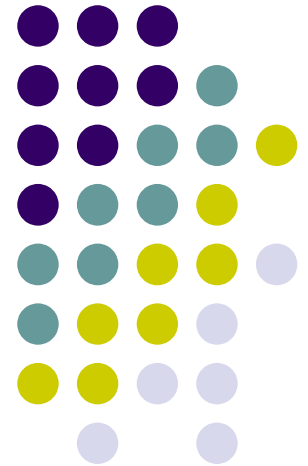


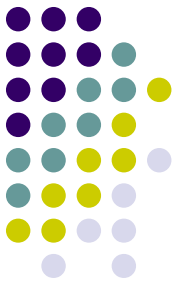
# Chapter ~~29~~->27

## Magnetic Fields



# PHYS 2321

## Week 9: Magnetism



### Day 1 Outline

1) Hwk: Ch. 27 P. 3-5,10,13,17,21,28, 33,39,49 -Due Friday

Read Ch. 27.1-7

2) Kirchhoff's laws (Loop rule, junction rule) (Ch 26)

3) Magnetic Fields and Forces (Ch 27)

a. Bar magnets (behavior and field lines)

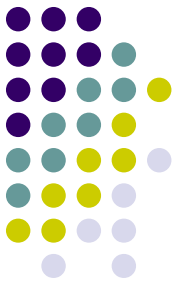
b. Force on current-carrying wire

c. Force on moving charged particles  $\vec{F}_B = q(\vec{v} \times \vec{B})$

\* Lorentz force:

Notes: Some still need to turn in Ch. 26 P. 1,2,5,7...31.

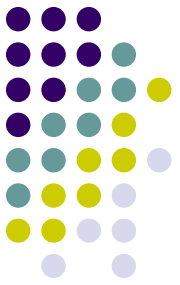
Ch. 25 & 26 graded. Mean = 9.2/10. Checked P.9,28, MQ 1,9.



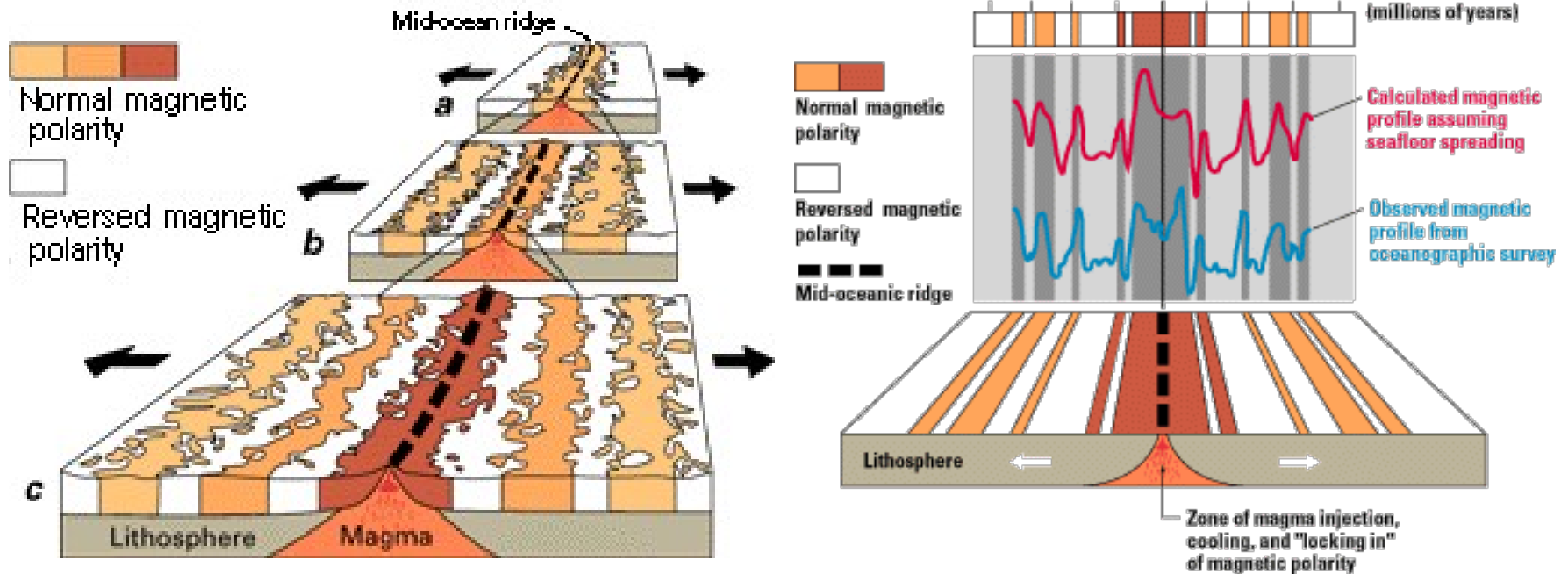
# A Brief History of Magnetism

- 13<sup>th</sup> century BC
  - Chinese used a compass
    - Uses a magnetic needle
    - Probably an invention of Arabic or Indian origin
- 800 BC
  - Greeks
    - Discovered magnetite ( $\text{Fe}_3\text{O}_4$ ) attracts pieces of iron

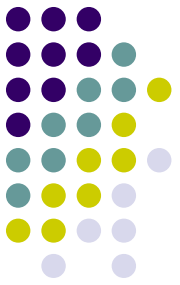
# A Brief History of Magnetism



- The mid-oceanic ridge between N. America and Europe shows that Earth's magnetic field has switched polarity.

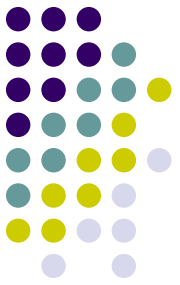


Figures by the USGS



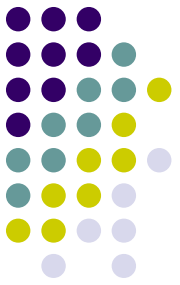
# Magnetic Poles

- 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



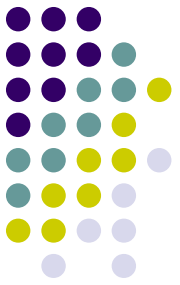
# Magnetic Poles, cont.

- 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 magnet's 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

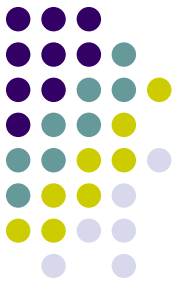
- The force between two poles varies as the inverse square of the distance between them
- A single magnetic pole has never been isolated (“No magnetic monopoles”)
  - In other words, magnetic poles are always found in pairs
  - All attempts so far to detect an isolated magnetic pole has been unsuccessful
    - No matter how many times a permanent magnetic is cut in two, each piece always has a north and south pole



# 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

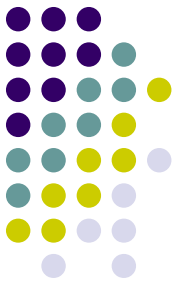




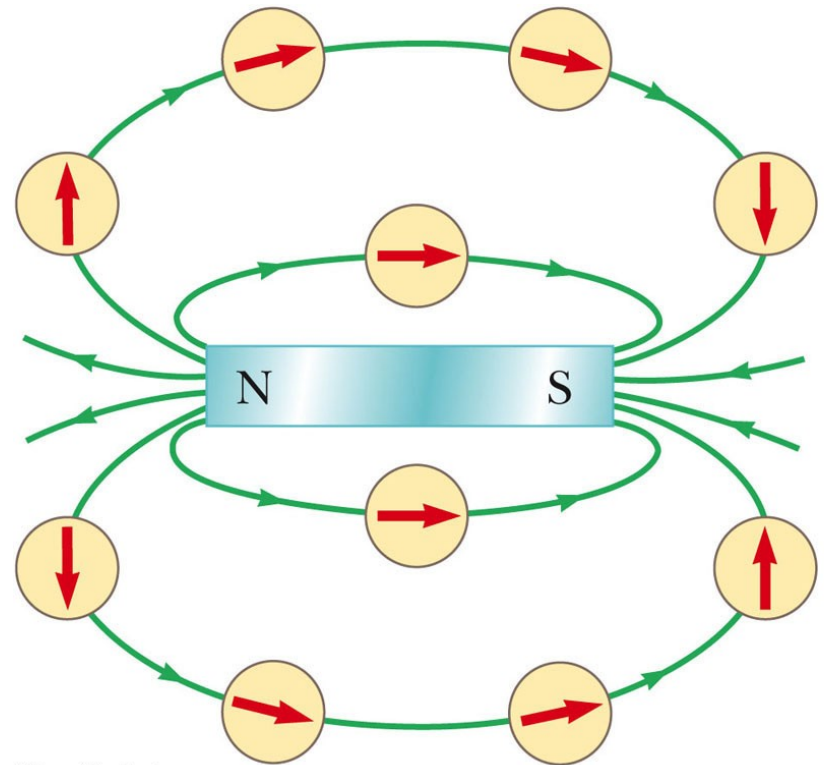
# Magnetic Fields, cont.

