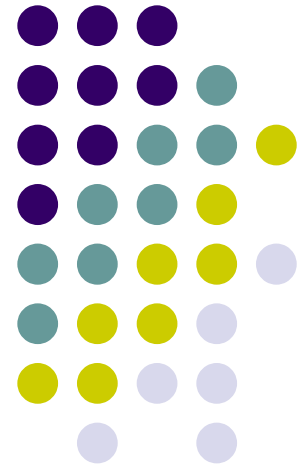


Chapter 29->27

Magnetic Fields

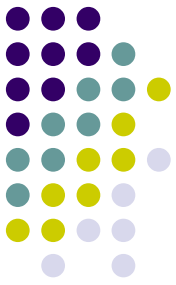


A Brief History of Magnetism

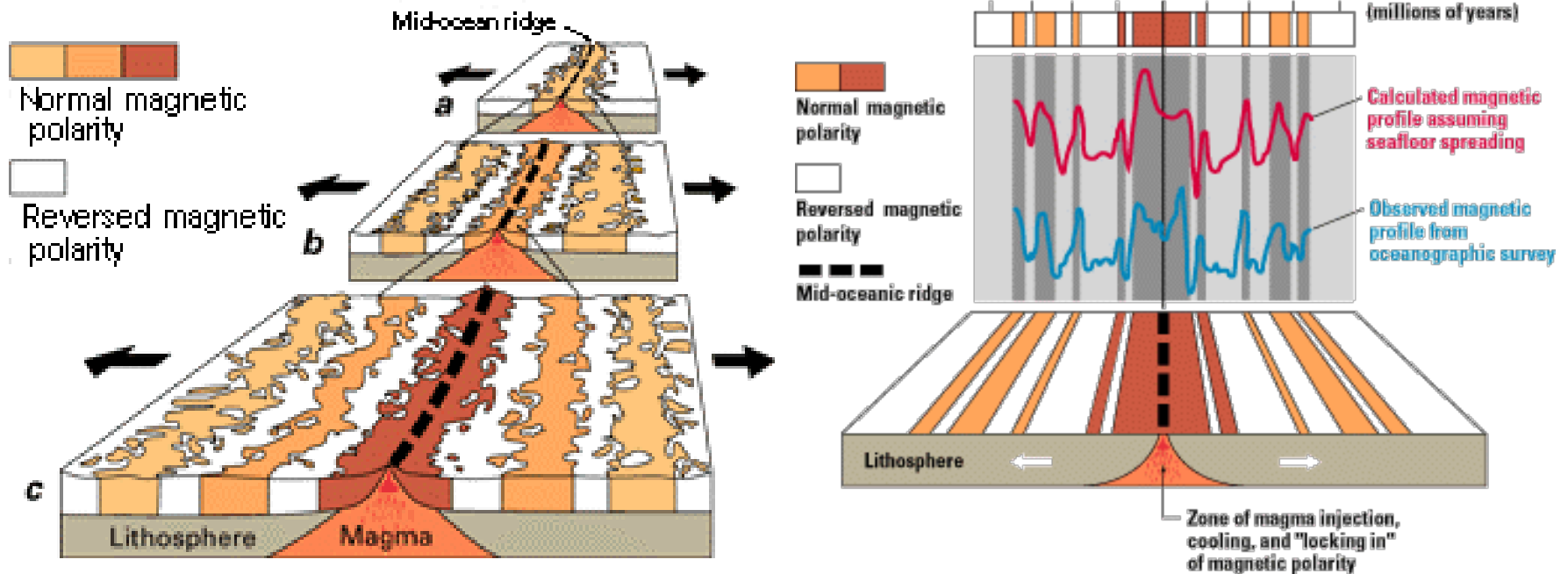


- 13th century BC
 - Chinese used a compass
 - Uses a magnetic needle
 - Probably an invention of Arabic or Indian origin
- 800 BC
 - Greeks
 - Discovered magnetite (Fe_3O_4) attracts pieces of iron

A Brief History of Magnetism



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

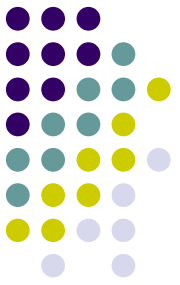


Figures by the USGS



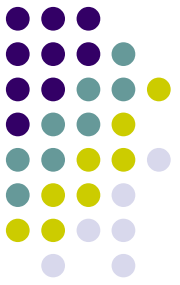
Magnetic Poles

- 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



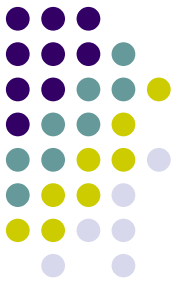
Magnetic Poles, final

- 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

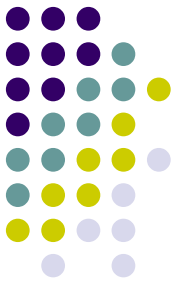
- Reminder: an electric field surrounds any electric charge
- The region of space surrounding any *moving* electric charge also contains a magnetic field
- A magnetic field also surrounds a magnetic substance making up a permanent magnet



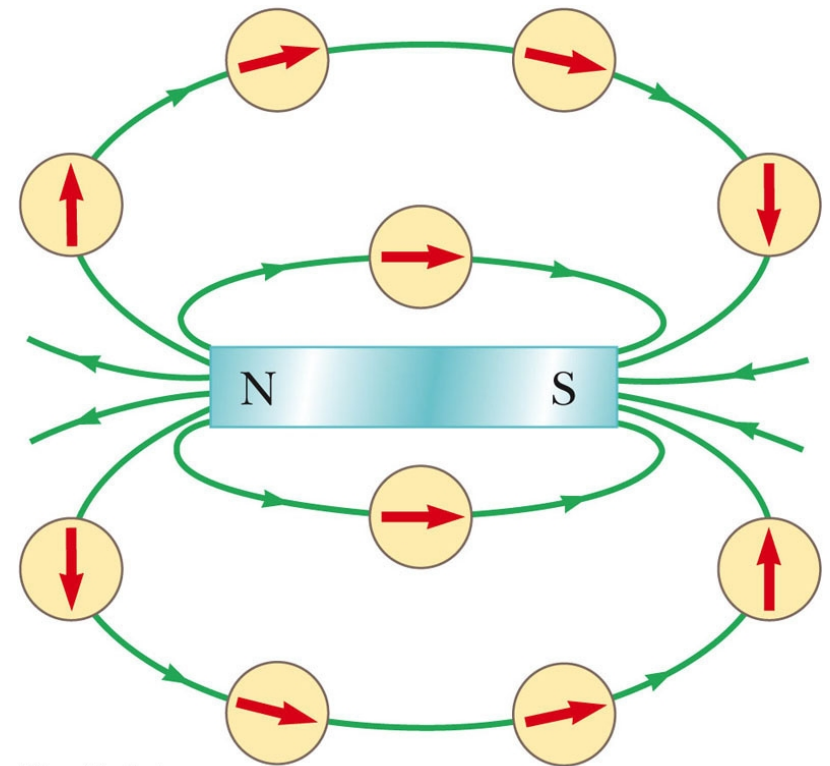
Magnetic Fields, cont.

