Chapter 29

<u>Magnetic Fields</u>

Outline

- 29.1 Magnetic Fields and Forces
- 29.2 Magnetic Force Acting on a Current-Carrying Conductor
- 29.4 Motion of a Charged Particle in a Uniform Magnetic Field
- 29.5 Applications Involving Charged Particles Moving in a Magnetic Field

Introduction

- **In this chapter, we show how to use the law of Biot and Savart to *calculate the magnetic field produced at some point* in space by a small current element**

History of Magnetism

- 1819
  - Hans Christian Oersted
    - Discovered the relationship between electricity and magnetism
    - An electric current in a wire deflected a nearby compass needle

Magnetic Poles

- Every magnet has two poles (North and South)
- Poles exert forces on one another (like electric charges)
- Like poles repel each other (N-N or S-S)
- Unlike poles attract each other (N-S)

Magnetic Poles, cont.

- 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

29.1 Magnetic Fields and Forces

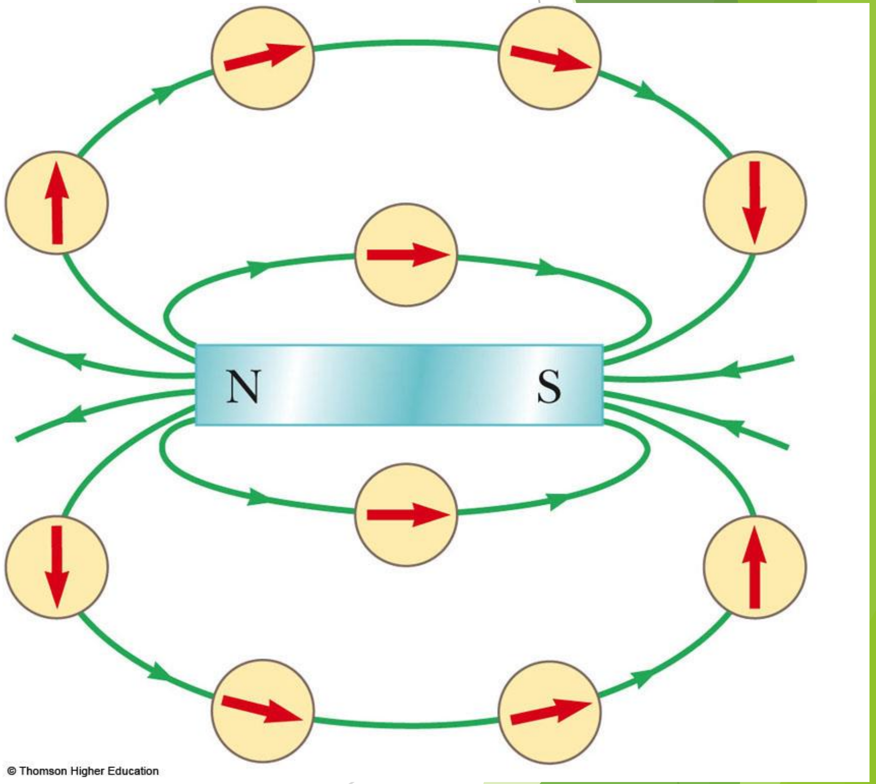
- An electric field surrounds any electric charge
- The region of space surrounding any *moving* electric charge also contains a magnetic field
- A magnetic field also surrounds a magnetic substance making up a permanent magnet

29.1 Magnetic Fields and forces, cont.

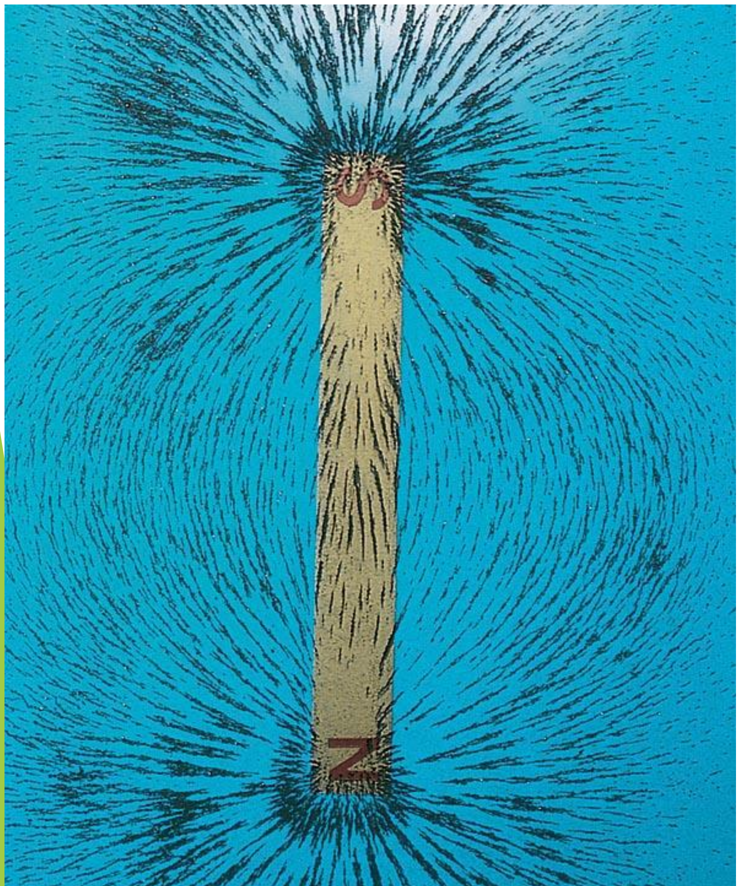
- A vector quantity
- Symbolized by $\vec{\mathbf{B}}$
- Direction is given by the direction a north pole of a compass needle points in that location

