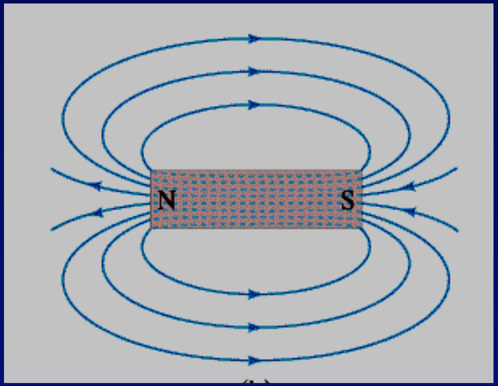
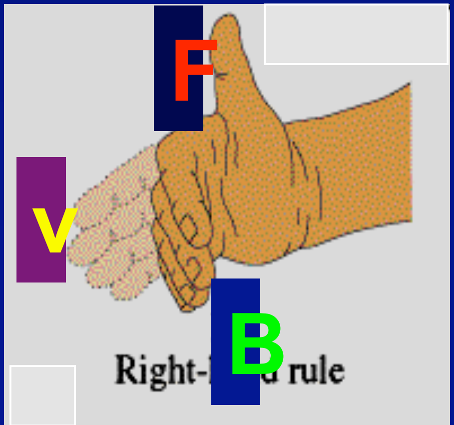
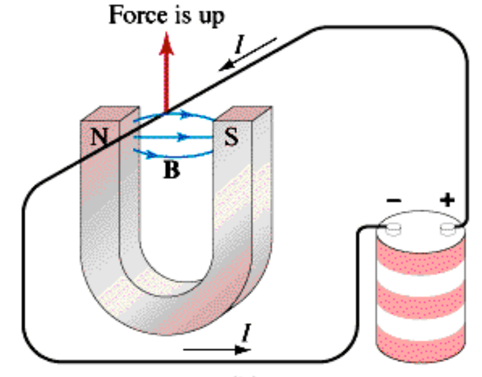
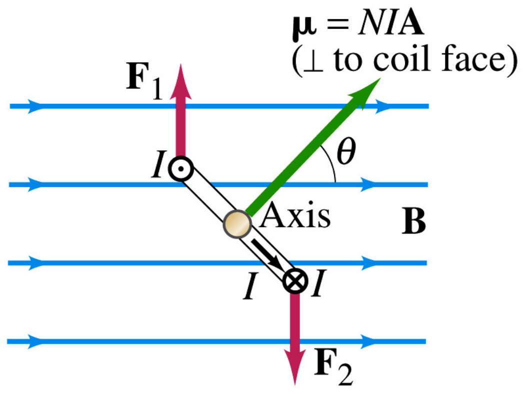
Chapter 27
Magnetic Field and Magnetic Forces

- Magnets and Magnetic Fields
- Magnetic force (Lorentz force)
  - force on a moving charge
  - force on a current in a wire
  - torque on a current loop
- mass spectrometer









Magnetism

New Topic

Magnetism

- Natural magnets were observed by Greeks more than 2500 years ago in *"Magnesia"* (northern Greece)
  - certain type of stone (lodestone) exert forces on similar stones
  - Small lodestone suspended with a string aligns itself in a north-south direction due to ***Earth's magnetic field!***

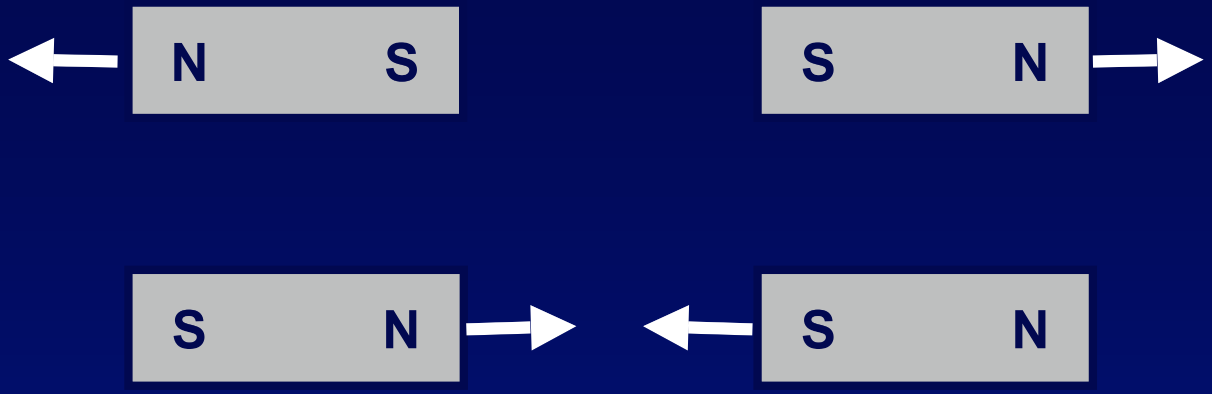
Direction of Magnetic Field

Drawing vectors in 3D

out of ⊙ page

in to ⊗ page

Bar Magnets

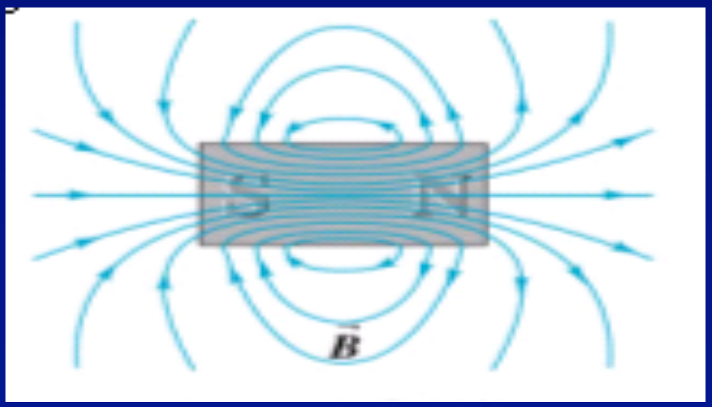


like poles repel

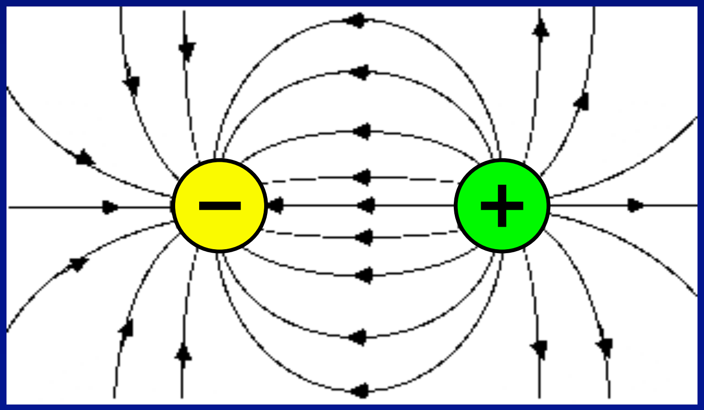
unlike poles attract

How do the magnets exert forces on each other?

via the magnetic field



Magnetic Dipole

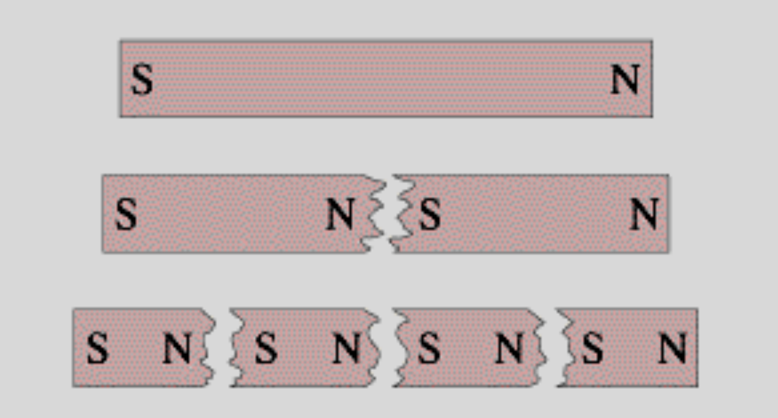


Electric Dipole

Isolated Magnetic “Poles”?

