Chapter 27

Magnetic Field and Magnetic Forces

PowerPoint® Lectures for
University Physics, Thirteenth Edition
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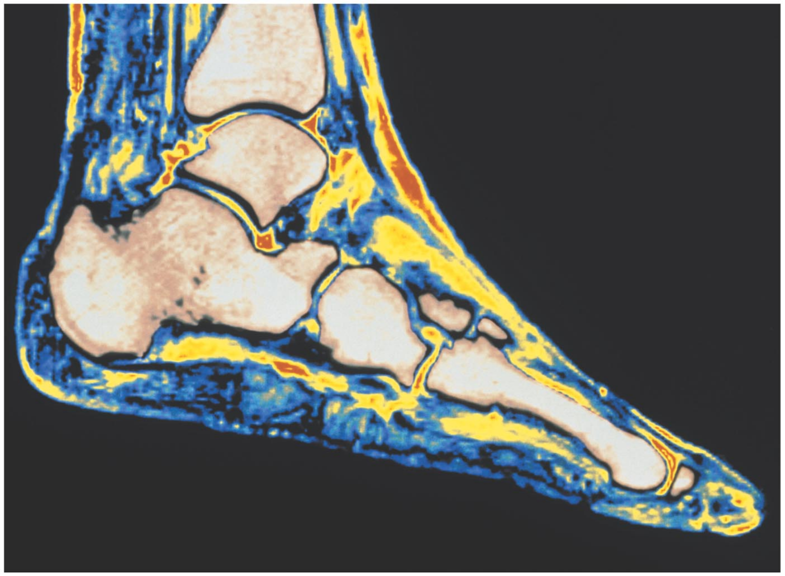
Goals for Chapter 27

- **Magnets** and the **forces they exert on each other**
- **Force** that a **magnetic field** exerts **on** a **moving charge**
- **Magnetic field lines** with **electric field lines**
- **Motion of a charged particle** in a **magnetic field**
- **Applications of magnetism** in physics and chemistry
- **Magnetic forces** on **current-carrying conductors**
- **Current loops in a magnetic field**

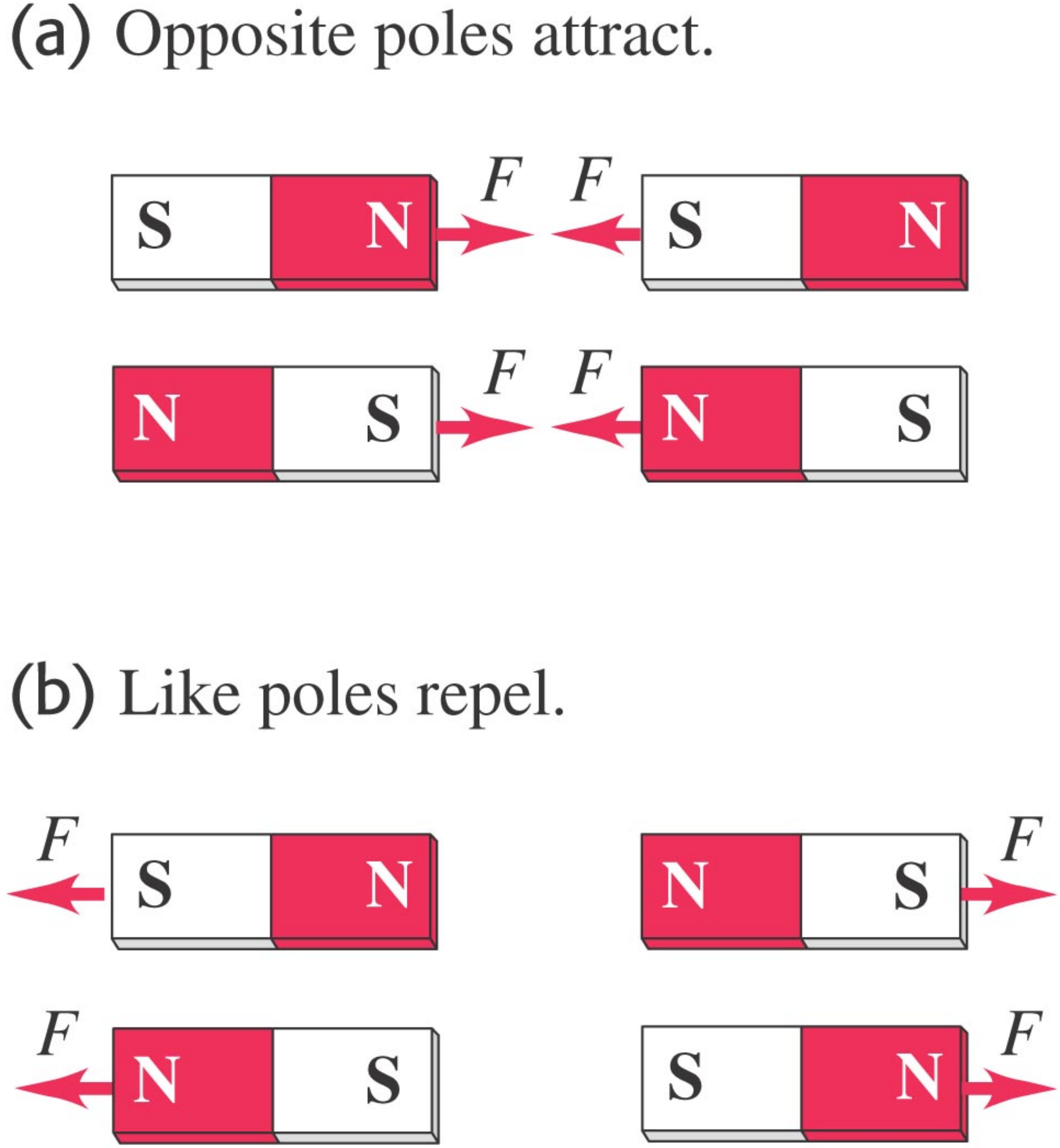
Introduction

- 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.



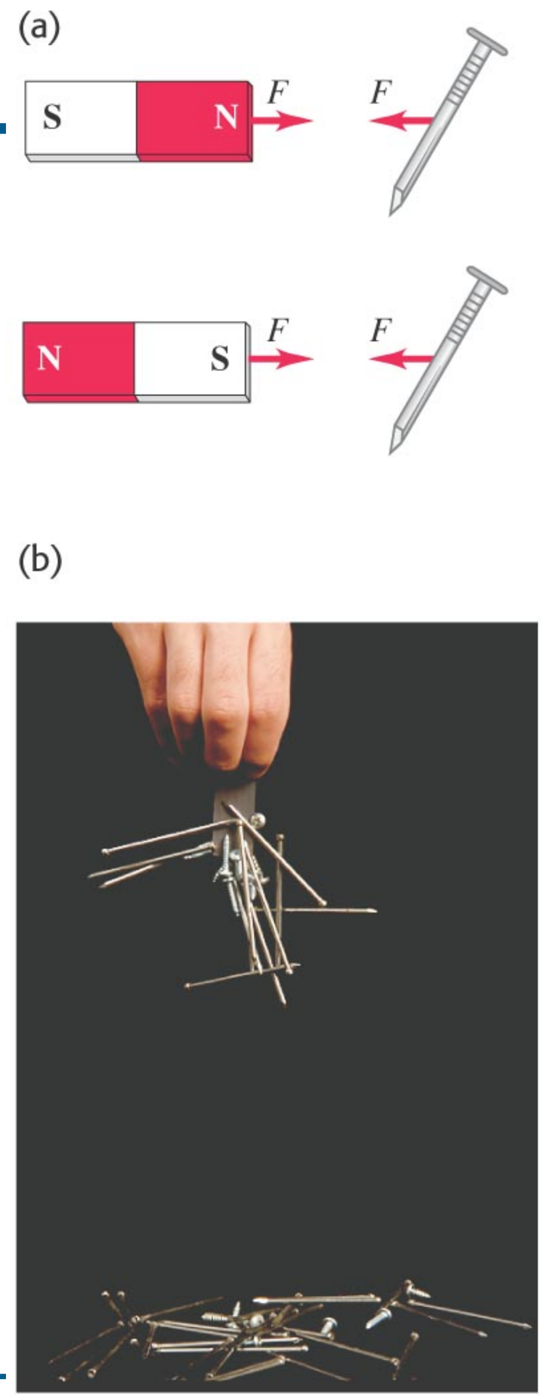
Magnetic poles

- Forces between magnetic poles.



Magnetism and certain metals

- Either pole of a permanent magnet will attract a metal like iron.

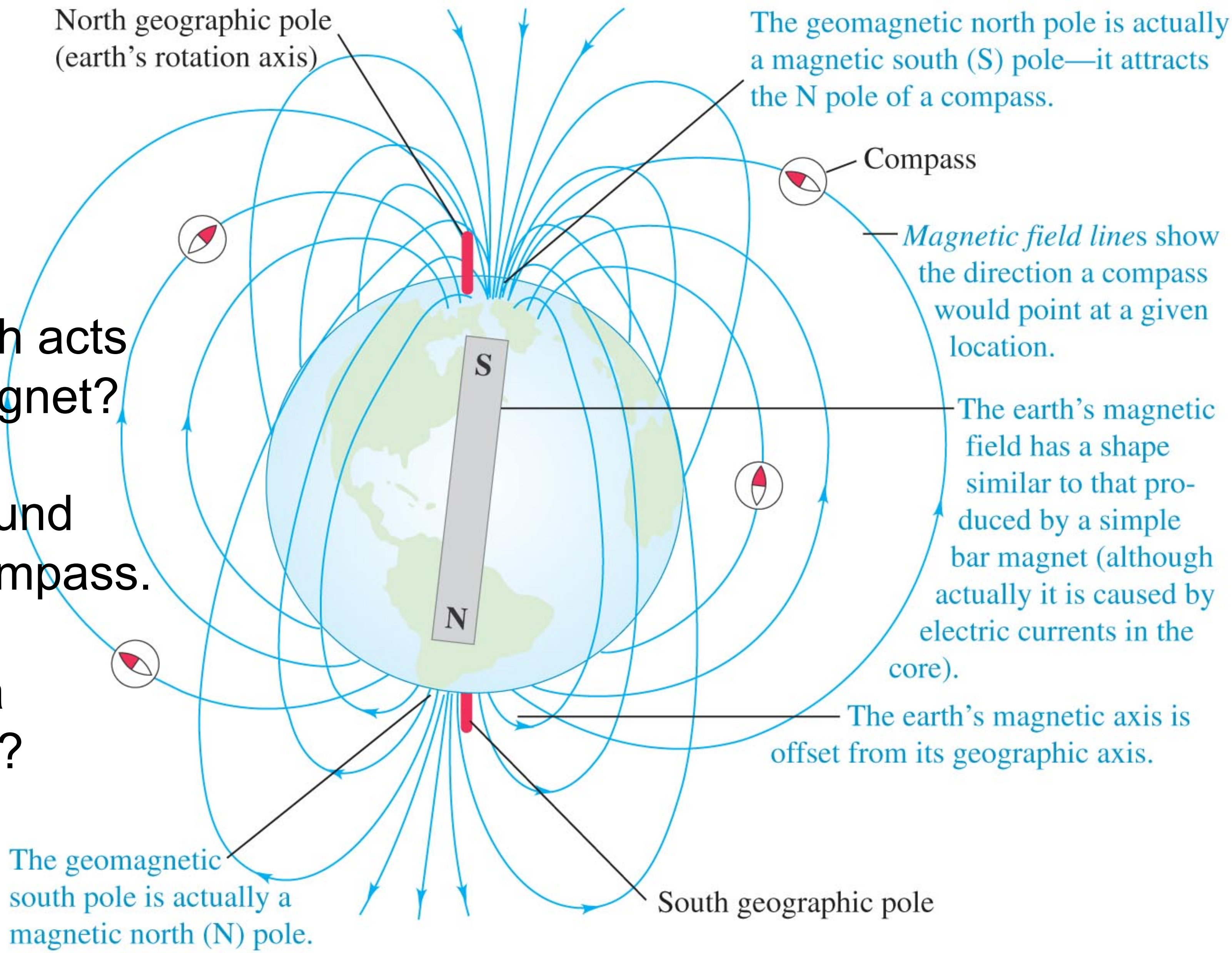


Magnetic field of the earth and its field lines

Why earth acts like a magnet?

Walk around with a compass.

What is a compass?

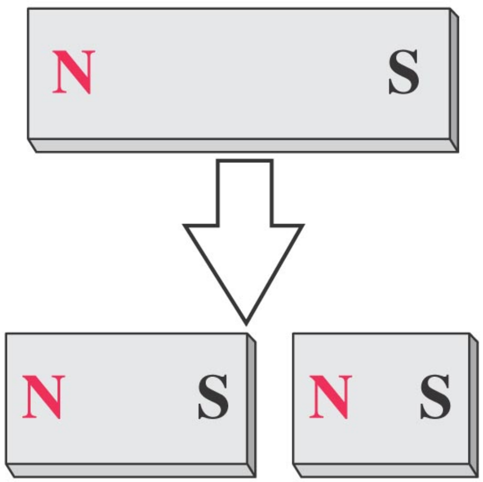


Magnetic monopoles

- Breaking a bar magnet does not separate its poles.
- There is no experimental evidence for *magnetic monopoles*.
- Why?

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

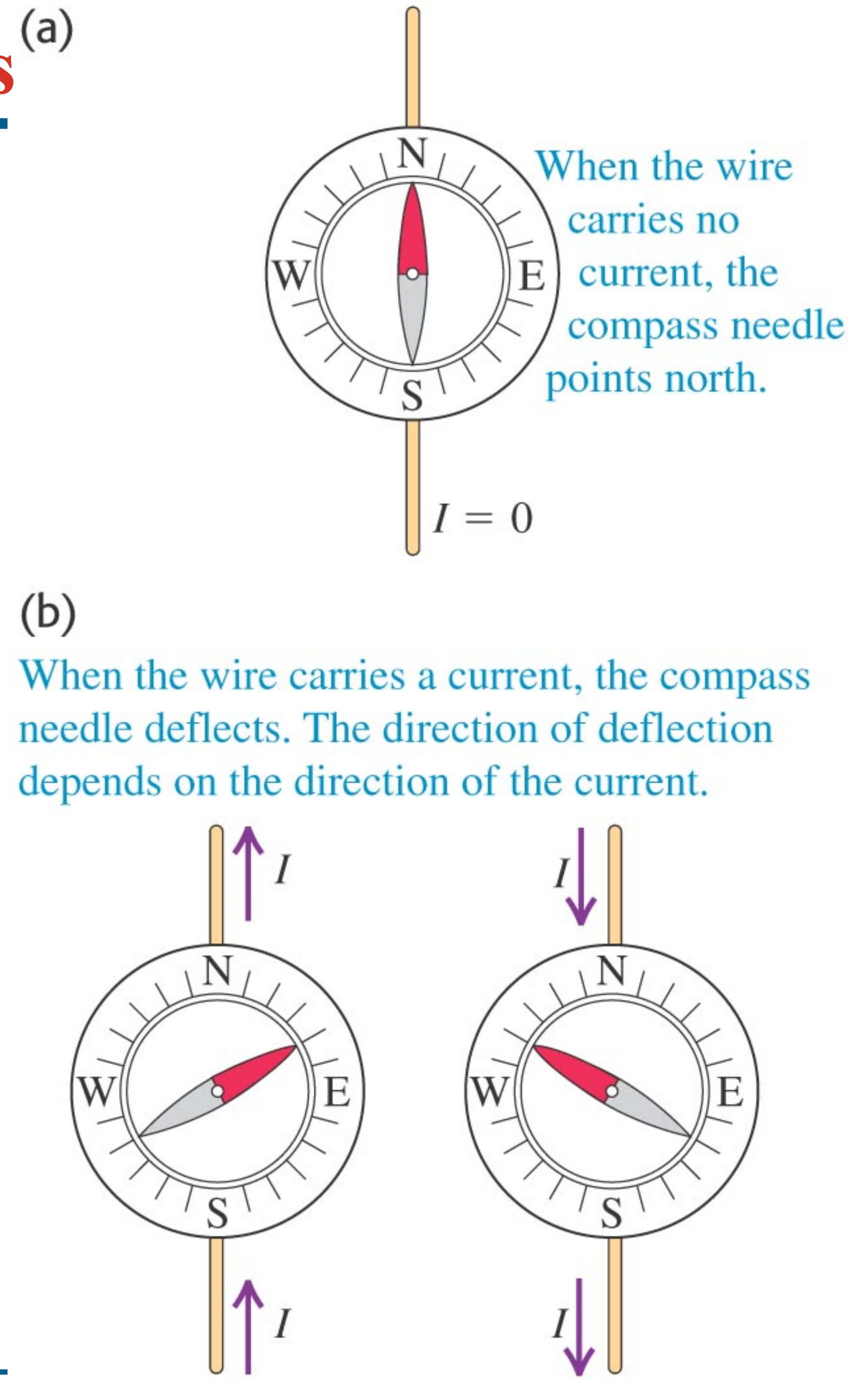
Breaking a magnet in two ...