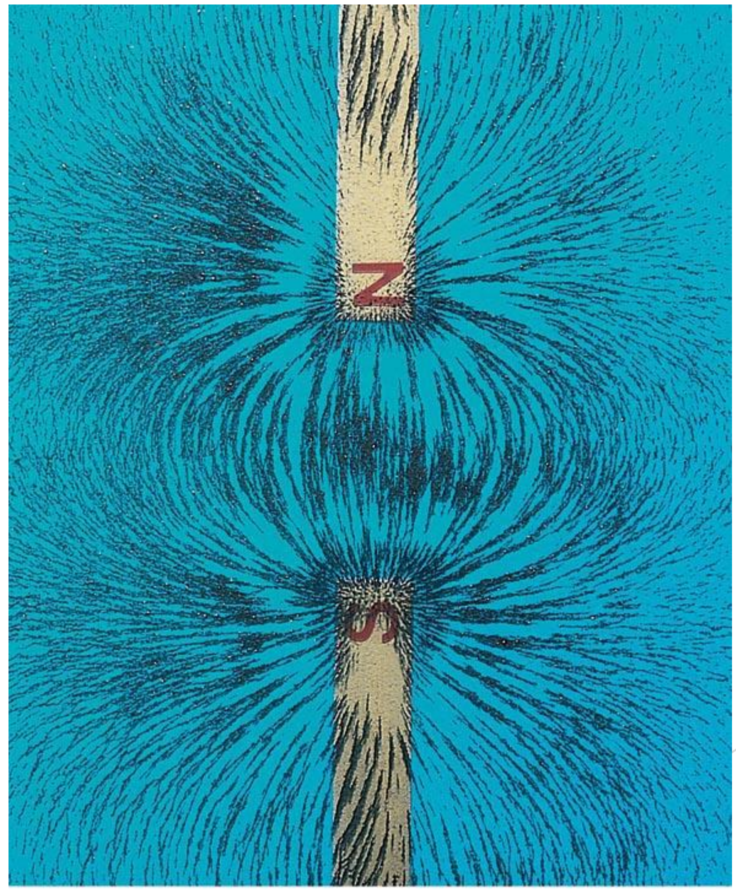
Magnetic Field Lines

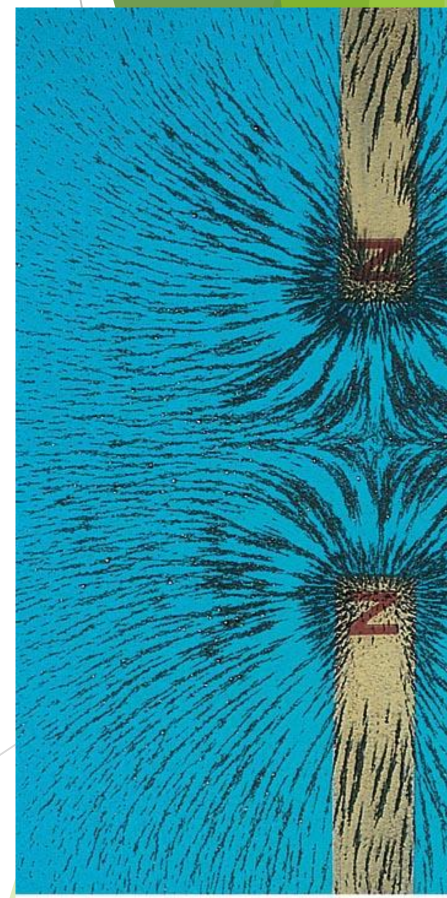
- The compass can be used to trace the field lines
- The lines outside the magnet point from the North pole to the South pole