- 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



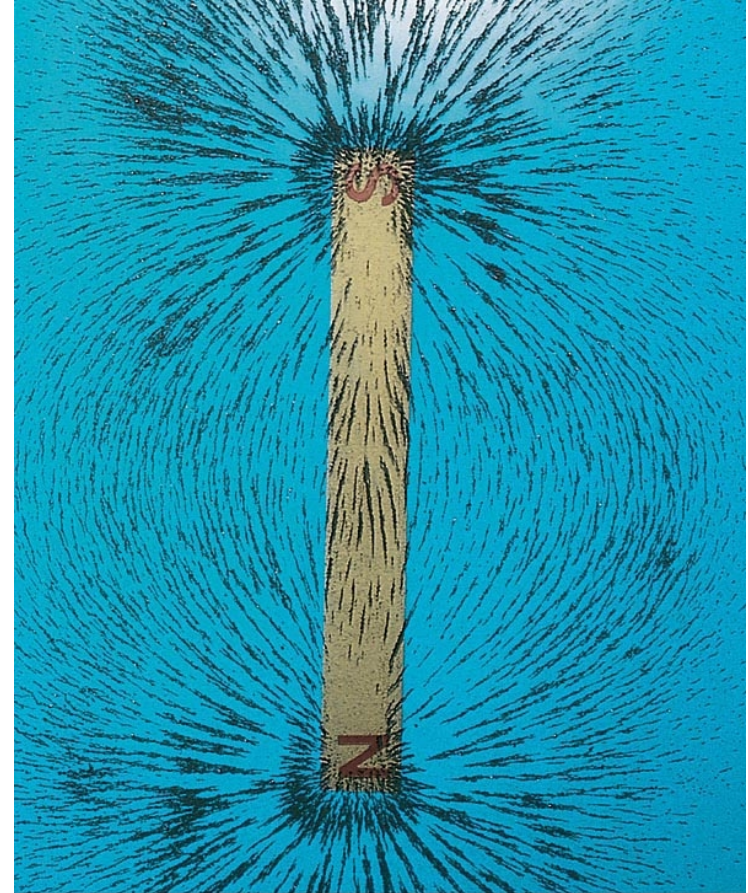
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Magnetic Field Lines, Bar Magnet



- 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

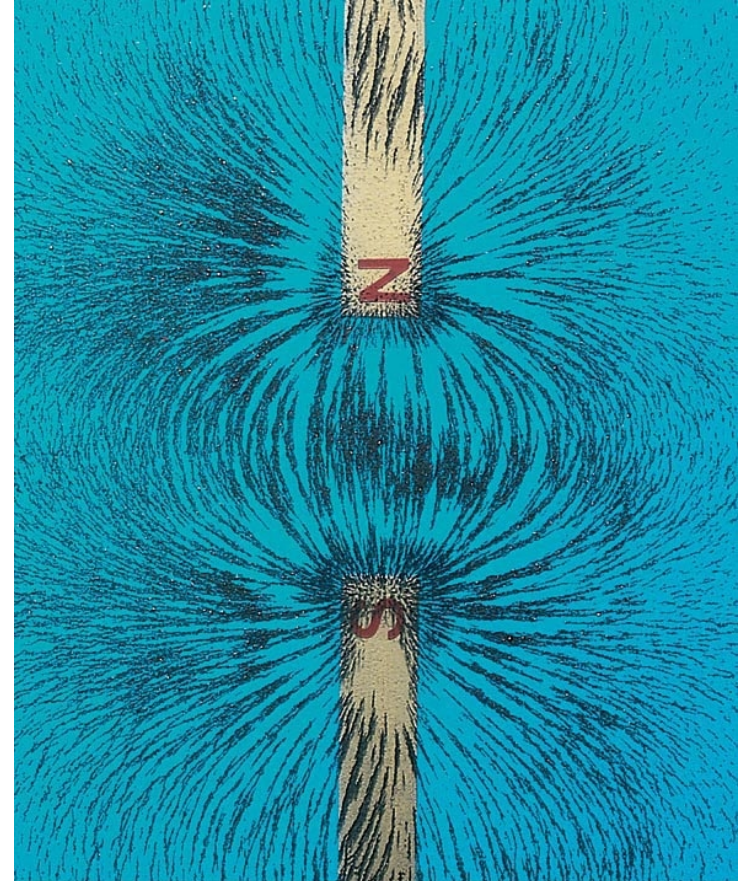


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Magnetic Field Lines, Unlike Poles

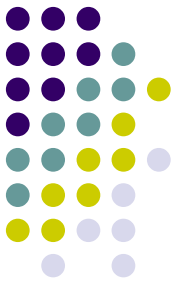


- Iron filings are used to show the pattern of the magnetic field lines
- The direction of the field is the direction a north pole would point
 - Compare to the electric field produced by an electric dipole

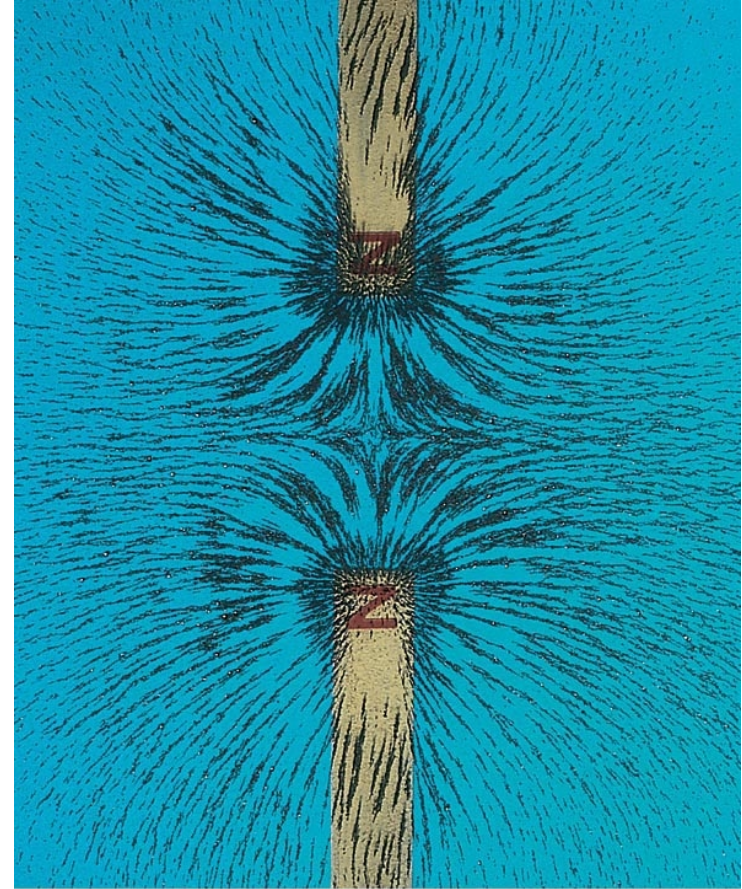


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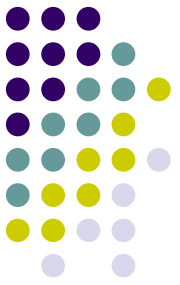
Magnetic Field Lines, Like Poles



- 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

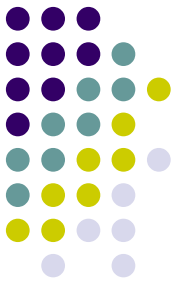
- The magnetic field at some point in space can be defined in terms of the magnetic force, \vec{F}_B
- The magnetic force will be exerted on a charged particle moving with a velocity, \vec{v}
 - Assume (for now) there are no gravitational or electric fields present

Force on a Charge Moving in a Magnetic Field



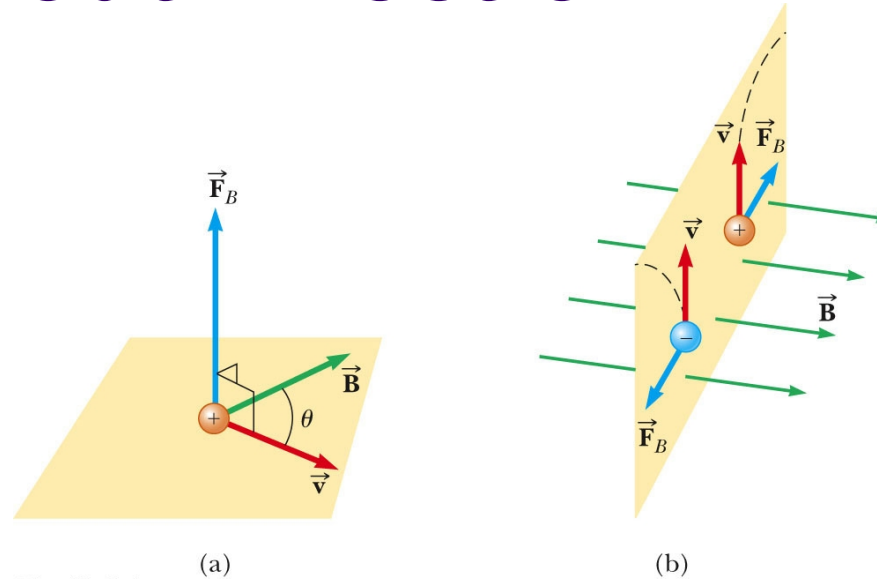
- The magnitude F_B of the magnetic force exerted on the particle is proportional to the charge, q , and to the speed, v , of the particle
- When a charged particle moves parallel to the magnetic field vector, the magnetic force acting on the particle is zero
- When the particle's velocity vector makes 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 θ is the angle the particle's velocity makes with the direction of the magnetic field