- Can you have an isolated magnetic pole (called: *magnetic monopole*)?
  - it would be a magnetic North or a South Pole all by itself! (just like an electric + or - charge)
- How can we isolate this magnetic charge?

Simple, right? Try cutting a bar magnet in half:

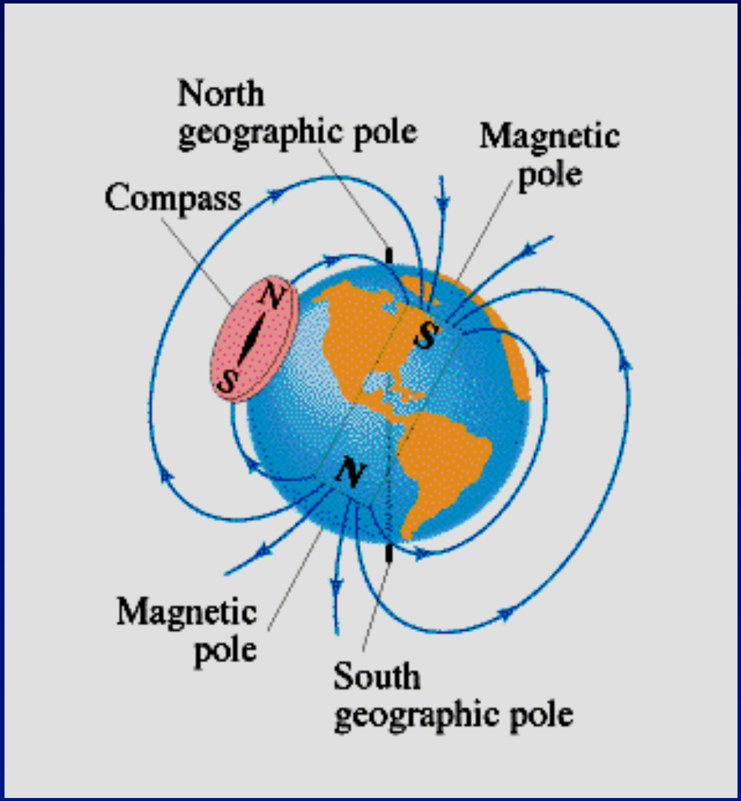


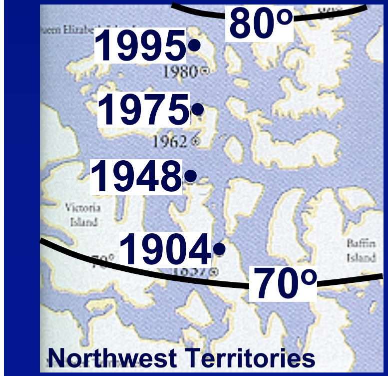
What you get is a bunch of little magnets!

No attempt yet has been successful in finding magnetic monopoles in nature!

Earth is a big magnet!

- The North pole of a small magnet (compass) points towards geographic North because Earth's magnetic South pole is up there!!





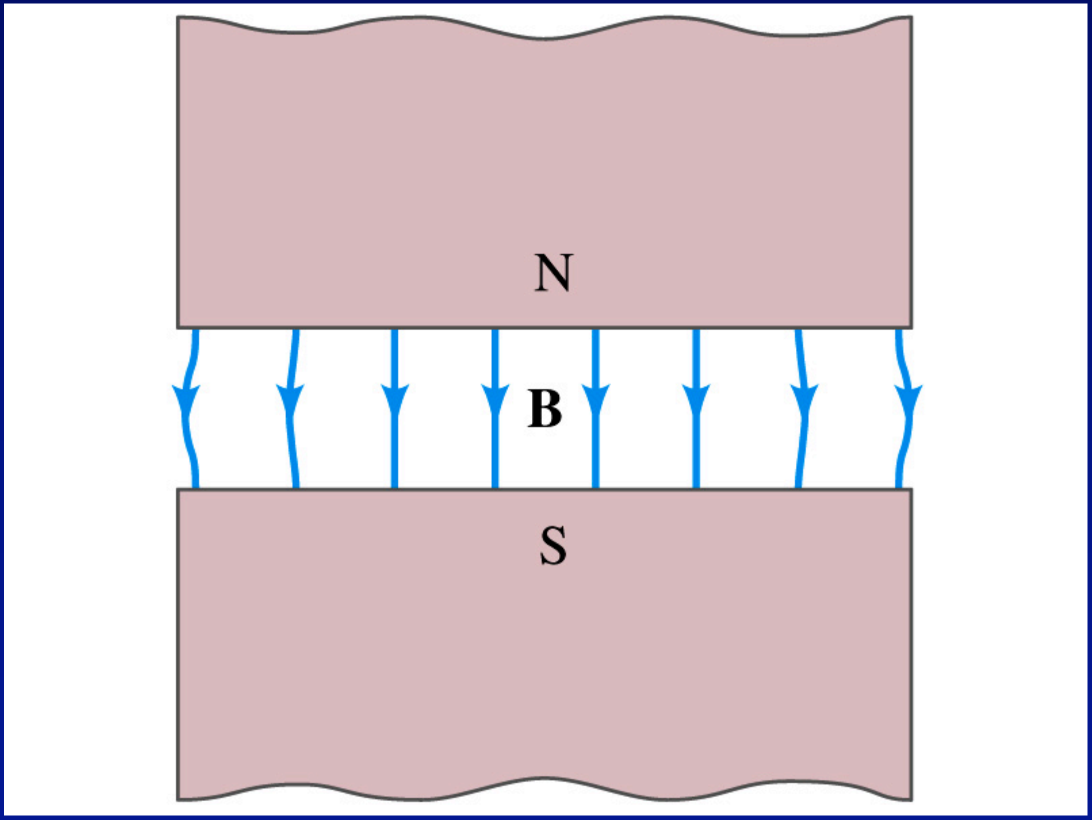
The magnetic pole is not at geographic north

compass corrections needed

The magnetic poles drift, and reverse polarity

Uniform Magnetic Field

- Magnetic field between two large poles of a magnet is nearly uniform except for the edges.