Magnetic field pattern surrounding a bar magnet as displayed with iron filings







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, $\vec{\mathbf{v}}$

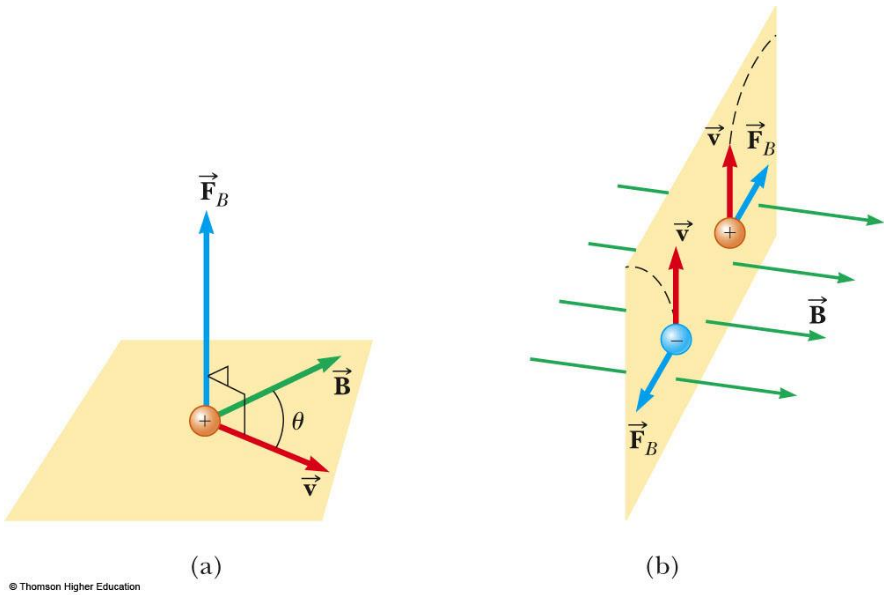
Properties of the magnetic force on a charge moving in a magnetic field B

- 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
- The magnitude and direction of F_B depend on the ***velocity of the particle*** and on ***the magnitude and direction of the magnetic field B***
- 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 both the velocity and the field

Properties of the magnetic force on a charge moving in a magnetic field B

- 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

Direction



- $\vec{\mathbf{F}}_B$ is perpendicular to both $\vec{\mathbf{v}}$ and $\vec{\mathbf{B}}$
- Oppositely directed forces exerted on oppositely charged particles will cause the particles to move in opposite directions

Force on a Charge Moving in a Magnetic Field

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

Magnitude of Magnetic Force

- The magnitude of the magnetic force on a charged particle is

$$F_B = |q|\, v\, B \sin \theta$$

  - 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
    - $\theta = 90^{\circ}$

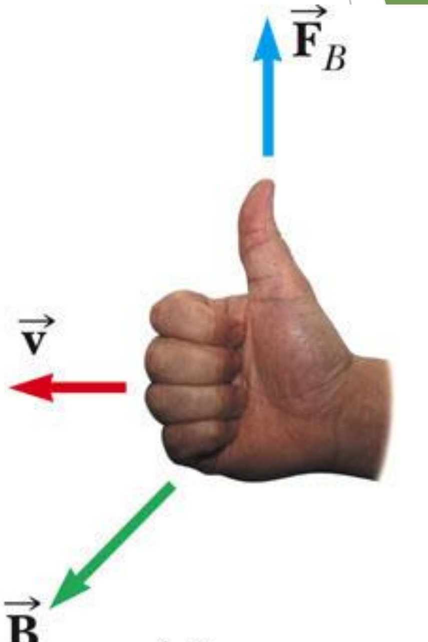
Units of Magnetic Field

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

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

Direction of the magnetic Force: Right-Hand Rule #1

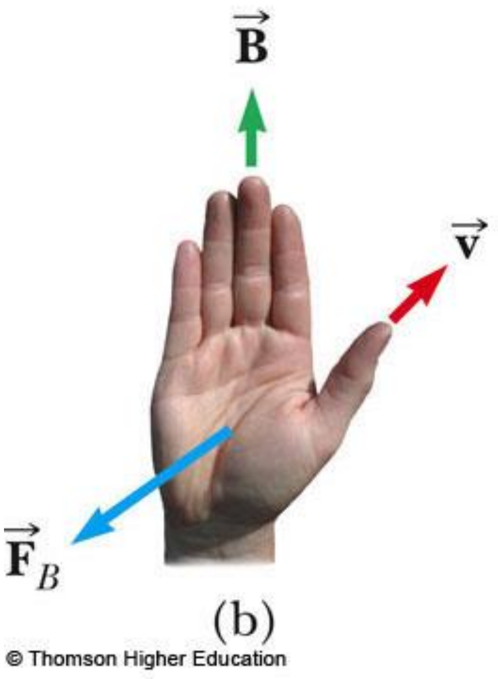
- The fingers point in the direction of $\vec{\mathbf{v}}$
- $\vec{\mathbf{B}}$ comes out of your palm
- The direction of $\vec{\mathbf{v}} \times \vec{\mathbf{B}}$, and the force on a positive charge, is the direction in which the thumb points



(a)

Direction of the magnetic Force: Right-Hand Rule #2

- Thumb is in the direction of $\vec{\mathbf{v}}$
- Fingers are in the direction of $\vec{\mathbf{B}}$
- Palm is in the direction of $\vec{\mathbf{F}}_B$
  - On a positive particle
  - As your hand pushing the particle
  - The force on a negative charge is in the opposite direction



Differences between electric and magnetic forces:

- Direction
  - 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 the particle's velocity
  - The magnetic force acts on a charged particle only when the particle is in motion.

