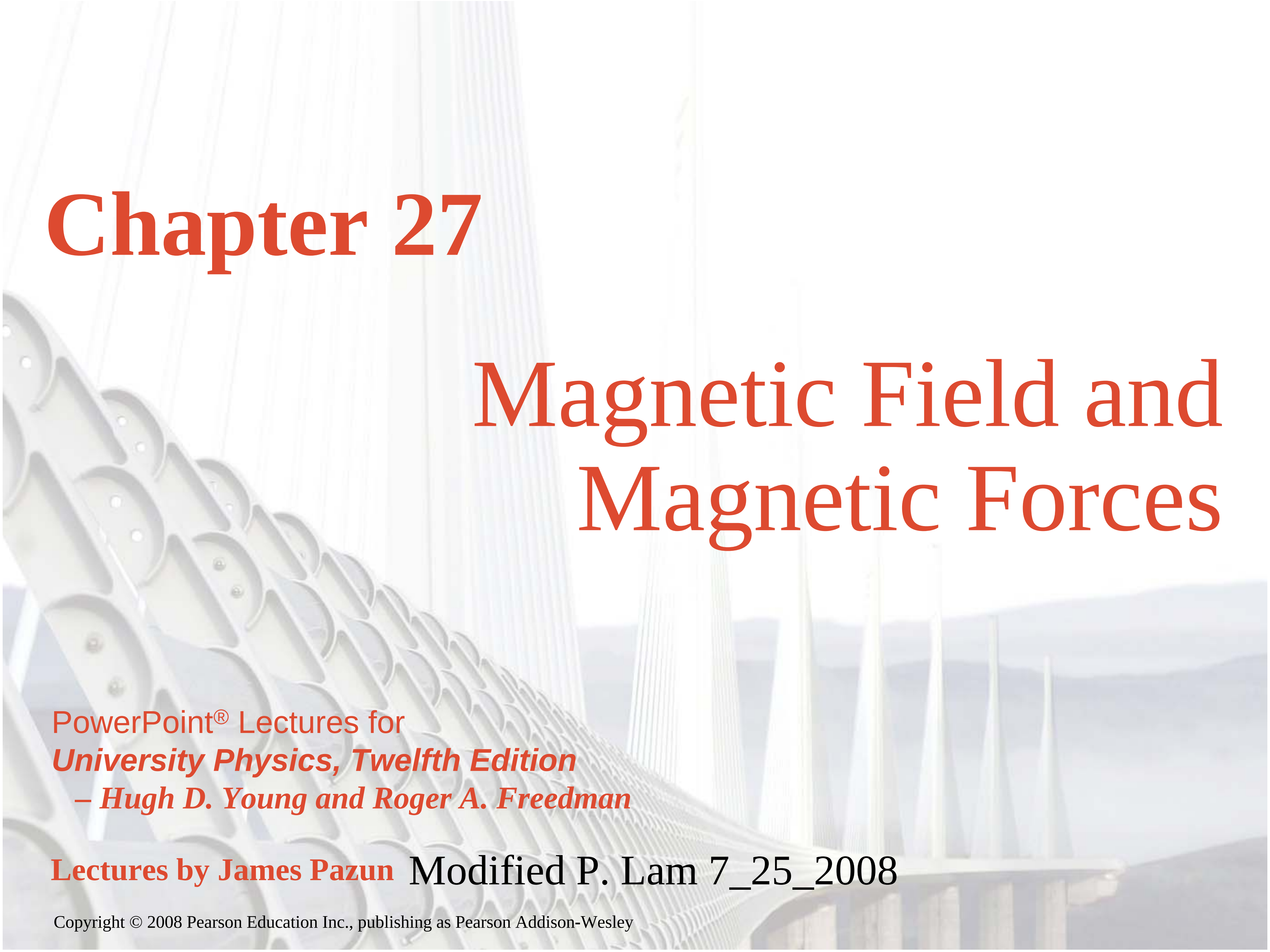


Chapter 27

Magnetic Field and Magnetic Forces

PowerPoint® Lectures for
University Physics, Twelfth Edition
– Hugh D. Young and Roger A. Freedman

Lectures by James Pazun Modified P. Lam 7_25_2008

Topics for Chapter 27

- Concept of magnetic forces and magnetic field
- Mapping magnetic field lines
- Motion of a charge particle in an uniform magnetic field
- Motion of a charge particle in an uniform magnetic and electric field
- Magnetic force and magnetic torque on a current loop.
- Intermission
- Applications
  - Velocity selector
  - Thomson’s e/m Experiment
  - Mass spectrometer
  - Hall Effect

Magnetic force and magnetic field

Summary of Field concept (most of these concepts are to be developed in this and next chapter):

(a) q_1 at rest and q_2 at rest

$q_1 \rightarrow$ generates an E - field $\rightarrow$ the E - field interacts with q_2

(E – field is given by Coulomb's Law)

(b) q_1 is moving but q_2 at rest

$q_1 \rightarrow$ generates both E - field and magnetic field $\rightarrow$ but only the E - field interacts with q_2

(E – field is given NOT by Coulomb's Law)

(c) q_1 is moving and q_2 is moving

$q_1 \rightarrow$ generates both E - field and magnetic field $\rightarrow$ both E - field and the magnetic - field interact with q_2

(*E*lectric force is much stronger than magnetic force.

In order to examine magnetic force only, we use electric current in a neutral conducting wire

in place of q_1)

(d) Electric current and a moving charge (q_2)

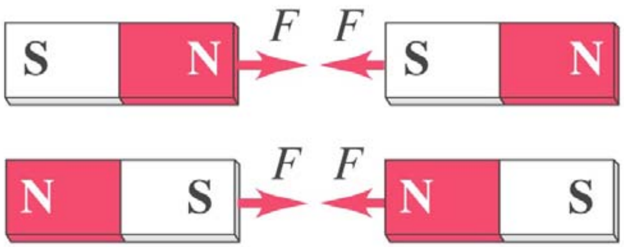
Electric current $\rightarrow$ generates magnetic field $\rightarrow$ magnetic field interacts with q_2

(*Actually*, electric current in a loop also generates a weak E - field)

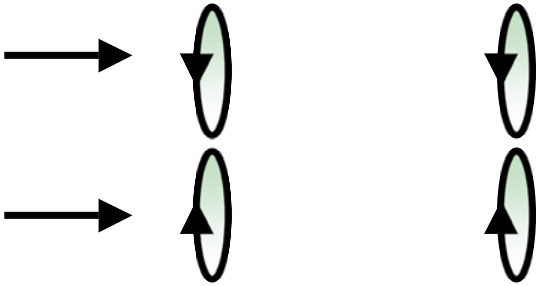
Interaction of magnets - its underlying cause

- Our present understanding is that inside a magnet are small current loops (motions of electrons inside the atom)
  - ***current loops moving in the same direction attract***
  - ***current loops moving in opposite direction repel***

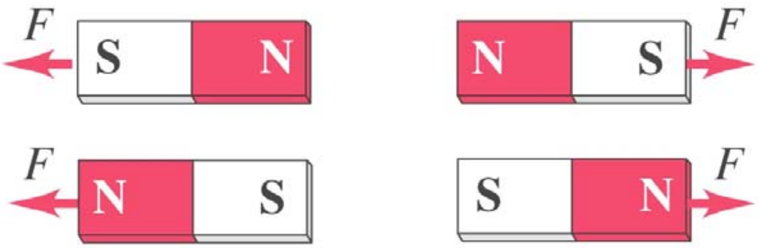
(a) Opposite poles attract.