Magnetic Force

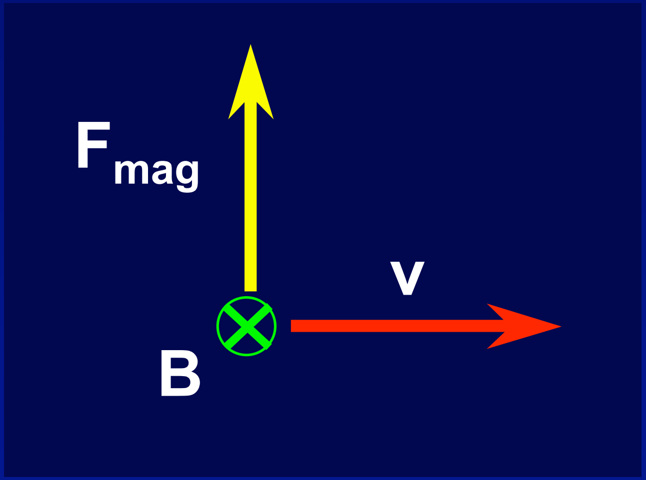
New Topic

The Magnetic Force

- What happens if you put a charged particle in a magnetic field?
  - it experiences a *magnetic force*! (Lorentz force)
- Magnitude depends on
  - Charge q
  - Velocity v
  - Field B
  - Angle between v and B

$$F_{magnetic} = q\,v\,B\,\sin\theta$$

- Direction is *"sideways"*
  - force is perpendicular to both v and B!

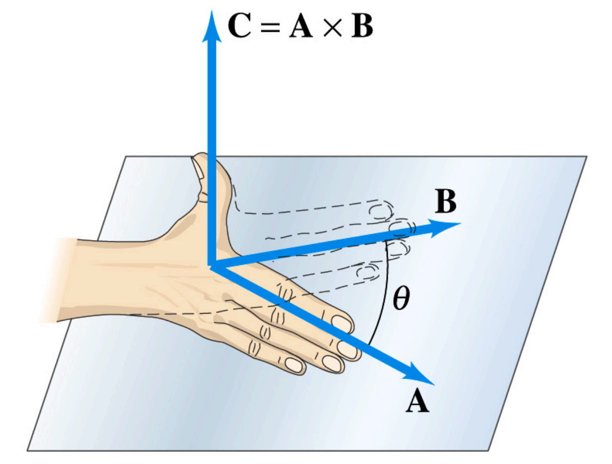


- Vector cross product

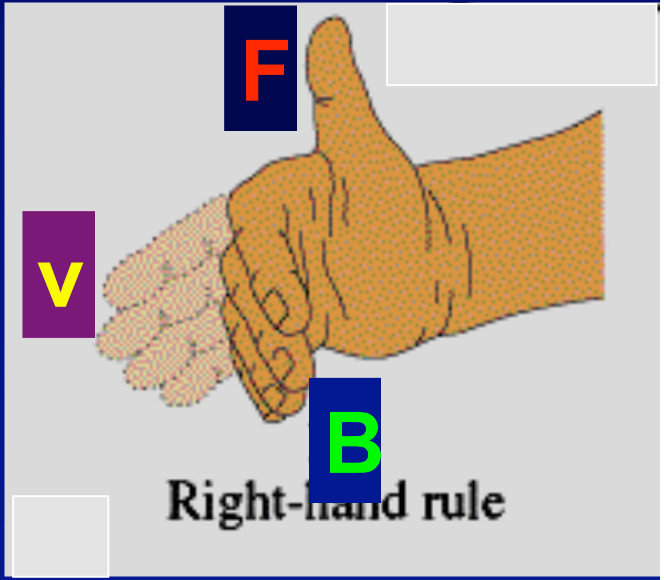
$$\vec{F} = q\vec{v} \times \vec{B}$$

Direction of the Magnetic Force

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



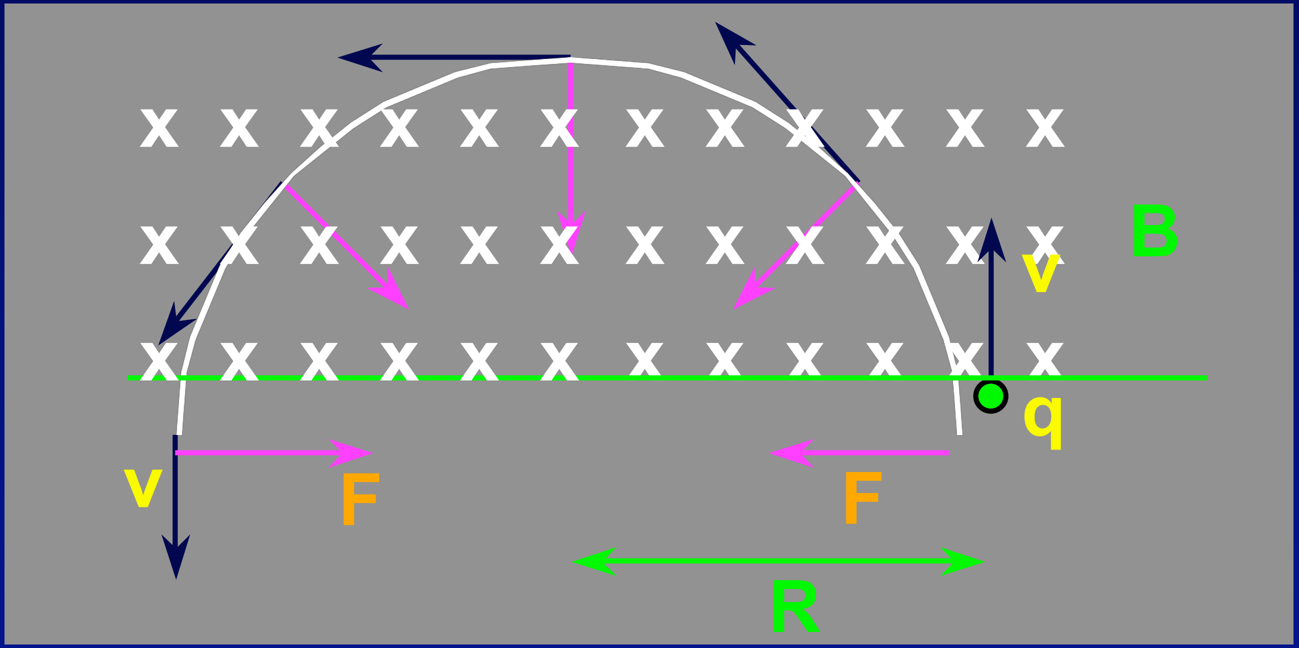
- Use the right-hand rule:
  - point your fingers along the direction of velocity
  - curl your fingers towards the magnetic field vector
  - your thumb will then point in the direction of the force



- Reverse direction if it's a negative charge!

Trajectory of a Charged Particle in a Constant Magnetic Field

- Suppose charge **+q** enters **B** field with velocity **v** in a perpendicular way. What will be the path followed by **q**?



- **Force** is always ⊥ to **velocity** and **B**.