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

Electric current and magnets

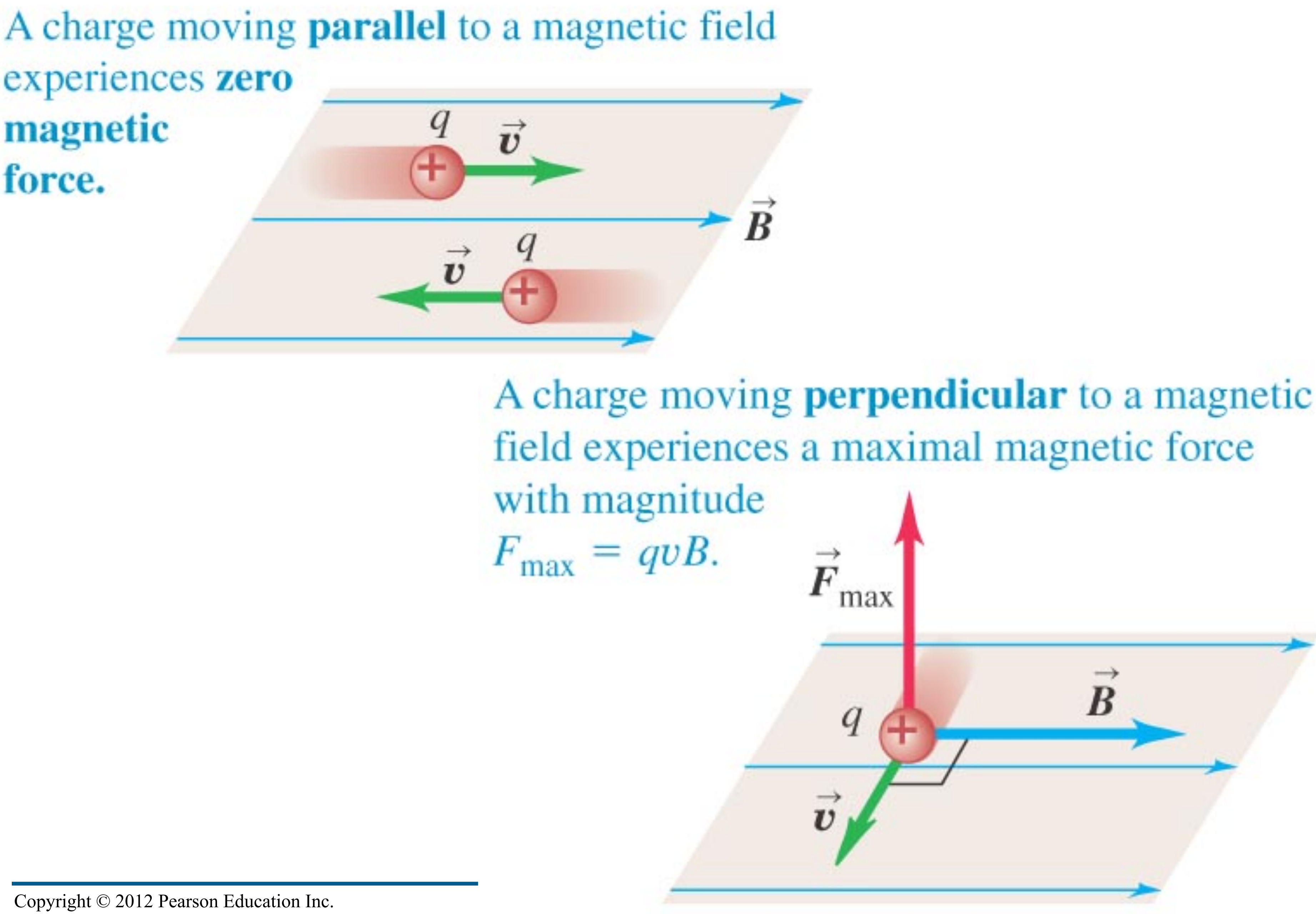
- In 1820, Hans Oersted discovered that **a current-carrying wire causes a compass to deflect**.
- Seems like there is a **connection between moving charge** and **magnetism**.



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.
- Then force of the magnetic field changes the speed of the moving charges that in-turn creates a secondary magnetic field and …
- Will come back to this later

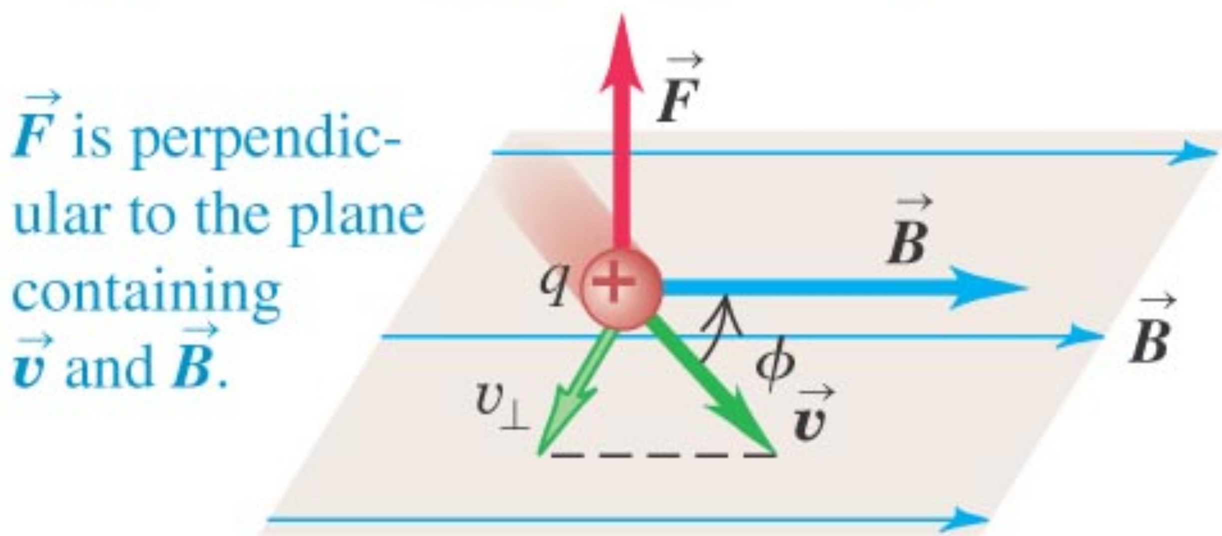
The magnetic force on a moving charge



The magnetic force on a moving charge

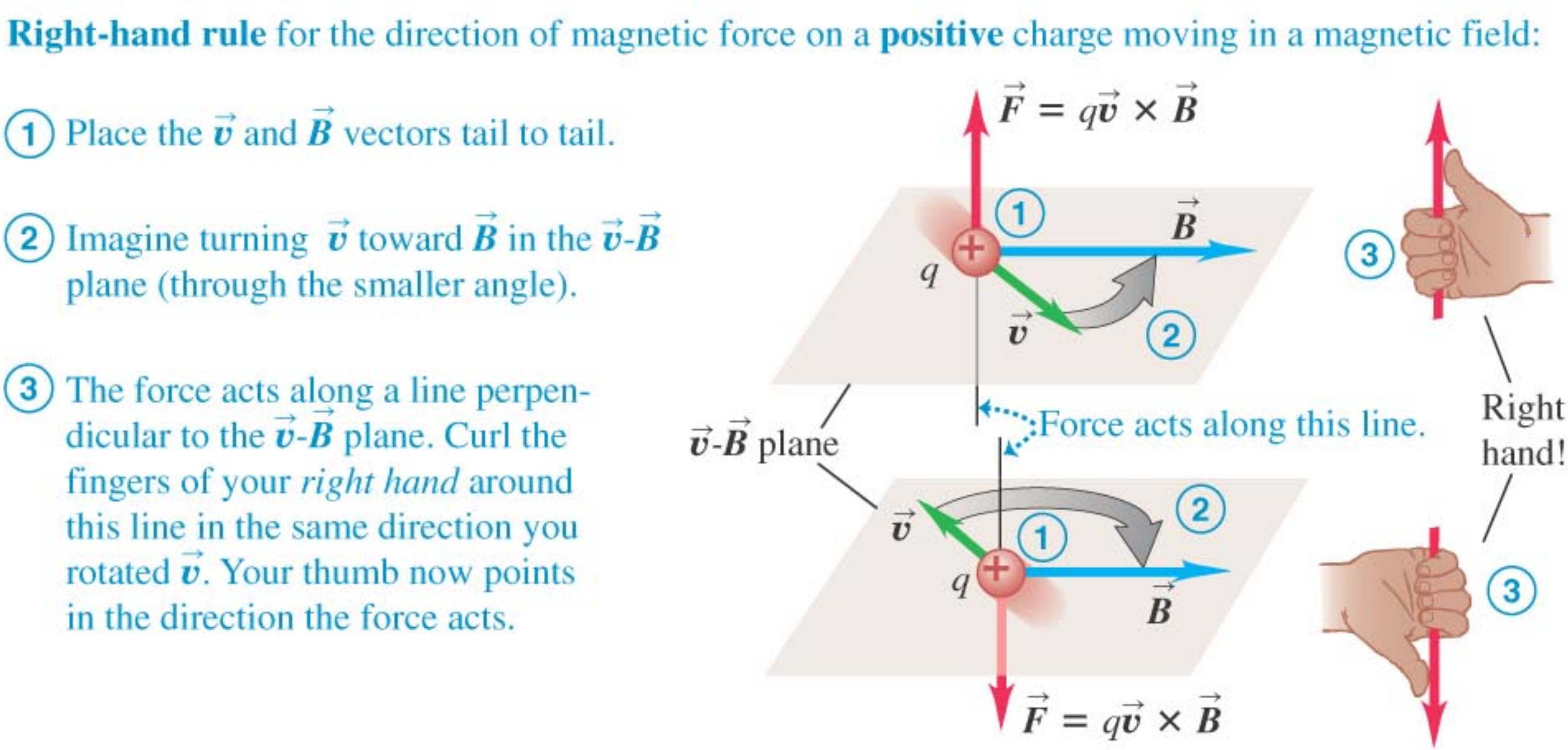
- The magnetic force on q is perpendicular to *both* the velocity of q and the magnetic field.
- The magnitude of the magnetic force is
  $F = |q|vB \sin\varphi$

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



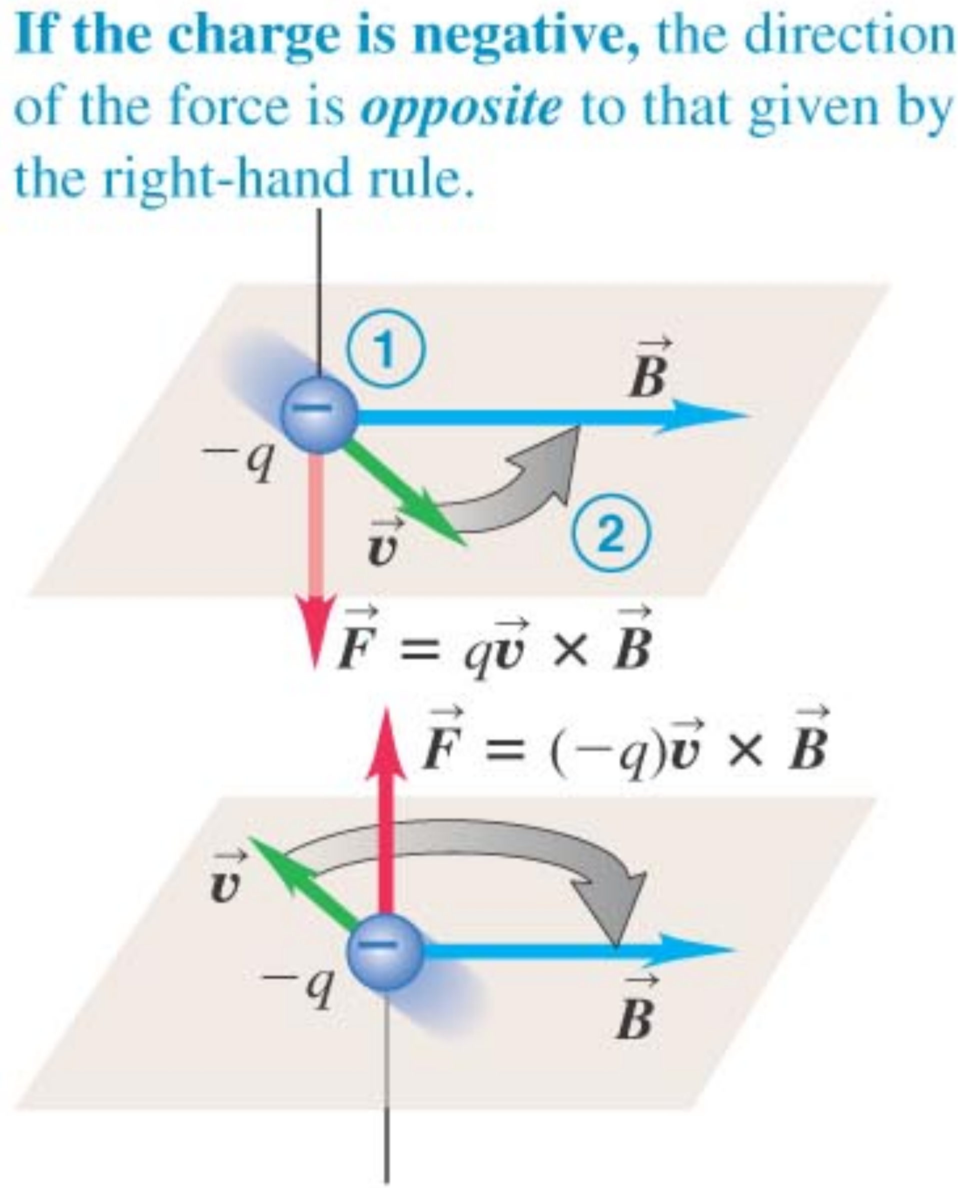
Magnetic force as a vector product of v and B

- The right-hand rule gives the direction of the force on a ***positive* charge**.



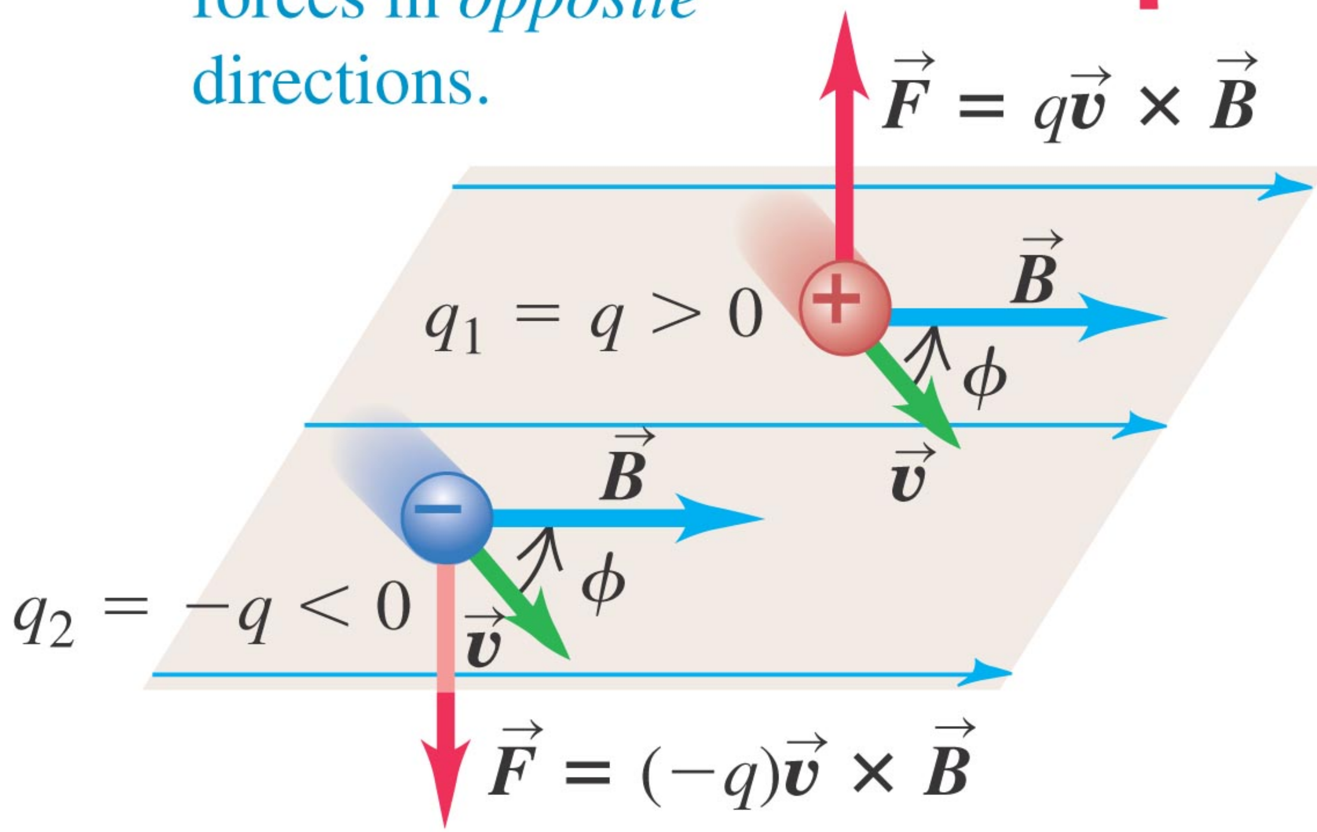
Magnetic force as a vector product of v and B

- Direction of the magnetic force on a ***negative*** **charge**.