- A vector quantity
- Symbolized by  $\vec{B}$
- Direction is given by the direction a north pole of a compass needle points in that location
- Magnetic field lines can be traced out by a compass

# Magnetic Field Lines, Bar Magnet Example



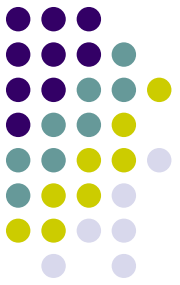
- The compass can be used to trace the field lines
- The lines outside the magnet point from the North pole to the South pole
- Inside, lines point South to North, continuing the loops



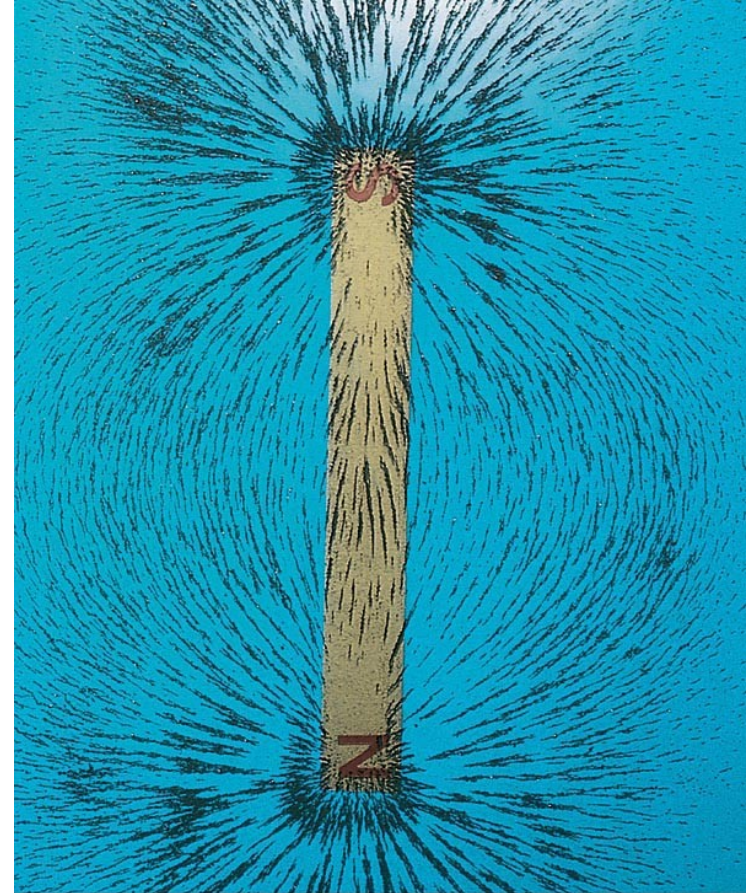
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# Magnetic Field Lines, Bar Magnet

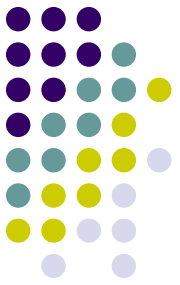


- Iron filings are used to show the pattern of the magnetic field lines
- The direction of the field is the direction a north pole would point

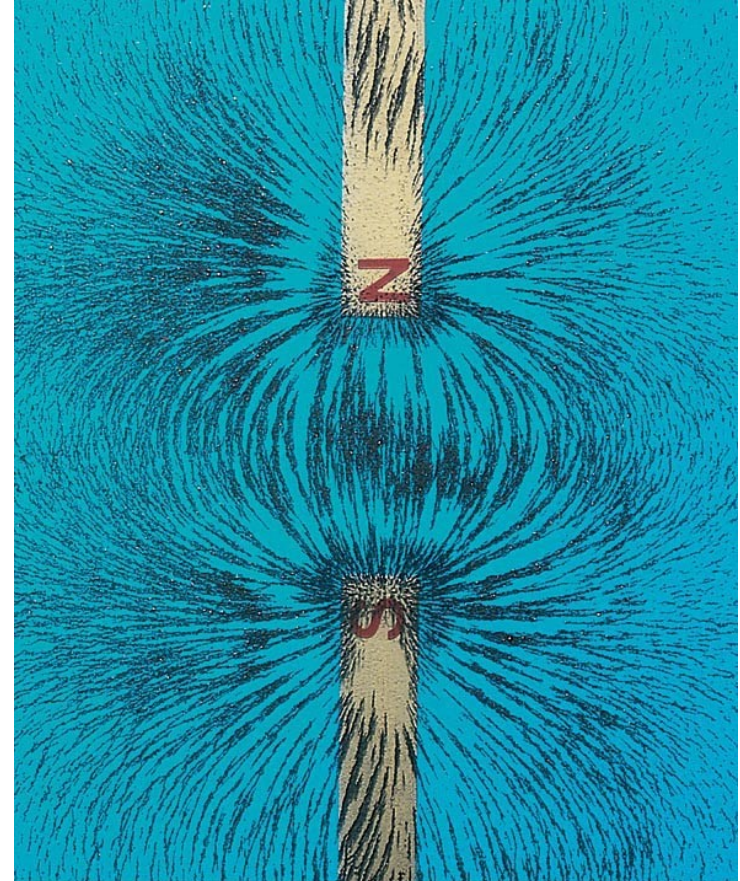


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# Magnetic Field Lines, Unlike Poles



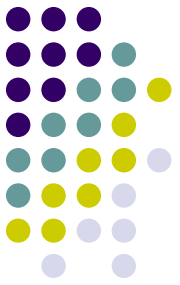
- Iron filings are used to show the pattern of the magnetic field lines
- The direction of the field is the direction a north pole would point
  - Compare to the electric field produced by an electric dipole



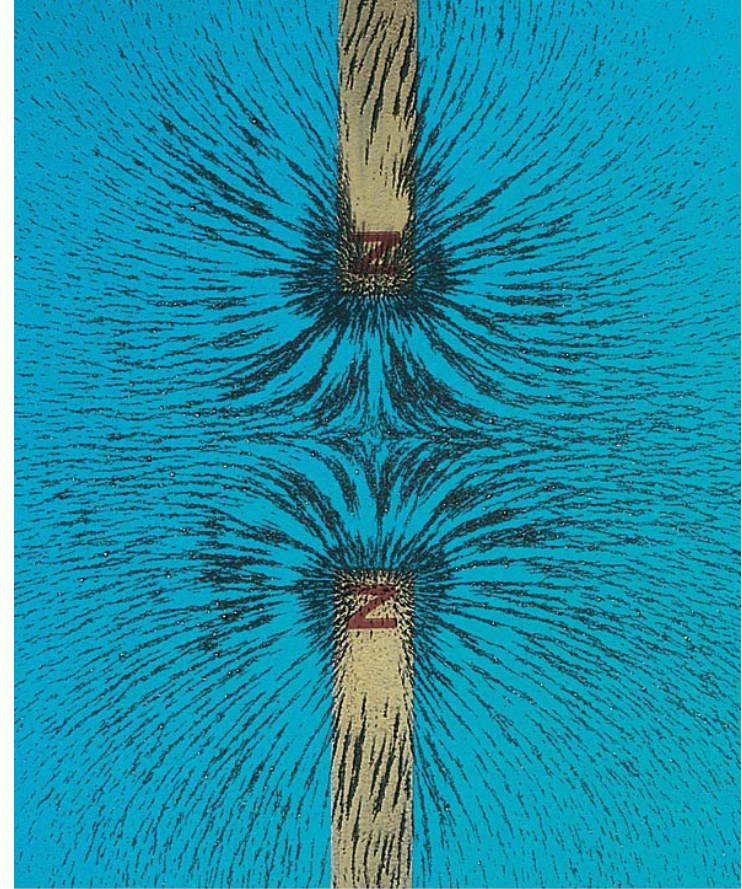
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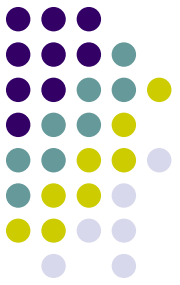
# Magnetic Field Lines, Like Poles



- Iron filings are used to show the pattern of the magnetic field lines
- The direction of the field is the direction a north pole would point
  - Compare to the electric field produced by like charges



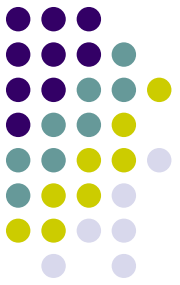
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# Definition of Magnetic Field

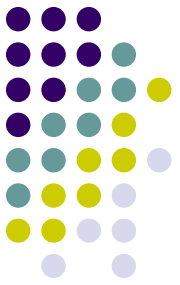
- The magnetic field at some point in space can be defined in terms of the magnetic force,  $\vec{F}_B$
- The magnetic force will be exerted on a charged particle moving with a velocity,  $\vec{v}$ 
  - Assume (for now) there are no gravitational or electric fields present

# 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 both the velocity and the field

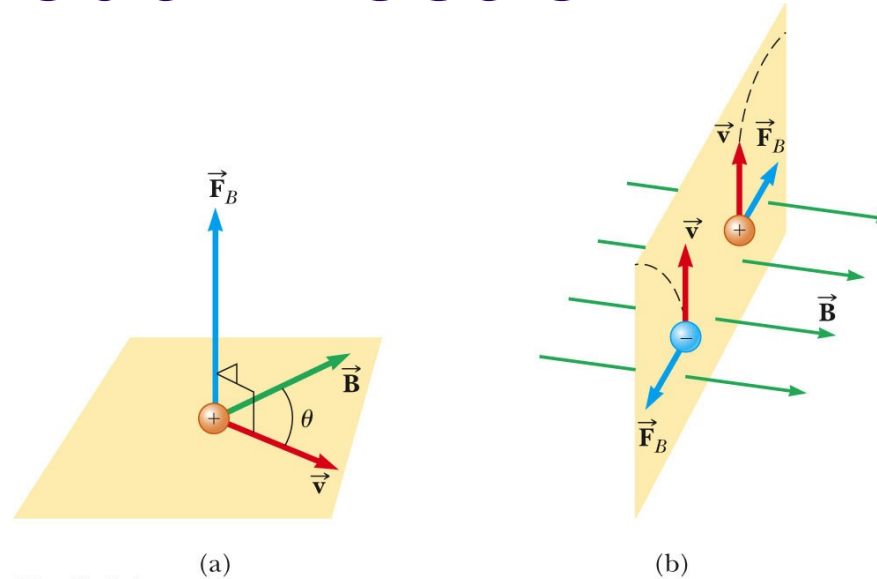
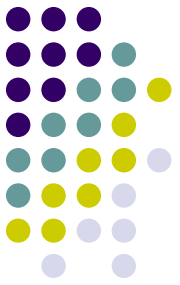
# $F_B$ on a Charge Moving in a Magnetic Field, final