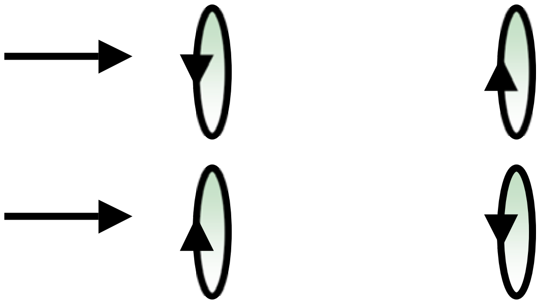
microscopic view
same direction current loops attract



(b) Like poles repel.



microscopic view
opposite direction current loops repel

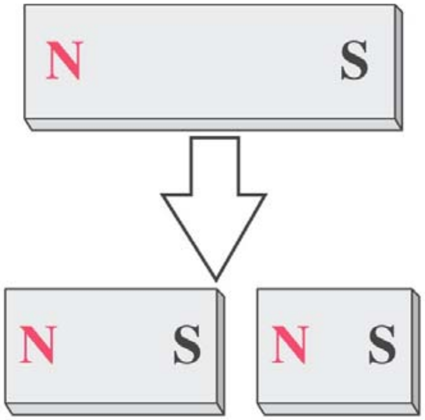


Magnetic pole(s)?

- We observed monopoles in electricity. A (+) or (−) alone was stable and field lines could be drawn around it.
- *Magnets cannot exist as monopoles.* If you break a bar magnet between N and S poles, you get two smaller magnets, each with its own N and S pole.

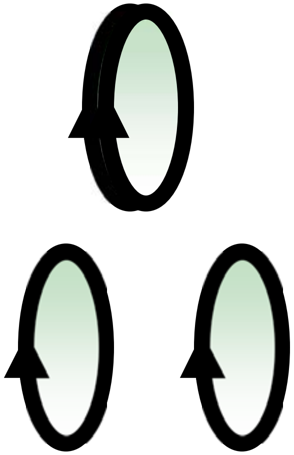
In contrast to electric charges, magnetic poles always come in pairs and can't be isolated.

Breaking a magnet in two ...



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

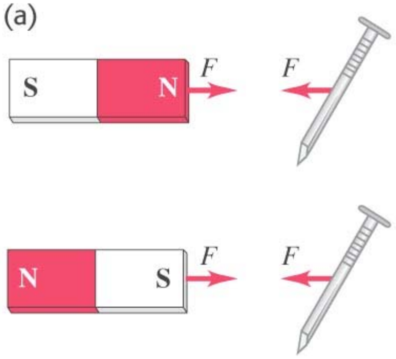
microscopic view

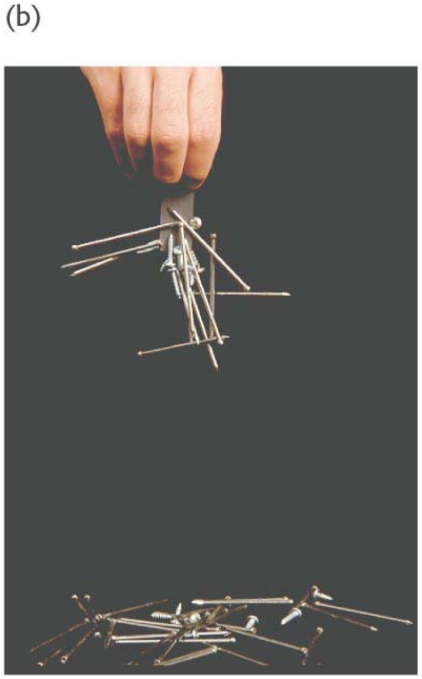


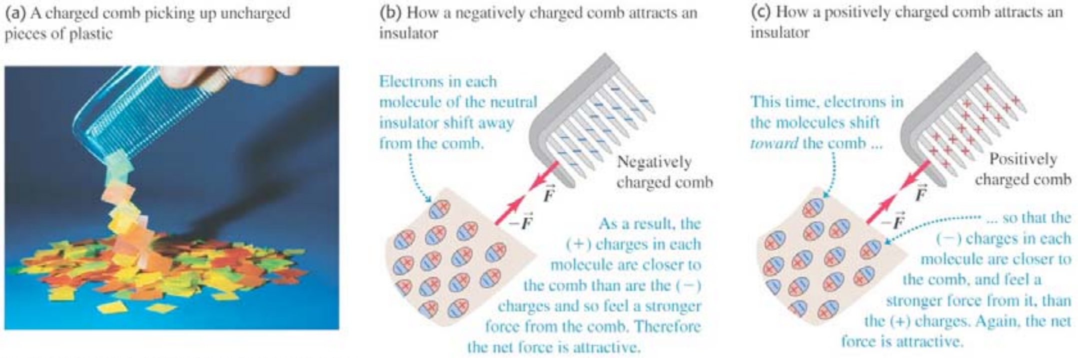
Sliding a thick current loop into half gives two thinner current loops

Magnetism and certain metals

- A permanent magnet will attract a metal like iron with either the north or south pole by inducing magnetic dipole in the iron
- similar to a positive charge or negative charge attract a neutral object by inducing a electric dipole in the neutral object






(a) A charged comb picking up uncharged pieces of plastic

(b) How a negatively charged comb attracts an insulator

Electrons in each molecule of the neutral insulator shift away from the comb.

As a result, the (+) charges in each molecule are closer to the comb than are the (−) charges and so feel a stronger force from the comb. Therefore the net force is attractive.

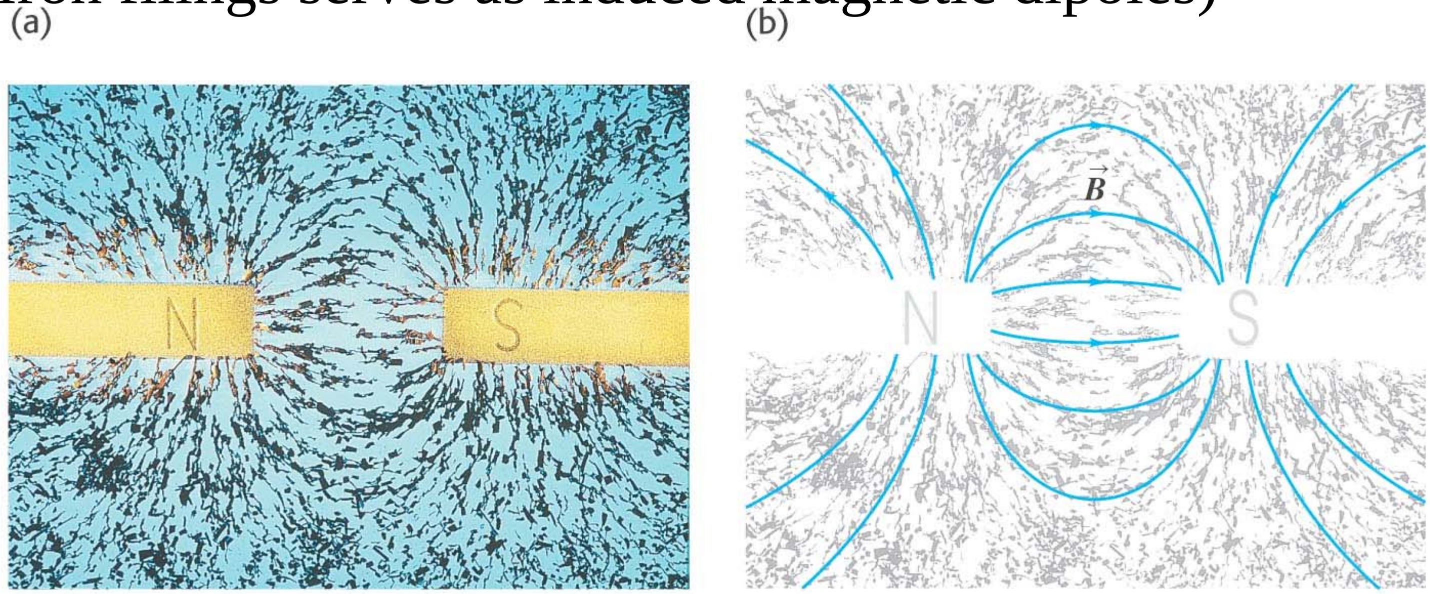
(c) How a positively charged comb attracts an insulator

This time, electrons in the molecules shift *toward* the comb ...