Equal velocities but opposite signs

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



Units of magnetic field B

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

$N = C\dfrac{m}{s} \times \text{unit of B}$

The SI unit of magnetic field B is **tesla**: $1\ T = 1\dfrac{N}{A \cdot m} = 1\dfrac{N}{C \cdot m/s}$

Another unit is the **gauss** : $1\ G = 10^{-4}\,T$

Gaussmeters : instruments measuring the magnetic field

Magnetic field of the earch is of the order of 1G or $10^{-4}T$

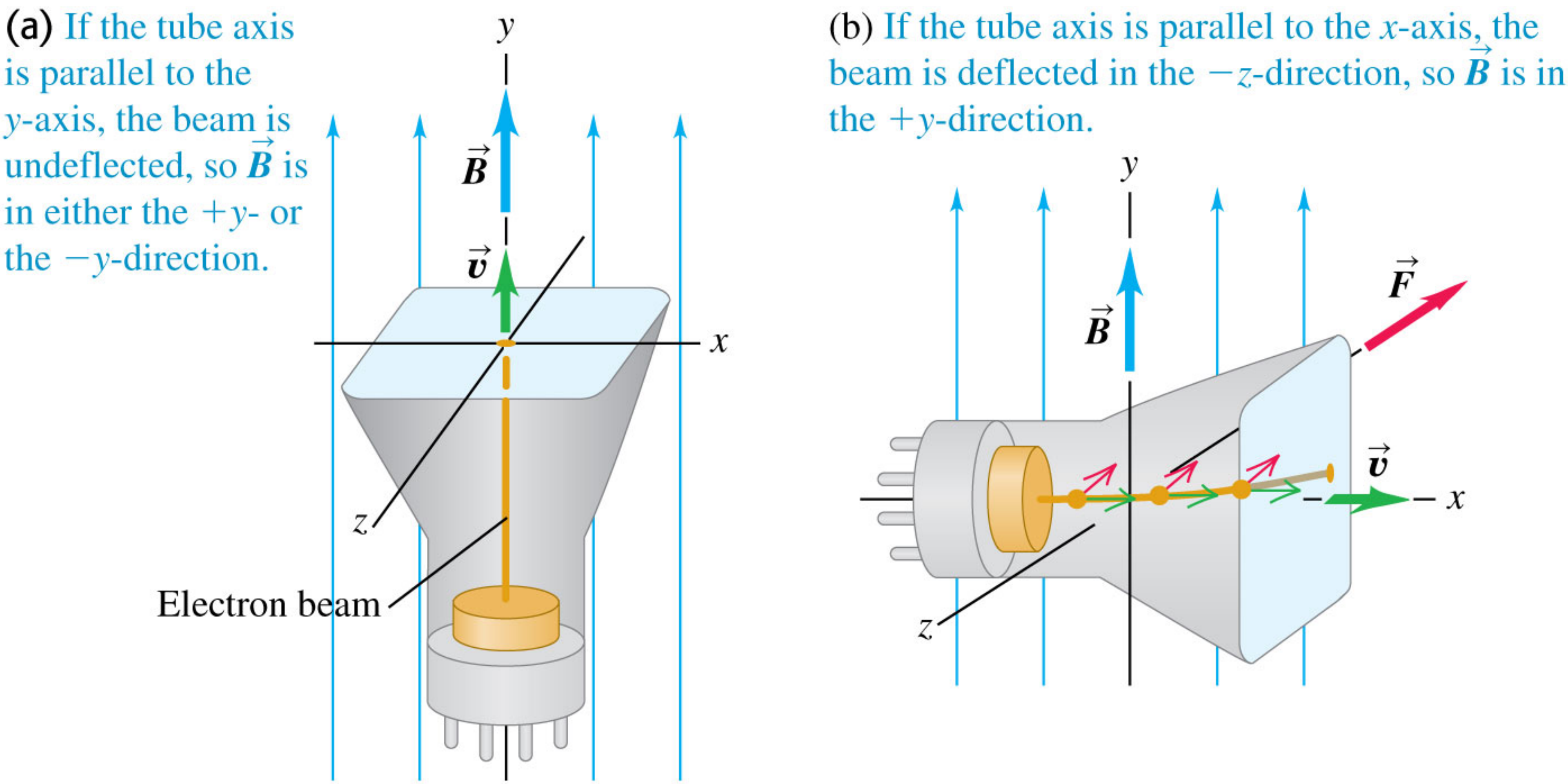
Largest B field produced int the lab:

~ 45T continuous & ~ 120T (pulsed ~ ms)

B of a surface of a neutron star $\sim 10^{8}T$

Determining the direction of a magnetic field

- A cathode-ray tube can be used to determine the direction of a magnetic field.



Problem-Solving Strategy 27.1 Magnetic Forces

IDENTIFY *the relevant concepts:* The equation $\vec{F} = q\vec{v} \times \vec{B}$ allows you to determine the magnetic force on a moving charged particle.

SET UP *the problem* using the following steps:

1. Draw the velocity $\vec{v}$ and magnetic $\vec{B}$ field with their tails together so that you can visualize the plane that contains them.
2. Determine the angle ϕ between $\vec{v}$ and $\vec{B}$.
3. Identify the target variables.

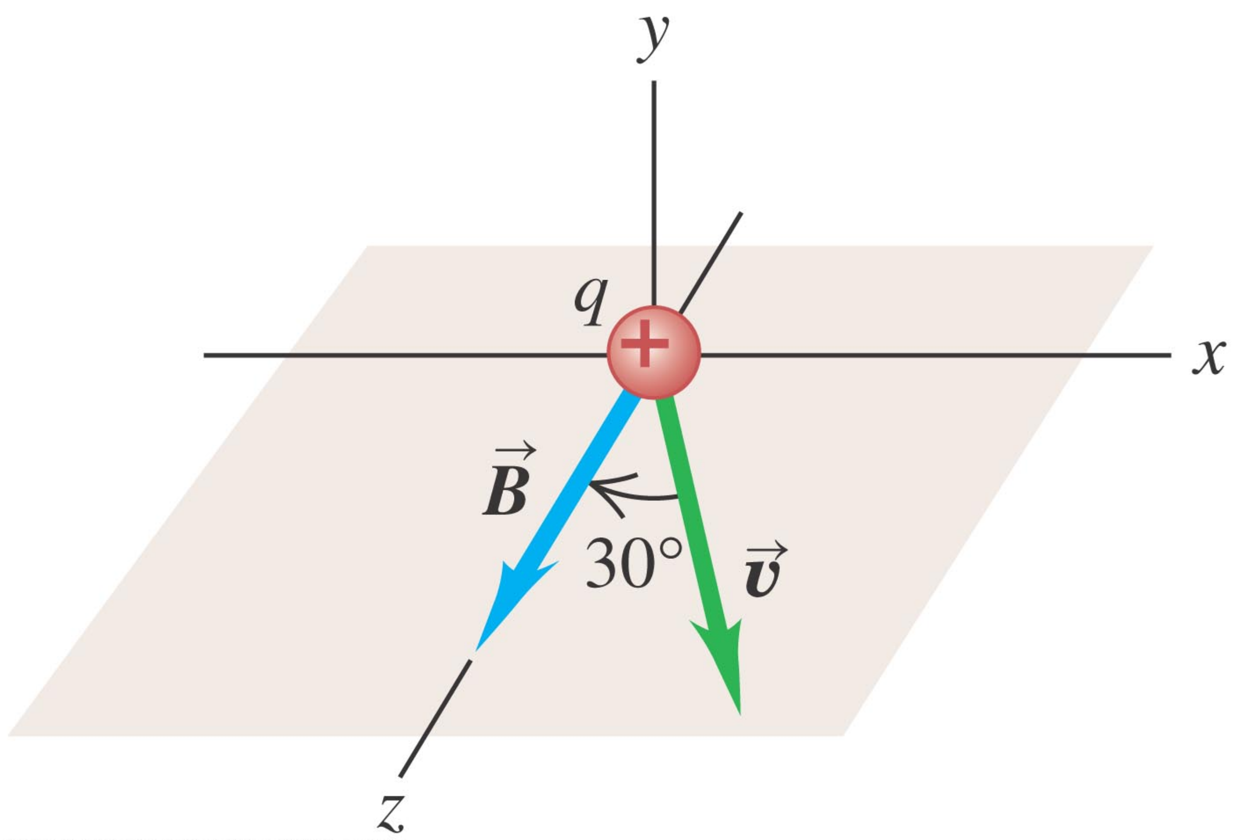
EXECUTE *the solution* as follows:

1. Express the magnetic force using Eq. (27.2), $\vec{F} = q\vec{v} \times \vec{B}$. Equation (27.1) gives the magnitude of the force, $F = qvB\sin\phi$.
2. Remember that $\vec{F}$ is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$. The right-hand rule (see Fig. 27.7) gives the direction of $\vec{v} \times \vec{B}$. If q is negative, $\vec{F}$ is *opposite* to $\vec{v} \times \vec{B}$.

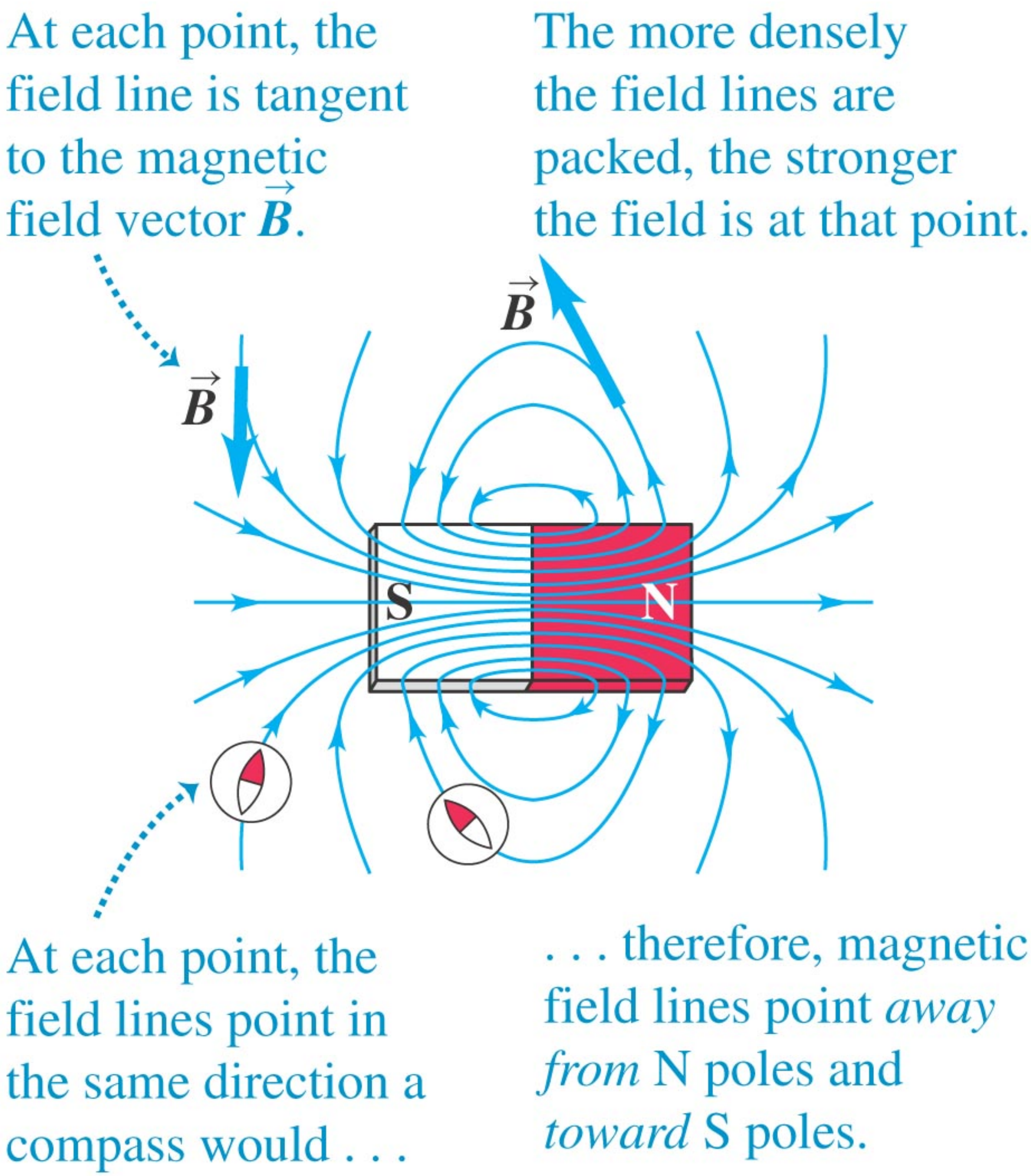
EVALUATE *your answer:* Whenever possible, solve the problem in two ways to confirm that the results agree. Do it directly from the geometric definition of the vector product. Then find the components of the vectors in some convenient coordinate system and calculate the vector product from the components. Verify that the results agree.

Magnetic force on a proton

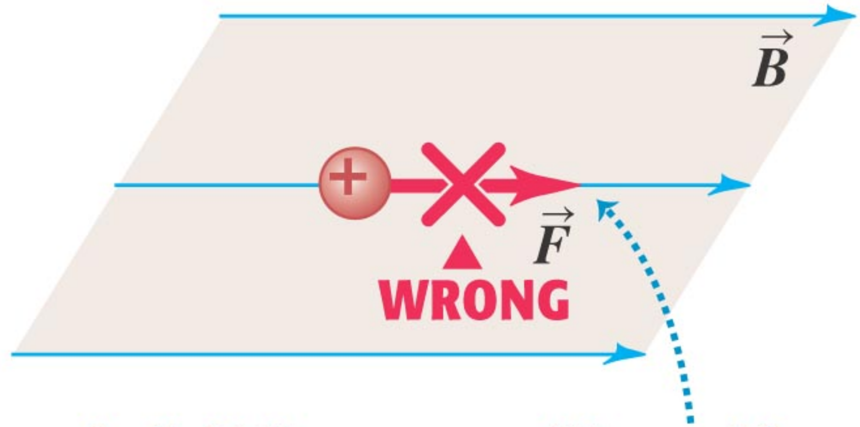
- Example 27.1 A beam of protons move with speed of 3.0E5m/s on x-z plane at an angle 30 degrees with respect to +z axis through a uniform B-field of 2.0T along positive z-direction.
- Find the force on the proton magnitude and direction



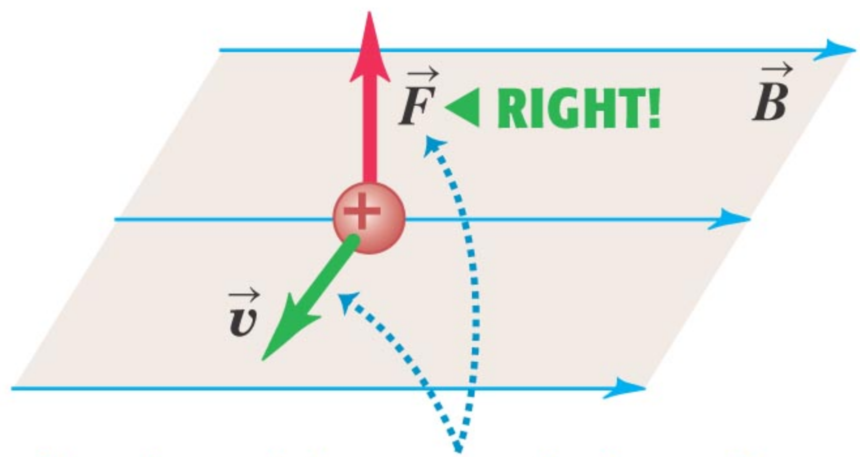
Magnetic field lines



Magnetic field lines are *not* lines of force



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 and magnetic Gauss's law

- We define the *magnetic flux* through a surface just as we defined the electric flux.

- Magnetic Gauss's law: The magnetic flux through any closed surface is zero.