Path will be a circle. F is the centripetal force needed to keep the charge in its circular orbit. Let's calculate radius R:

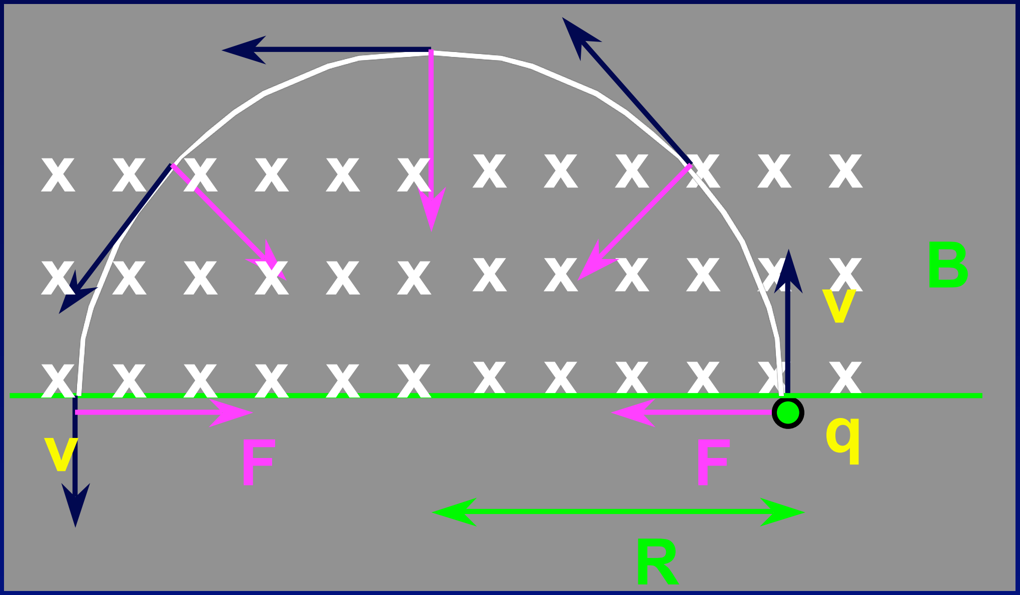
Radius of Circular Orbit

magnetic force:

$$F = qvB$$

centripetal force:

$$F = m\frac{v^2}{R}$$



$$\Rightarrow \quad qvB = m\frac{v^2}{R}$$

$$\Rightarrow \quad \boxed{R = \frac{mv}{qB}}$$

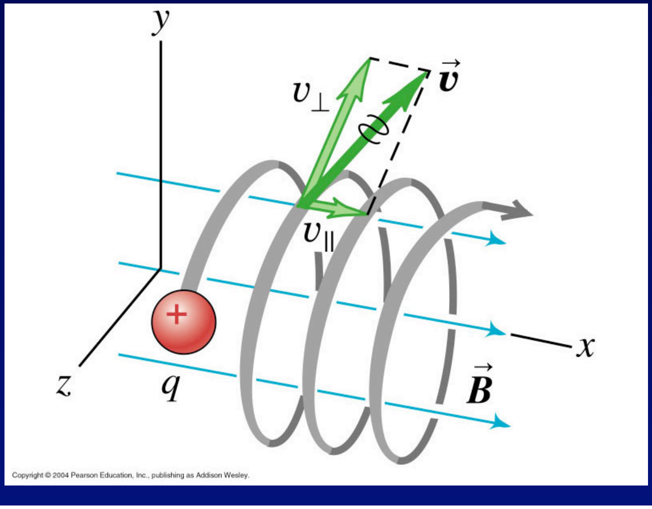
This is an important result:

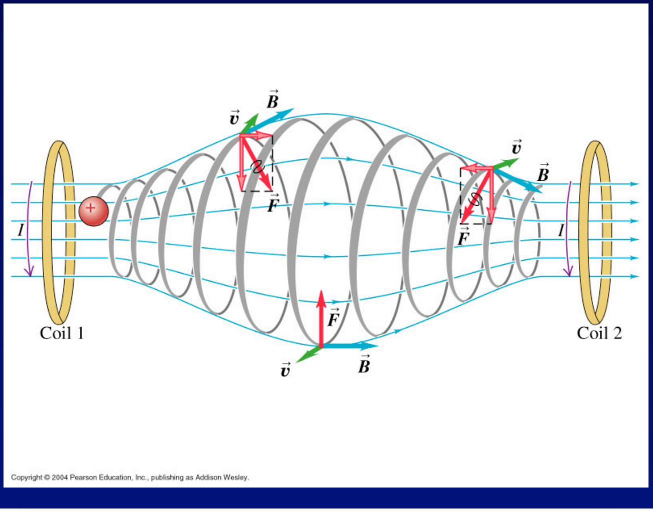
It relates atomic quantities (m and q) to quantities we can measure (R, v, B) in a lab.

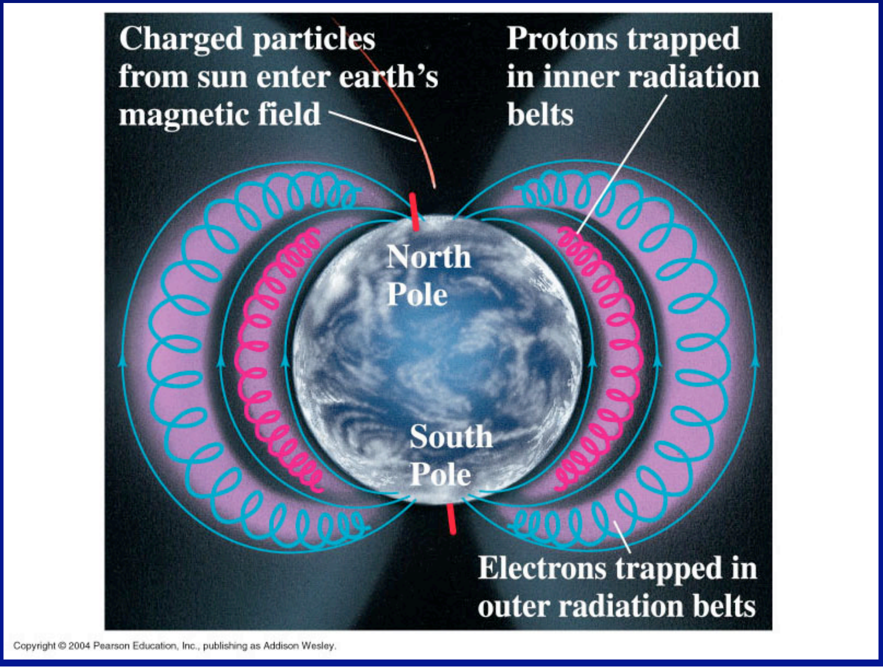
What happens if the charged particle enters the field at an general angle (3-dimensional) ?