... so that the (−) charges in each molecule are closer to the comb, and feel a stronger force from it, than the (+) charges. Again, the net force is attractive.

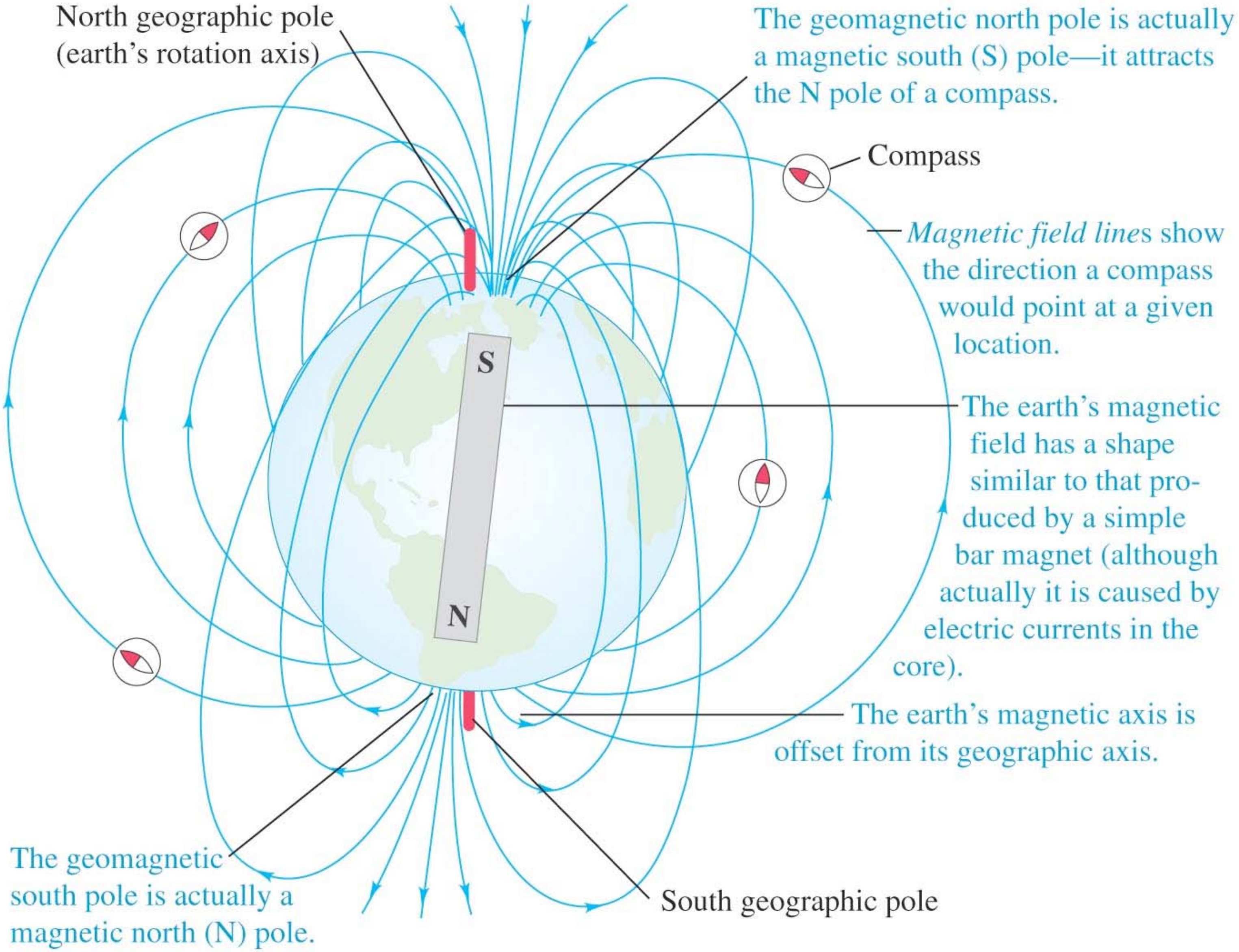
Mapping magnetic field (B-field) lines

Electric dipole lines up with E-field lines.
By analogy,
magnetic dipole lines up with magnetic field (B-field) lines
(Iron filings serves as induced magnetic dipoles)



Convention: B-field lines origins from N-pole and terminates at S-pole

The magnetic poles about our planet



North geographic pole (earth's rotation axis)

The geomagnetic north pole is actually a magnetic south (S) pole—it attracts the N pole of a compass.

Compass

Magnetic field lines show the direction a compass would point at a given location.

The earth's magnetic field has a shape similar to that produced by a simple bar magnet (although actually it is caused by electric currents in the core).

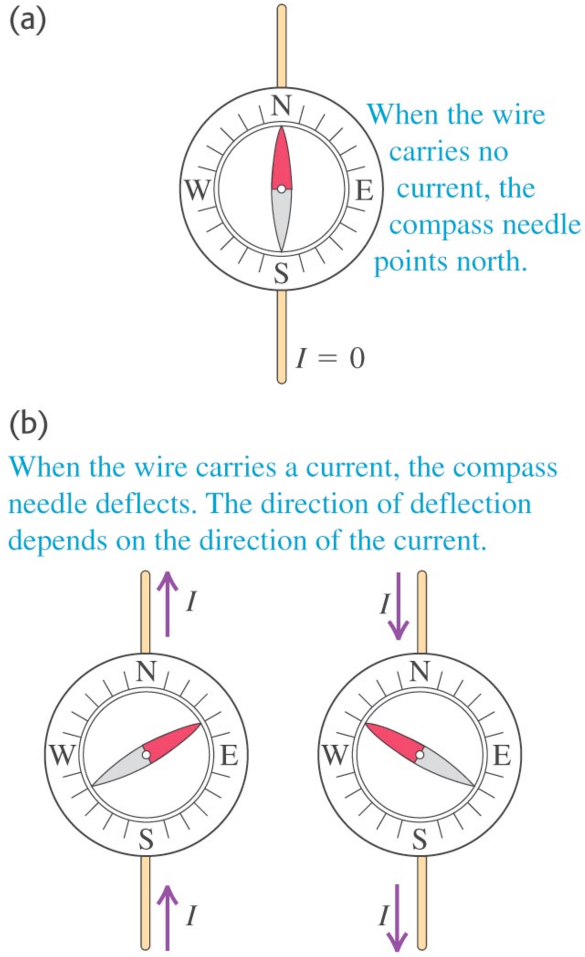
The earth's magnetic axis is offset from its geographic axis.

South geographic pole

The geomagnetic south pole is actually a magnetic north (N) pole.

Experiment that electric current generates magnetic field

- In 1820, Hans Oersted ran a series of experiments with conducting wires run near a sensitive compass. The result was dramatic. The orientation of the wire and the direction of the flow both moved the compass needle.
- There had to be something magnetic about current flow.



When the wire carries no current, the compass needle points north.

When the wire carries a current, the compass needle deflects. The direction of deflection depends on the direction of the current.

