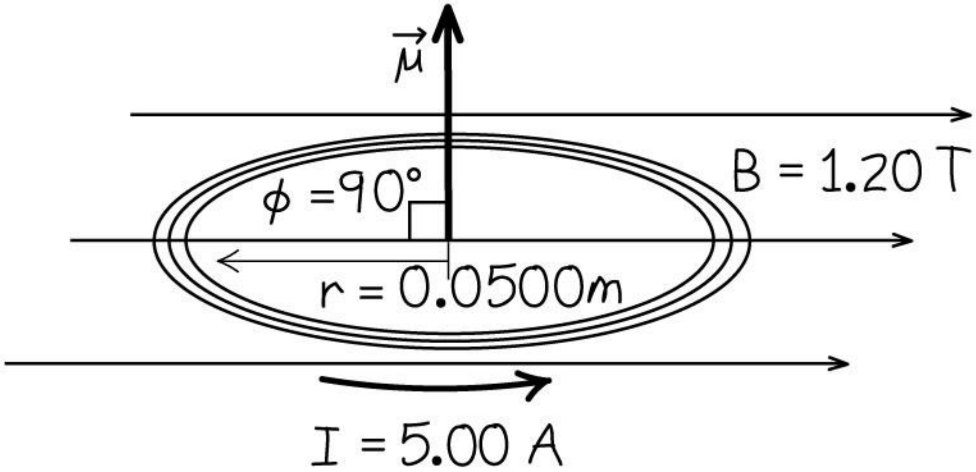
- Follow the text discussion of magnetic torque and magnetic moment. Figure 27.32 at the right illustrates the right-hand rule to determine the direction of the magnetic moment of a current loop.



- Follow the discussion of the potential energy of a magnetic dipole in a magnetic field.

Magnetic torque and potential energy of a coil

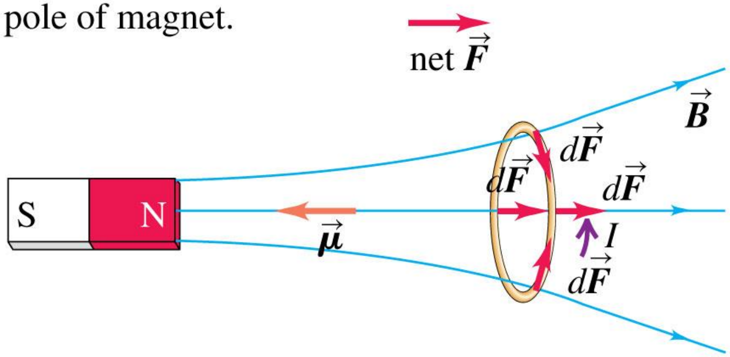
- Follow Example 27.9 using Figure 27.35 below.
- Follow Example 27.10.



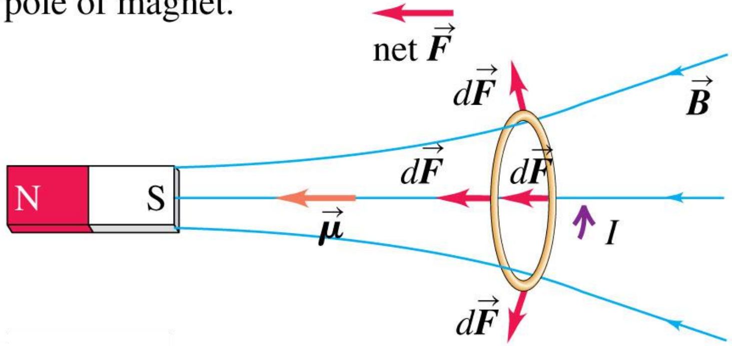
How magnets work

- Follow the discussion in the text of magnetic dipoles and how magnets work. Use Figures 27.36 (below) and 27.37 (right).

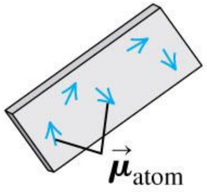
(a) Net force on this coil is away from north pole of magnet.



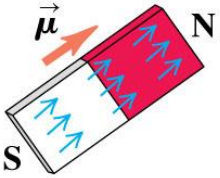
(b) Net force on same coil is toward south pole of magnet.