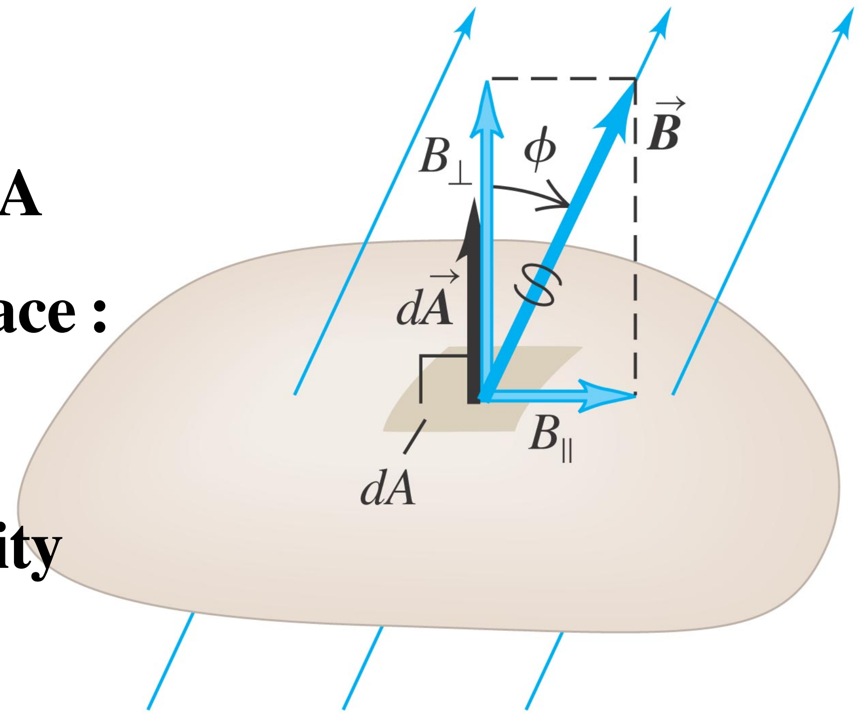
$$\Phi_B = \int B_\perp \, dA = \int B \cos\Phi \, dA = \int \mathbf{B} \bullet d\mathbf{A}$$

Magnetic flux through a closed surface :

$$\oint \mathbf{B} \bullet d\mathbf{A} = 0$$

Magnetic field or **magnetic flux density**

$$B = \frac{d\Phi_B}{dA_\perp}$$



Units of magnetic flux

$$\Phi_B = B_\perp A$$

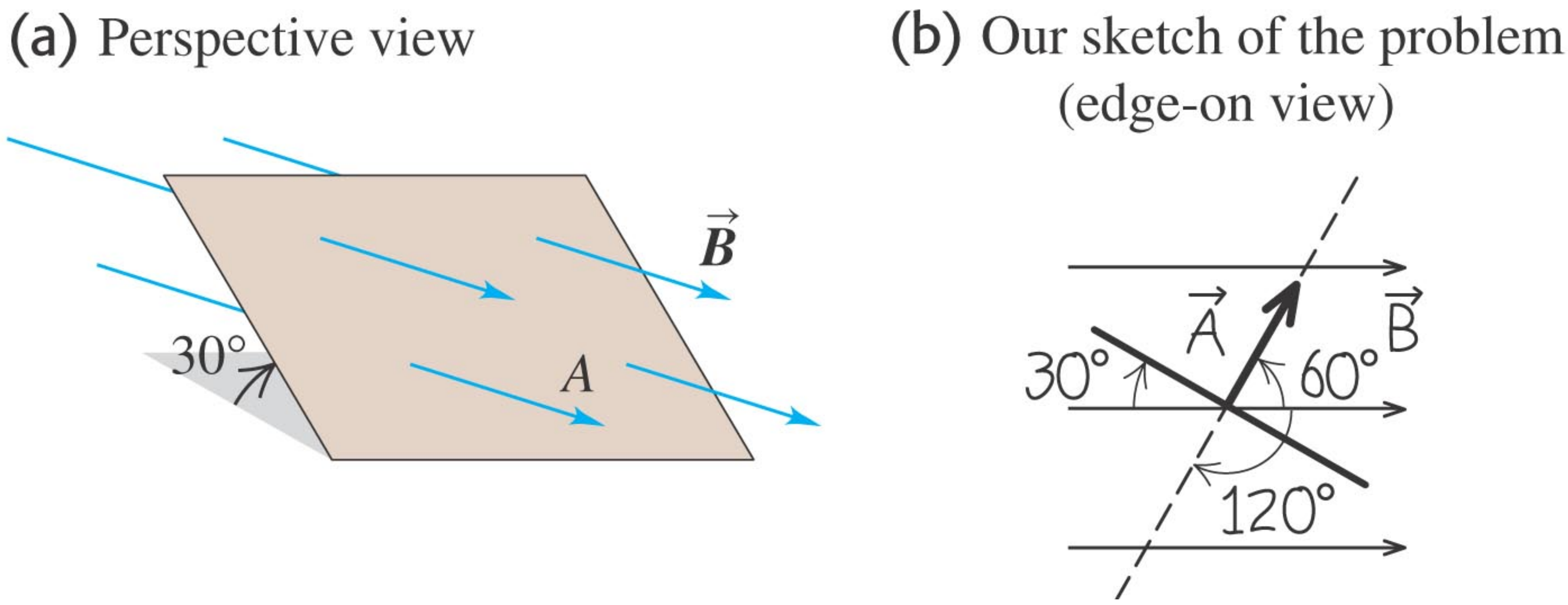
$$1\textbf{weber} = 1T \cdot 1m^2 = 1N \cdot \frac{m}{A}$$

$$1Wb = 1T \cdot m^2$$

Magnetic flux calculations

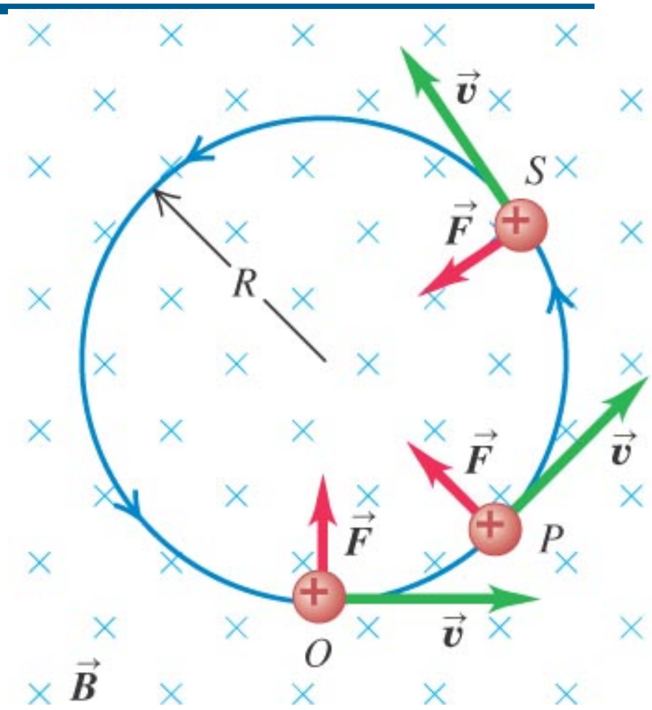
- Example 27.2: Area is $3.0 cm^2$ in a uniform B-field. Magnetic flux through the surface is 0.90mWb. Calculate the magnitude magnetic field.

- What is the direction of the area vector

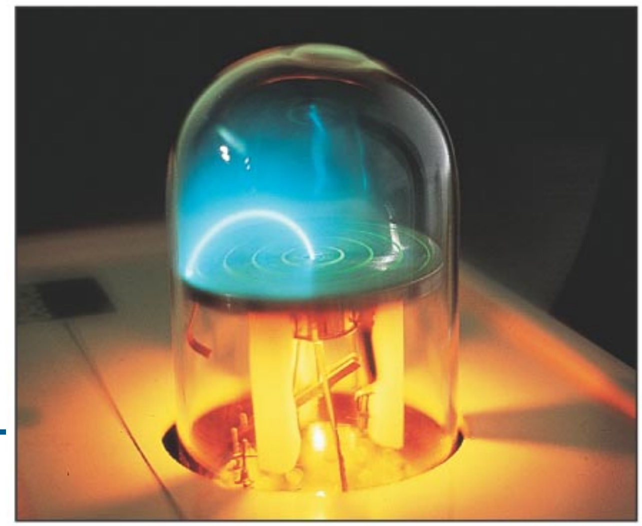


Motion of charged particles in a magnetic field

- A charged particle in a magnetic field always moves with constant speed.
- 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***.
- Why path of the electron beam glows in this picture?

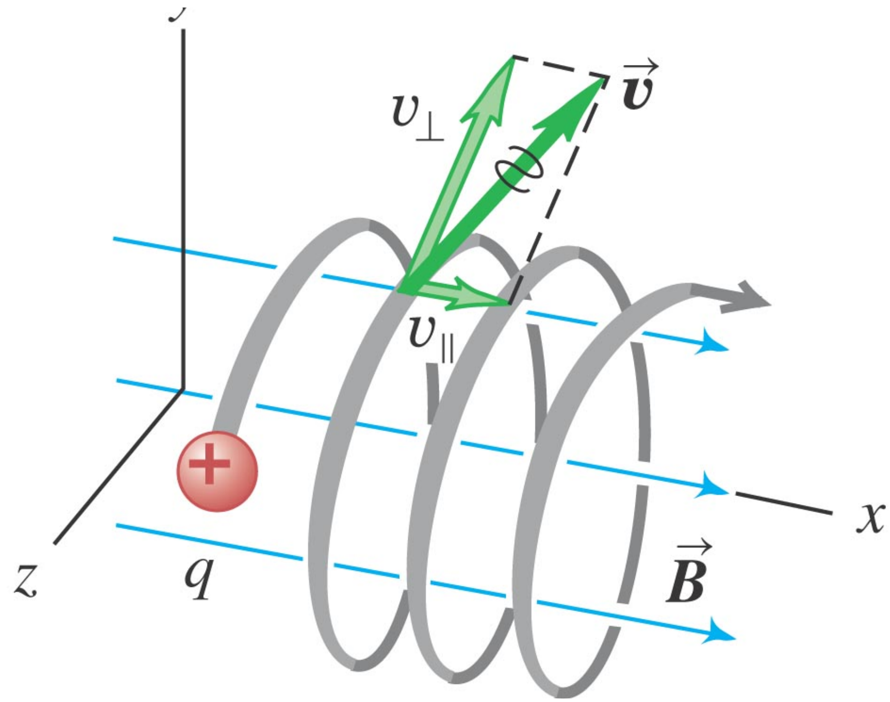


(b) An electron beam (seen as a blue arc) curving in a magnetic field



Helical motion

- If the particle has velocity components parallel to and perpendicular to the field, its path is a *helix*.
- The speed and kinetic energy of the particle remain constant.



Problem-Solving Strategy: Motion in Magnetic Fields

IDENTIFY *the relevant concepts:* In analyzing the motion of a charged particle in electric and magnetic fields, you will apply Newton's second law of motion, $\sum \vec{F} = m\vec{a}$, with the net force given by $\sum \vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$. Often other forces such as gravity can be neglected. Many of the problems are similar to the trajectory and circular-motion problems in Sections 3.3, 3.4, and 5.4; it would be a good idea to review those sections.

SET UP *the problem* using the following steps:

1. Determine the target variable(s).
2. Often the use of components is the most efficient approach. Choose a coordinate system and then express all vector quantities (including, and) in terms of their components in this system.

EXECUTE *the solution* as follows:

1. If the particle moves perpendicular to a uniform magnetic field, the trajectory is a circle with a radius and angular speed given by Eqs. (27.11) and (27.12), respectively.
2. If your calculation involves a more complex trajectory, use $\sum \vec{F} = m\vec{a}$ in component form: $\sum F_x = ma_x$, and so forth. This approach is particularly useful when both electric and magnetic fields are present.

EVALUATE *your answer:* Check whether your results are reasonable.

Magnetron inside a microwave oven

- Magnetron inside a microwave oven accelerates electrons.
- Accelerated charges emit radiation.
- 2450 MHz is the frequency of rotation of electrons that leads to 2450 MHz frequency of microwave radiation.
-

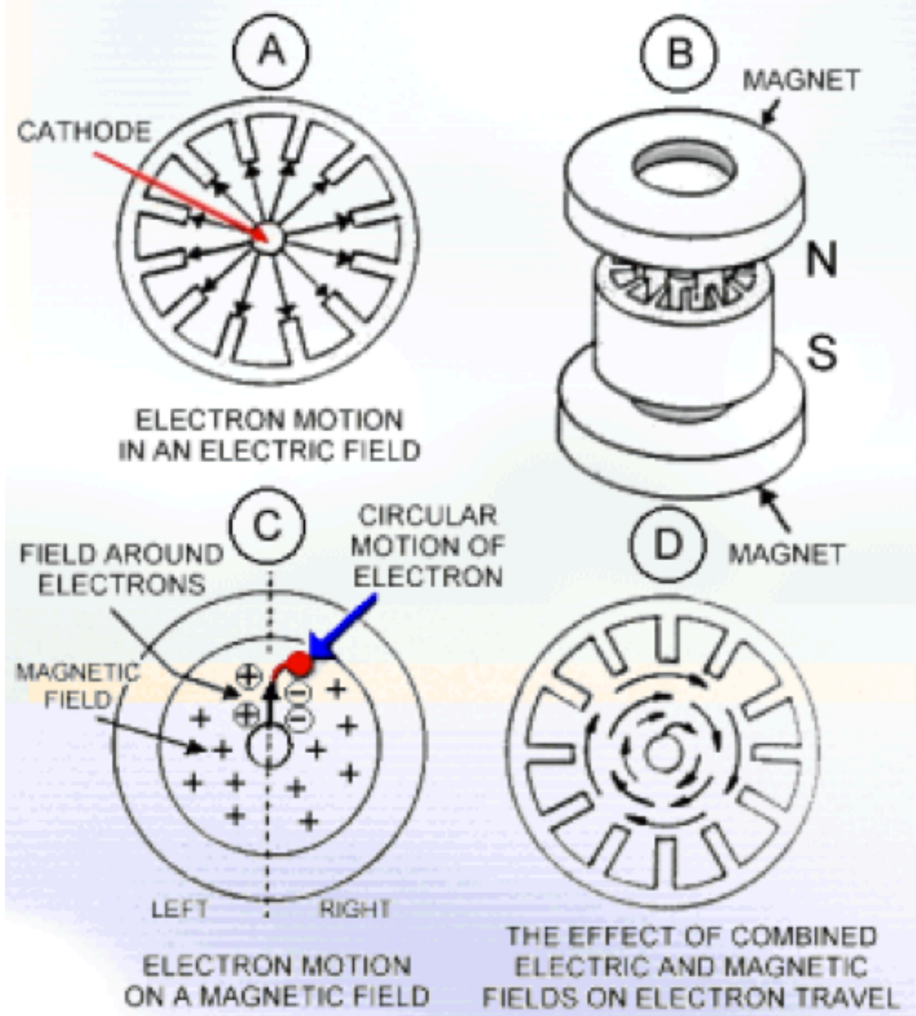


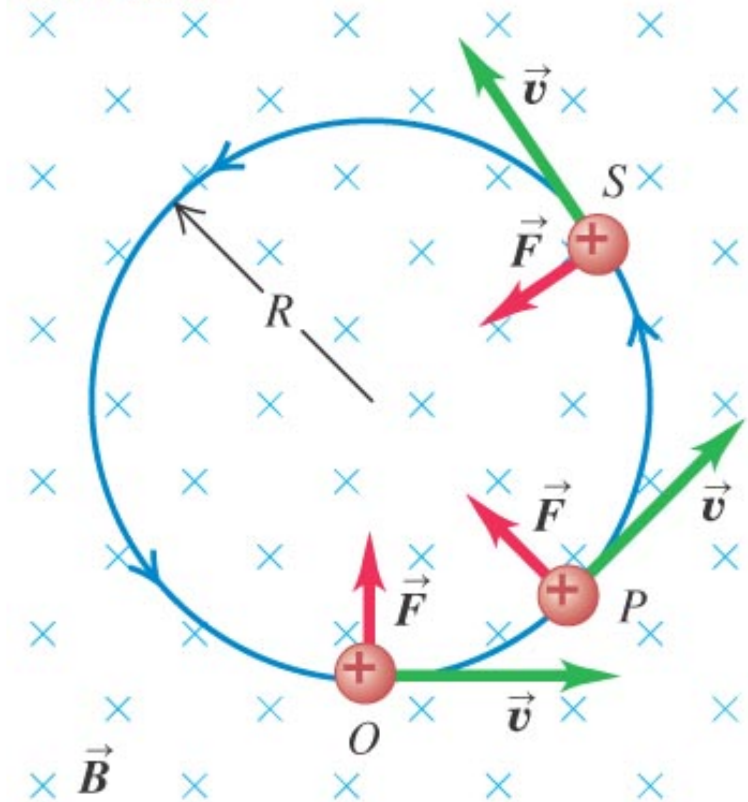
Figure 3 Electron motion in a magnetron tube (Courtesy of Michael S. Wagner)

Moving charged particle in a uniform magnetic field

- Example 27.3
  A magnetron in a microwave oven emits EM waves with frequency 2450 MHz. What magnetic field strength is required for electrons to move in a circular path with this frequency?