Differences between electric and magnetic forces:

- Work
  - The electric force does work in displacing a charged particle, whereas the magnetic force associated with a steady magnetic field does no work when a particle is displaced because the force is perpendicular to the displacement
  - ***The kinetic energy of a charged particle moving through a magnetic field cannot be altered by the magnetic field alone***

Quick Quiz 29.1

The north-pole end of a bar magnet is held near a positively charged piece of plastic. The plastic is

(a) attracted

(b) repelled

(c) unaffected by the magnet

Quick Quiz 29.2

A charged particle moves with velocity vin a magnetic field **B**. The magnetic force on the particle is a maximum when **v** is

(a) parallel to B

(b) perpendicular to B

(c) zero

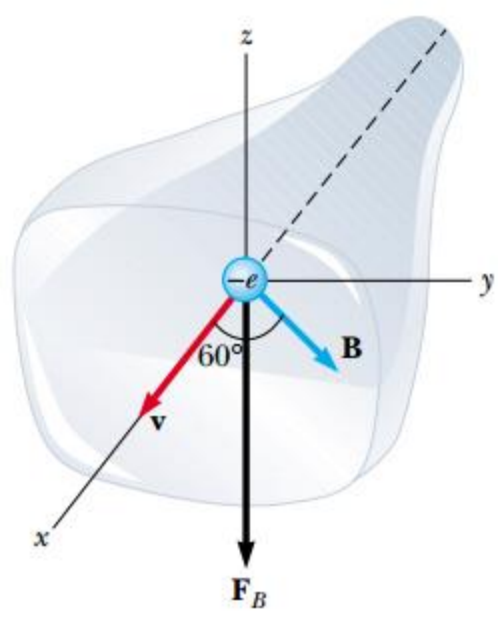
Some Approximate Magnetic Field Magnitudes	
Source of Field	**Field Magnitude (T)**
Strong superconducting laboratory magnet	30
Strong conventional laboratory magnet	2
Medical MRI unit	1.5
Bar magnet	10^{-2}
Surface of the Sun	10^{-2}
Surface of the Earth	0.5×10^{-4}
Inside human brain (due to nerve impulses)	10^{-13}

Example 29.1 An Electron Moving in a Magnetic Field

An electron in a television picture tube moves toward the front of the tube with a speed of $8.0\text{x}10^6$ m/s along the x axis. Surrounding the neck of the tube are coils of wire that create a magnetic field of magnitude 0.025T,directed at an angle of 60° to the x axis and lying in the xy

plane.

calculate the magnetic force on t electron

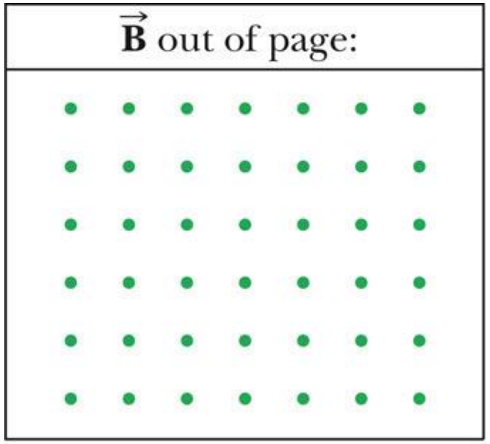


29.2 Magnetic Force Acting on a Current-Carrying Conductor

- **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; hence, the resultant force exerted by the field on the wire is the vector sum of the individual forces exerted on all the charged particles making up the current.**

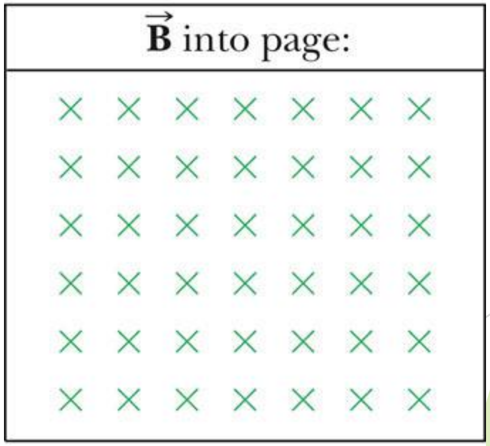
Notation Notes

- The dots indicate the direction is ***<u>out of the page</u>***



(a)

- The crosses represent the arrows ***<u>going into the page</u>***



(b)