- 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  $\theta$  is the angle the particle's velocity makes with the direction of the magnetic field



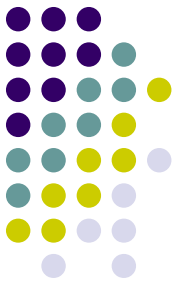
# More About Direction



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

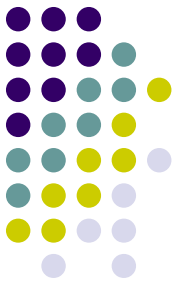
# Force on a Charge Moving in a Magnetic Field, Formula



- The properties can be summarized in a vector equation:

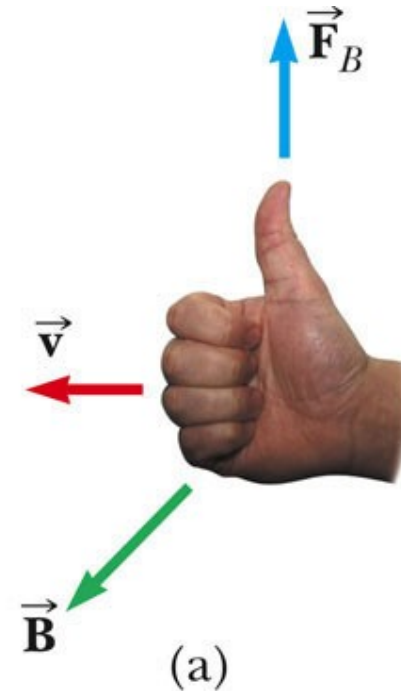
$$\vec{F}_B = q (\vec{v} \times \vec{B})$$

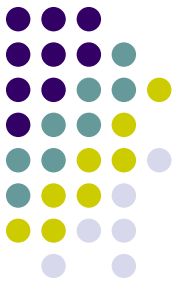
- $\vec{F}_B$  is the magnetic force
- $q$  is the charge
- $\vec{v}$  is the velocity of the moving charge
- $\vec{B}$  is the magnetic field



# Direction: Right-Hand Rule #1

- The fingers point in the direction of  $\vec{v}$
- Orient hand so fingers bend towards  $\mathbf{B}$
- The thumb points in the direction of  $\mathbf{F}_B$  which is the direction of the force on the particle.

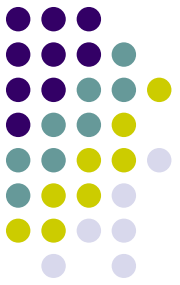




# More About Magnitude of $F$

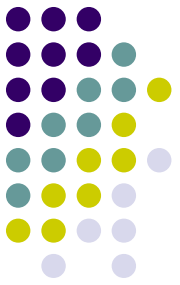
- The magnitude of the magnetic force on a charged particle is  $F_B = |q| v B \sin \theta$ 
  - $\theta$  is the smaller angle between  $v$  and  $B$
  - $F_B$  is zero when the field and velocity are parallel or antiparallel
    - $\theta = 0$  or  $180^\circ$
  - $F_B$  is a maximum when the field and velocity are perpendicular
    - $\theta = 90^\circ$

# Differences Between Electric and Magnetic Fields

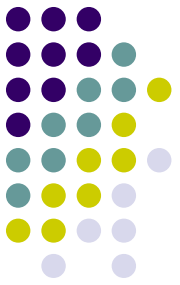


- Direction of force
  - The electric force acts along the direction of the electric field
  - The magnetic force acts perpendicular to the magnetic field
- Motion
  - The electric force acts on a charged particle regardless of whether the particle is moving
  - The magnetic force acts on a charged particle only when the particle is in motion

# More Differences Between Electric and Magnetic Fields

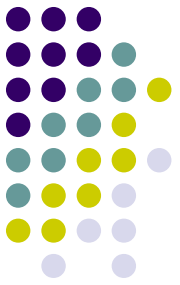


- Work
  - The electric force does work in displacing a charged particle
  - The magnetic force associated with a steady magnetic field **does no work** when a particle is displaced
    - This is because the force is perpendicular to the displacement



## Work in Fields, cont.

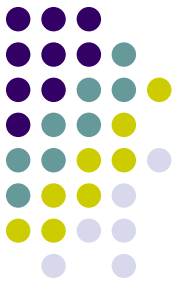
- The kinetic energy of a charged particle moving through a magnetic field cannot be altered by the magnetic field alone
- When a charged particle moves with a given velocity through a magnetic field, the field can alter the direction of the velocity, but not the speed or the kinetic energy



# Units of Magnetic Field

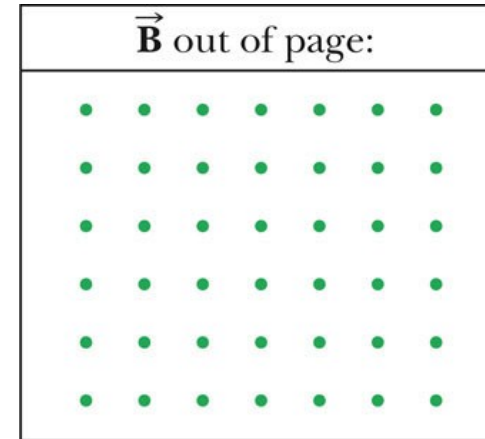
- The SI unit of magnetic field is the tesla (T)  
(Technically, a tesla is a magnetic flux density.  
It can be multiplied by an area to get total magnetic flux through that area measured in weber, Wb. )
  - Wb is a weber
- A non-SI commonly used unit is a gauss (G)
  - $1 \text{ T} = 10^4 \text{ G}$



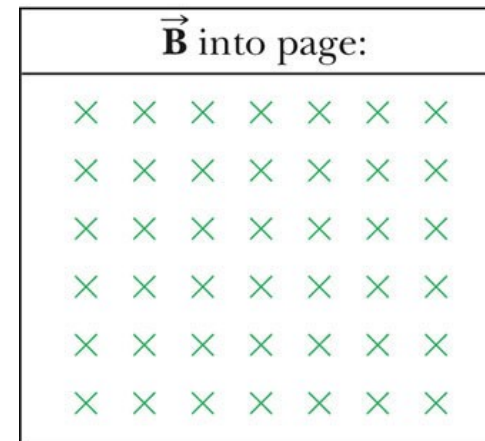


# Notation Notes

- 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

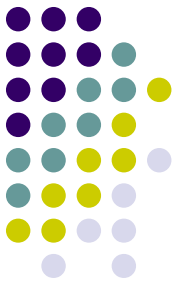


(a)

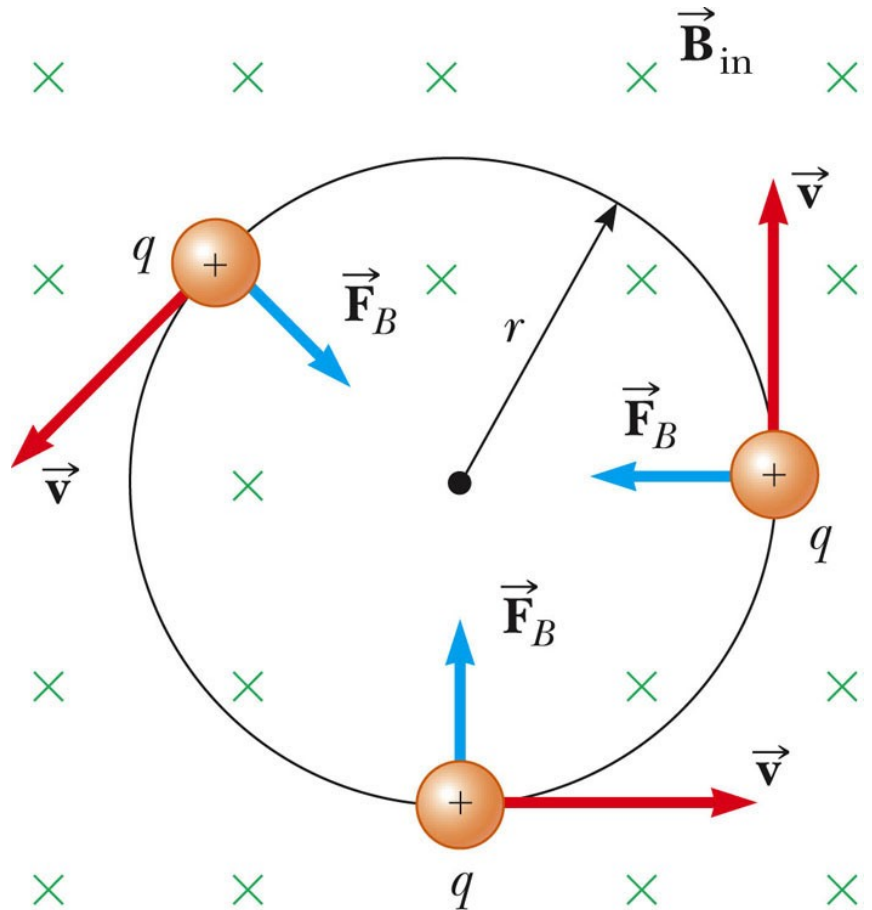


(b)