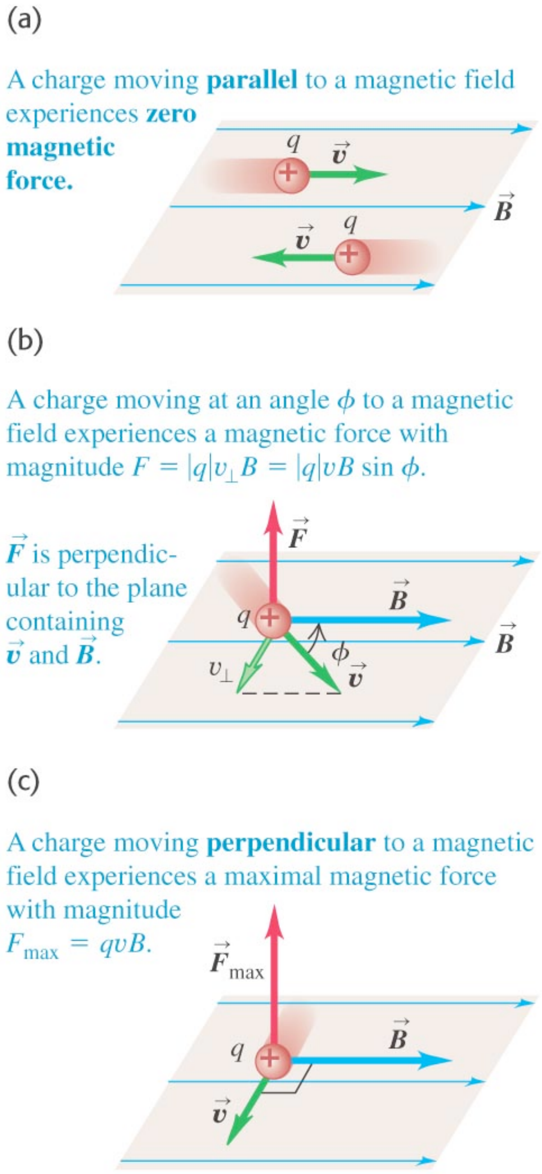
Magnetic force on a moving charge

- In this chapter, we will focus on how a given magnetic field affects a moving charge. The next chapter will deal with how to generate a given magnetic field.

Unlike electric force ($\vec{F}_E = q\vec{E}$), magnetic force is given by a cross-product:

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

$\vec{v}$ is the velocity of the moving charge (NOT the velocity of the magnet)



(a)

A charge moving **parallel** to a magnetic field experiences **zero magnetic force.**

(b)

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

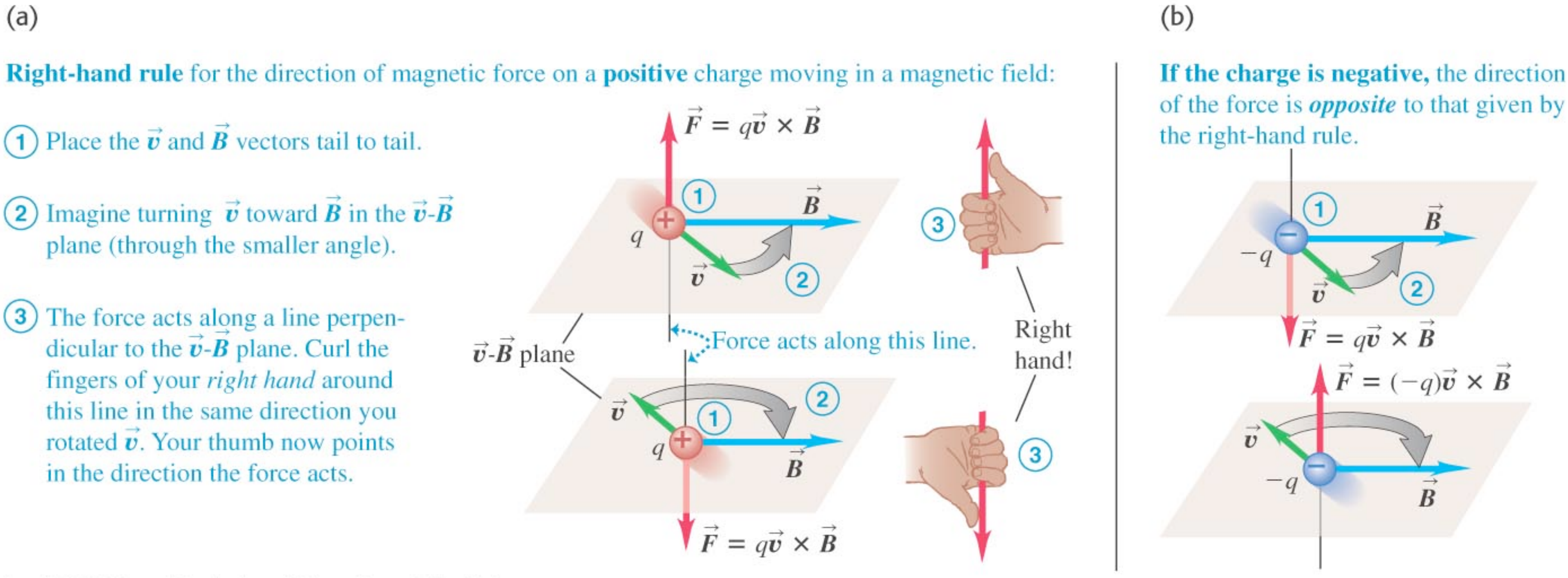
$\vec{F}$ is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$.

(c)

A charge moving **perpendicular** to a magnetic field experiences a maximal magnetic force with magnitude $F_{max} = qvB$.

The "right-hand rule" for cross-product

- This is for a positive charge moving in a magnetic field.
- Place your hand out as if you were getting ready for a handshake. Your fingers represent the velocity vector of a moving charge.
- Move the fingers of your hand toward the magnetic field vector.
- Your thumb points in the direction of the force between the two vectors.



(a)

Right-hand rule for the direction of magnetic force on a **positive** charge moving in a magnetic field:

① Place the $\vec{v}$ and $\vec{B}$ vectors tail to tail.

② Imagine turning $\vec{v}$ toward $\vec{B}$ in the $\vec{v}$-$\vec{B}$ plane (through the smaller angle).

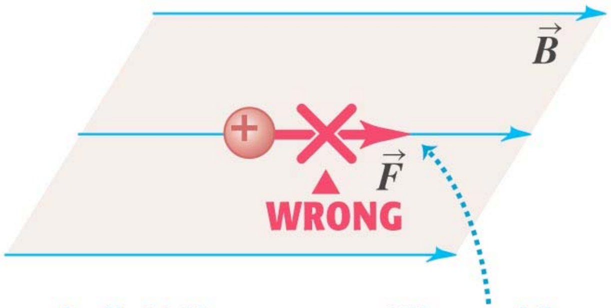
③ The force acts along a line perpendicular to the $\vec{v}$-$\vec{B}$ plane. Curl the fingers of your *right hand* around this line in the same direction you rotated $\vec{v}$. Your thumb now points in the direction the force acts.

(b)

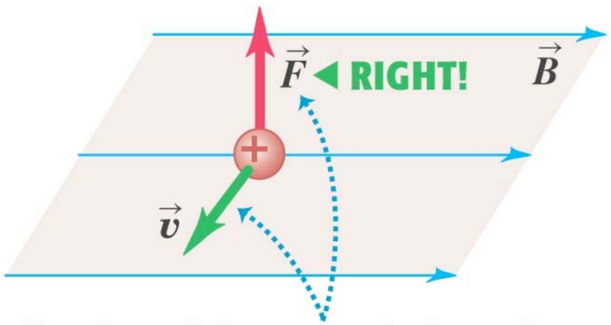
If the charge is negative, the direction of the force is ***opposite*** to that given by the right-hand rule.

Reminder: B-Field lines are not lines of force

- The lines tracing the magnetic field crossed through the velocity vector of a moving charge will give the direction of force by the RHR.



Magnetic field lines are *not* “lines of force.” The force on a charged particle is not along the direction of a field line.