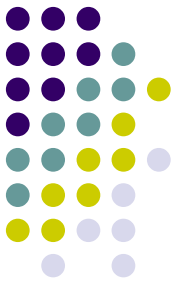
More About Direction



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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

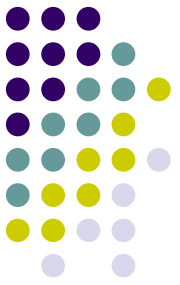
Force on a Charge Moving in a Magnetic Field, Formula



- The properties can be summarized in a vector equation:

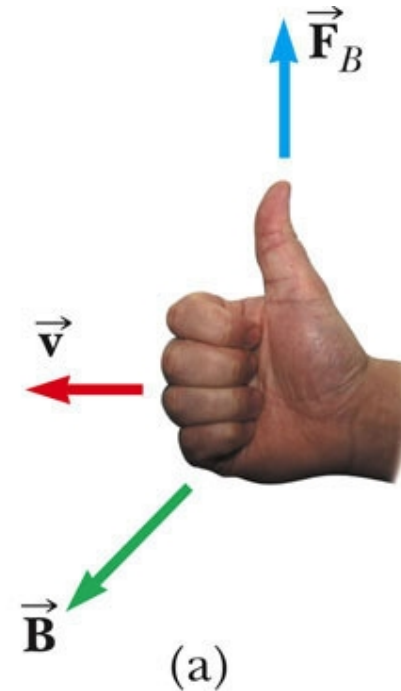
$$\vec{F}_B = q (\vec{v} \times \vec{B})$$

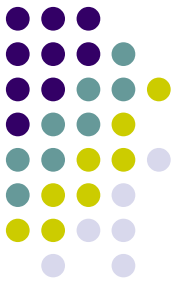
- \vec{F}_B is the magnetic force
- q is the charge
- \vec{v} is the velocity of the moving charge
- \vec{B} is the magnetic field



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.

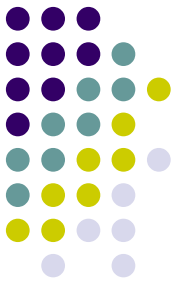




More About Magnitude of F

- The magnitude of the magnetic force on a charged particle is $F_B = |q| v B \sin \theta$
 - 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
 - $\theta = 90^\circ$

Differences Between Electric and Magnetic Fields

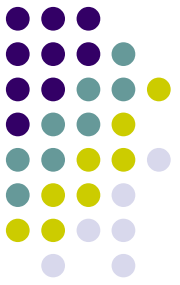


- Direction of force
 - The electric force acts along the direction of the electric field
 - The magnetic force acts perpendicular to the magnetic field
- Motion
 - The electric force acts on a charged particle regardless of whether the particle is moving
 - The magnetic force acts on a charged particle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



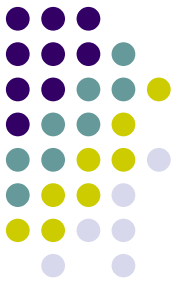
Work in Fields, cont.

- 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



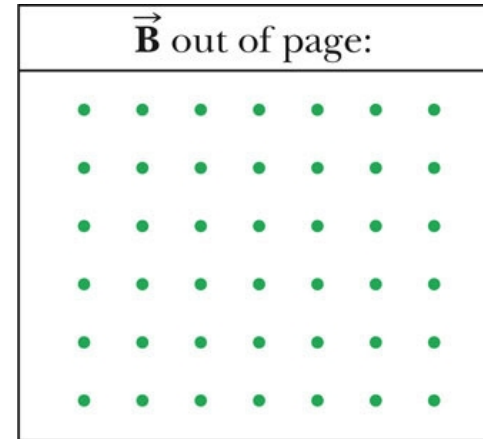
Units of Magnetic Field

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

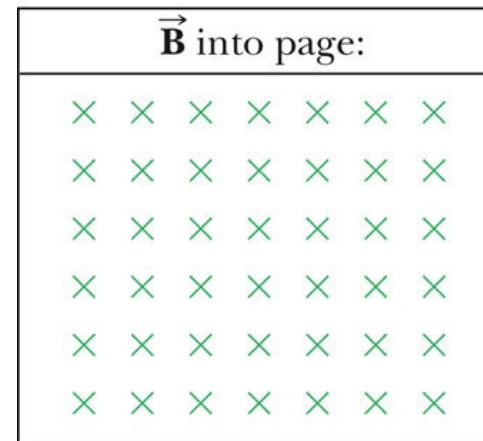


Notation Notes

- 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

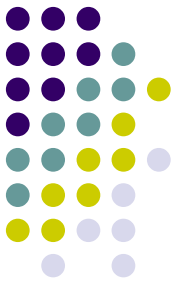


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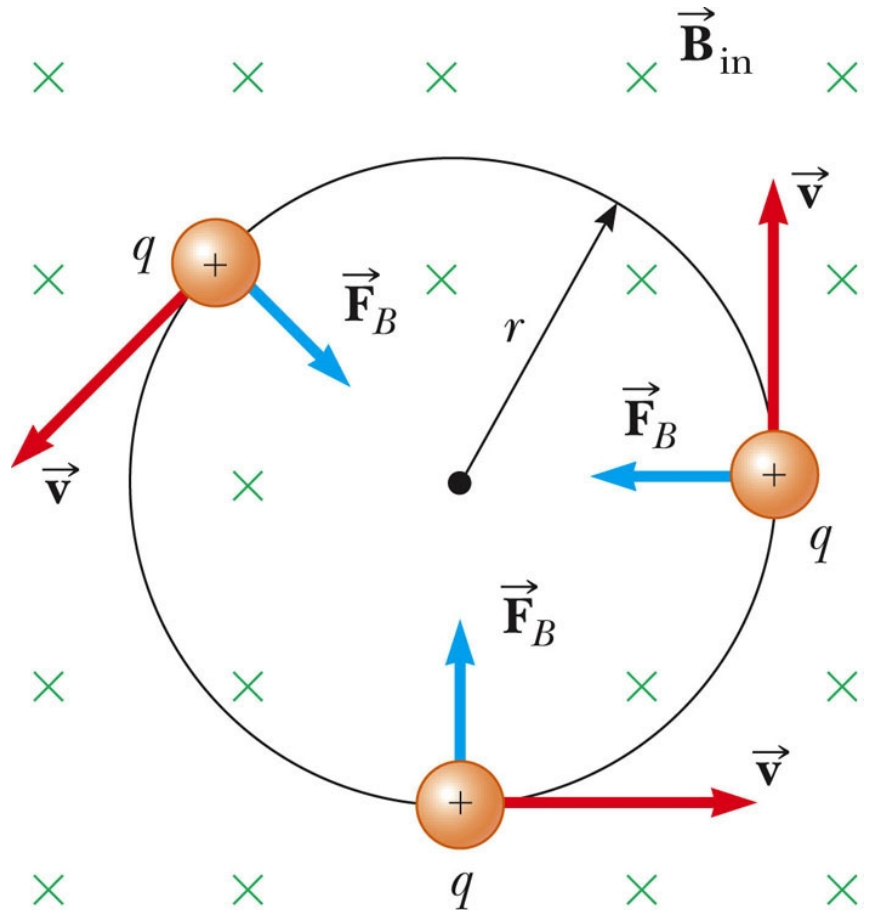