# Charged Particle in a Magnetic Field

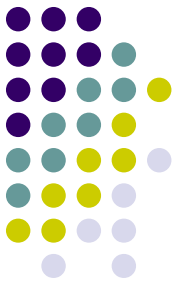


- Consider a particle moving in an external magnetic field with its velocity perpendicular to the field
- The force is always directed toward the center of the circular path
- The magnetic force causes a centripetal acceleration, changing the direction of the velocity of the particle



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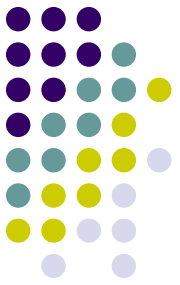
# Force on a Charged Particle

- For  $q$  in uniform circular motion:  $q \vec{v} \times \vec{B} = qvB$
- Equating the magnetic and centripetal forces:

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

- 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



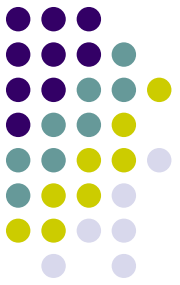
- The angular speed of the particle is

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

- The angular speed,  $\omega$ , is also referred to as the **cyclotron frequency**
- The period of the motion is

$$P = \frac{2\pi}{\omega}$$

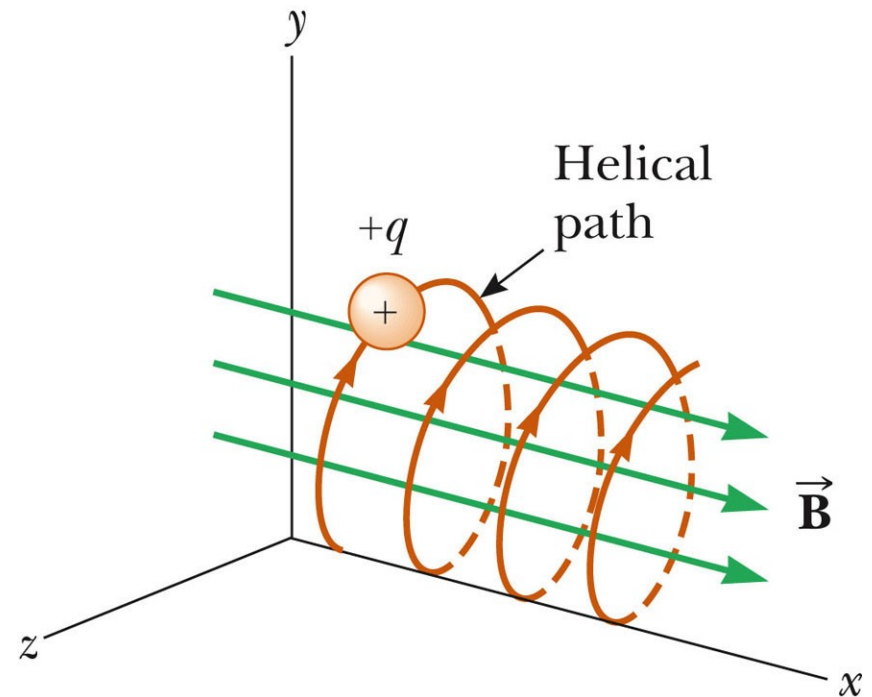
# Motion of a Particle, General



- 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

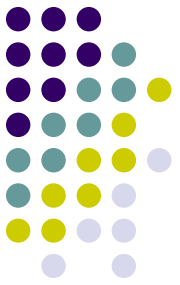
$$v_{\perp} = \sqrt{v_y^2 + v_z^2}$$

- Use the active figure to vary the initial velocity and observe the resulting motion



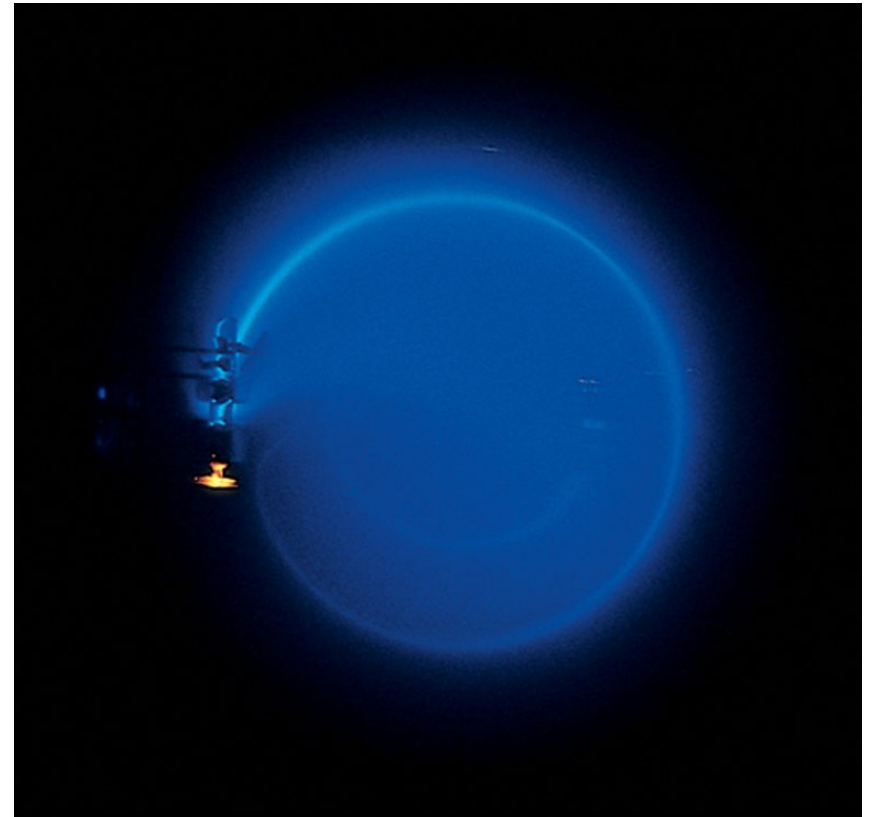
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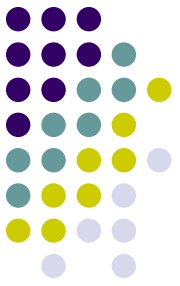
# Bending of an Electron Beam

- Electrons are accelerated from rest through a potential difference
- The electrons travel in a curved path
- Conservation of energy will give  $v$
- Other parameters can be found

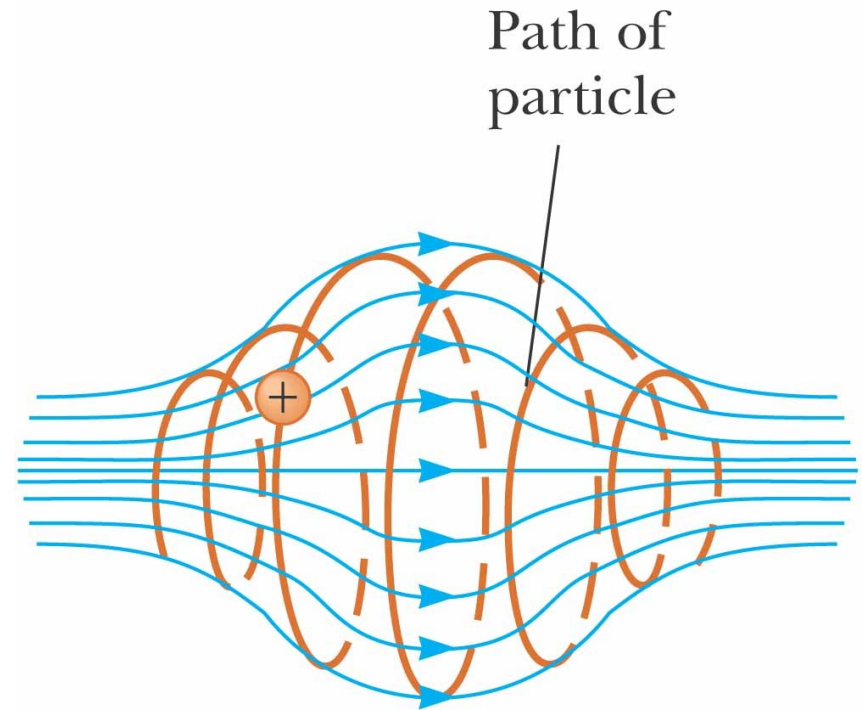


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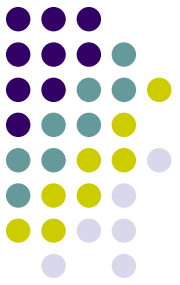
# Particle in a Nonuniform Magnetic Field