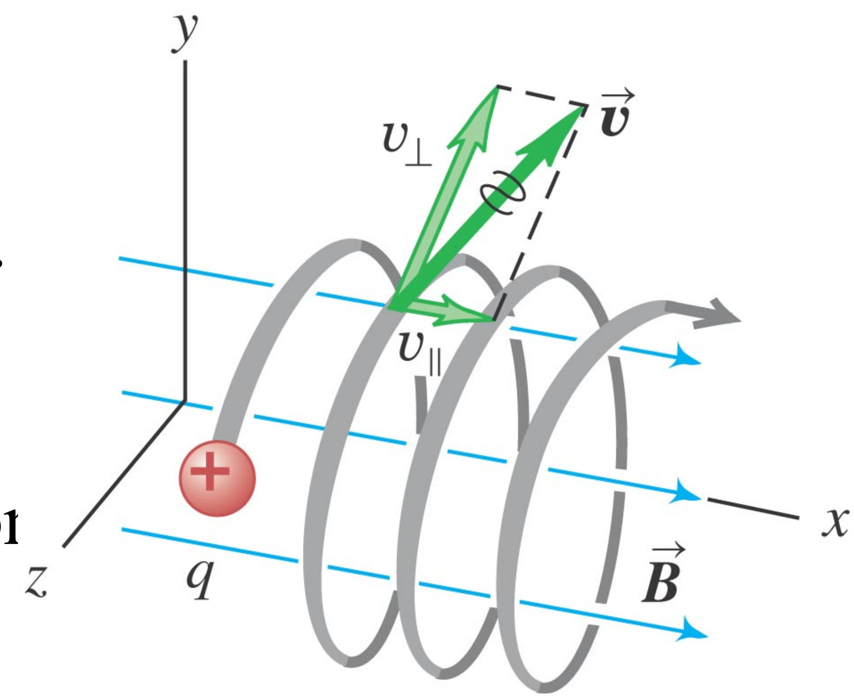
(a) The orbit of a charged particle in a uniform magnetic field

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.



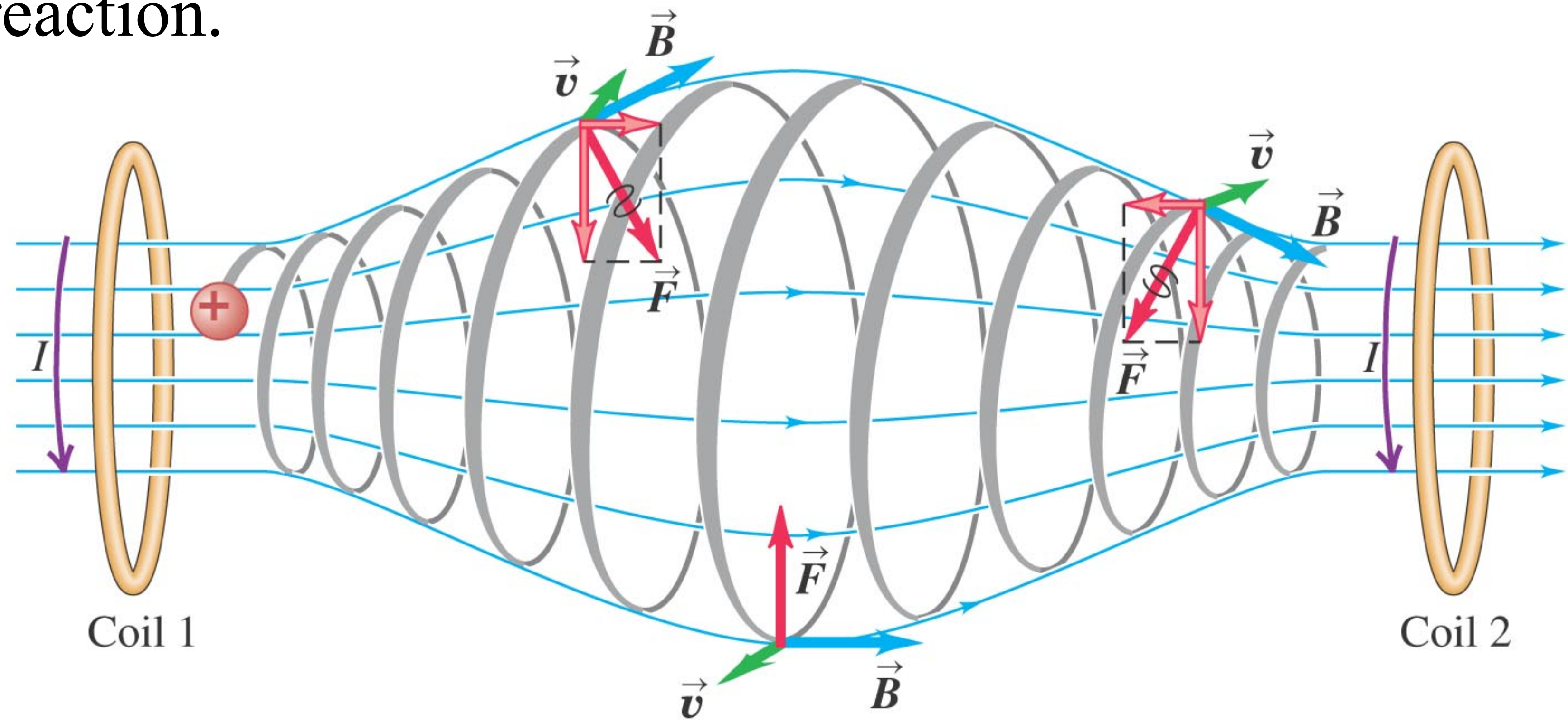
Moving charged particle in a uniform magnetic field

- Example 27.4: In this figure the charged particle is proton and the 0.500 T uniform magnetic field is along the x-axis. At t=0 the proton's velocity is (1.50E5m/s, 0m/s,2.00E5m/s). Find:
  - the force on proton
  - acceleration of the proton.
  - radius of the helical path
  - angular speed of the protoı
  - pitch of the helix



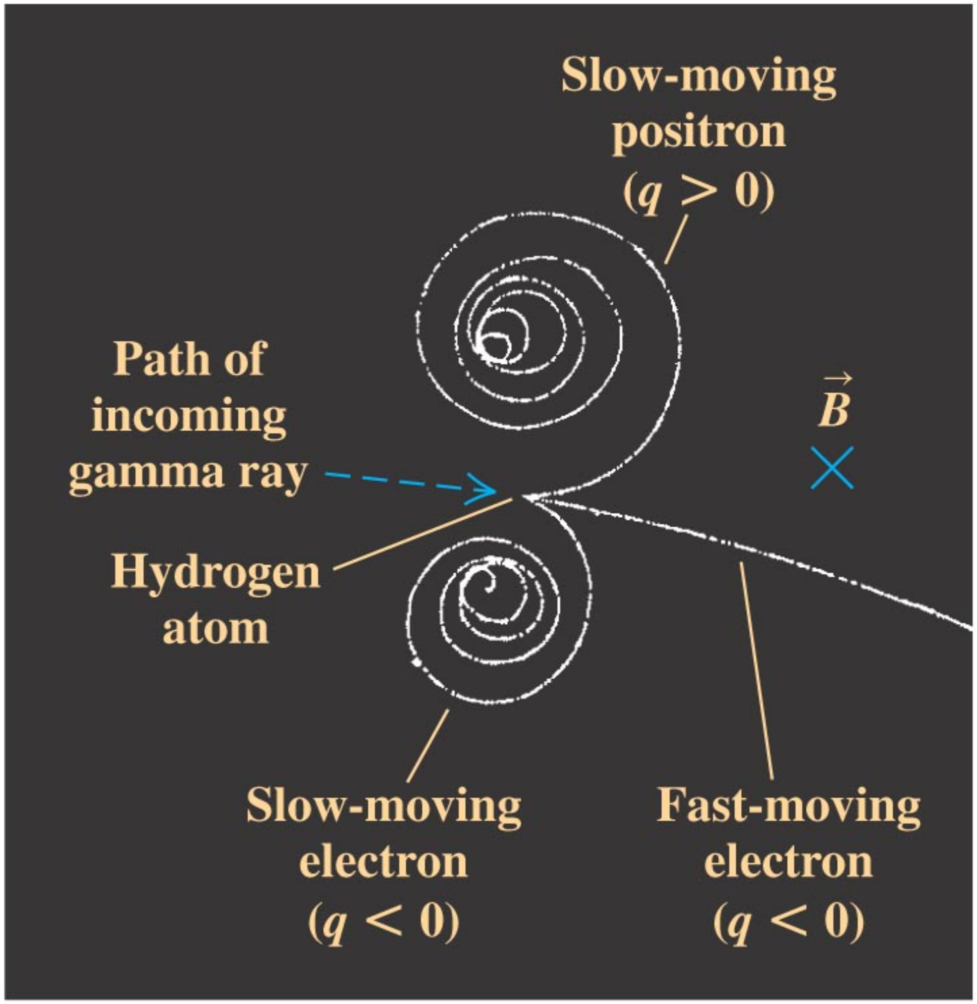
A nonuniform magnetic field

- Charges trapped in a *magnetic bottle*, which results from a non-uniform magnetic field. Used for containing ionized gas at high temperatures that any container will melt. Applications in fusion reactors that produces energy by colliding very high energy plasma and fusion reaction.



Bubble chamber (1952 by Donald A. Glaser)

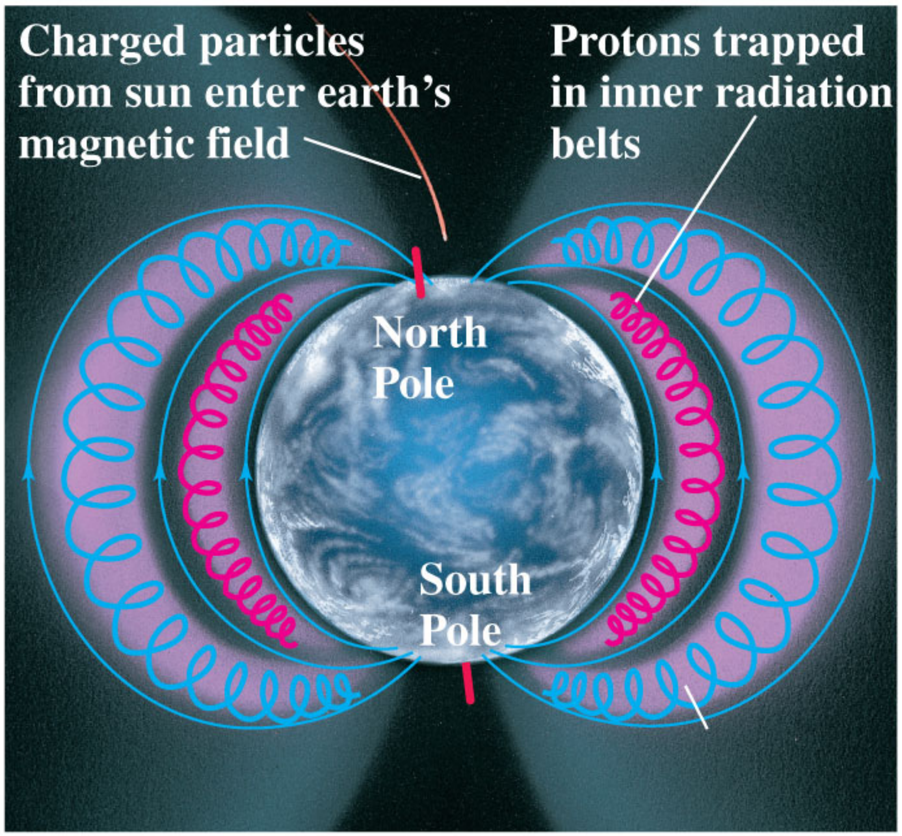
- A bubble chamber is a vessel filled with a **superheated transparent liquid** (most often **liquid hydrogen**) used to detect electrically charged particles moving through it.
- In a pair production experiment high energy gamma rays hit hydrogen atoms and the tracks of charged particles in a bubble chamber curl under influence of a magnetic field



A nonuniform magnetic field

- The Van Allen radiation belts and the resulting aurora **borealis** (north wind) and aurora ***australis*** . These belts are due to the earth's nonuniform

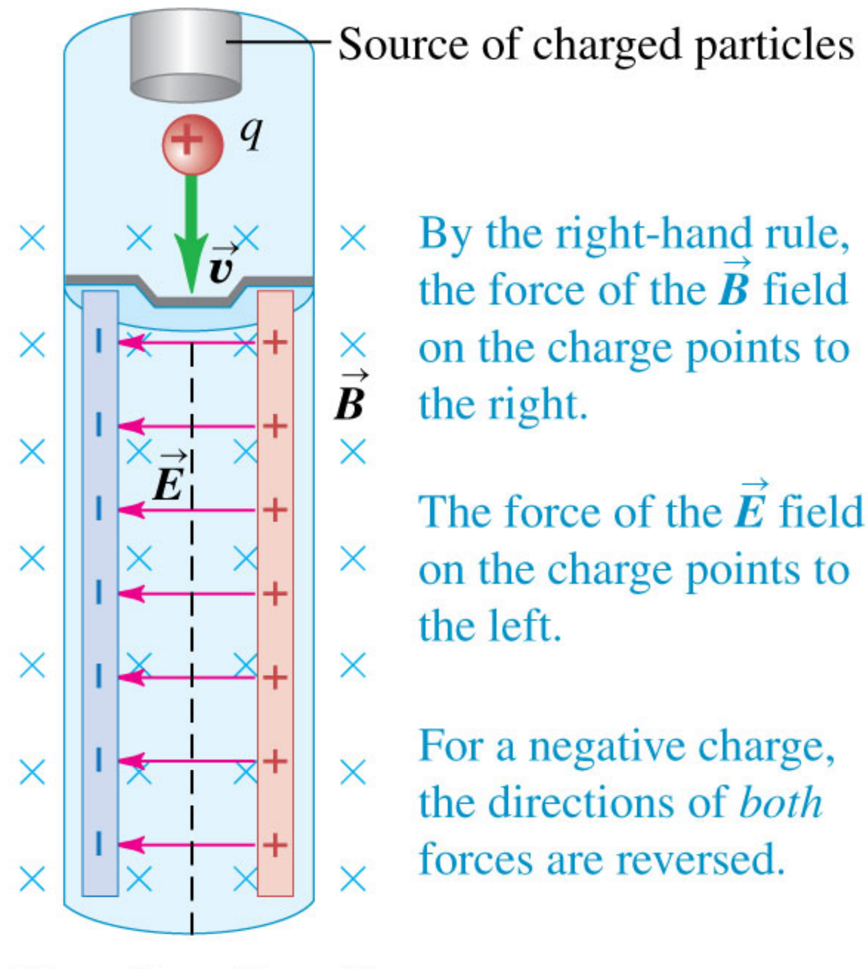
(a)

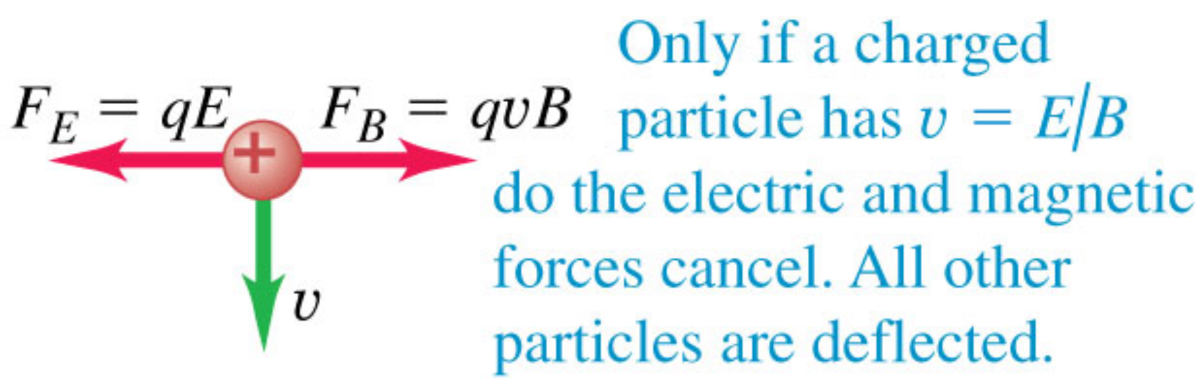


(b)