Force on a Wire

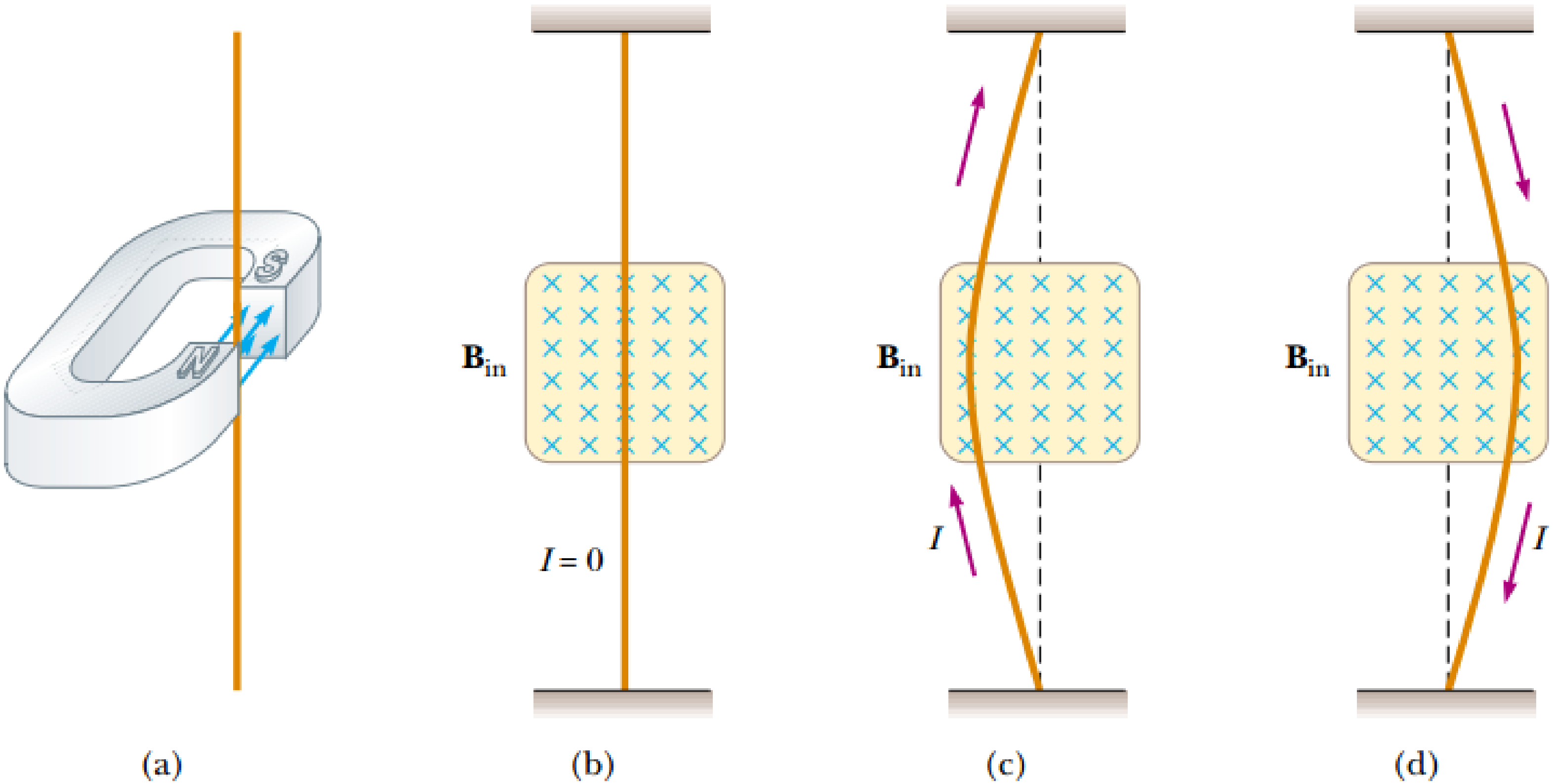
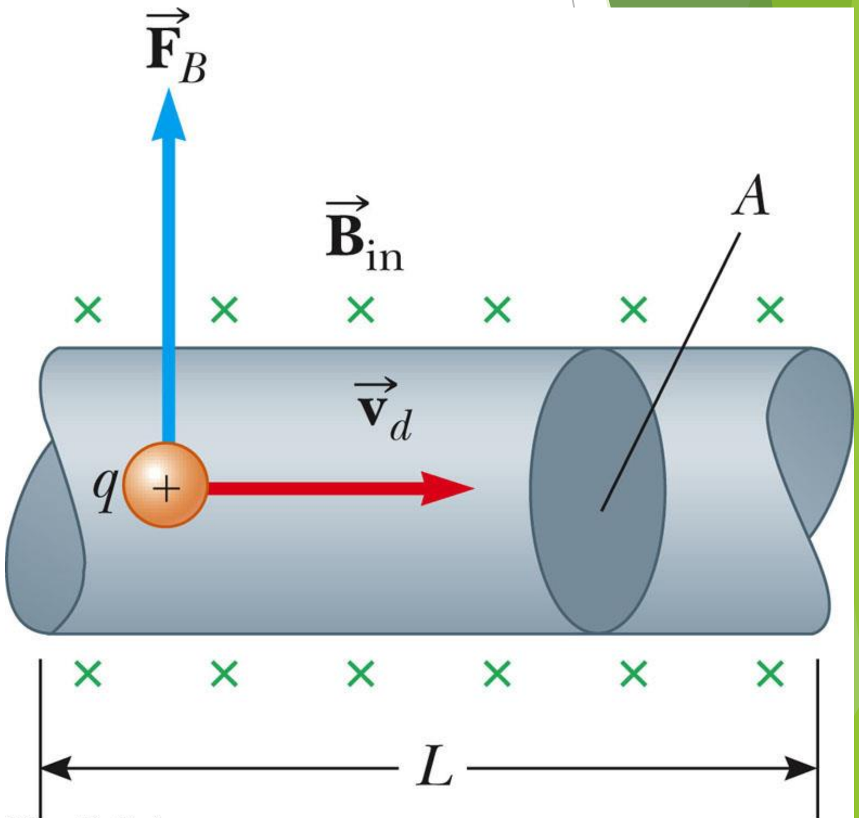