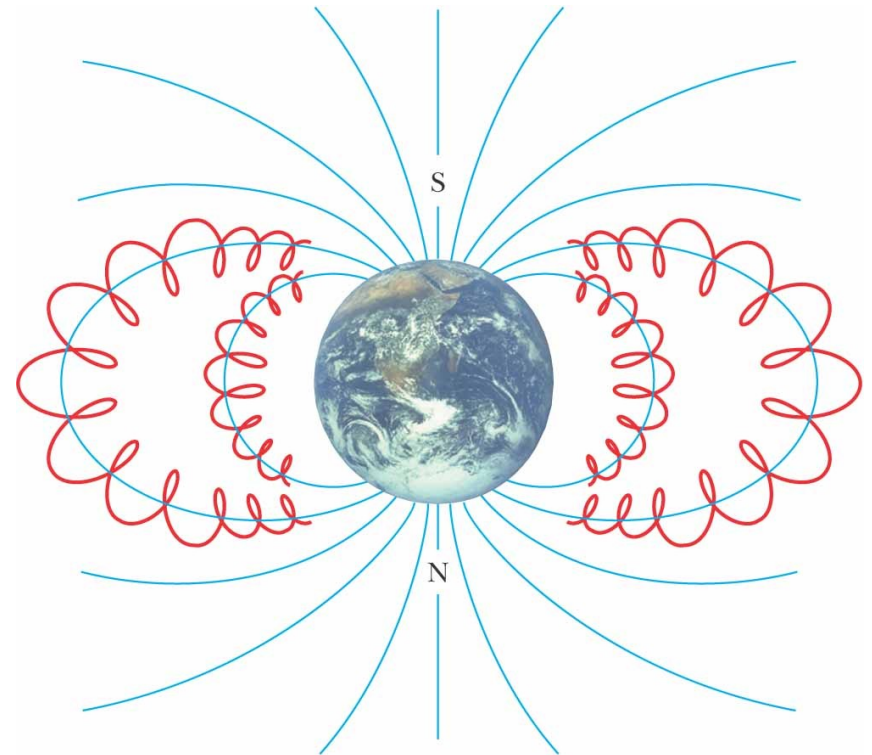
- The motion is complex
- For example, the particles can oscillate back and forth between two positions
- This configuration is known as a *magnetic bottle*



# Van Allen Radiation Belts

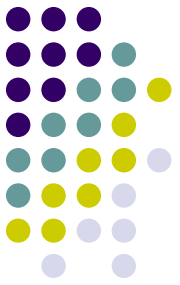


- The Van Allen radiation belts consist of charged particles surrounding the Earth in doughnut-shaped regions
- The particles are trapped by the Earth's magnetic field
- The particles spiral from pole to pole
  - May result in Auroras





# Charged Particles Moving in Electric and Magnetic Fields

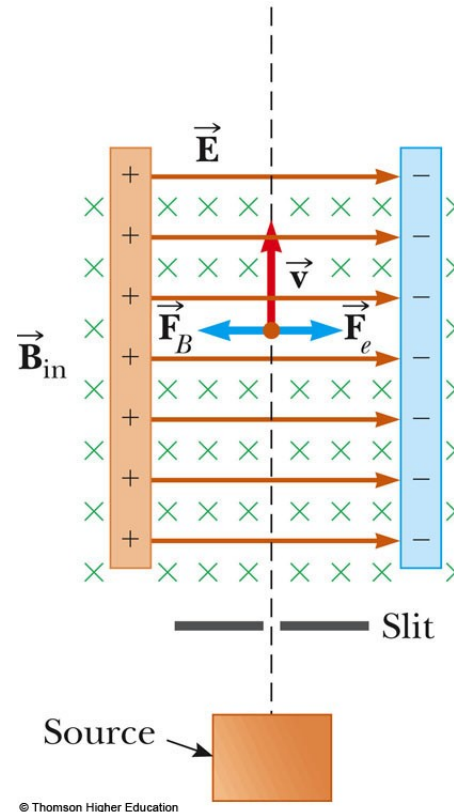


- In many applications, charged particles will move in the presence of both magnetic and electric fields
- In that case, the total force is the sum of the forces due to the individual fields
- In general:

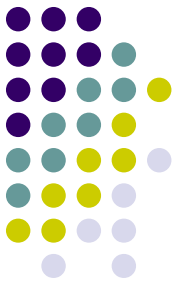
$$\vec{F} = q \{ \vec{E} + \vec{v} \times \vec{B} \}$$

# Velocity Selector

- Used when particles of a certain velocity are needed.
- A uniform electric field is perpendicular to a uniform magnetic field



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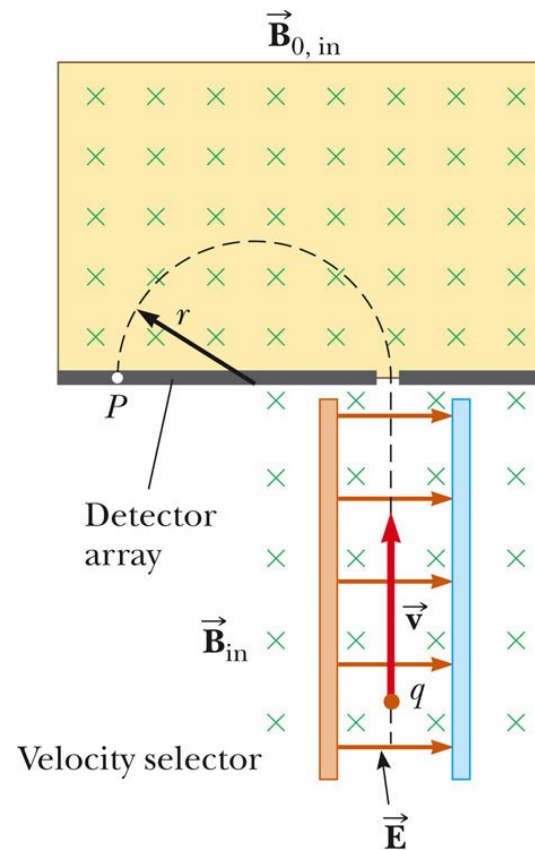


# Velocity Selector, cont.

- 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  
$$v = E / B$$

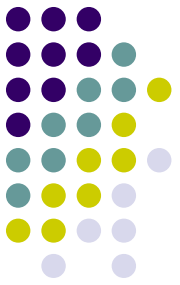
# Mass Spectrometer

- A mass spectrometer separates ions according to their mass-to-charge ratio
- A beam of ions passes through a velocity selector and enters a second magnetic field



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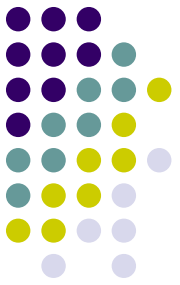
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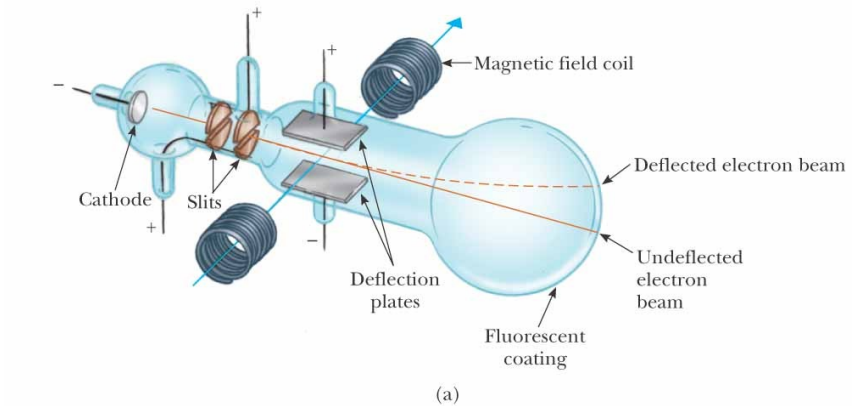
# Mass Spectrometer, cont.

- After entering the second magnetic field, the ions move in a semicircle of radius  $r$  before striking a detector at  $P$
- If the ions are positively charged, they deflect to the left
- If the ions are negatively charged, they deflect to the right

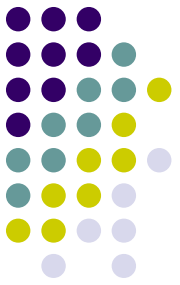
# Thomson's $e/m$ Experiment



- Electrons are accelerated from the cathode
- They are deflected by electric and magnetic fields
- The beam of electrons strikes a fluorescent screen
- $e/m$  was measured



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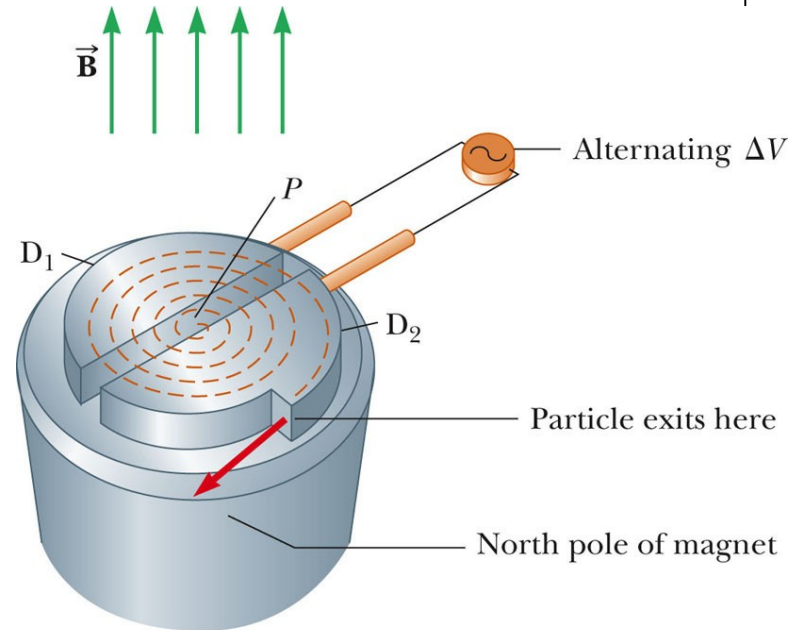