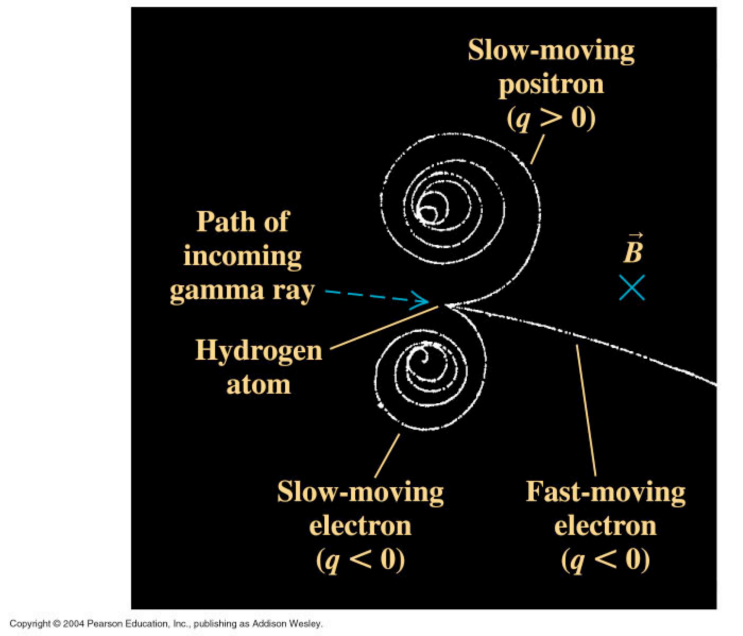
It spirals!

magnetic bottle





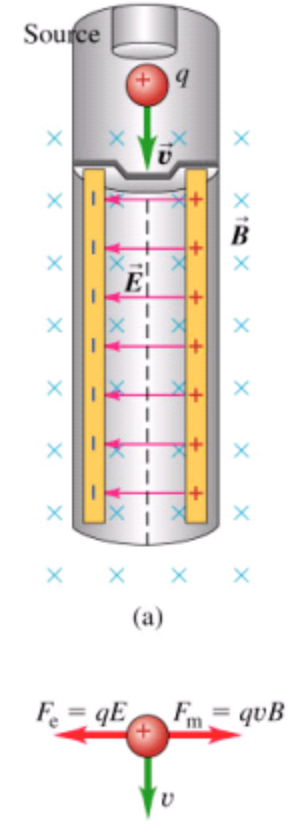




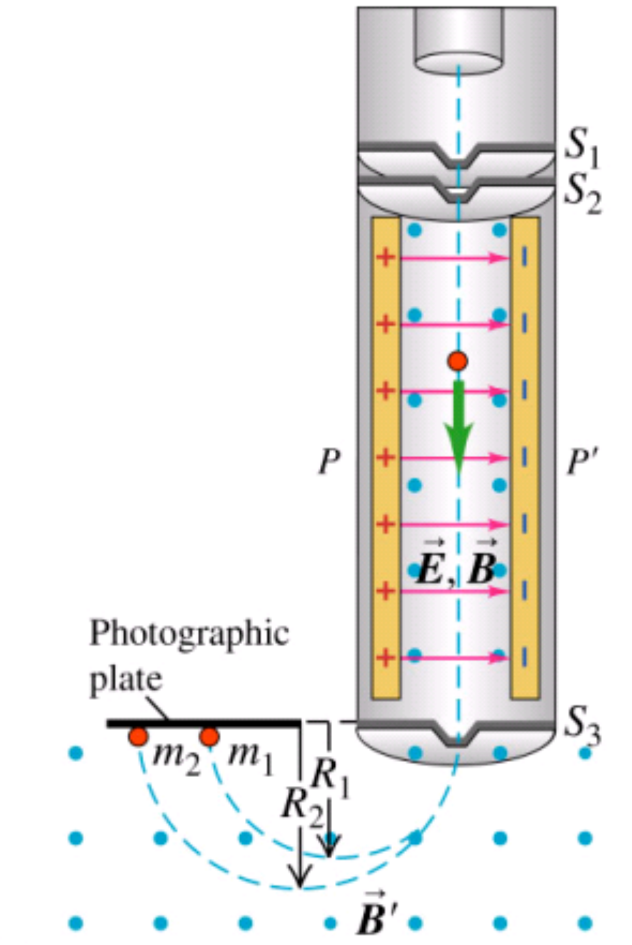
What if both the electric and magnetic fields are present?

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

- *Velocity selector*
  - q E = q v B
  - v = E / B
- *Only those charged particles with v=E/B can pass through.*



Mass Spectrometer



- *Velocity selector*
  - q E = q v B
  - v = E / B
- *Only those particles with v can pass through.*