Figure 29.7 (a) A wire suspended vertically between the poles of a magnet. (b) The setup shown in part (a) as seen looking at the south pole of the magnet, so that the magnetic field (blue crosses) is directed into the page. When there is no current in the wire, it remains vertical. (c) When the current is upward, the wire deflects to the left. (d) When the current is downward, the wire deflects to the right.

Force on a Wire

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



Magnetic Force on a Wire

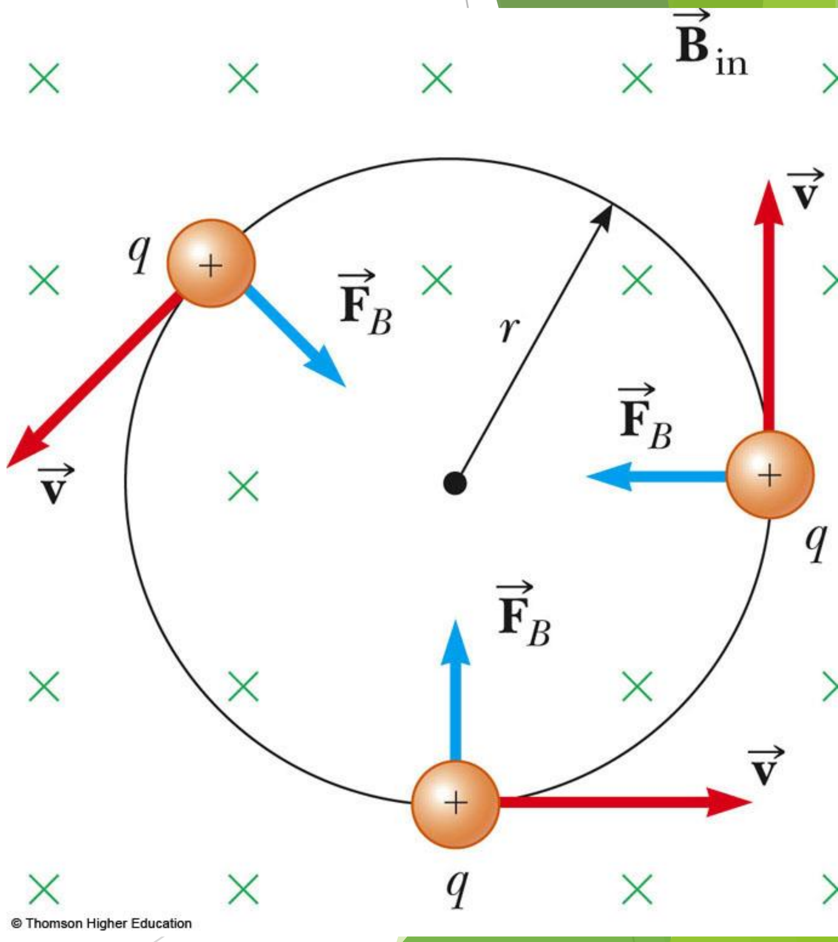
- In terms of the current, this becomes

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

  - 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

29.4 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 p
- The particle moves in a circle because the magnetic force F is perpendicular to v and B and has a constant magnitude qvB



Force on a Charged Particle

- Equating the magnetic and centripetal forces:

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

- Solving for r:

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

The radius of the path

29.4 Charged Particle in a Magnetic Field

- ***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***

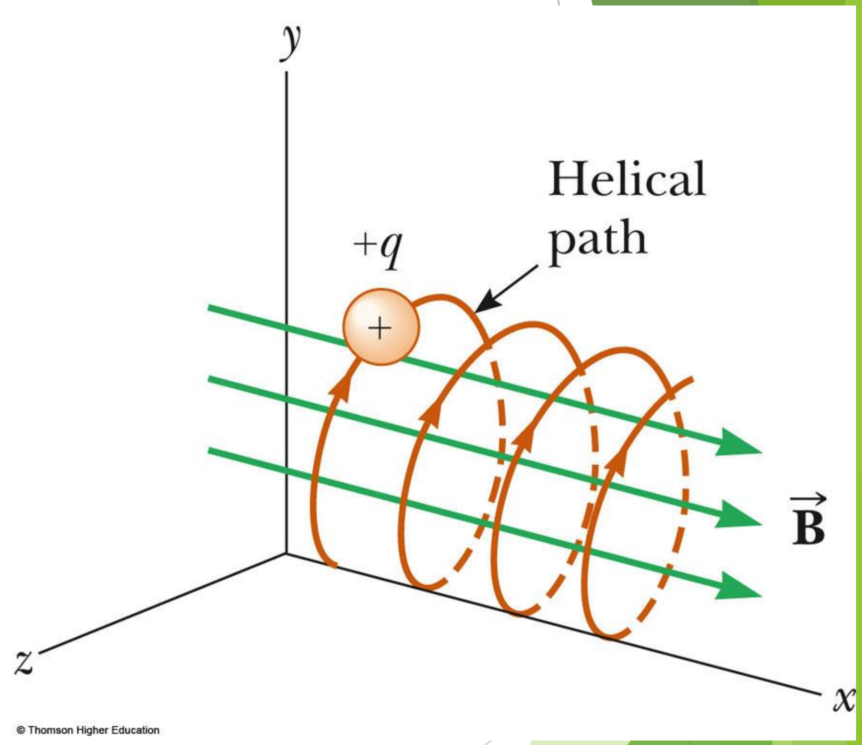
$$T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}$$

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, but we replace the velocity with

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



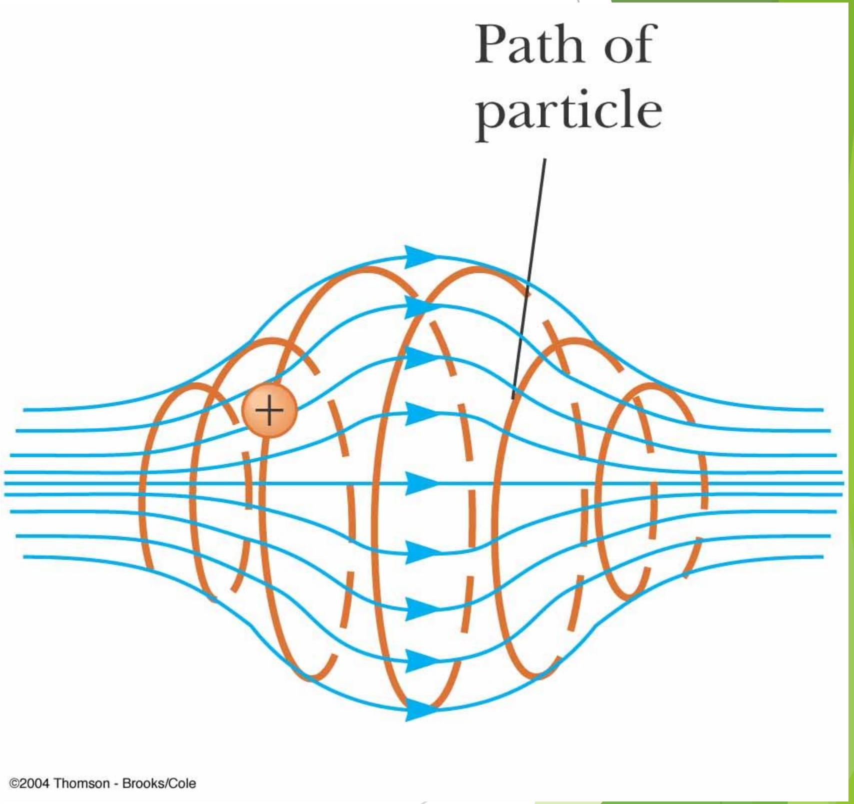
29.4 Charged Particle in a Magnetic Field