(b)

Charged Particle in a Magnetic Field

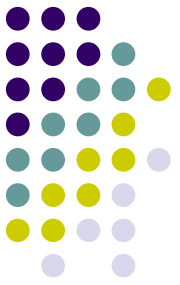


- Consider a particle moving in an external magnetic field with its velocity perpendicular to the field
- The force is always directed toward the center of the circular path
- The magnetic force causes a centripetal acceleration, changing the direction of the velocity of the particle



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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



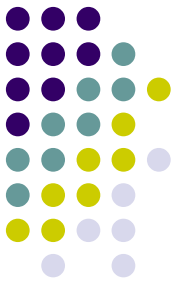
- The angular speed of the particle is

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

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

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

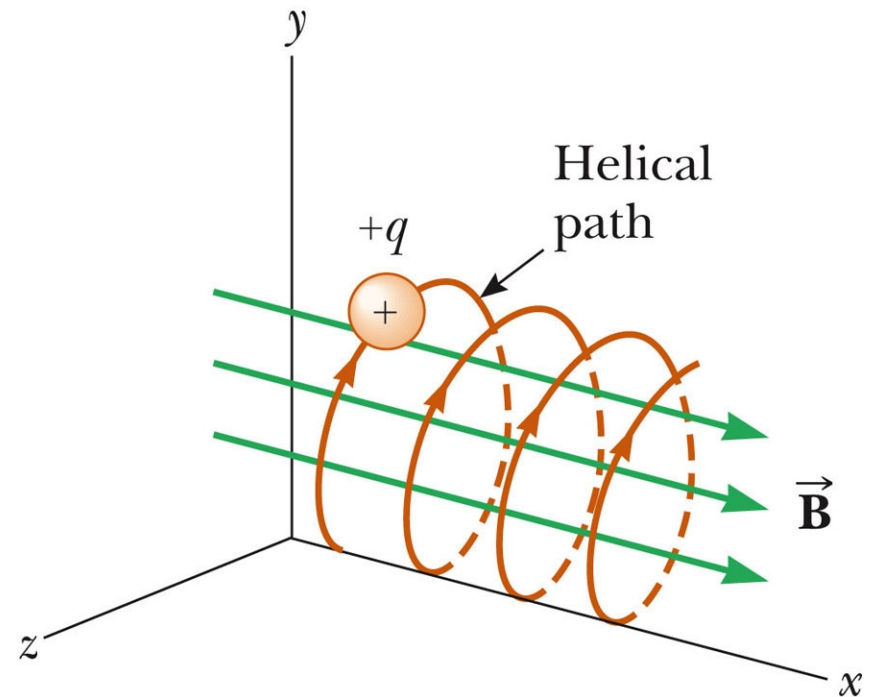
Motion of a Particle, General



- 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

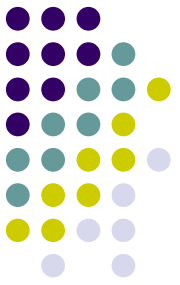
$$v_{\perp} = \sqrt{v_y^2 + v_z^2}$$

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



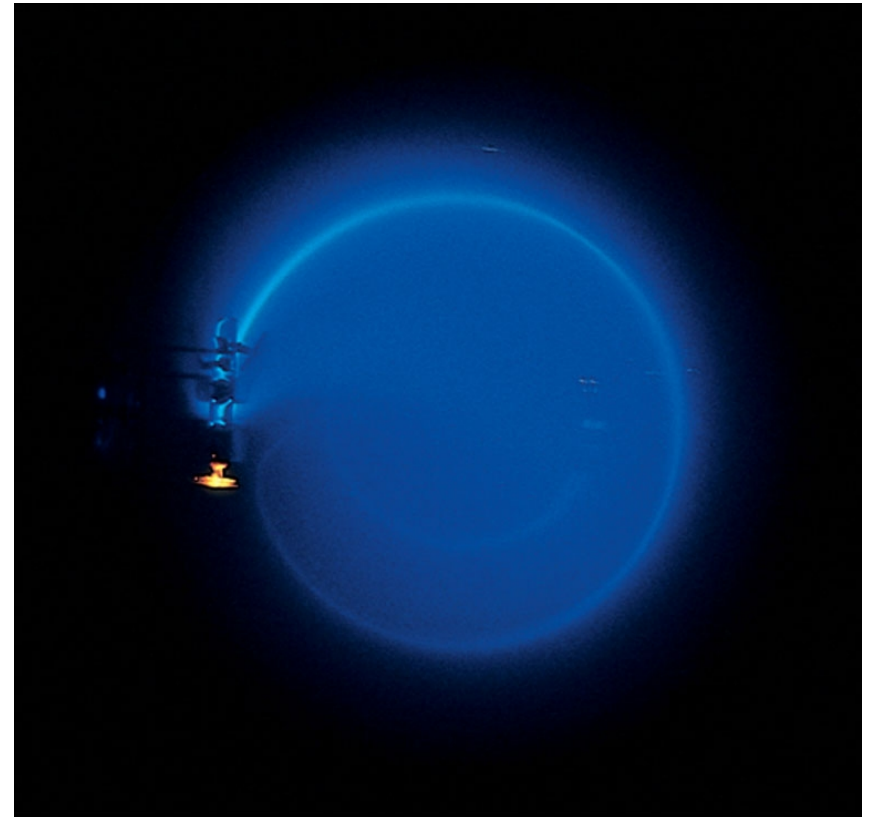
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Bending of an Electron Beam

- 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

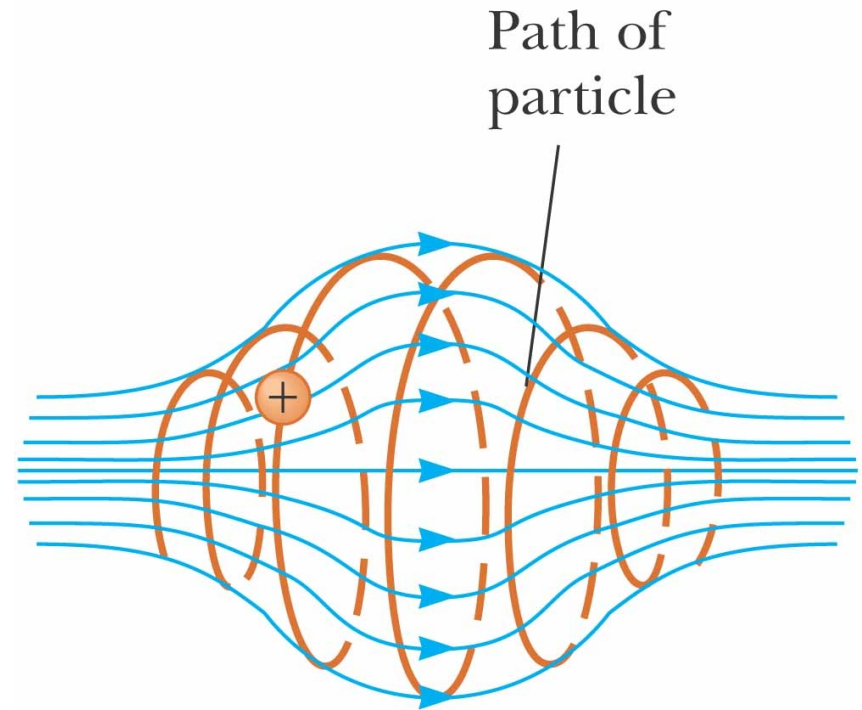


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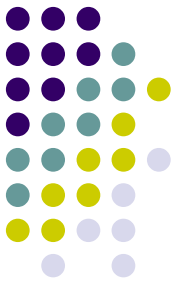
Particle in a Nonuniform Magnetic Field