Velocity selector

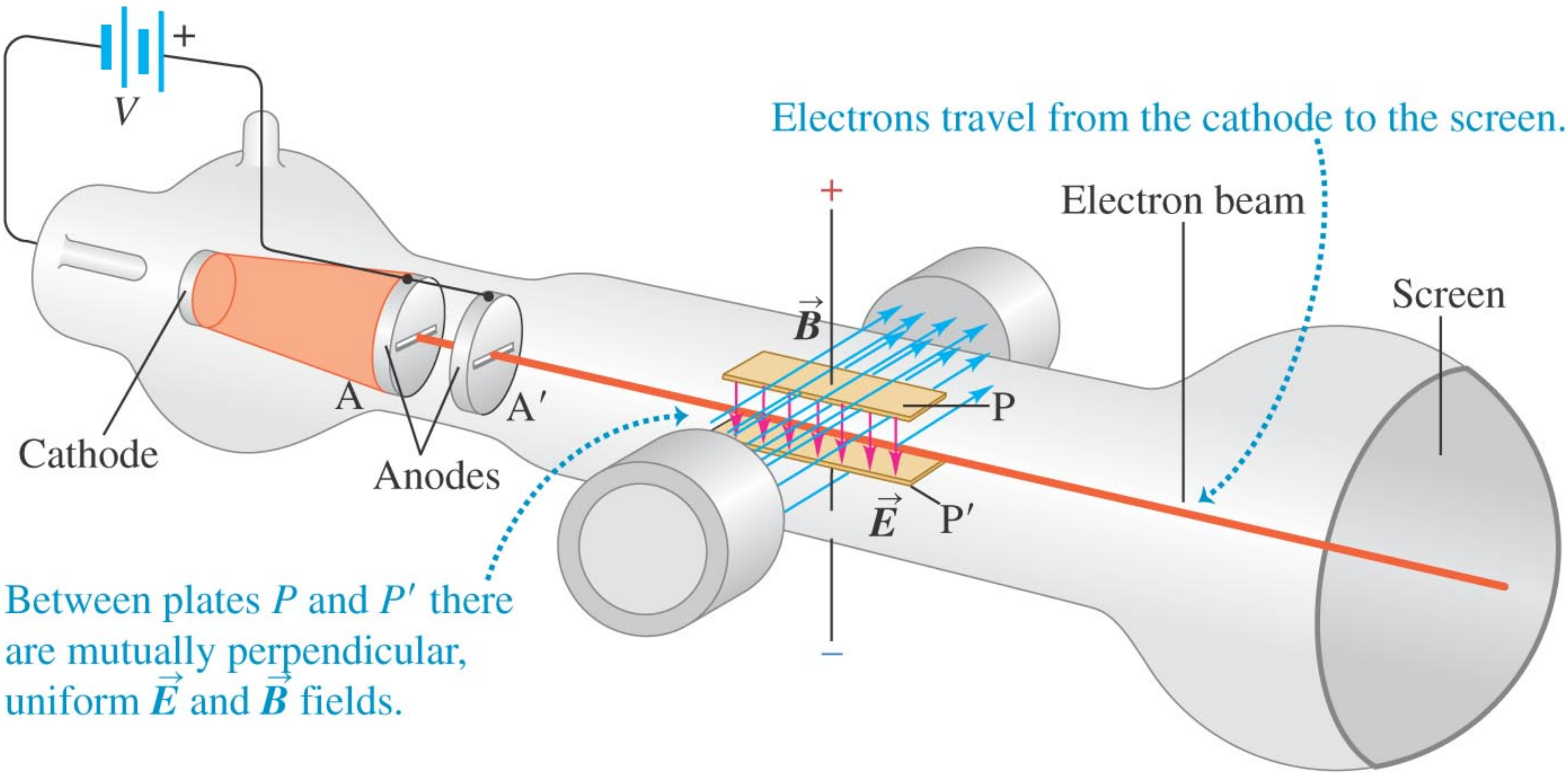
- A *velocity selector* uses **perpendicular electric and magnetic fields** to select particles of a specific speed from a beam.
- What is the velocity of the undeflected particles?





Thomson's *e/m* experiment

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



An e/m experiment

- 27.5 In a Thomson experiment the accelerating potential is 150 V and a deflecting electric field is 6.0E6N/C

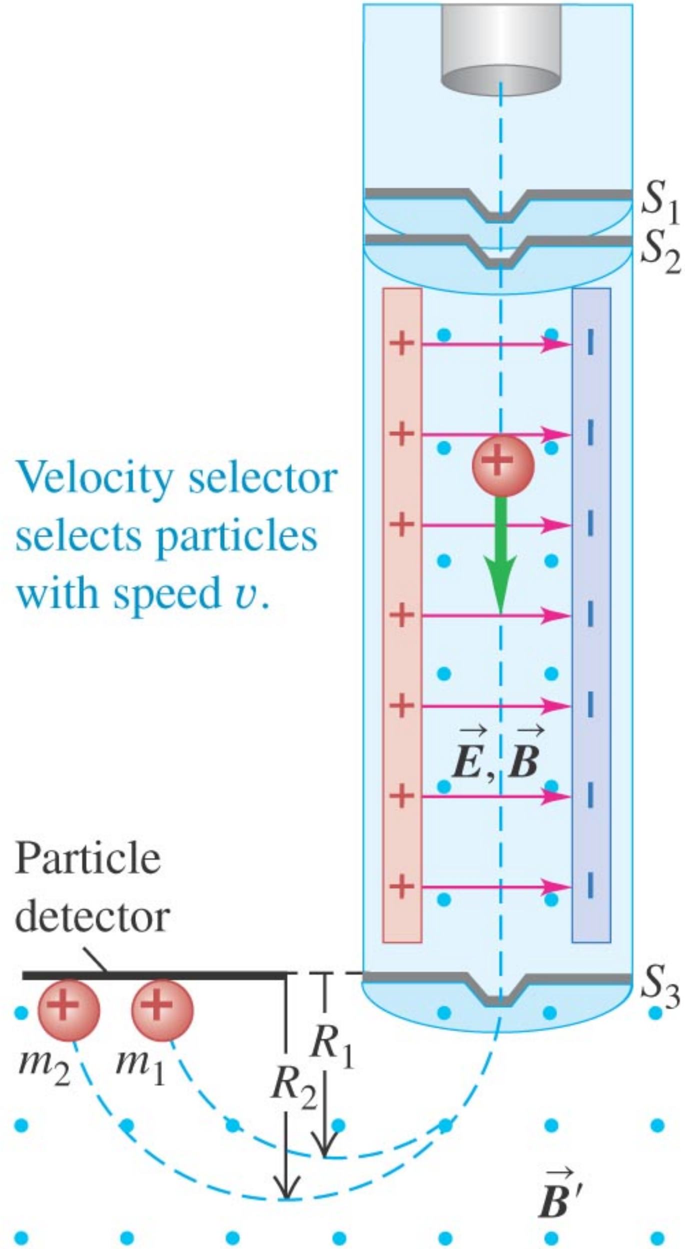
a) At what fraction of speed of light do the electrons move?

b) What magnitude of the magnetic field you would need?

c) With this magnetic field what will happen to the electron beam if you increase the accelerating potential above 150 V?

Mass spectrometer

- A *mass spectrometer* measures the masses of ions.
- The Bainbridge mass spectrometer first uses a velocity selector. Then the magnetic field separates the particles by mass.



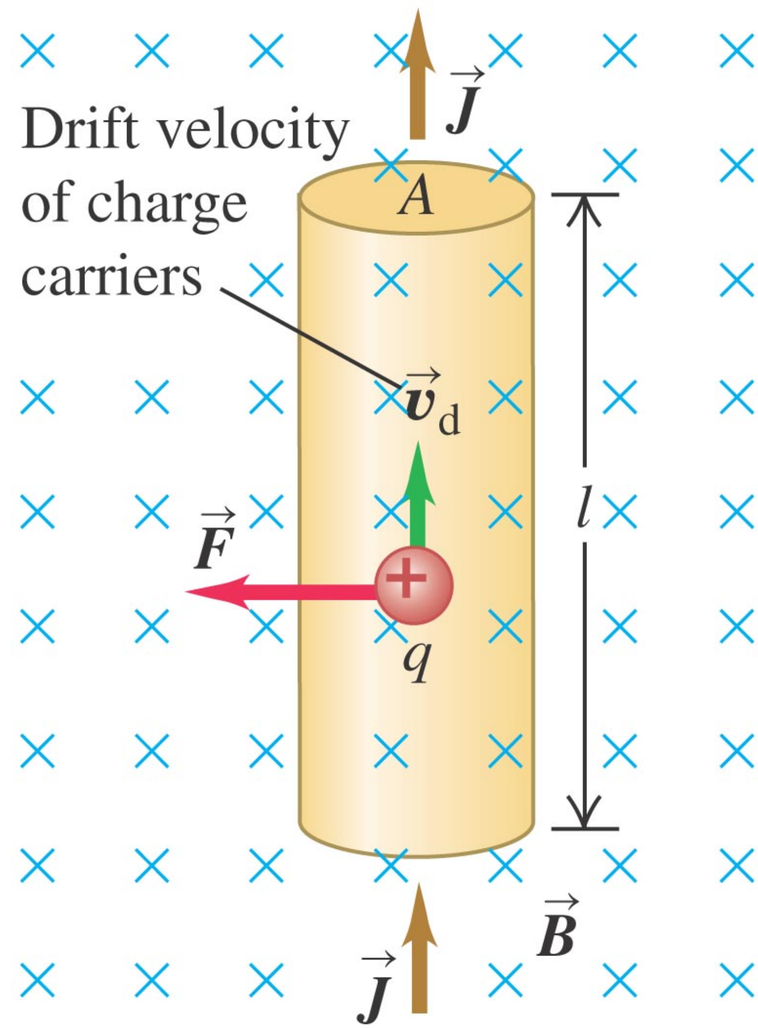
Magnetic field separates particles by mass; the greater a particle's mass, the larger is the radius of its path.

The magnetic force on a current-carrying conductor

- Figure shows the magnetic force on a moving positive charge in a conductor.

$$\mathbf{F} = I\,\mathbf{l} \times \mathbf{B}$$

$$d\mathbf{F} = I d\mathbf{l} \times \mathbf{B}$$

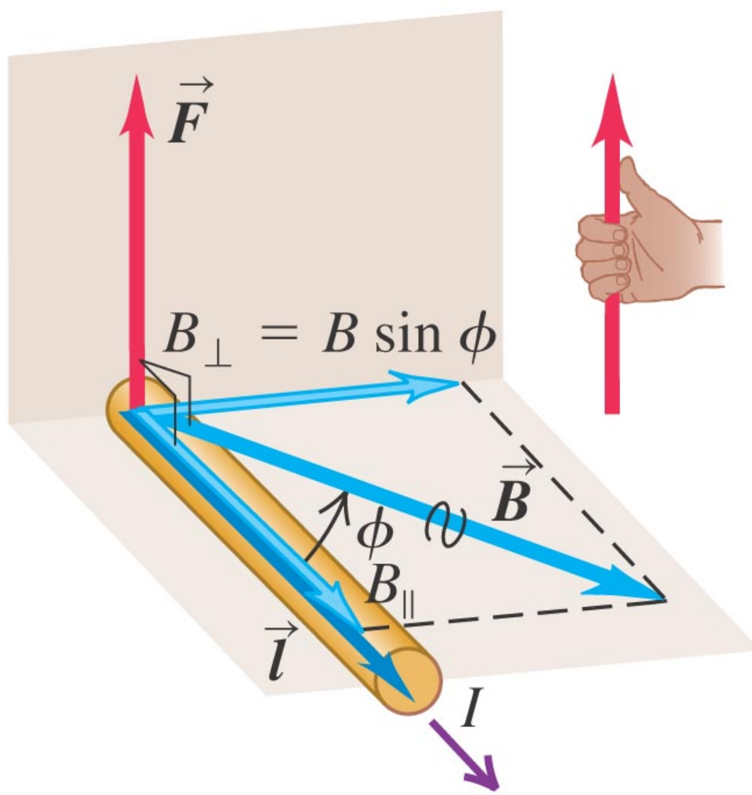


The magnetic force on a current-carrying conductor

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

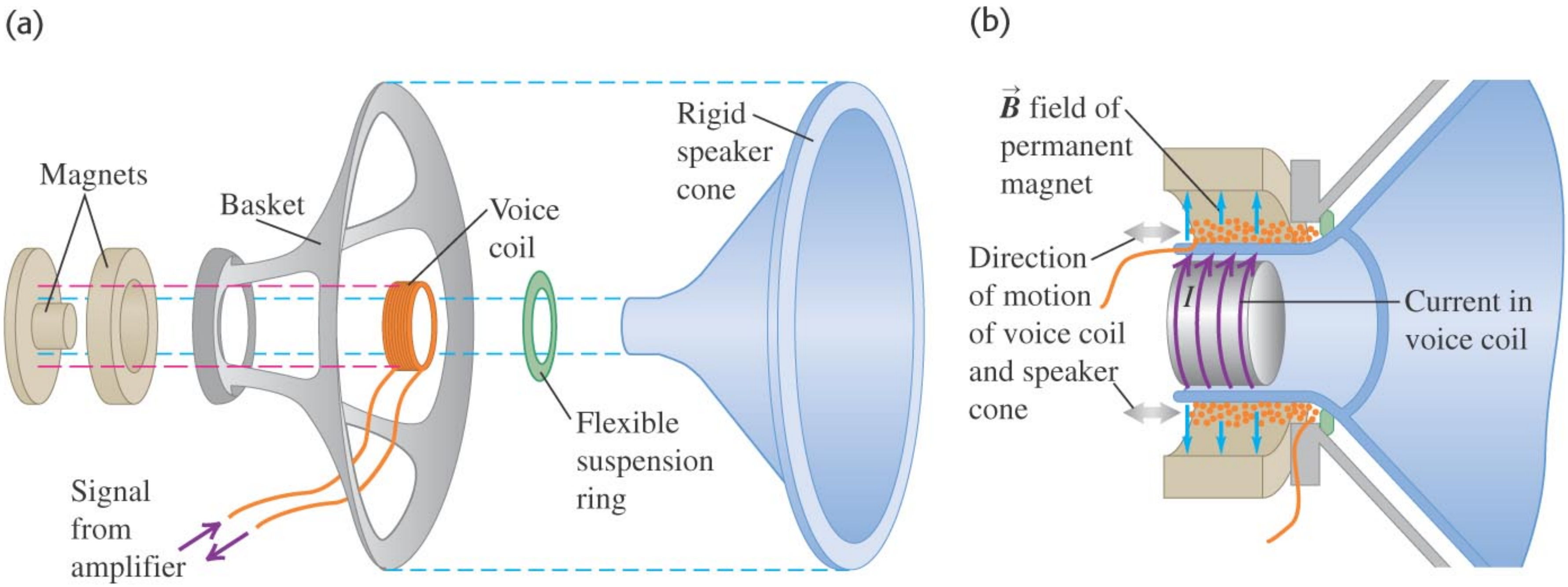
- Magnitude is $F = IlB_{\perp} = IlB \sin \phi$.
- Direction of $\vec{F}$ is given by the right-hand rule.

- force is perpendicular to the wire segment and the magnetic field.



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 levitation

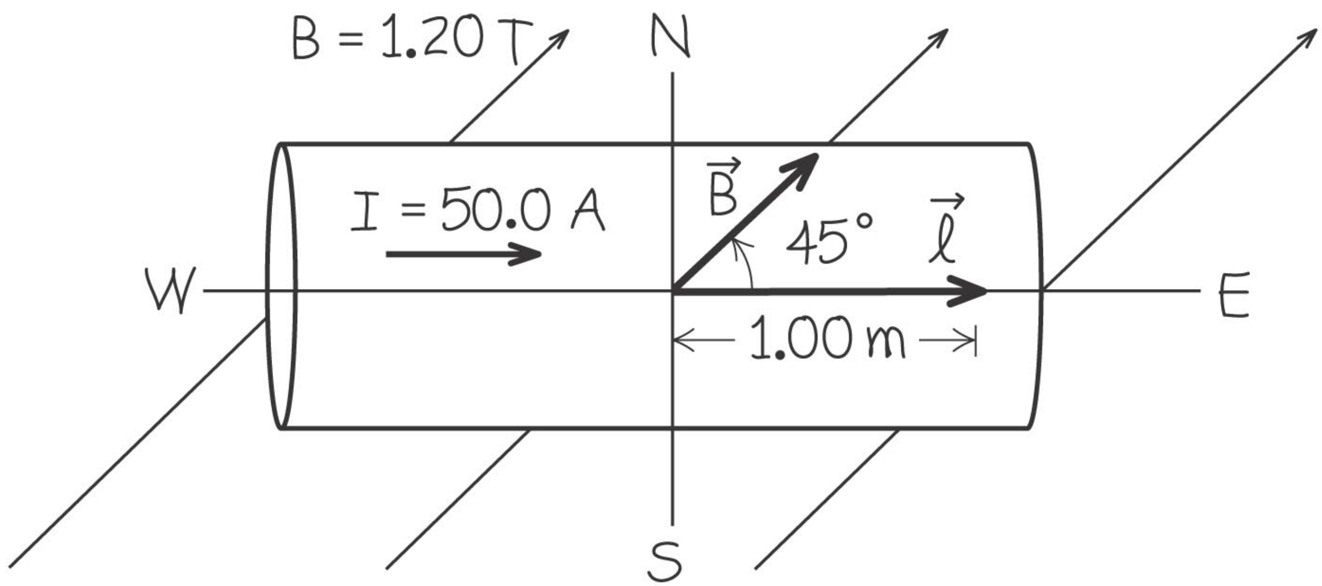
What is the direction of the magnetic field if we want to levitate a current carrying rod horizontally? Current is flowing from right to left.

Magnetic force on a straight conductor

- Example 27.7 A straight horizontal copper rod carries a current of 50.0A between poles of a large magnet 1.20T as shown.