- <u>Example 29.6</u>

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

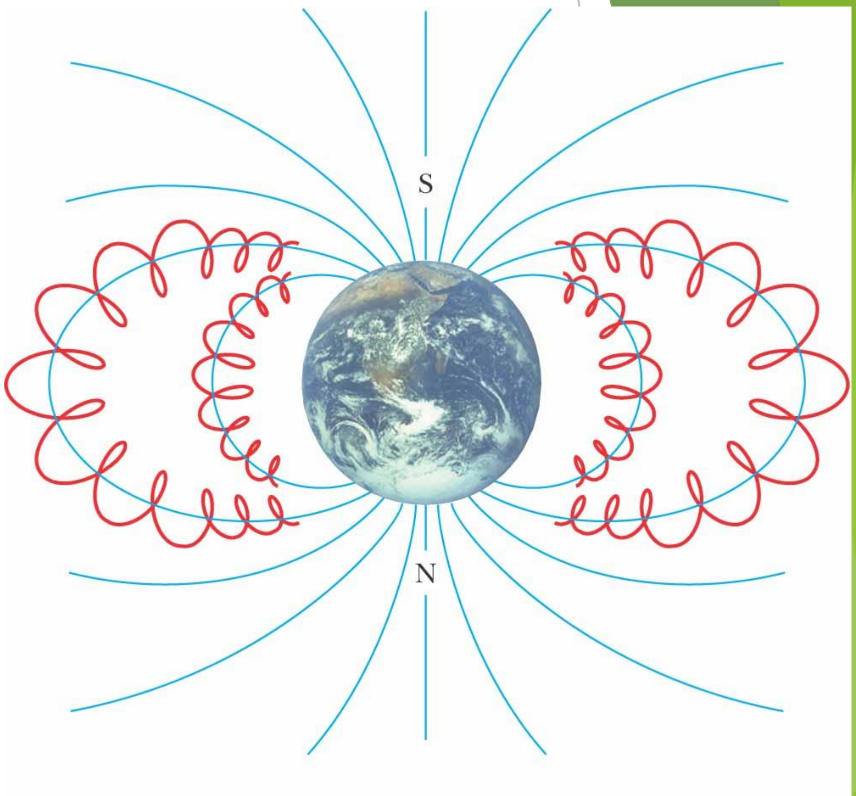
Particle in a Nonuniform Magnetic Field

- 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 magnetic field
- The particles spiral from pole to pole
  - May result in Auroras



29.5 Applications Involving Charged Particles Moving in a Magnetic Field

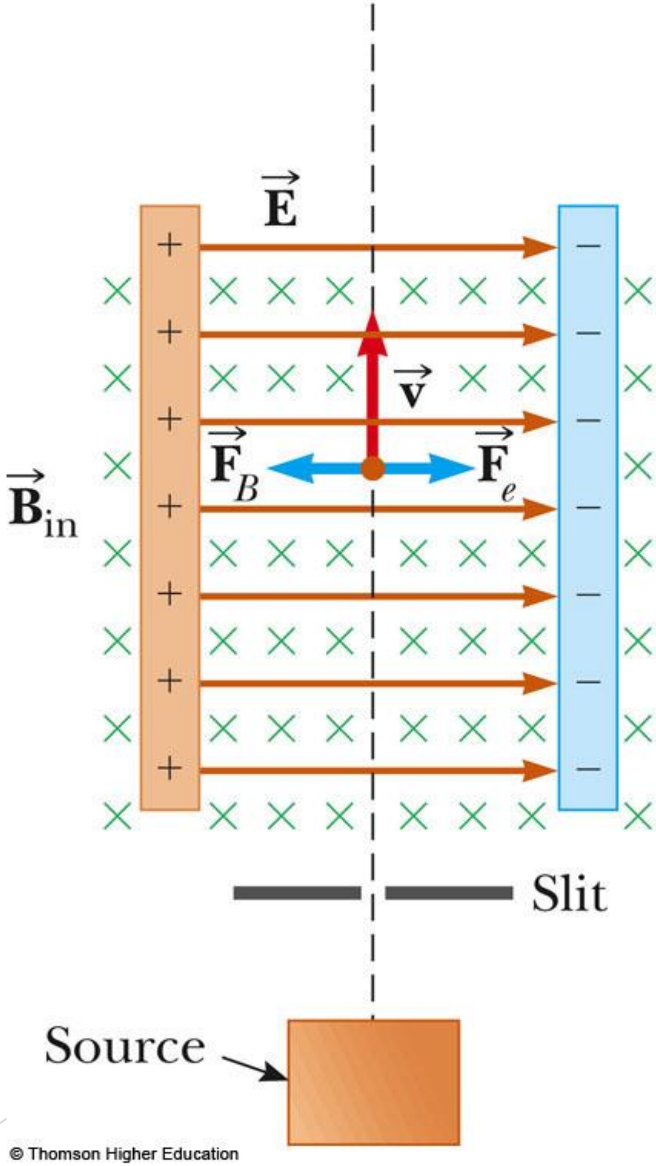
- In many applications, charged particles will move in the presence of both magnetic and electric fields
- In that case, the total force is the sum of the forces due to the individual fields
- In general:

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

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



Velocity Selector, cont.

- 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

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

Velocity Selector, final

- Only those particles with the given speed will pass through the two fields undeflected
- The magnetic force exerted on particles moving at 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

Chapter Problems

Problem 9 Page 919

A proton moves with a velocity of $\mathbf{v} = (2\hat{\mathbf{i}} - 4\hat{\mathbf{j}} + \hat{\mathbf{k}})$ m/s in a region in which the magnetic field is $\mathbf{B} = (\hat{\mathbf{i}} + 2\hat{\mathbf{j}} - 3\hat{\mathbf{k}})$ T. What is the magnitude of the magnetic force this charge experiences?

Problem 12 Page 919

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

Chapter Problems

Problem 30 Page 920

A singly charged positive ion has a mass of $3.20x10^{-26}$ kg. After being accelerated from rest through a potential difference of 833V, the ion enters a magnetic field of 0.920T along a direction perpendicular to the direction of the field. Calculate the radius of the path of the ion in

the field