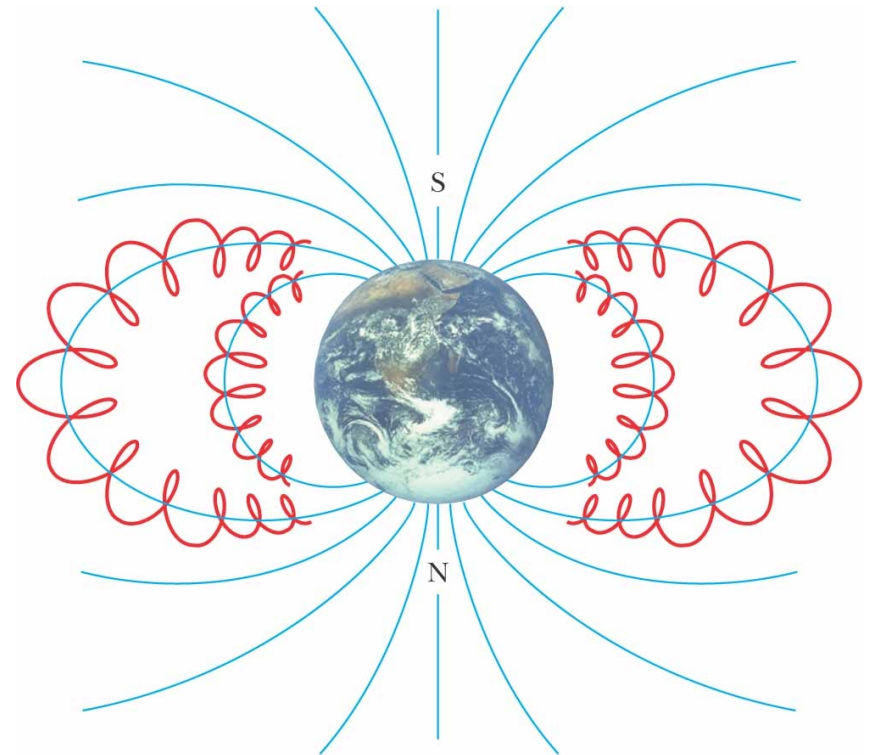
- The motion is complex
- For example, the particles can oscillate back and forth between two positions
- This configuration is known as a *magnetic bottle*



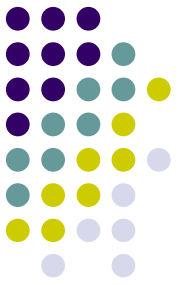
Van Allen Radiation Belts



- 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

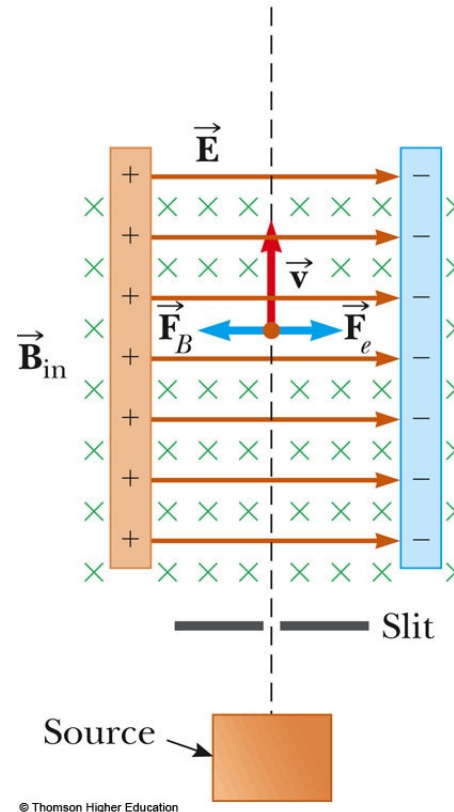


- In many applications, charged particles will move in the presence of both magnetic and electric fields
- In that case, the total force is the sum of the forces due to the individual fields
- In general:

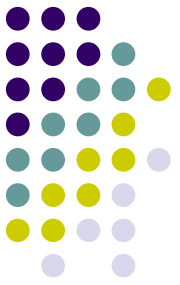
$$\vec{F} = q \left\{ \vec{E} + (\vec{v} \times \vec{B}) \right\}$$

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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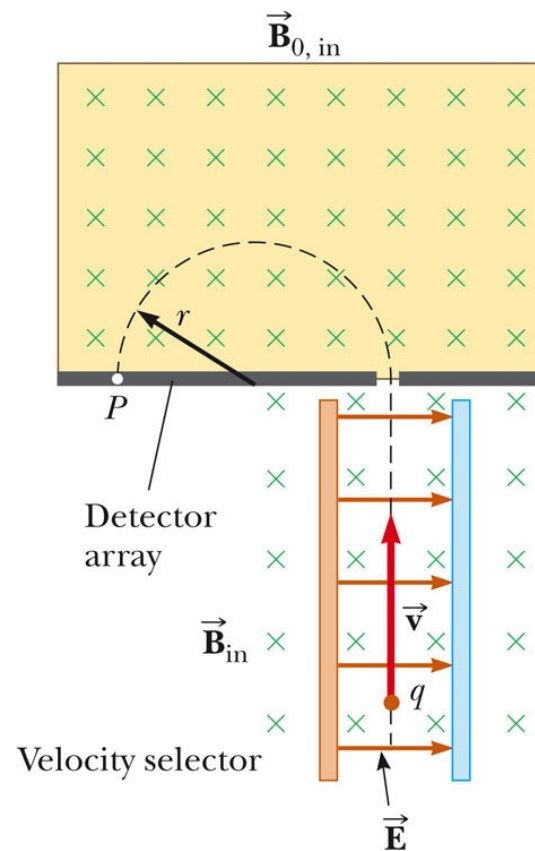


Velocity Selector, cont.

- 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
$$v = E / B$$

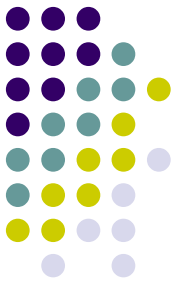
Mass Spectrometer

- 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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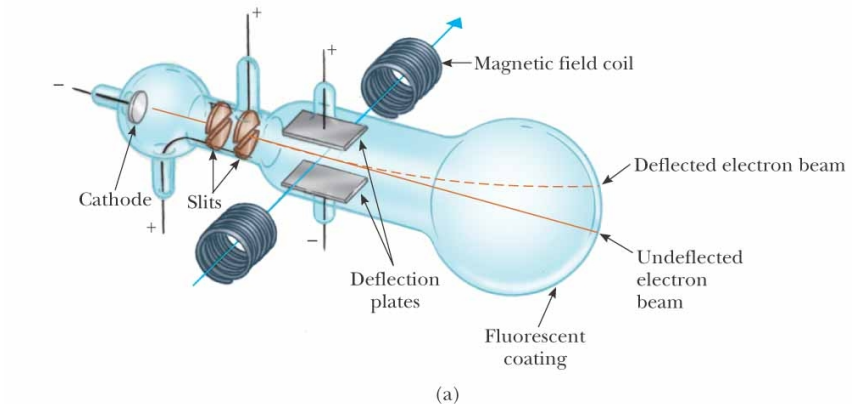
Mass Spectrometer, cont.