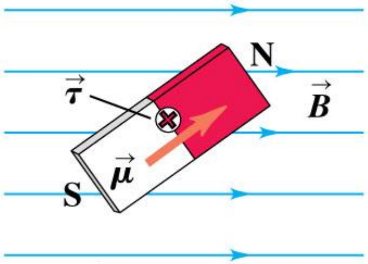
(a) Unmagnetized iron: magnetic moments are oriented randomly.



(b) In a bar magnet, the magnetic moments are aligned.

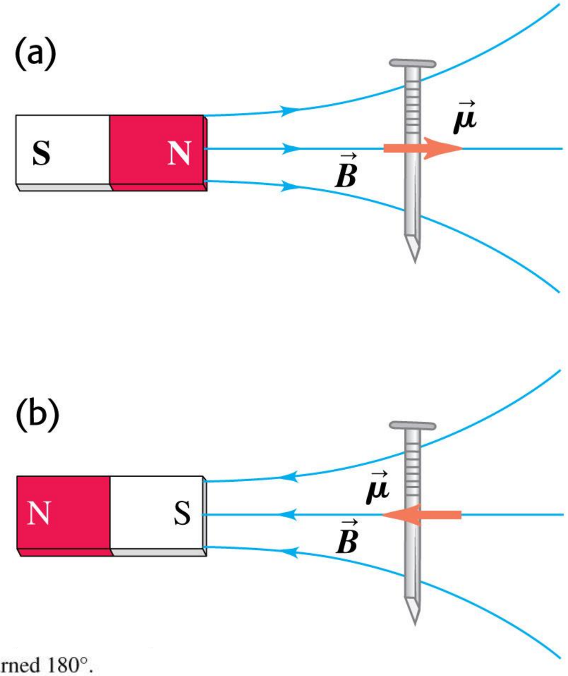


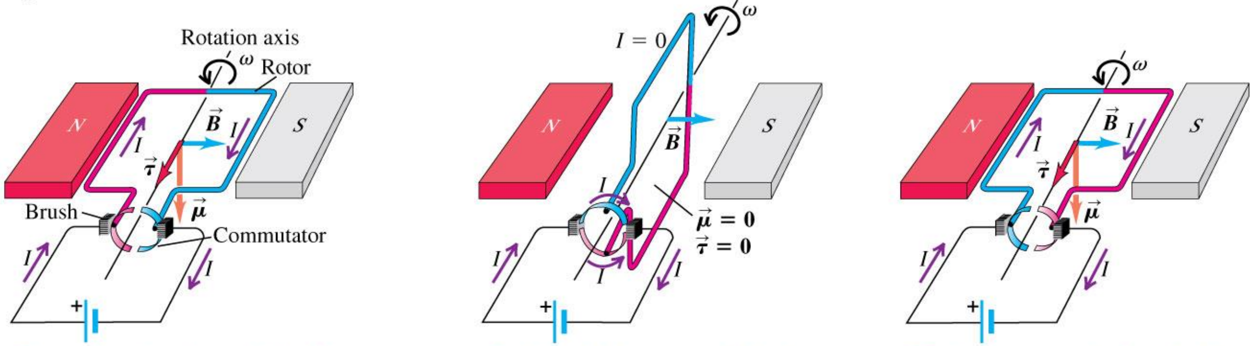
(c) A magnetic field creates a torque on the bar magnet that tends to align its dipole moment with the $\vec{B}$ field.



The direct-current motor

- Follow the discussion in the text of the direct-current motor. Use Figures 27.38 (right) and 27.39 (below).
- Follow Example 27.11.





(a) Brushes are aligned with commutator segments.

- Current flows into the red side of the rotor and out of the blue side.
- Therefore the magnetic torque causes the rotor to spin counterclockwise.

(b) Rotor has turned 90°.

- Each brush is in contact with both commutator segments, so the current bypasses the rotor altogether.
- No magnetic torque acts on the rotor.

(c) Rotor has turned 180°.

- The brushes are again aligned with commutator segments. This time the current flows into the blue side of the rotor and out of the red side.
- Therefore the magnetic torque again causes the rotor to spin counterclockwise.

The Hall Effect

- Follow the discussion of the Hall effect in the text using Figure 27.41 below.
- Follow Example 27.12.