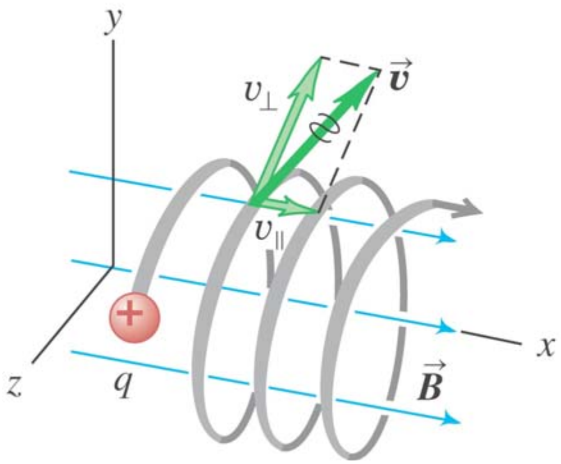
The direction of the magnetic force depends on the velocity $\vec{v}$, as expressed by the magnetic force law $\vec{F} = q\vec{v} \times \vec{B}$.

Note : $\vec{F}$ is perpendicular to $\vec{v}$ and $\vec{B}$

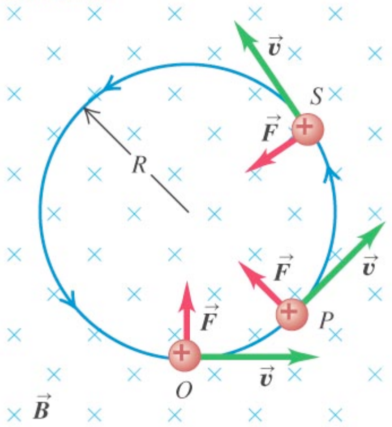
(property of a cross - product)

Motion of charged particles in a magnetic field

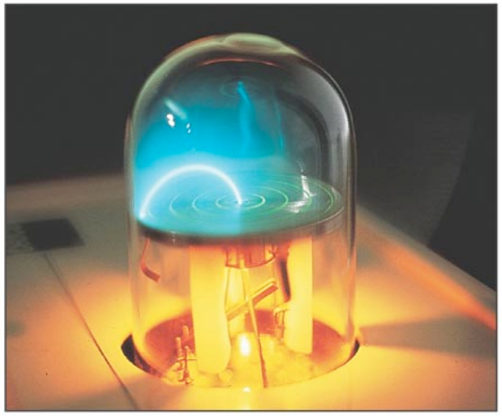
- A charged particle moves in a circular path in a plane perpendicular to the magnetic field (F is perpendicular to v=> centripetal force => circular path; the charge particle must have a non-zero initial velocity, other the force is zero)
- A charge particle moves in a helical path if the initial velocity has a component along the B-field


This particle's motion has components both parallel ($v_{\parallel}$) and perpendicular ($v_{\perp}$) to the magnetic field, so it moves in a helical path.

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


A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.

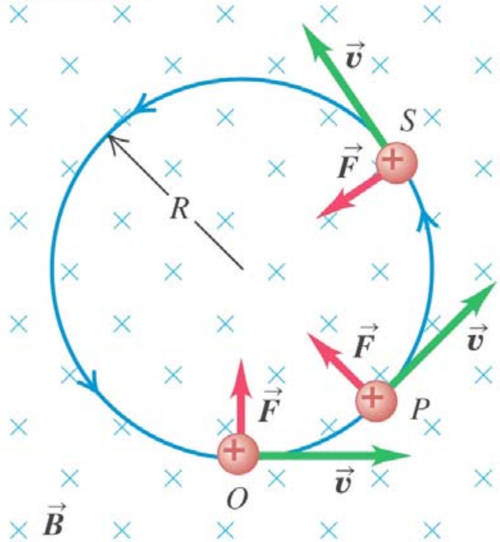
(b) An electron beam (seen as a blue arc) curving in a magnetic field



Motion of charged particles in a magnetic field

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

A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.



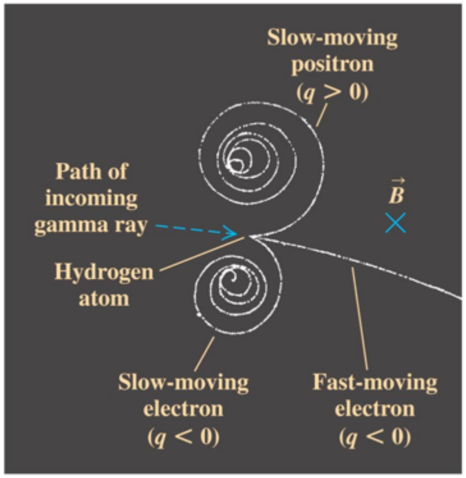
Uniform B-field points
into the page

$$\vec{F} = m\vec{a}$$

$$|q|vB = m\frac{v^2}{R}$$

$$\Rightarrow R = \frac{mv}{|q|B}$$

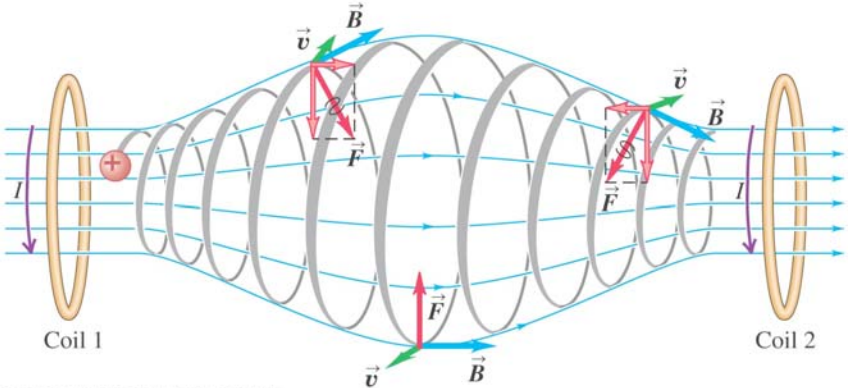
Note : The radius formula is valid for both positive and negative charge. However, for negative charge the charge moving in clockwise direction in order to generate centripetal force pointing to the center.



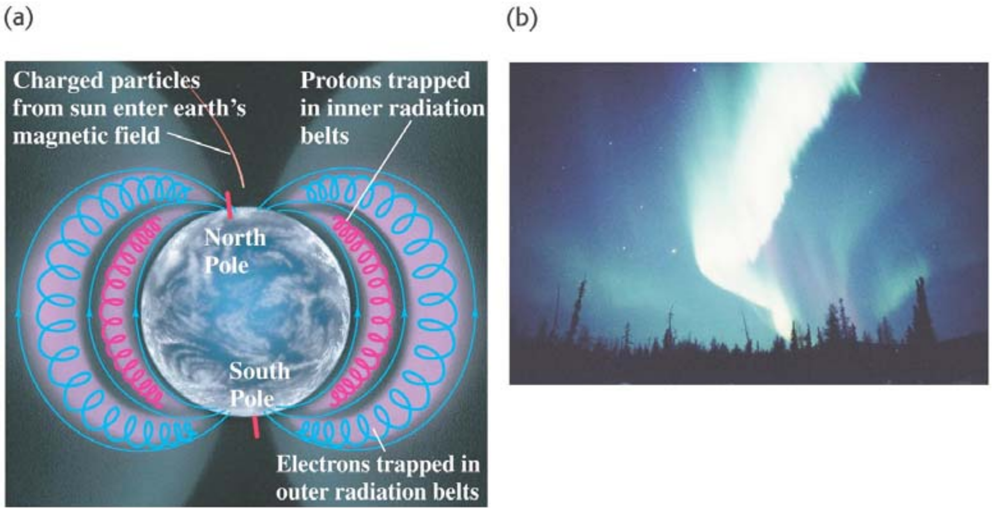
Why the trajectory
spirals inward?