- 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

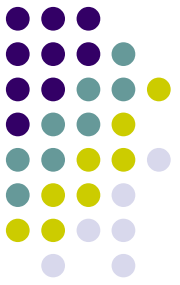
Thomson's e/m Experiment



- 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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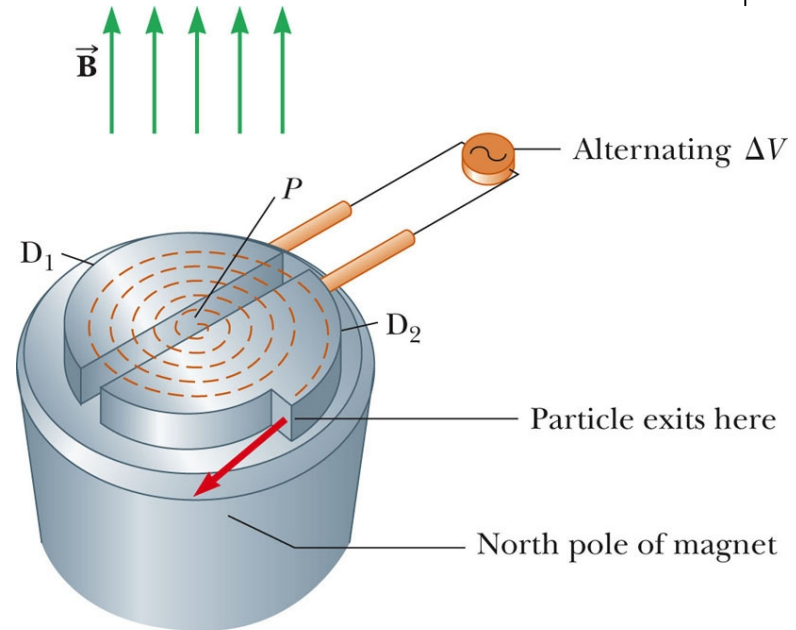


Cyclotron

- 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)

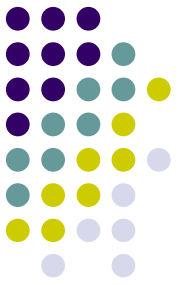
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(b)

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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

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

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

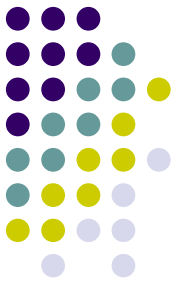
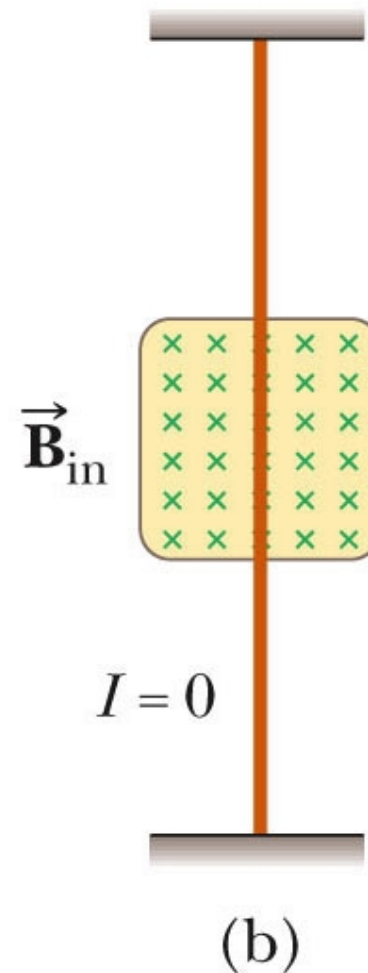
Magnetic Force on a Current Carrying Conductor



- 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

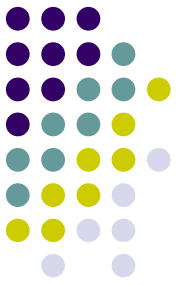
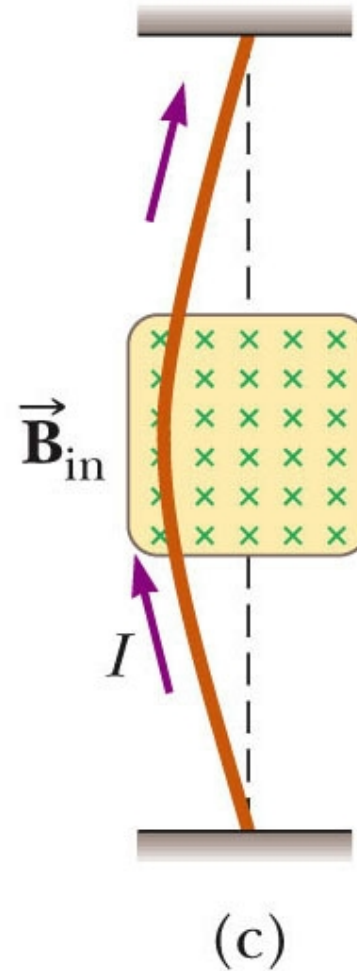
Force on a Wire

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



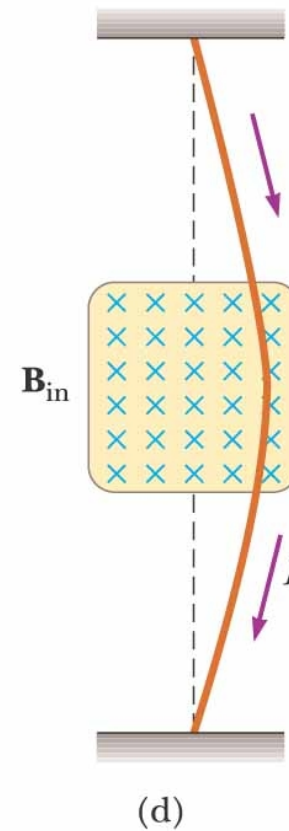
Force on a Wire (2)

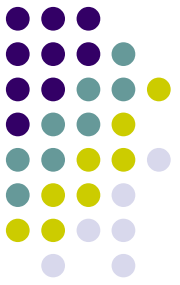
- The magnetic field is into the page
- The current is up the page
- The force is to the left



Force on a Wire, (3)

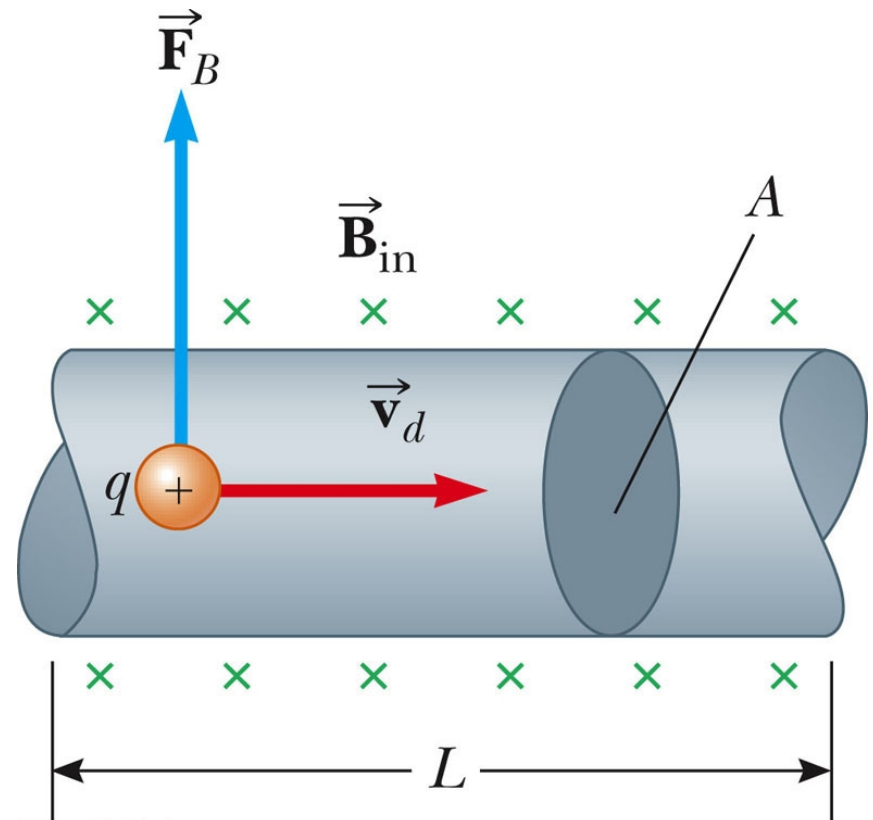
- The magnetic field is into the page
- The current is down the page
- The force is to the right