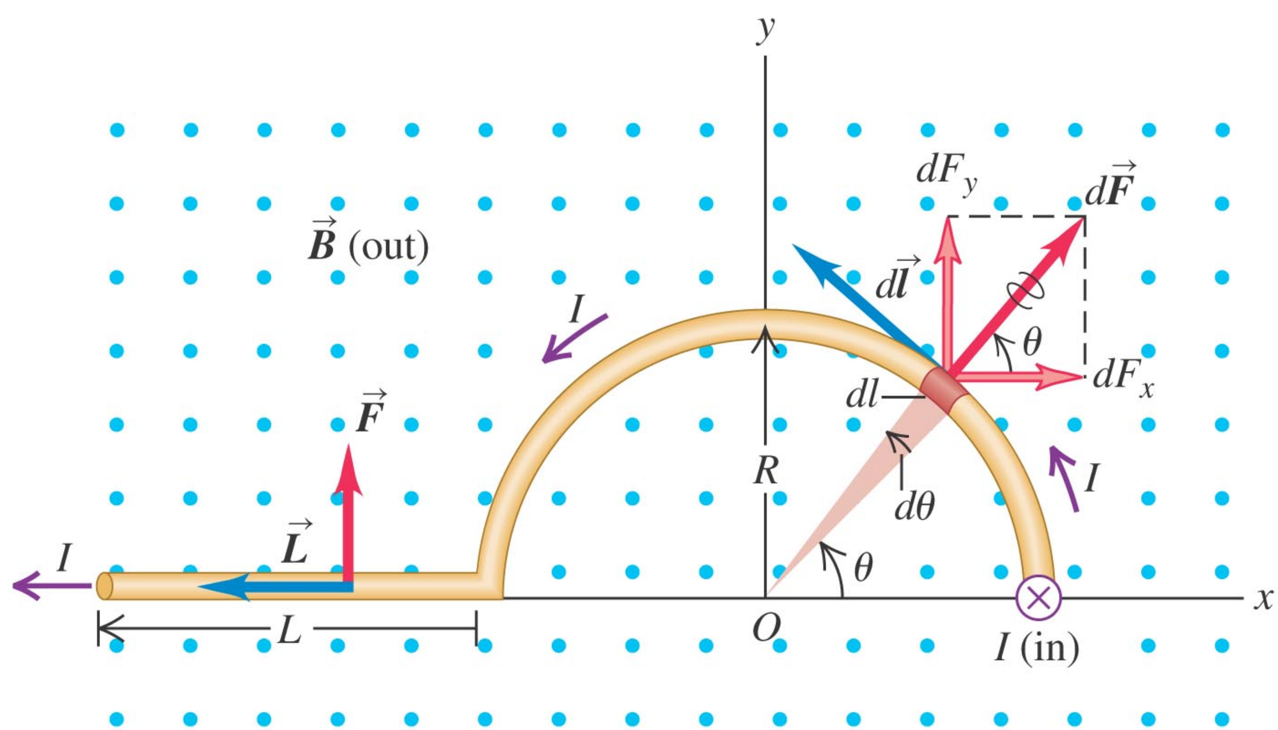
  a) Find the magnitude and direction of the force on a one meter section of the rod.

  b) While keeping the rod horizontal how should it be oriented to maximize the magnitude of the force? What is the force magnitude in this case.



Magnetic force on a curved conductor

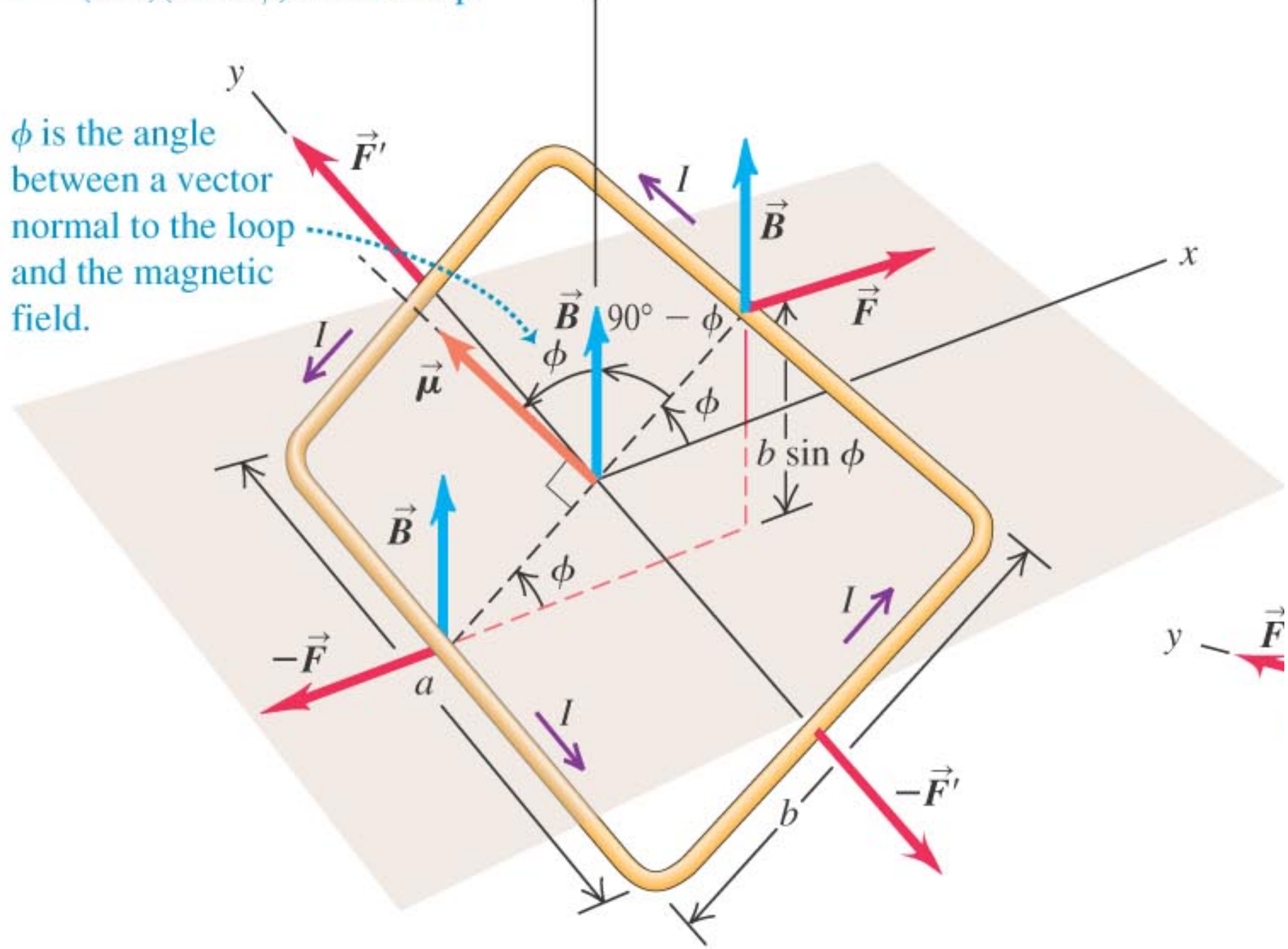
Example 27.8 The B-field is uniform as shown. The wire has a segment sticking out of the plane with current direction into the page and the curved part and straight part again. Find the total magnetic force on these segments of wire.



Force and torque on a current loop

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

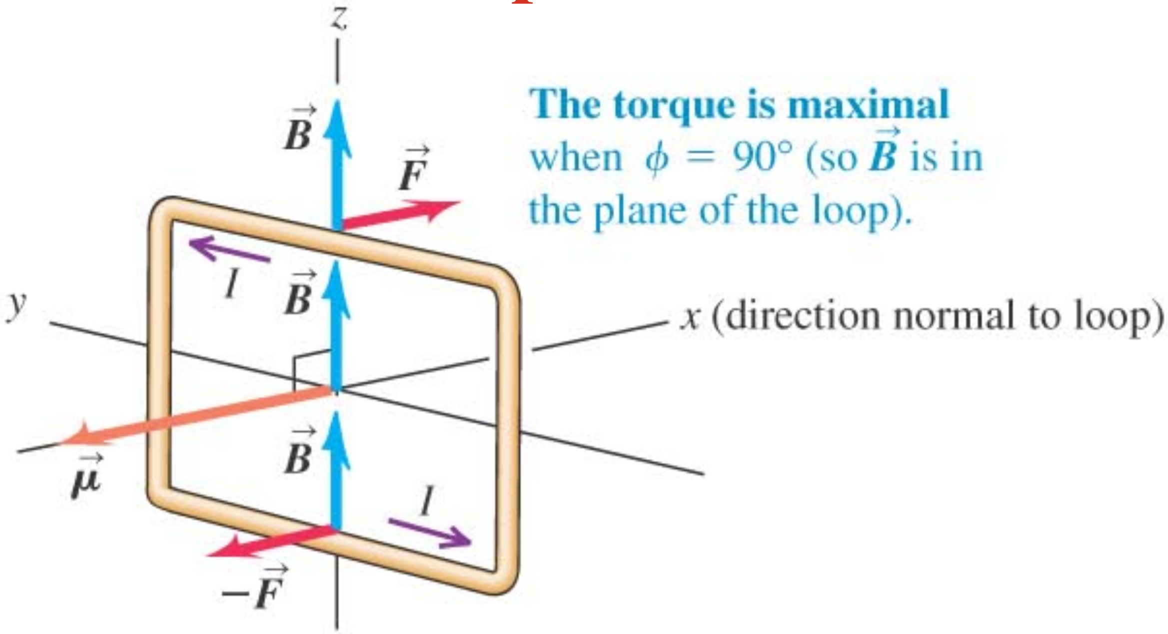
However, the forces on the *a* sides of the loop ($\vec{F}$ and $-\vec{F}$) produce a torque $\tau = (IBa)(b \sin \phi)$ on the loop.



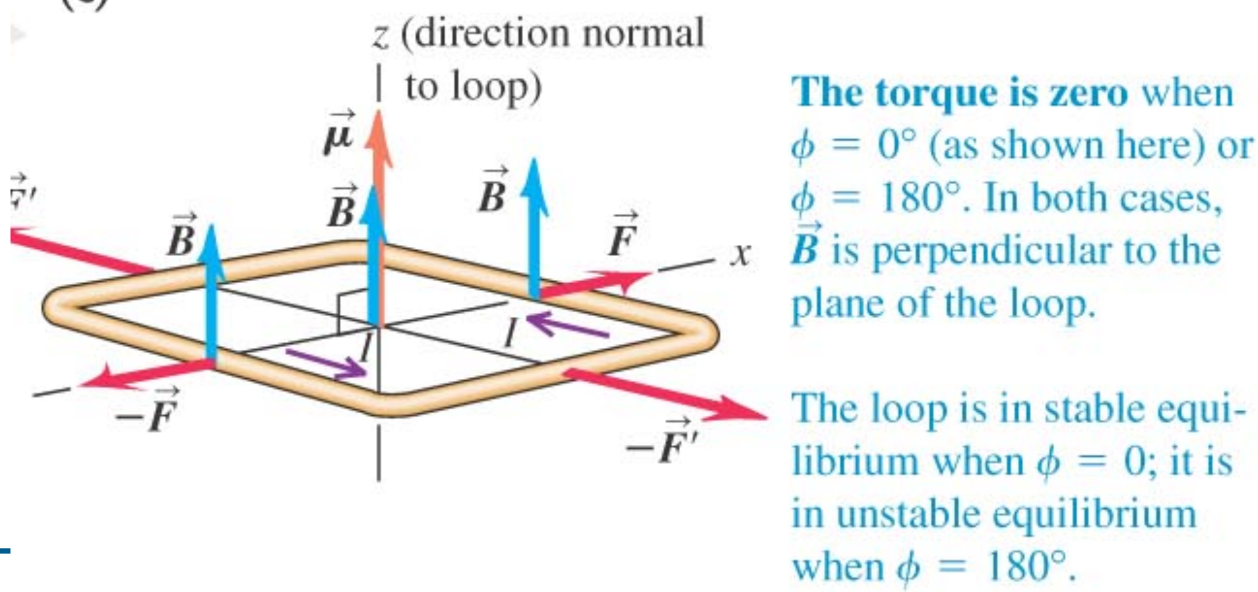
Force and torque on a current loop

- 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.

(b)

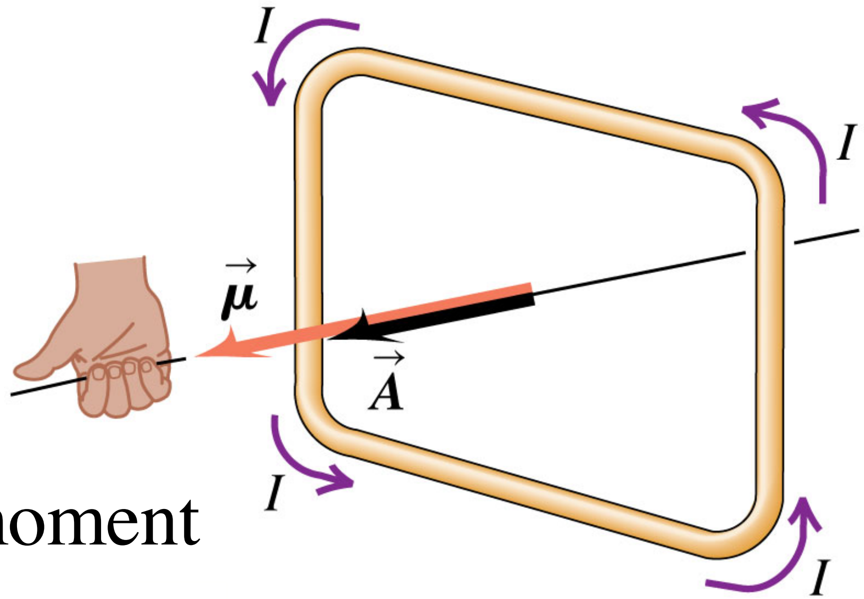


(c)



Magnetic moment

- The right-hand rule to determine the direction of the magnetic moment of a current loop.



$\vec{\mu} = I\vec{A}$ magnetic dipole moment

Torque on a current loop or magnetic dipole

$$\tau = \mu B \sin\phi$$

$$\vec{\tau} = \vec{\mu} \times \mathbf{B}$$

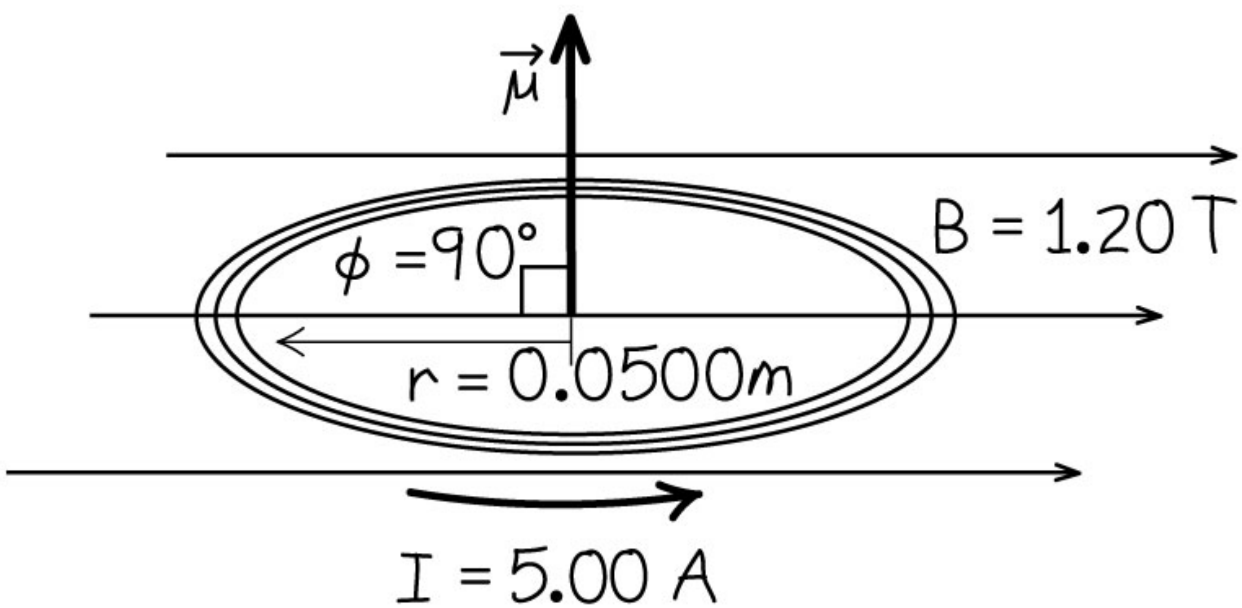
Potential energy for a magnetic dipole

$$U = -\vec{\mu} \bullet B = -\mu B \cos\phi$$

Magnetic torque and potential energy of a coil

- Example 27.9 circular coil of 0.0500 m radius with 30 turns in a horizontal plane. It carries a current of 5.00 A in a counterclockwise viewed from above located in a uniform magnetic field of 1.20T to the right. Find the magnetic moment and torque.