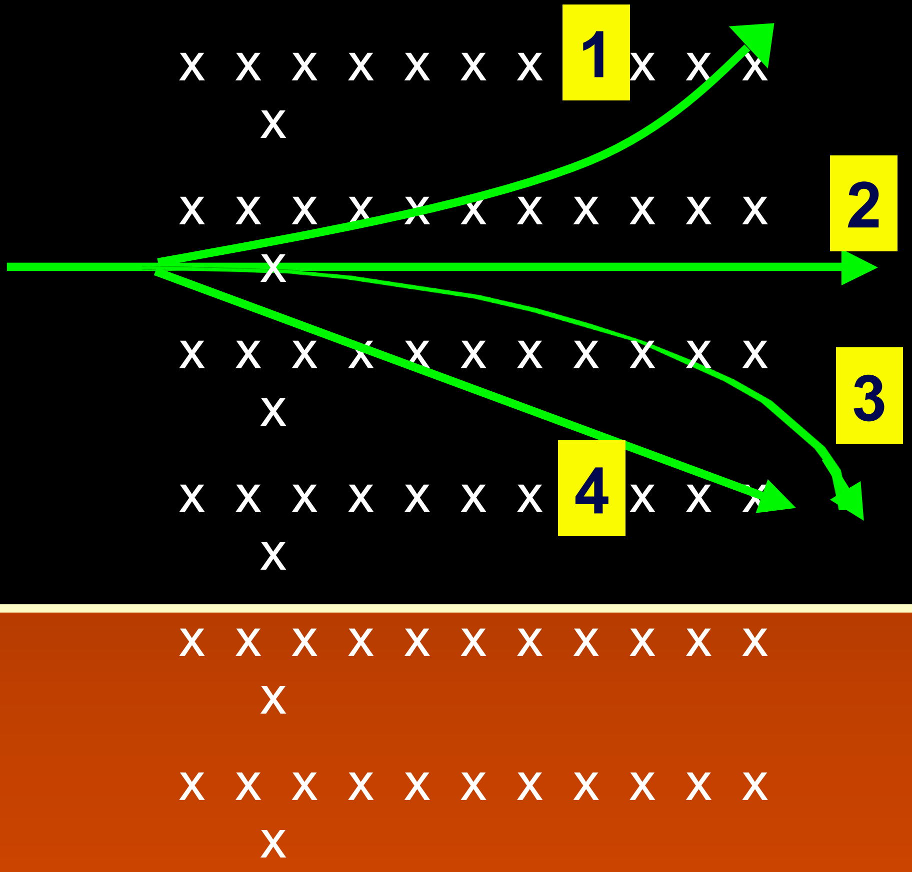
- **Bending in a magnetic field**

$$qvB' = mv^2 / r$$

$$m = qBB'r / E$$

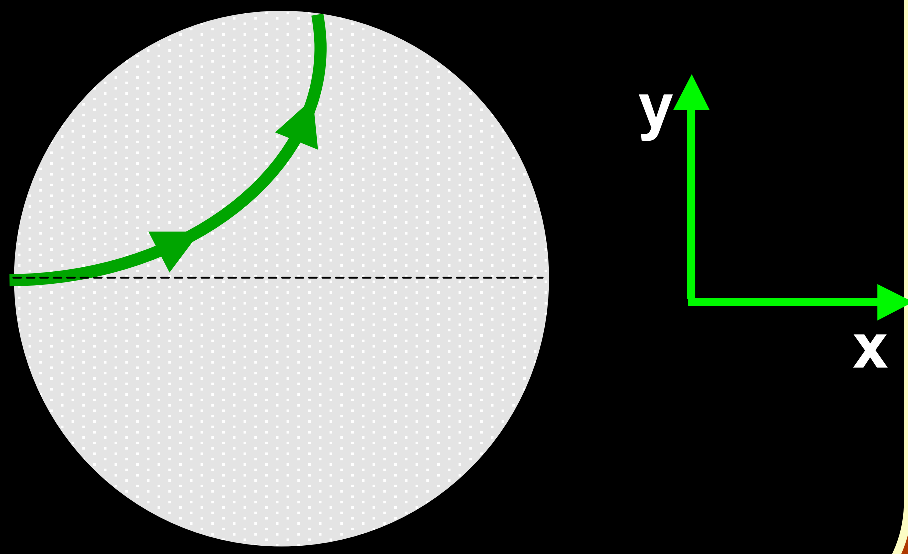
ConcepTest 27.1 Magnetic force

- **A beam of electrons enters a magnetic field region left to right. What path will the electrons follow?**



ConcepTest 27.2 Magnetic Force

- A proton beam has the trajectory in a magnetic field region as shown. What is the direction of the magnetic field B?



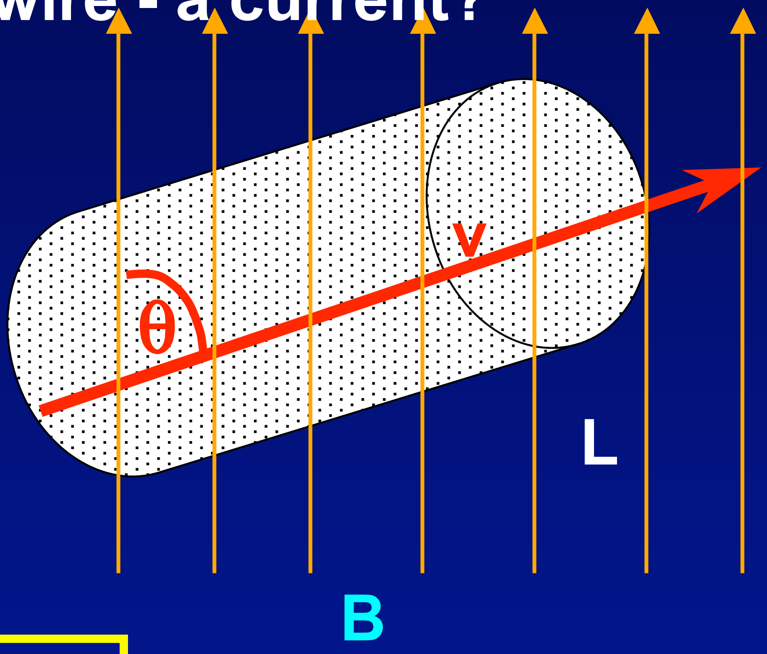
(1) + y
(2) - y
(3) + x
(4) + z (out of page)
(5) - z (into page)

Magnetic Force on an Electric Current

New Topic

Magnetic Force on a Current-Carrying Wire

- If a magnetic field acts on *one* charged particle, what about *many* charges flowing through a wire - a current?
  - Assume that there are N charges inside the length L of the wire

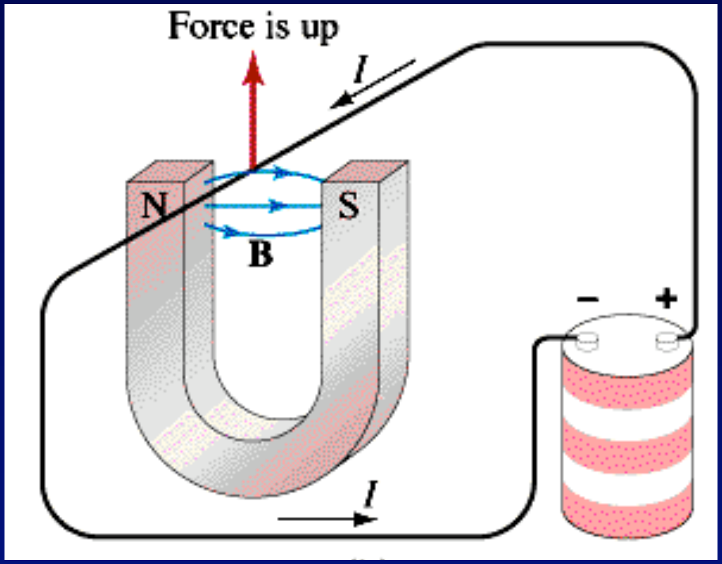


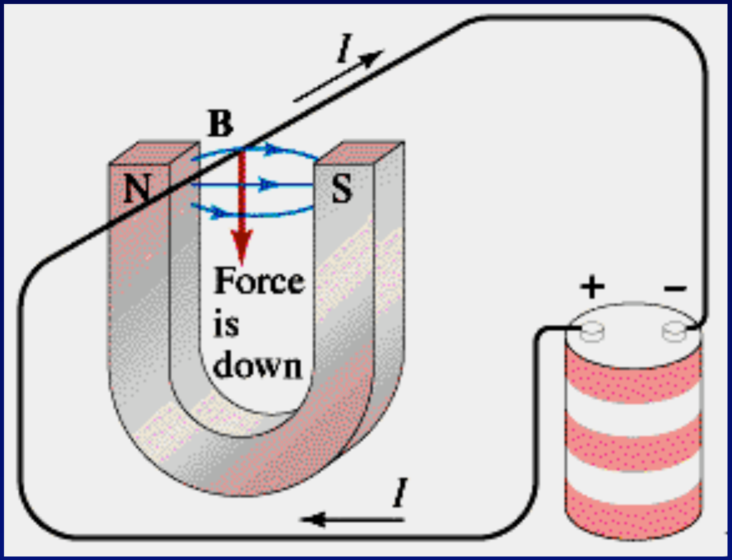
$$➧\ F = \underbrace{N}_{\text{number of charges}}\ \underbrace{q\, v\, B \sin\theta}_{\text{force on one charge}}$$