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
 - $\vec{F}_{tot} = q (\vec{v}_d \times \vec{B}) nAL$





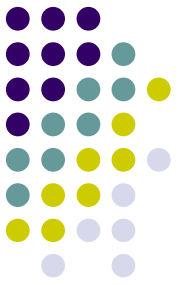
Force on a Wire, (4)

- 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

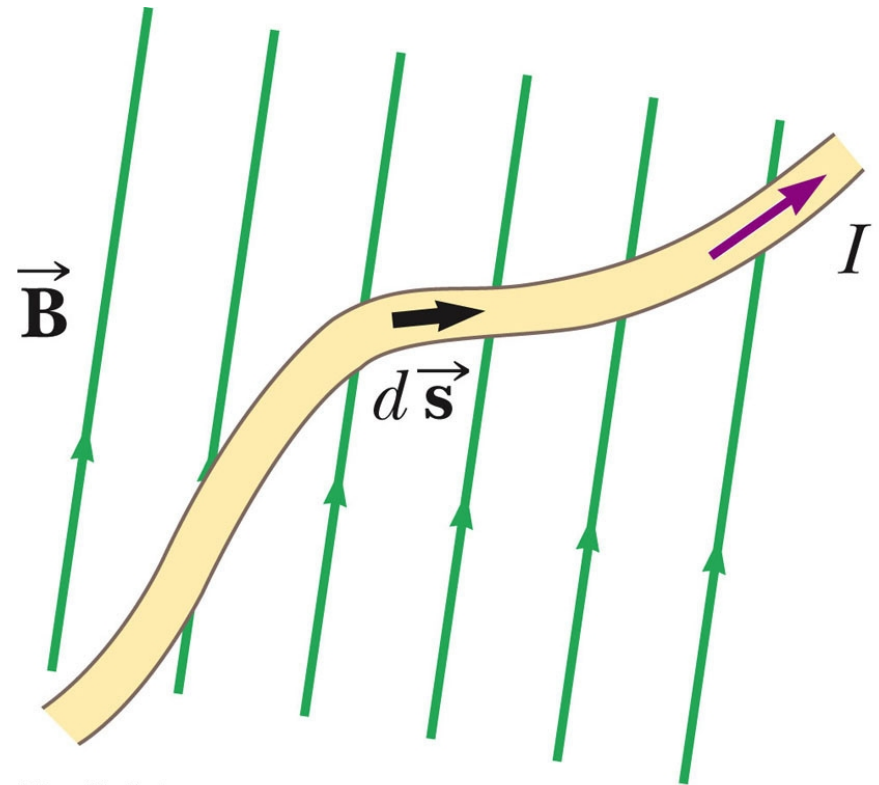


- Consider a small segment of the wire,
- The force exerted on this segment is

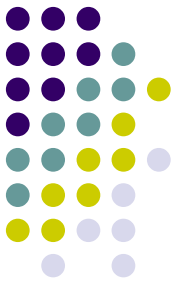
$$d\vec{F}_B = I d\vec{s} \times \vec{B}$$

- The total force is

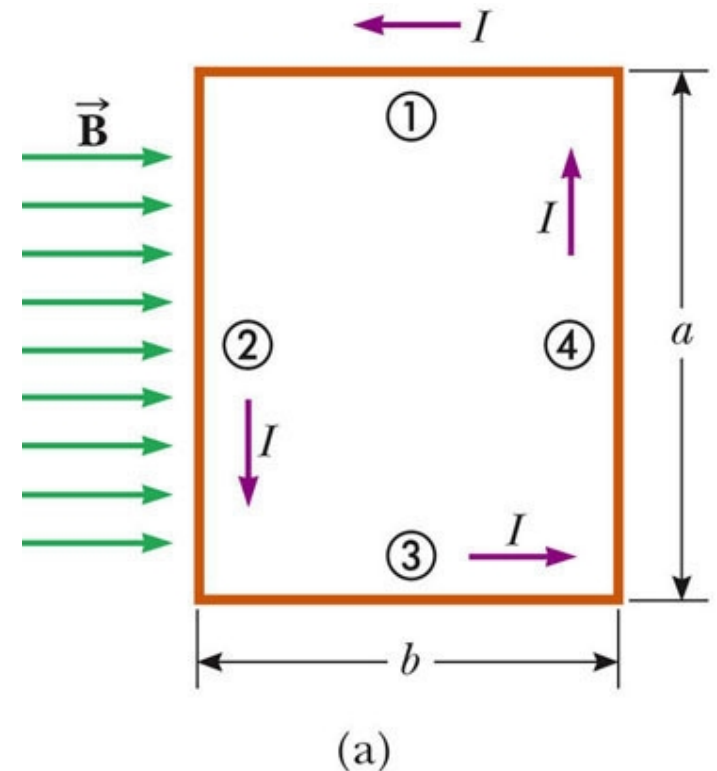
$$\vec{F}_B = \int I d\vec{s} \times \vec{B}$$



Torque on a Current Loop



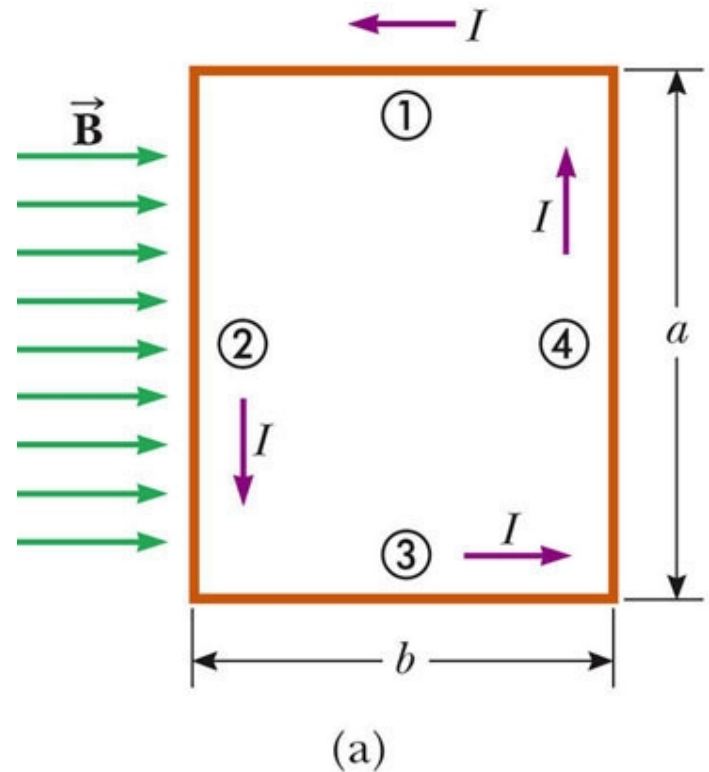
- The rectangular loop carries a current I in a uniform magnetic field
- No magnetic force acts on sides 1 & 3
 - The wires are parallel to the field and $\mathbf{\Lambda} \cdot \mathbf{B} = 0$



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

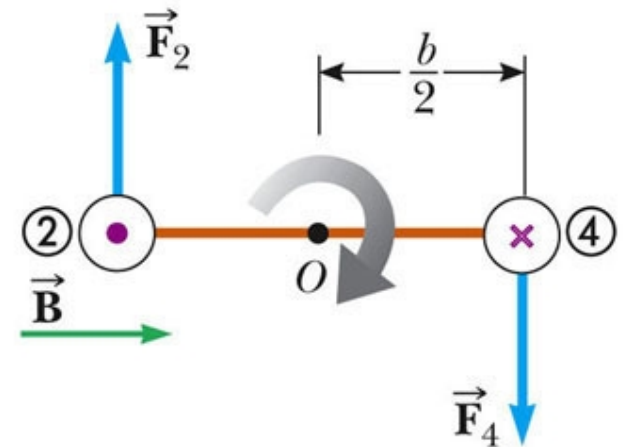


Torque on a Current Loop, 3



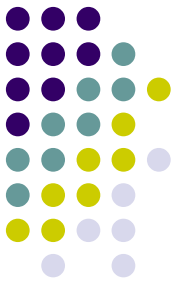
- The forces are equal and in opposite directions, but not along the same line of action
- The forces produce a torque around point O