# Cyclotron

- A **cyclotron** is a device that can accelerate charged particles to very high speeds
- The energetic particles produced are used to bombard atomic nuclei and thereby produce reactions
- These reactions can be analyzed by researchers

# Cyclotron, 2

- $D_1$  and  $D_2$  are called *dees* because of their shape
- A high frequency alternating potential is applied to the dees
- A uniform magnetic field is perpendicular to them



(a)

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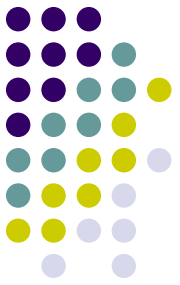


(b)

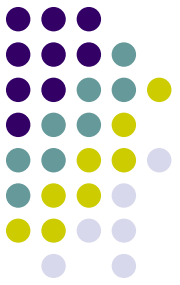
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# Cyclotron, 3



- A positive ion is released near the center and moves in a semicircular path
- The potential difference is adjusted so that the polarity of the dees is reversed in the same time interval as the particle travels around one dee
- This ensures the kinetic energy of the particle increases each trip



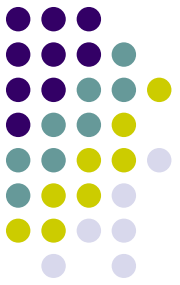
# Cyclotron, final

- The cyclotron's operation is based on the fact that  $T$  is independent of the speed of the particles and of the radius of their path

$$K = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$

- When the energy of the ions in a cyclotron exceeds about 20 MeV, relativistic effects come into play

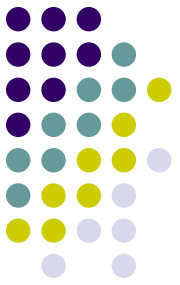
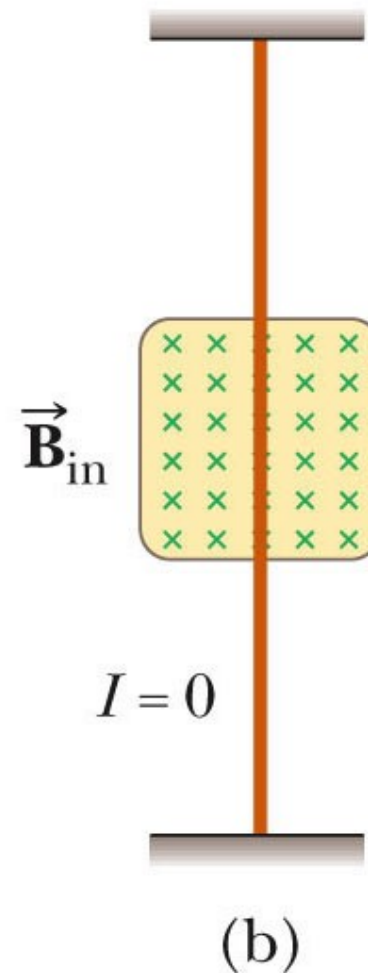
# Magnetic Force on a Current Carrying Conductor



- 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

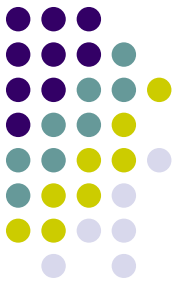
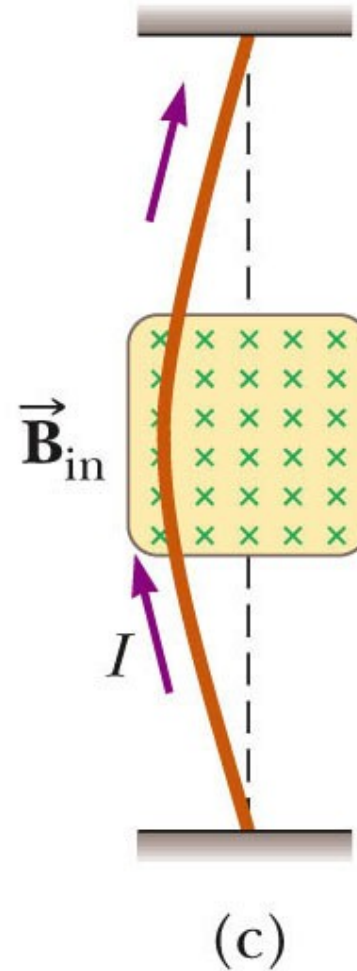
# Force on a Wire

- In this case, there is no current, so there is no force
- Therefore, the wire remains vertical



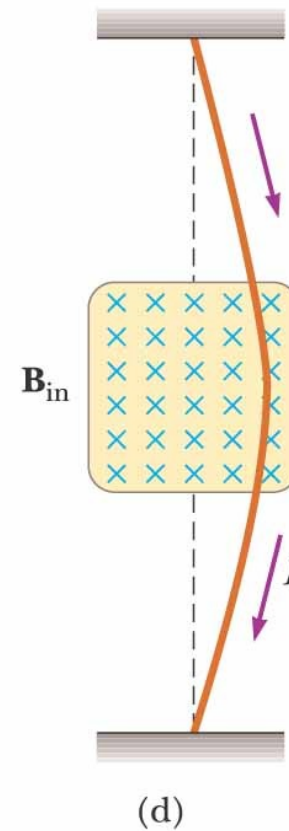
## Force on a Wire (2)

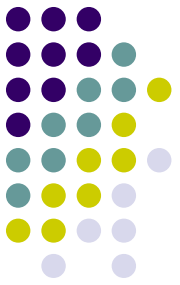
- The magnetic field is into the page
- The current is up the page
- The force is to the left



# Force on a Wire, (3)

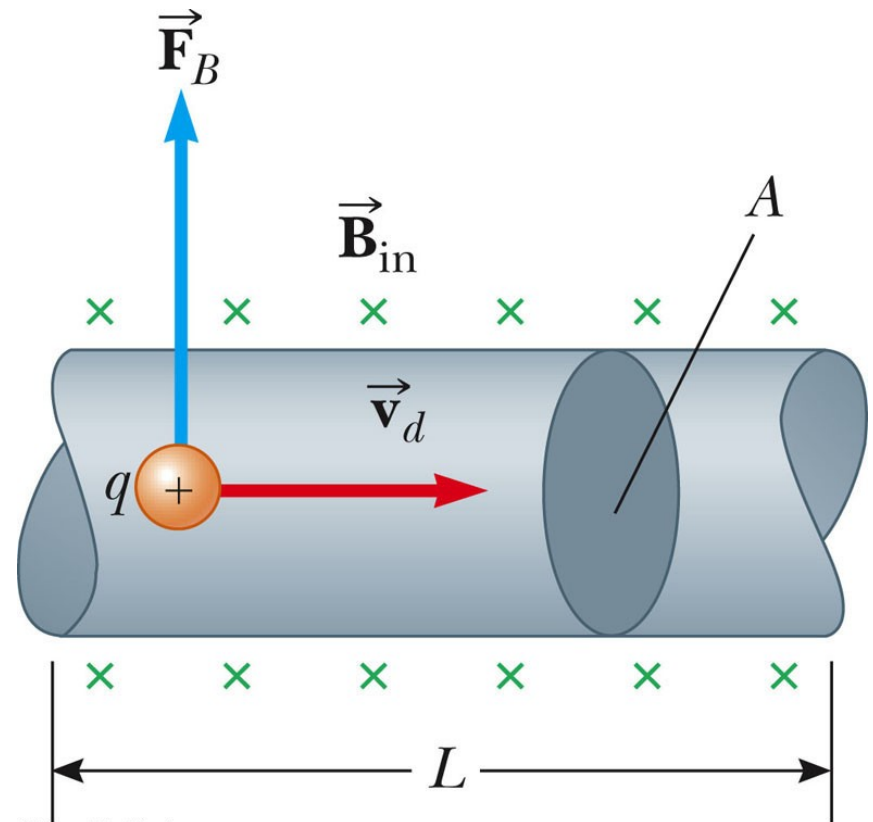
- The magnetic field is into the page
- The current is down the page
- The force is to the right

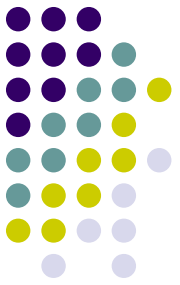




# Force on a Wire, equation

- The magnetic force is exerted on each moving charge in the wire
  - $\vec{F} = q \{ \vec{v}_d \times \vec{B} \}$
- The total force is the product of the force on one charge and the number of charges
  - $\vec{F} = (q \vec{v}_d \times \vec{B}) nAL$