A magnetic bottle

- Moving charge particles can be confined by magnetic field (called magnetic bottle - a method used in control nuclear fusion to contain the charge particle at a million Kelvin.



- Figure 27.20 below shows the real-world examples of charge particle traps along the Earth magnetic field lines…giving rise to northern lights and southern lights - charge particle radiates lights as it accelerates.



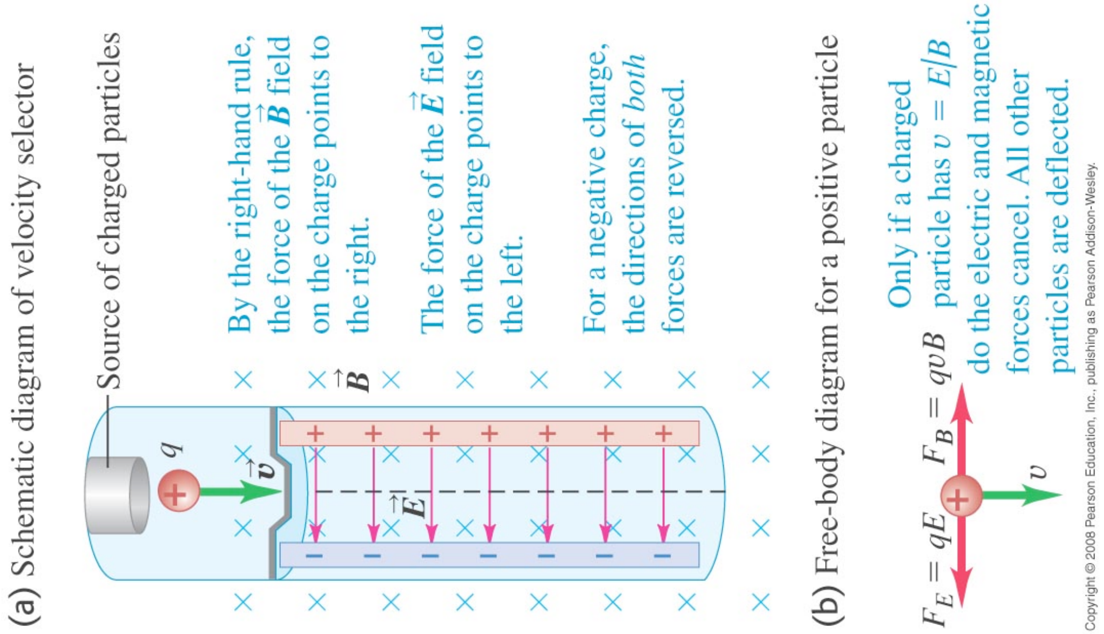
Motion of a charge in both E and B-field

Total force on a charge q by E and B - field :

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

Special example: Uniform E and B-field perpendicular to each other.

Initital velocity is perpendicular to both E and B-field.



(a) Schematic diagram of velocity selector

Source of charged particles

By the right-hand rule, the force of the $\vec{B}$ field on the charge points to the right.

The force of the $\vec{E}$ field on the charge points to the left.

For a negative charge, the directions of *both* forces are reversed.

(b) Free-body diagram for a positive particle

Only if a charged particle has $v = E/B$ do the electric and magnetic forces cancel. All other particles are deflected.

If the initial velocity is just the right amount, the net force is zero=>velocity =constant

If initial velocity is greater=>positive charge will move upward

If initial velocity is smaller=> positive charge will move downward

This is the principle for a velocity selector device

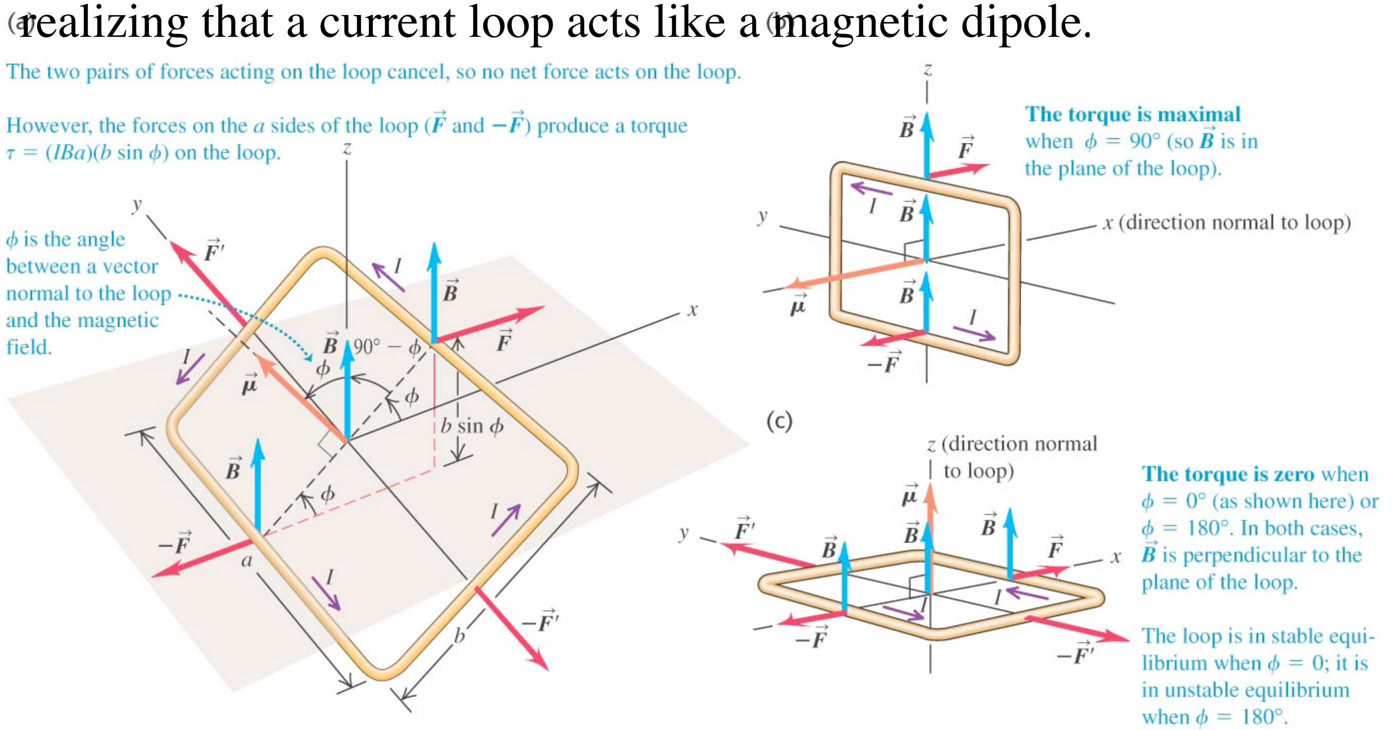
Magnetic Force and torque on a current loop

Force on a current segment of length ℓ :

$$\vec{F} = (\vec{I} \times \vec{B})\ell$$

Another way of understanding the torque is

realizing that a current loop acts like a magnetic dipole.



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

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

ϕ is the angle between a vector normal to the loop and the magnetic field.

The torque is maximal when $\phi = 90°$ (so $\vec{B}$ is in the plane of the loop).

The torque is zero when $\phi = 0°$ (as shown here) or $\phi = 180°$. In both cases, $\vec{B}$ is perpendicular to the plane of the loop.