$$\Rightarrow \boxed{F = I\, L\, B \sin\theta}$$

Uniform Magnetic force on a straight segment of current-carrying wire

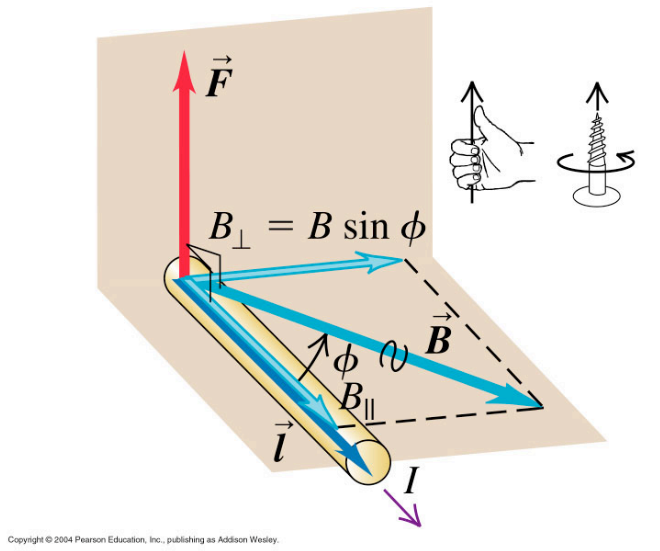
Magnetic Force on a Current-Carrying Wire





$$\vec{F} = I\vec{l} \times \vec{B}$$

The right-hand-rule



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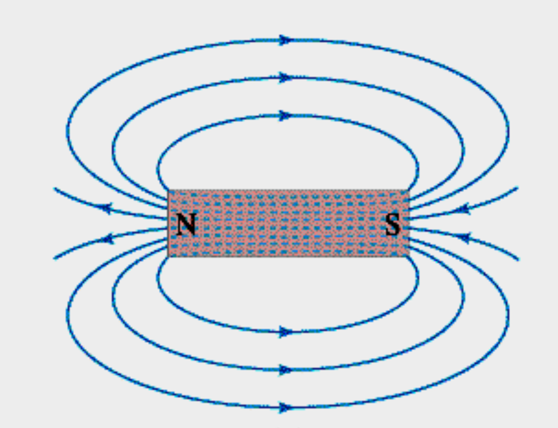
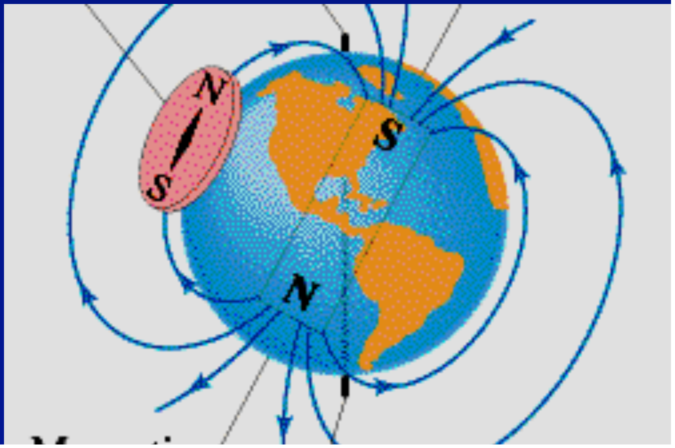
Question: **When is the force greatest?**

Definition of the *magnetic field*

- **From the expression for force on a current-carrying wire:**
  - $B = F_{max} / I L$
  - **SI unit: 1 N / A·m ≡ 1 tesla (T)**
  - **another unit: 1 gauss (G) = 10^{-4} tesla**



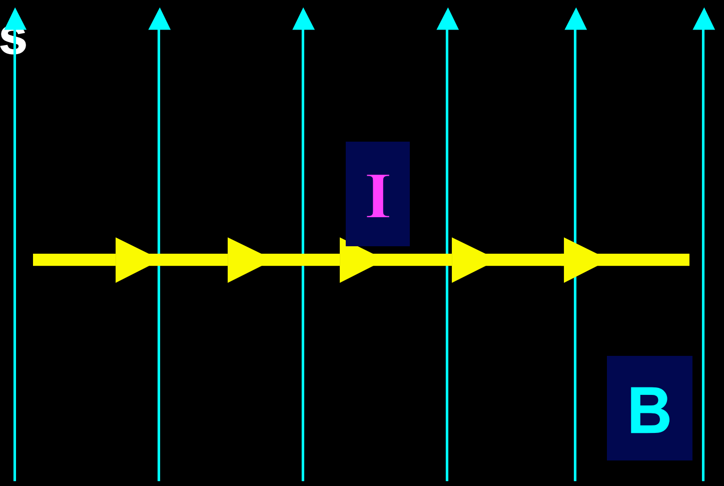
- **Some sample magnetic field strengths:**
  - **Earth: B = 0.5 G = 0.5 x 10^{-4} T**
  - **electromagnet: B = 2 Tesla**



ConcepTest 27.3 Magnetic force on a wire

- A horizontal wire carries a current and is in a vertical magnetic field. What is the direction of the force on the wire?

(1) left
(2) right
(3) zero
(4) into the page
(5) out of the page



Torque due to Magnetic Force

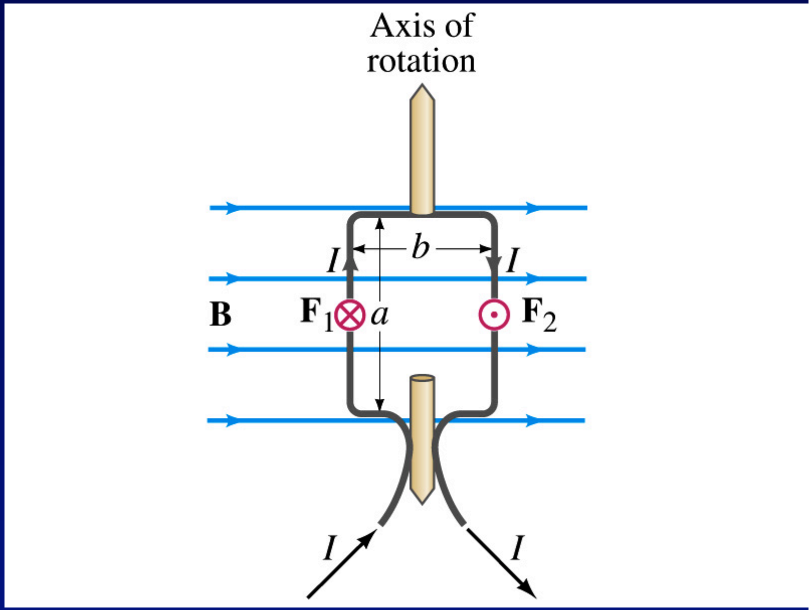
New Topic

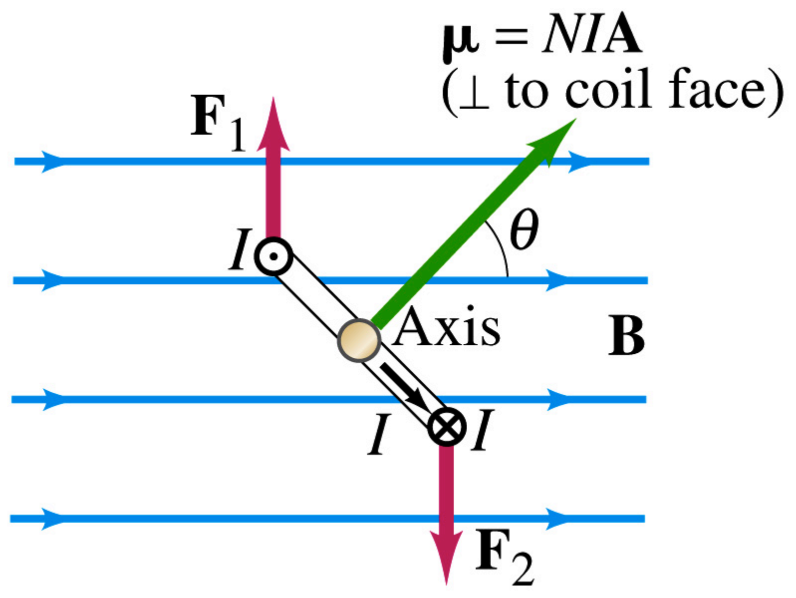
Torque on a Current Loop

- What happens if a closed loop of wire is put in a magnetic field?
  - It rotates!