View loop from **below**:



(b)

Torque on a Current Loop, Equation



- The maximum torque is found by:

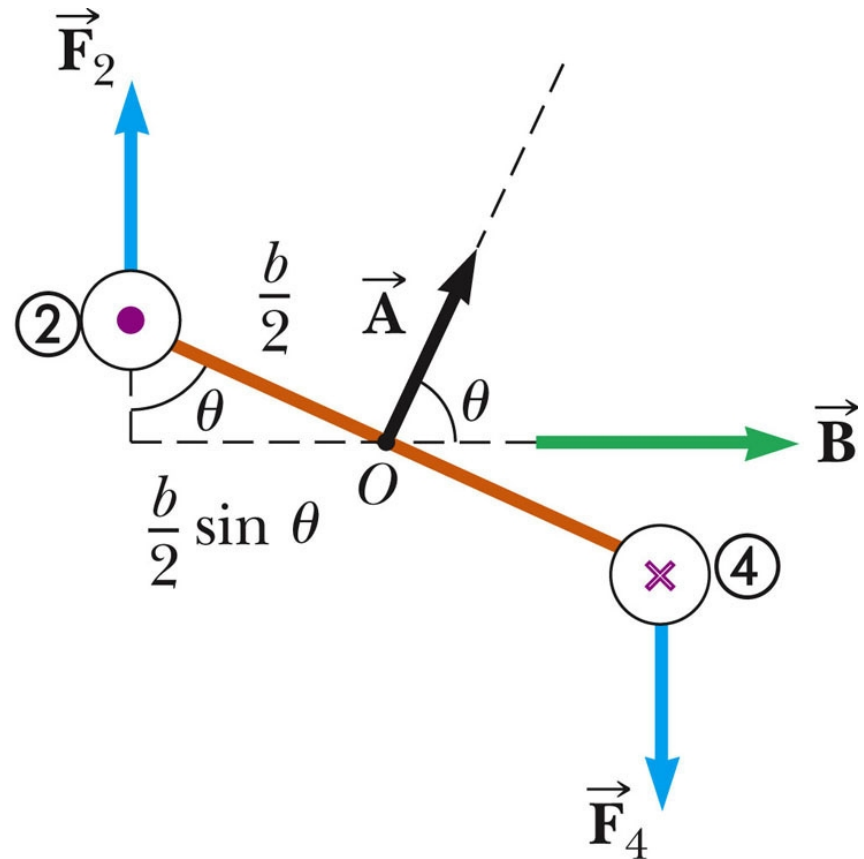
$$\tau = IaB \frac{b}{2} + IaB \frac{b}{2} = IaBb$$

- 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



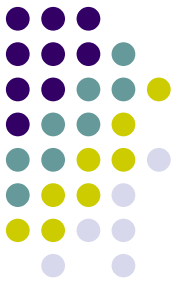
- The torque has a maximum value when the field is perpendicular to the normal to the plane of the loop
- The torque is zero when the field is parallel to the normal to the plane of the loop
- $\tau = I \vec{A} \times \vec{B}$ where \vec{A} is perpendicular to the plane of the loop and has a magnitude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



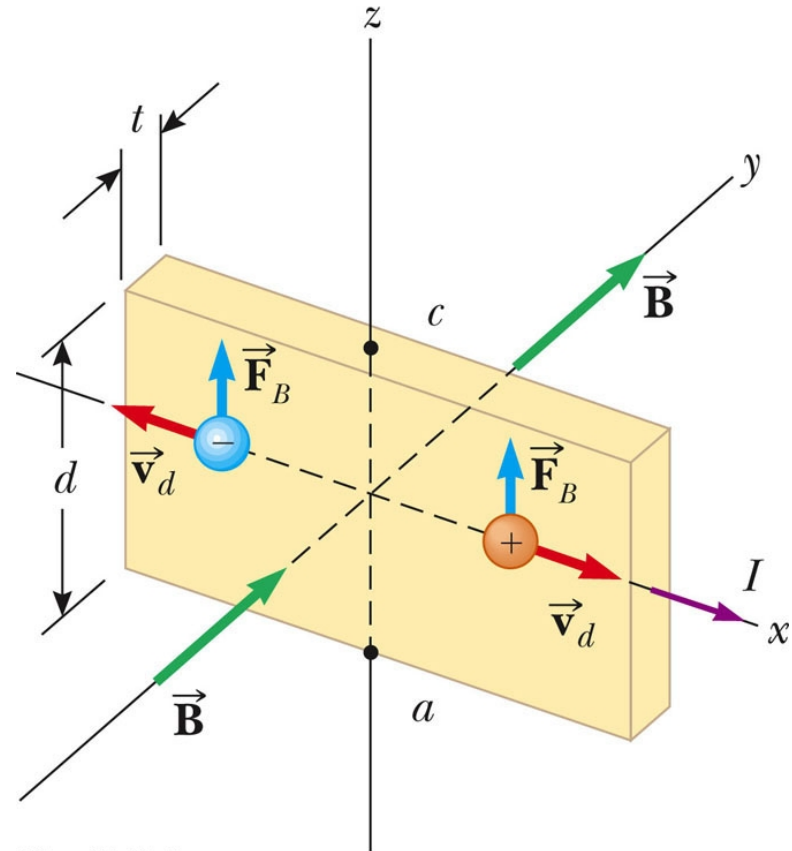
Hall Effect, cont.

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

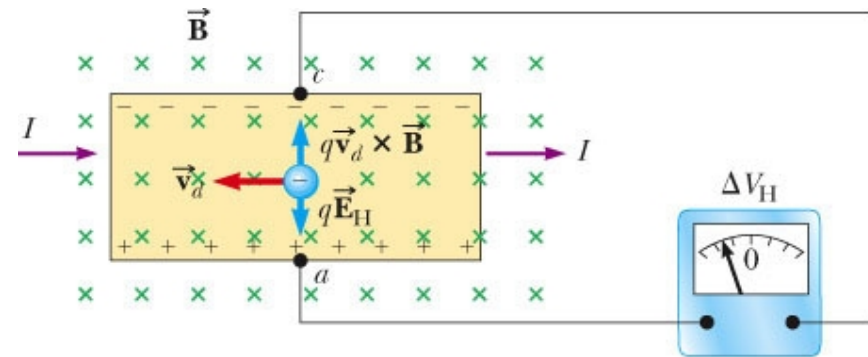
Hall Voltage



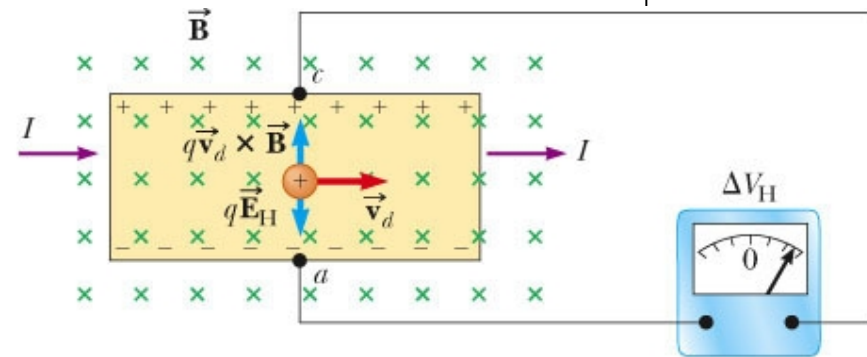
- This shows an arrangement for observing the Hall effect
- The Hall voltage is measured between points a and c



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