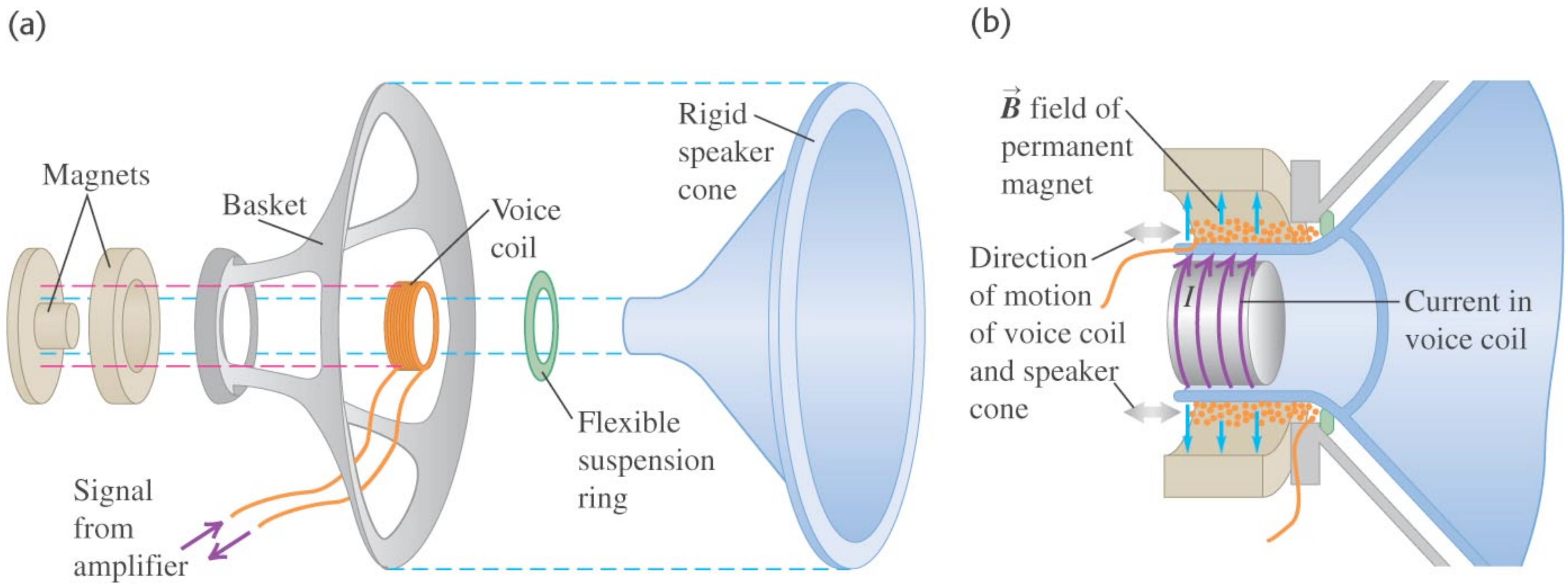
The loop is in stable equilibrium when $\phi = 0$; it is in unstable equilibrium when $\phi = 180°$.

Note: For uniform B-field, the net force on a current loop (or magnetic dipole) is zero while the net torque is non-zero.

In a non-uniform B-field both the net force and net torque will be non-zero

Loudspeaker engineering

- To create music, we need longitudinal pulses in the air. The speaker cone is a very clever combination of induced and permanent magnetism arranged to move the cone to create compressions in the air. Figure 27.28 illustrates this below.



Current loop in a non-uniform B-field; net force is non-zero.

Net force depends on the amount of current which depends on the original sound signal which was converted to electrical signal.

Intermission

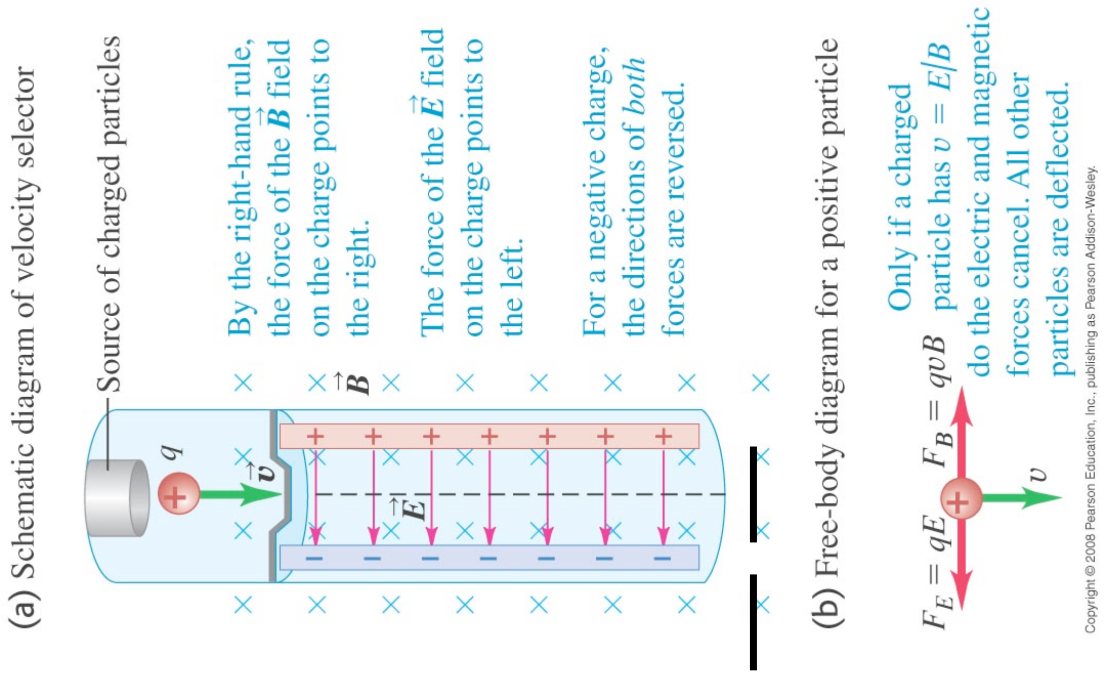
Velocity selector

Total force on a charge q by E and B - field :

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

Velocity selector: Uniform E and B-field perpendicular to each other.

Initial velocity is perpendicular to both E and B-field.



If the initial velocity is just the right amount, the net force is zero=>velocity =constant=E/B

If initial velocity is greater=>positive charge will move upward

If initial velocity is smaller=> positive charge will move downward

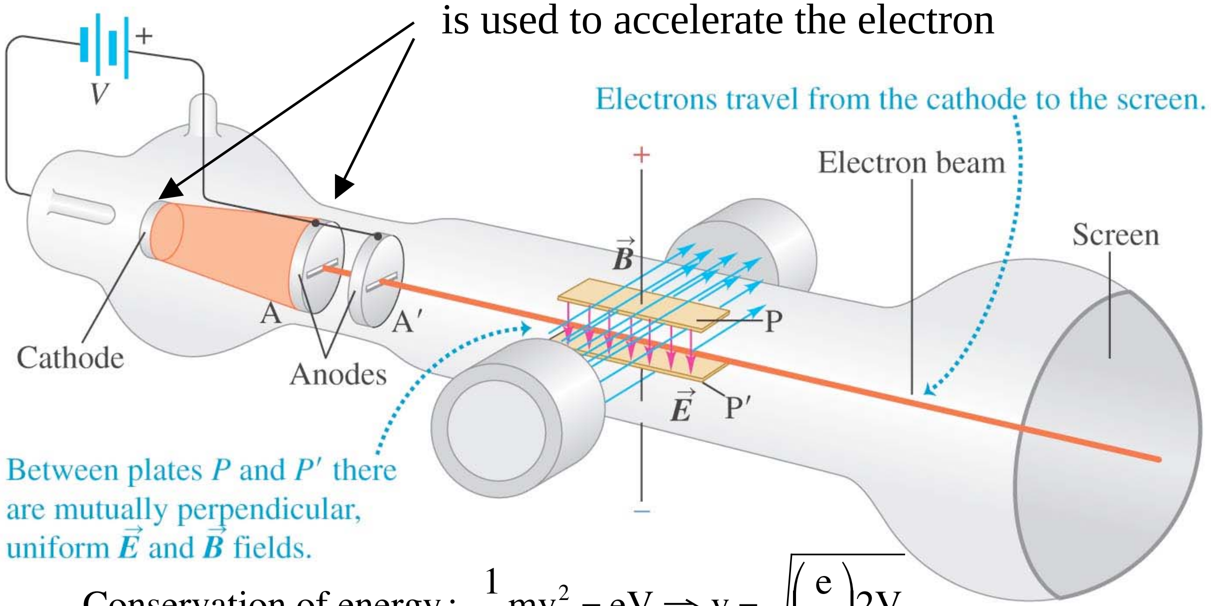
This is the principle for a velocity selector device

Place a slit with small opening to allow only particle with horizontal velocity to go through

J.J. Thompson’s e/m experiment to characterize the electron

- Thompson’s experiment.