# Force on a Wire, (4)

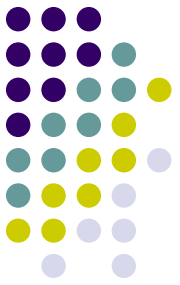
- In terms of the current, this becomes

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

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



# Force on a Wire, Arbitrary Shape



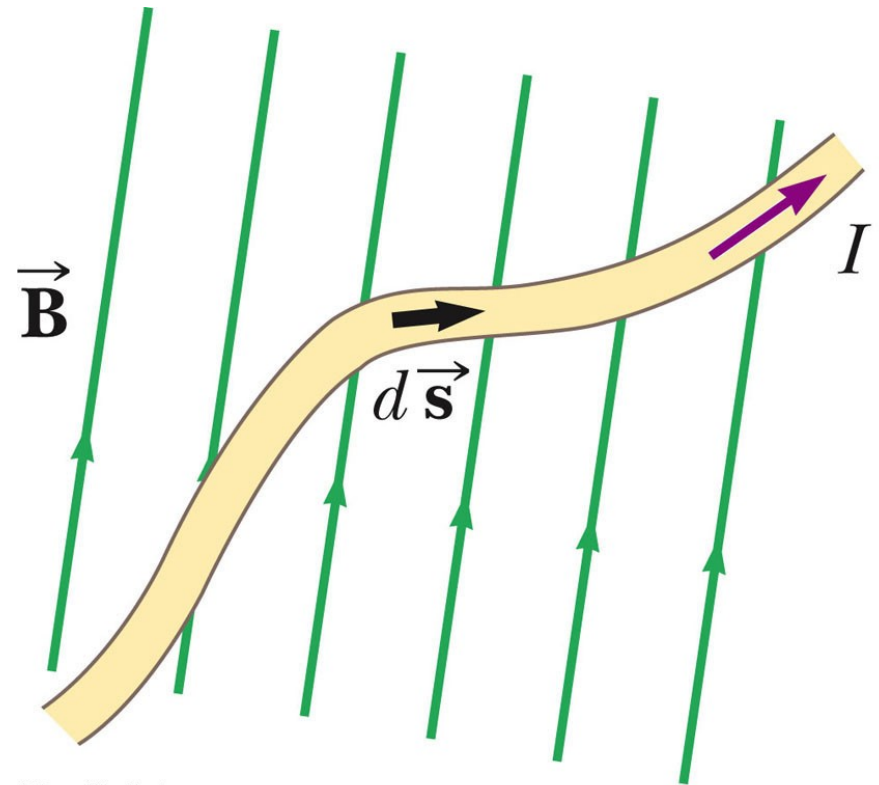
- Consider a small segment of the wire,  $d\vec{F}_B = Id \hat{i} \hat{i}$

- The force exerted on this segment is

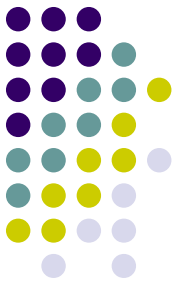
$$d\vec{F}_B = Id \hat{i} \hat{i}$$

- The total force is

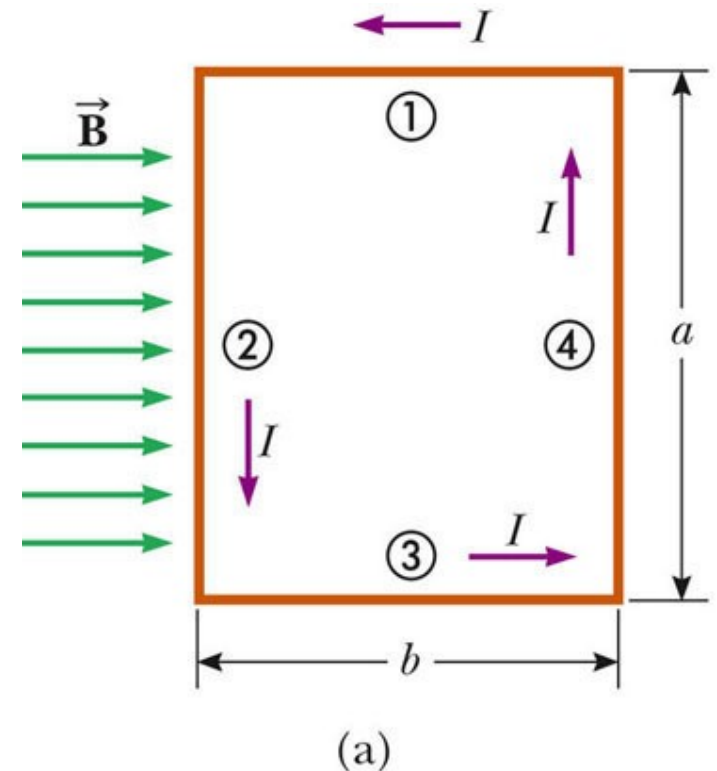
$$\vec{F}_B = Id \hat{i} \hat{i}$$



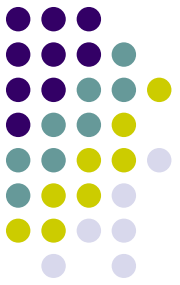
# Torque on a Current Loop



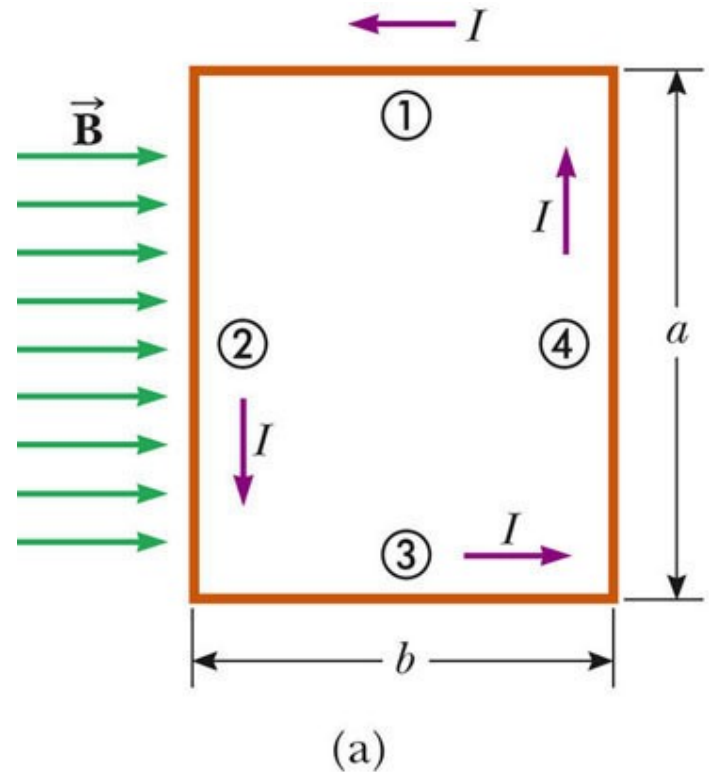
- The rectangular loop carries a current  $I$  in a uniform magnetic field
- No magnetic force acts on sides 1 & 3
  - The wires are parallel to the field and  $\mathbf{\Lambda} \cdot \mathbf{B} = 0$



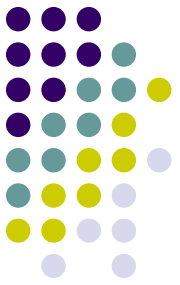
# Torque on a Current Loop, 2



- There is a force on sides 2 & 4 since they are perpendicular to the field
- The magnitude of the magnetic force on these sides will be:
  - $F_2 = F_4 = I a B$
- The direction of  $F_2$  is out of the page
- The direction of  $F_4$  is into the page

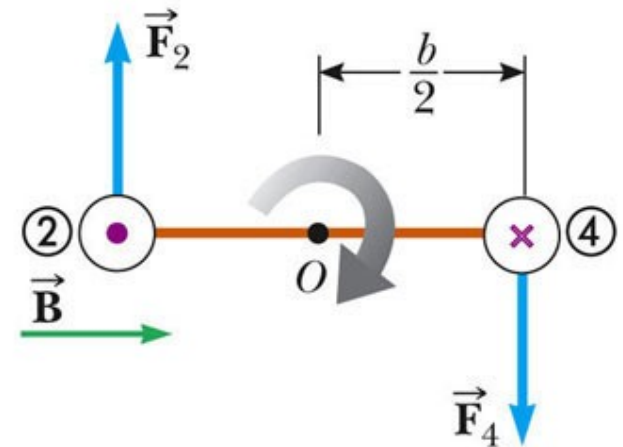


# Torque on a Current Loop, 3



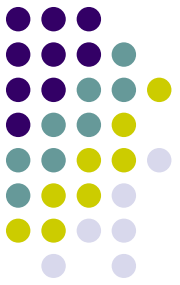
- The forces are equal and in opposite directions, but not along the same line of action
- The forces produce a torque around point  $O$

View loop from **below**:



(b)

# Torque on a Current Loop, Equation

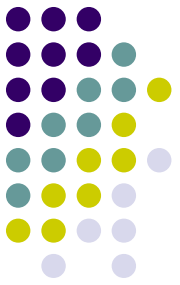


- The maximum torque is found by:

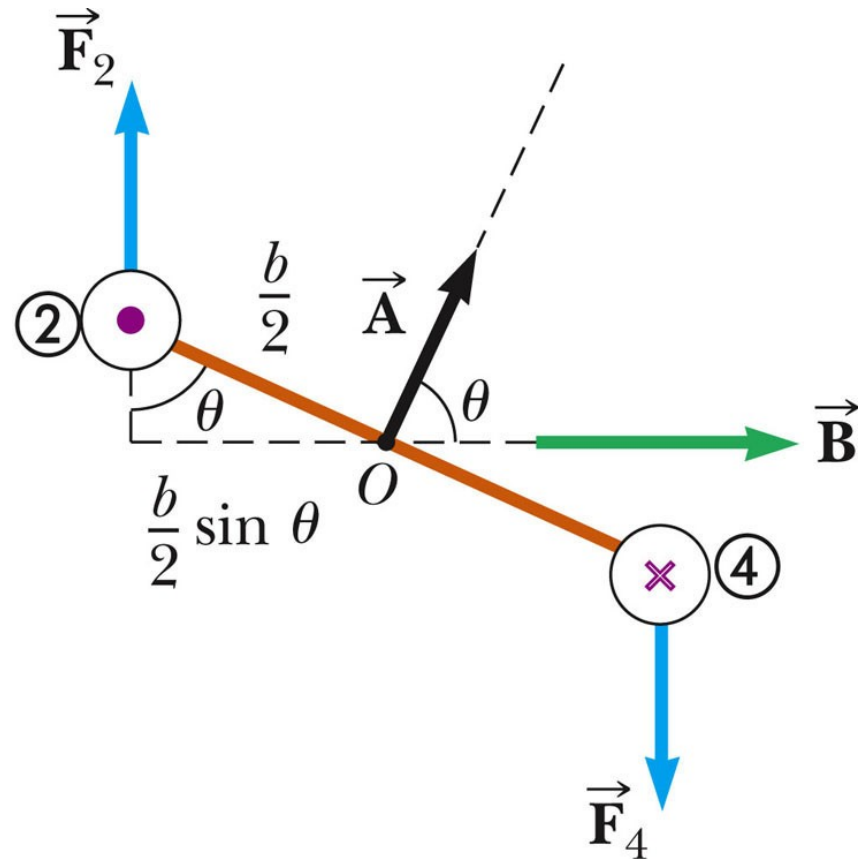
$$\tau = IaB \frac{b}{2} + IaB \frac{b}{2} = IaBb$$

- The area enclosed by the loop is  $ab$ , so  $\tau_{\max} = IAB$ 
  - This maximum value occurs only when the field is parallel to the plane of the loop

# Torque on a Current Loop, General



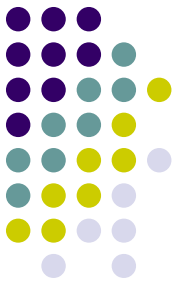
- Assume the magnetic field makes an angle of  $\theta < 90^\circ$  with a line perpendicular to the plane of the loop
- The net torque about point  $O$  will be  $\tau = IAB \sin \theta$
- Use the active figure to vary the initial settings and observe the resulting motion



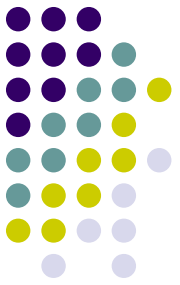
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PLAY  
ACTIVE FIGURE

# Torque on a Current Loop, Summary



- The torque has a maximum value when the field is perpendicular to the normal to the plane of the loop
- The torque is zero when the field is parallel to the normal to the plane of the loop
- $\tau = I \vec{A} \times \vec{B}$  where  $\vec{A}$  is perpendicular to the plane of the loop and has a magnitude equal to the area of the loop

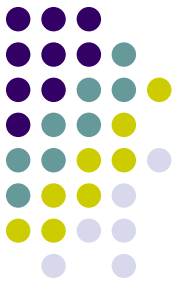


# Direction

- A right-hand rule can be used to determine the direction of  $\mathbf{A}$
- Curl your fingers in the direction of the current in the loop
- Your thumb points in the direction of  $\mathbf{A}$

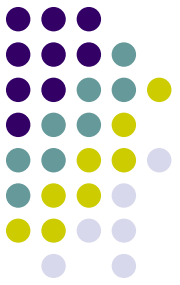






# Hall Effect

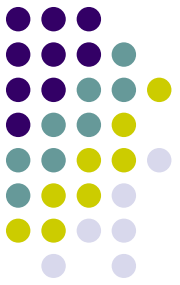
- When a current carrying conductor is placed in a magnetic field, a potential difference is generated in a direction perpendicular to both the current and the magnetic field
- This phenomena is known as the Hall effect
- It arises from the deflection of charge carriers to one side of the conductor as a result of the magnetic forces they experience



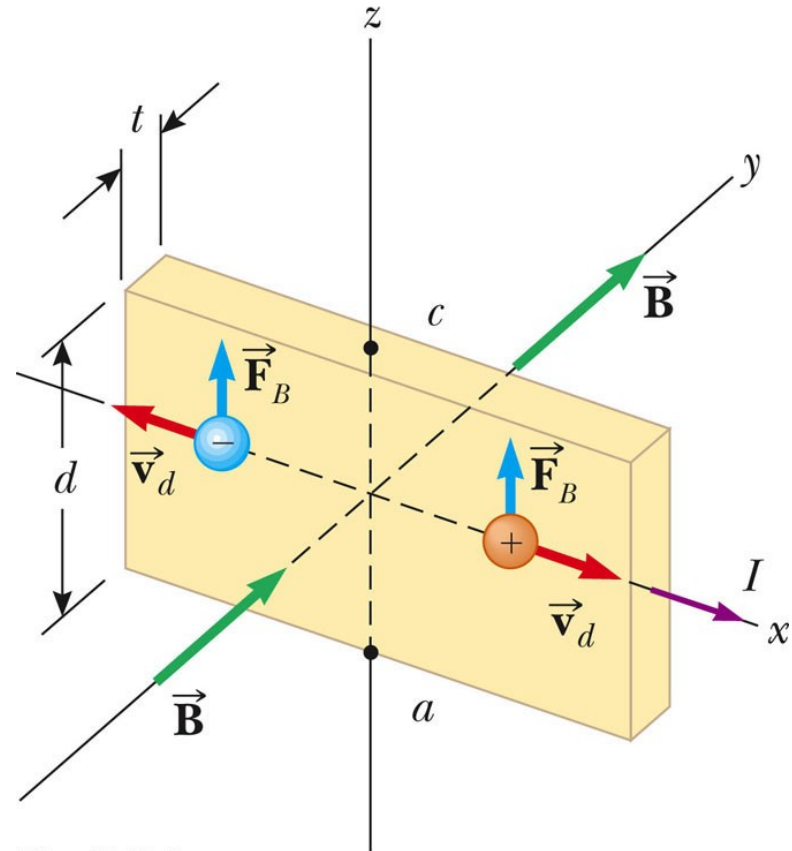
# Hall Effect, cont.

- The Hall effect gives information regarding the sign of the charge carriers and their density
- It can also be used to measure magnetic fields

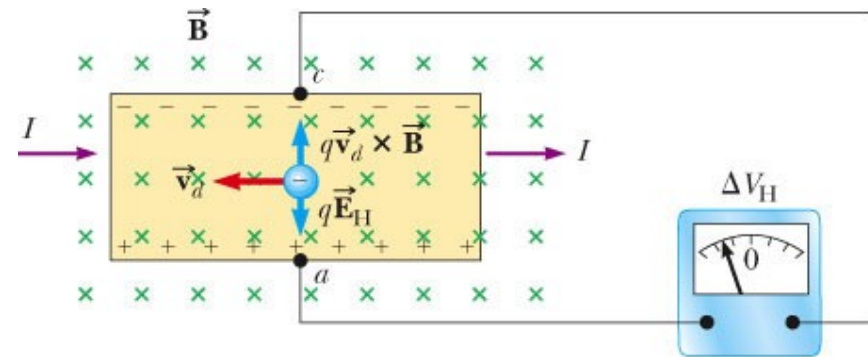
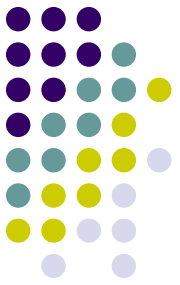
# Hall Voltage



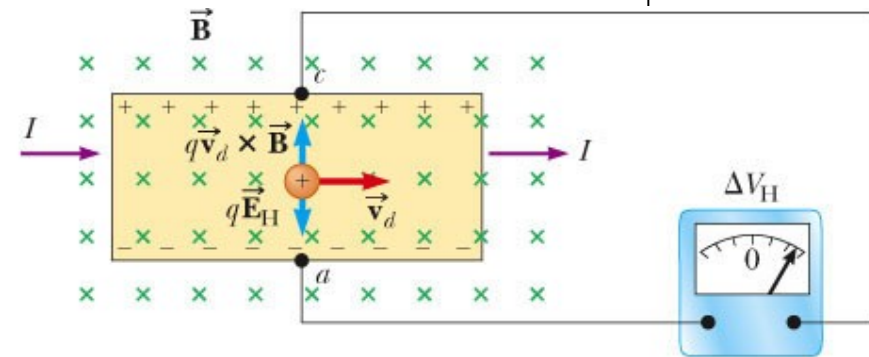
- This shows an arrangement for observing the Hall effect
- The Hall voltage is measured between points  $a$  and  $c$



# Hall Voltage, cont



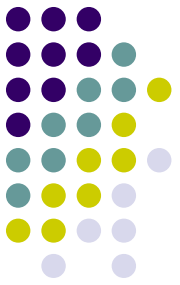
(a)



(b)

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- When the charge carriers are negative, the upper edge of the conductor becomes negatively charged
  - c is at a lower potential than a
- When the charge carriers are positive, the upper edge becomes positively charged
  - c is at a higher potential than a



# Hall Voltage, final

- $\Delta V_H = E_H d = v_d B d$ 
  - $d$  is the width of the conductor
  - $v_d$  is the drift velocity
  - If  $B$  and  $d$  are known,  $v_d$  can be found
- $\Delta V_H = \frac{I B}{n q t} = \frac{R_H I B}{t}$ 
  - $R_H = 1 / nq$  is called the Hall coefficient
  - A properly calibrated conductor can be used to measure the magnitude of an unknown magnetic field