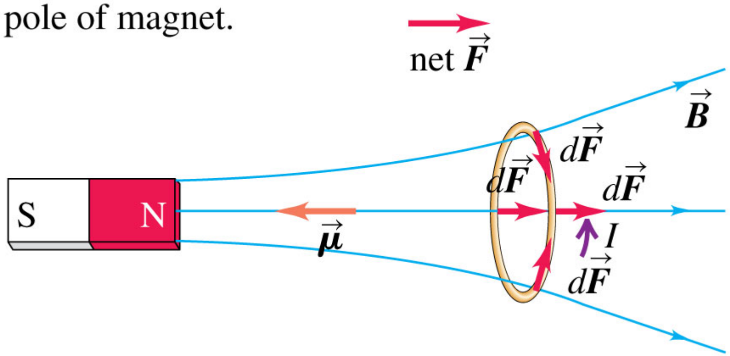
- 27.10 If the coil rotates from its original position to a position where the magnetic moment is parallel to B what is the change in potential energy?



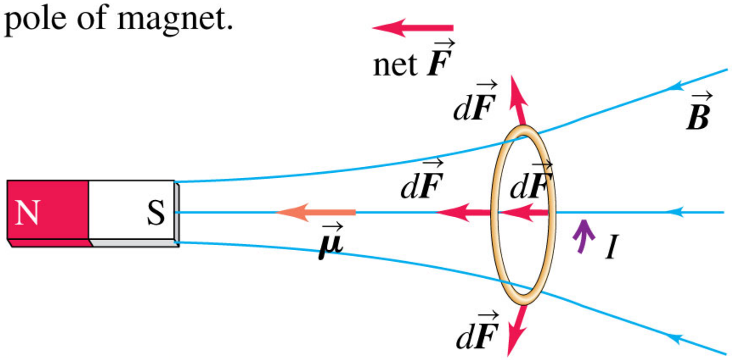
How magnets work

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

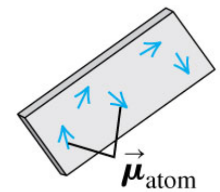
(a) Net force on this coil is away from north pole of magnet.



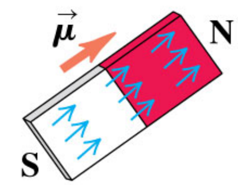
(b) Net force on same coil is toward south pole of magnet.



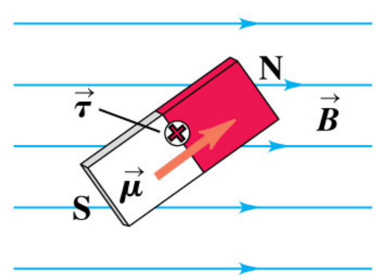
(a) Unmagnetized iron: magnetic moments are oriented randomly.



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

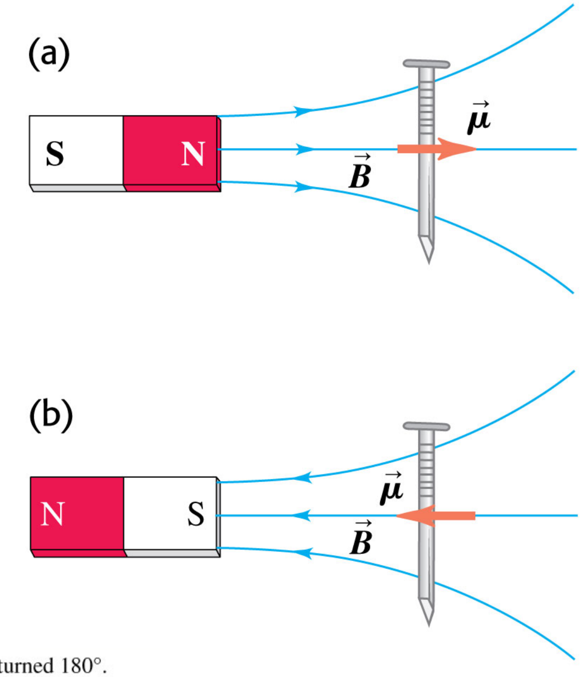


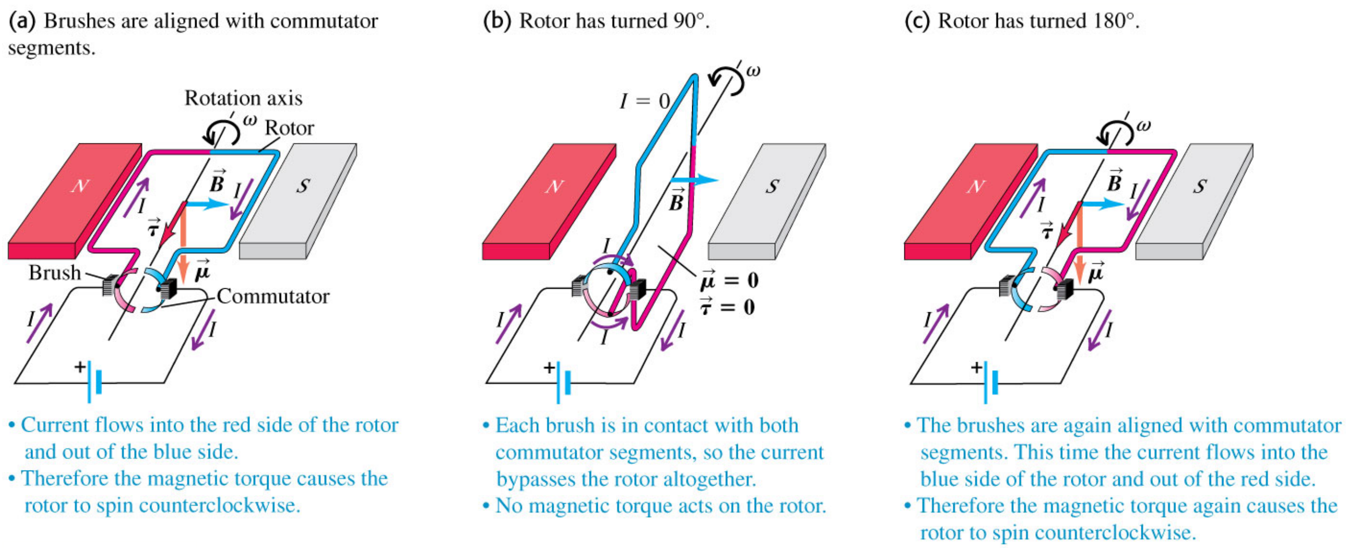
(c) A magnetic field creates a torque on the bar magnet that tends to align its dipole moment with the $\vec{B}$ field.



The direct-current motor

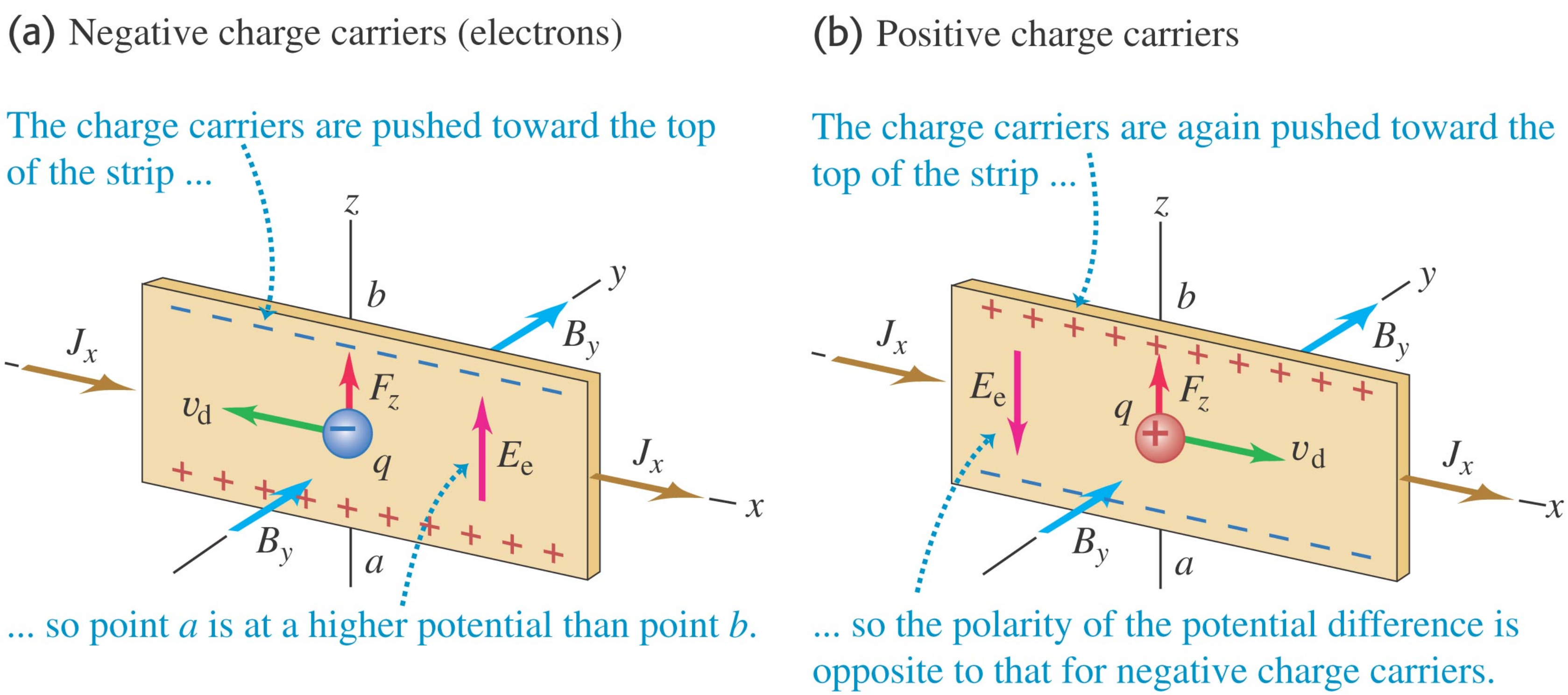
- Follow the discussion in the text of the direct-current motor. Use Figures 27.38 (right) and 27.39 (below).
- Follow Example 27.11.





The Hall Effect

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



Q27.1

A beam of electrons (which have negative charge *q*) is coming straight toward you. You put the north pole of a magnet directly above the beam. The magnetic field $\vec{B}$ from the magnet points straight down. Which way will the electron beam deflect?

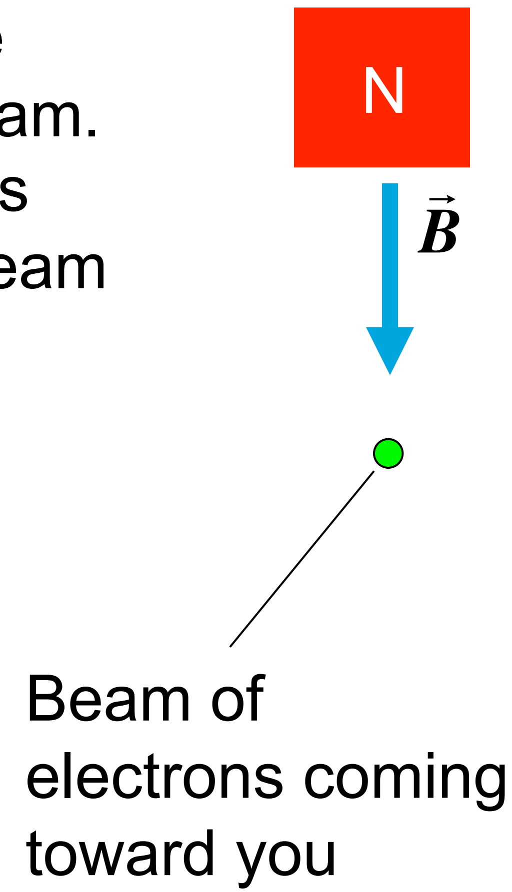
A. upward

B. downward

C. to the left

D. to the right

E. It won't deflect at all.



Q27.2

When a charged particle moves through a magnetic field, the direction of the magnetic force on the particle at a certain point is

A. in the direction of the magnetic field at that point.

B. opposite to the direction of the magnetic field at that point.

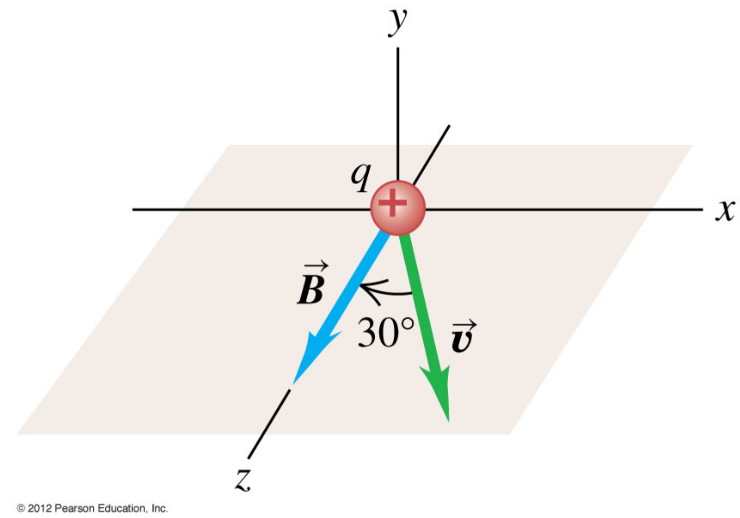
C. perpendicular to the magnetic field at that point.

D. none of the above

E. The answer depends on the sign of the particle's electric charge.

Q27.3

A particle with a positive charge moves in the *xz*-plane as shown. The magnetic field is in the positive *z*-direction. The magnetic force on the particle is in



A. the positive *x*-direction.

B. the negative *x*-direction.

C. the positive *y*-direction.

D. the negative *y*-direction.

E. none of these

Q27.4

A particle with charge *q* = –1 C is moving in the positive *z*-direction at 5 m/s. The magnetic field at its position is

$$\vec{B} = \left(3\hat{i} - 4\hat{j}\right)\ \mathrm{T}$$

What is the magnetic force on the particle?

A. $\left(20\hat{i} + 15\hat{j}\right)\ \mathrm{N}$

B. $\left(20\hat{i} - 15\hat{j}\right)\ \mathrm{N}$

C. $\left(-20\hat{i} + 15\hat{j}\right)\ \mathrm{N}$

D. $\left(-20\hat{i} - 15\hat{j}\right)\ \mathrm{N}$

E. none of these

Q27.5

A positively charged particle moves in the positive *z*-direction. The magnetic force on the particle is in the positive *y*-direction. What can you conclude about the *x*-component of the magnetic field at the particle's position?

A. $B_x > 0$

B. $B_x = 0$

C. $B_x < 0$

D. not enough information given to decide

Q27.6

A positively charged particle moves in the positive *z*-direction. The magnetic force on the particle is in the positive *y*-direction. What can you conclude about the *y*-component of the magnetic field at the particle's position?

A. $B_y > 0$

B. $B_y = 0$

C. $B_y < 0$

D. not enough information given to decide

Q27.7

A positively charged particle moves in the positive *z*-direction. The magnetic force on the particle is in the positive *y*-direction. What can you conclude about the *z*-component of the magnetic field at the particle's position?

A. $B_z > 0$

B. $B_z = 0$

C. $B_z < 0$

D. not enough information given to decide

Q27.8

Under what circumstances is the total magnetic flux through a closed surface *positive?*

A. if the surface encloses the north pole of a magnet, but not the south pole

B. if the surface encloses the south pole of a magnet, but not the north pole

C. if the surface encloses both the north and south poles of a magnet

D. none of the above

Q27.9

When a charged particle moves through a magnetic field, the trajectory of the particle at a given point is

A. parallel to the magnetic field line that passes through that point.

B. perpendicular to the magnetic field line that passes through that point.

C. neither parallel nor perpendicular to the magnetic field line that passes through that point.

D. any of the above, depending on circumstances.

Q27.10

A charged particle moves through a region of space that has both a uniform electric field and a uniform magnetic field. In order for the particle to move through this region at a constant velocity,

A. the electric and magnetic fields must point in the same direction.

B. the electric and magnetic fields must point in opposite directions.

C. the electric and magnetic fields must point in perpendicular directions.

D. The answer depends on the sign of the particle's electric charge.

Q27.11

A circular loop of wire carries a constant current. If the loop is placed in a region of uniform magnetic field, the *net magnetic force* on the loop is

A. perpendicular to the plane of the loop, in a direction given by a right-hand rule.

B. perpendicular to the plane of the loop, in a direction given by a left-hand rule.

C. in the same plane as the loop.

D. zero.

E. The answer depends on the magnitude and direction of the current and on the magnitude and direction of the magnetic field.

Q27.12

A circular loop of wire carries a constant current. If the loop is placed in a region of uniform magnetic field, the *net magnetic torque* on the loop

A. tends to orient the loop so that its plane is perpendicular to the direction of the magnetic field.

B. tends to orient the loop so that its plane is edge-on to the direction of the magnetic field.

C. tends to make the loop rotate around its axis.

D. is zero.

E. The answer depends on the magnitude and direction of the current and on the magnitude and direction of the magnetic field.