Voltage difference between Cathode and Anode (conducting plates) is used to accelerate the electron



$$\text{Conservation of energy: } \frac{1}{2}mv^2 = eV \Rightarrow v = \sqrt{\left(\frac{e}{m}\right)2V}$$

$$\text{Velocity selector: } v = \frac{E}{B}$$

$$\Rightarrow \frac{E}{B} = \sqrt{\left(\frac{e}{m}\right)2V} \Rightarrow \left(\frac{e}{m}\right) = \left(\frac{E}{B}\right)^2 \frac{1}{2V}$$

For a given E and B, Thompson adjusted the voltage V until the electron comes out in a straight line (hitting the center of the screen), thereby determining the charge to mass ratio of an electron

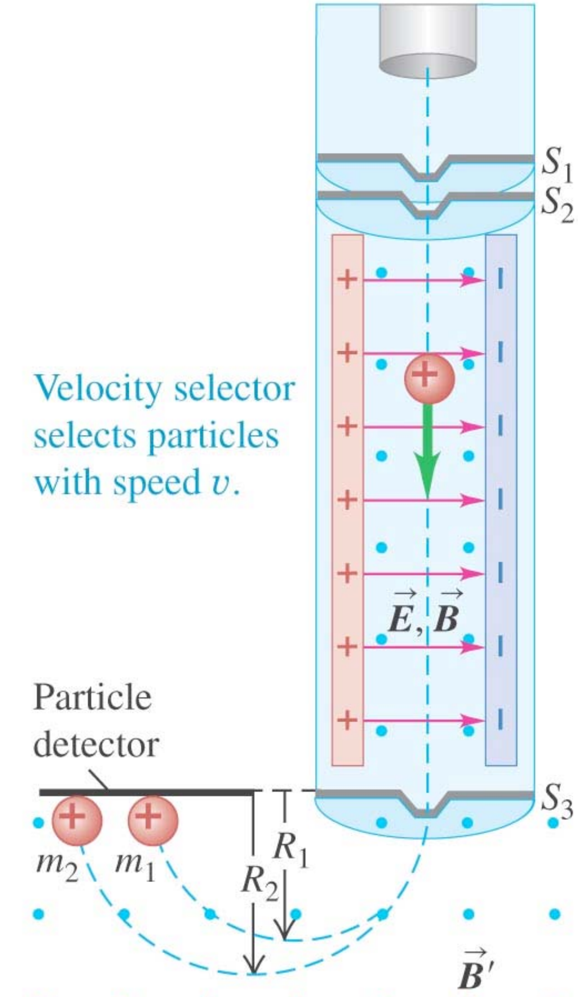
Bainbridge's mass spectrometer

- Using the same concept as Thompson, Bainbridge was able to construct a device that would only allow one mass in flight to reach the detector.
- neutral atoms are converted to charge ion by heating (generally, remove one electron)
- Only charge ion with the right velocity will exit the velocity selector.

$$R = \frac{mv}{qB}$$

Heavier isotope will have a larger radius.

$\mathrm{q} = 1.6\mathrm{x}10^{-19}\,\mathit{Coulomb}$ for charge ion with one electron removed.

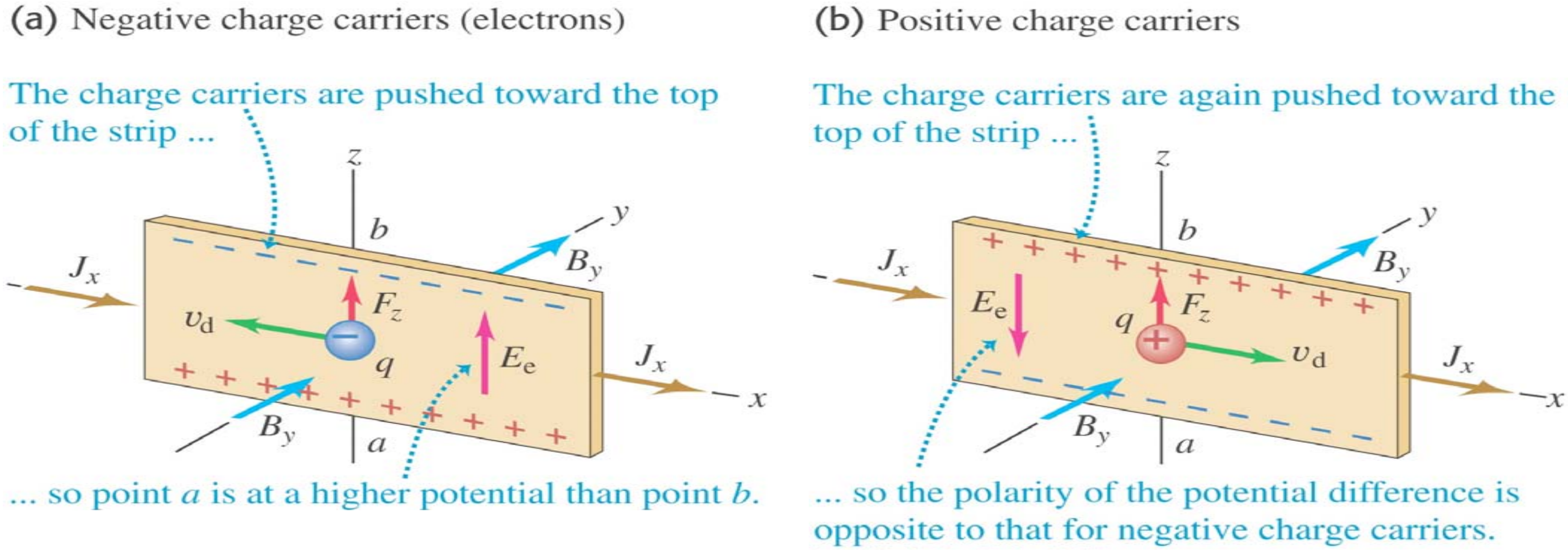


Magnetic field separates particles by mass; the greater a particle's mass, the larger is the radius of its path.

The Hall Effect

The Hall effect: A current through a conducting material will develop a transverse voltage (Hall voltage) when the material is placed in a B-field.

The concept is similar to the velocity selector except that the electric field (“the Hall voltage) is generated by the deflected charge carriers rather than an external E-field.


(a) Negative charge carriers (electrons)

The charge carriers are pushed toward the top of the strip ...

... so point a is at a higher potential than point b.

(b) Positive charge carriers

The charge carriers are again pushed toward the top of the strip ...

... so the polarity of the potential difference is opposite to that for negative charge carriers.

Application of the Hall effect:

(1) It is easy to measure voltage; the Hall effect is used for precision measurement of magnetic field.

(2) The Hall voltage developed by positive carrier has opposite sign compared to negative carrier. The Hall effect is used to determine the sign of the current carrier in semi-conductors.