$$\tau = NIAB\sin\theta$$

- Torque
  - N is the number of loops
  - I is the current in one loop
  - A is the area of the loop
  - B is the magnetic field
  - θ is the angle between B and the perpendicular to the face of the loop



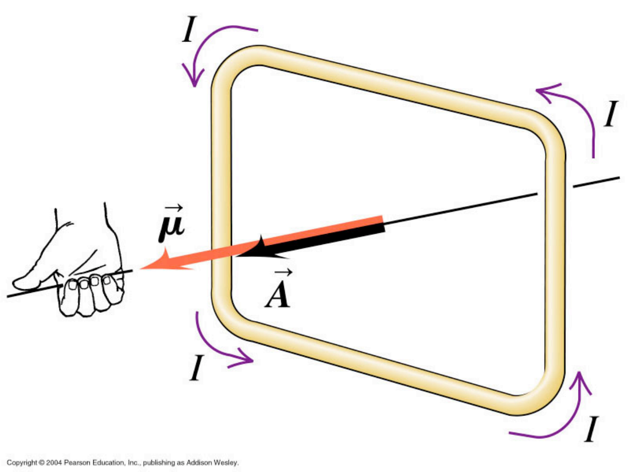


Torque on a Current Loop

$$\tau = NIAB\sin\theta$$

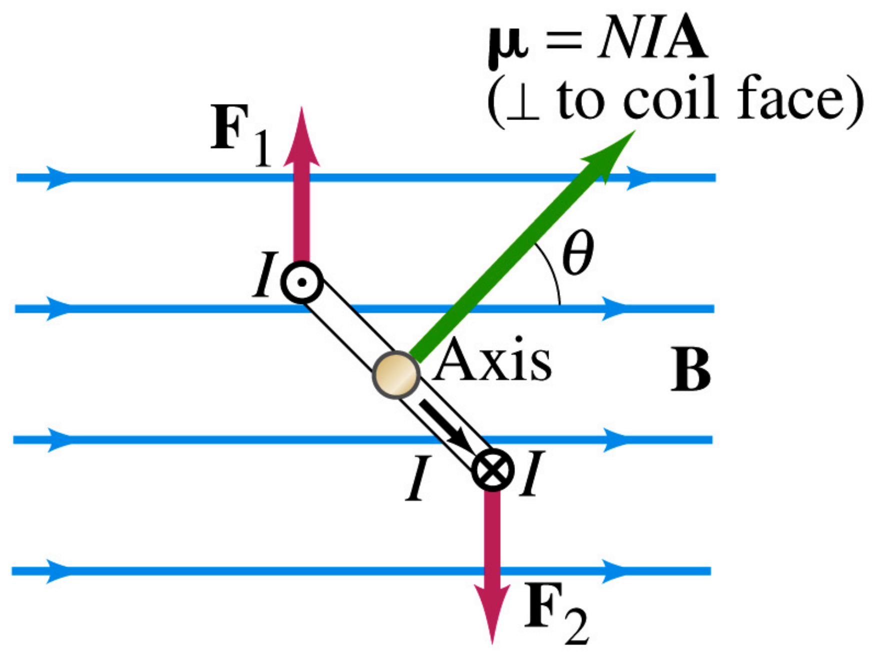
- Define magnetic dipole moment

$$\vec{\mu} = NI\vec{A}$$



- Then the torque can be written as a vector cross product

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



- The potential energy is

$$U = -\vec{\mu} \cdot \vec{B}$$

Mass spectrometer

New Topic

How the electron was discovered?

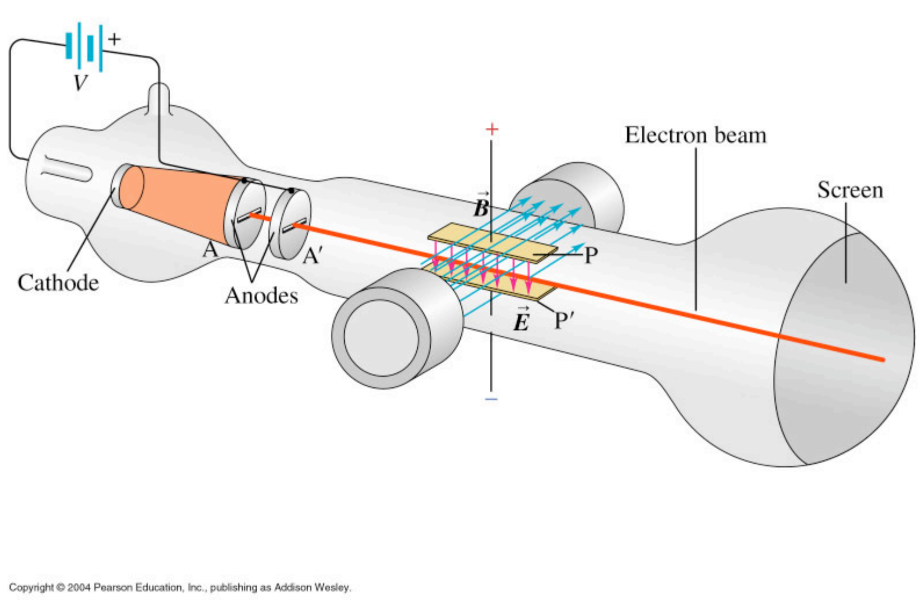
- J.J. Thomson's e/m experiment in 1897.

Electrons are first accelerated by a voltage

$$eV = \frac{1}{2}mv^2$$

Then, only electrons with a particular speed can pass through a region of uniform E and B fields and land straight on the screen:

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



$$\frac{e}{m} = \frac{E^2}{2VB^2} = 1.758820174(71)\times10^{11}\ \text{C/kg}$$

15 years later, R. Millikan measured the electron charge precisely $e=1.602176462(63)\text{x}10^{-19}$ C, which led to the electron mass $m=9.10938188(72)\text{x}10^{-31}$ kg.

ConcepTest 27.4 velocity selector

- **What direction would a magnetic field have to point so that a beam of *electrons* traveling to the right could go *undeflected* through a region where there is a uniform *electric field* that is pointing vertically up?**

(1) Up (parallel to *E*)

(2) Down (antiparallel to *E*)

(3) Into the page

(4) Out of the page

(5) This is impossible to accomplish