

Magnetism
The Magnetic Force

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

B

B

B

Bar Magnet

- Bar magnet ... two poles: N and S
Like poles repel; Unlike poles attract.
- Magnetic Field lines: (defined in same way as electric field lines, direction and density)

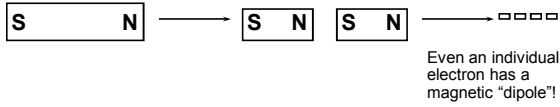
Electric Field Lines
of an Electric Dipole

Magnetic Field Lines
of a bar magnet

Magnetic Monopoles

- Perhaps there exist magnetic charges, just like electric charges. Such an entity would be called a magnetic monopole (having + or - magnetic charge).
- How can you isolate this magnetic charge?

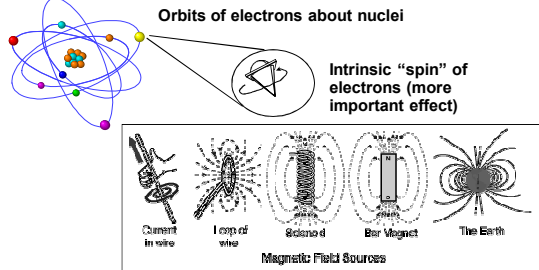
Cut a bar magnet in half:



- Many searches for magnetic monopoles
- No monopoles have ever been found:

Source of Magnetic Fields?

- What is the source of magnetic fields, if not magnetic charge?
- Answer: electric charge in motion!
 ← e.g., current in wire surrounding cylinder (solenoid) produces very similar field to that of bar magnet.
- Therefore, understanding source of field generated by bar magnet lies in understanding currents at atomic level within bulk matter.



Magnetic Field Units

- $F = q \times v \times B$
- SI units: N-s/C-m = Tesla
- 1 Tesla = 10,000 Gauss
- Earth's magnetic field is approximately 0.5 Gauss
- Refrigerator magnets are about 100 Gauss
- Superconducting electromagnets can be as much as 40 Tesla



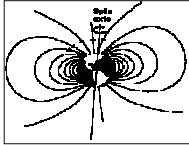

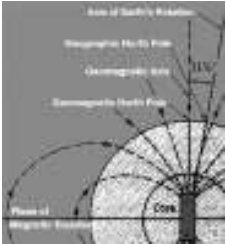
Carl Friedrich Gauss
1777-1855



Nikola Tesla
1856- 1943

Earth's Magnetic Field

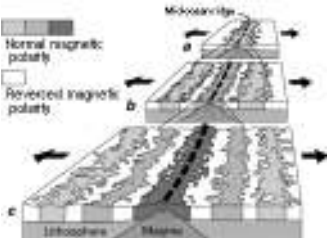
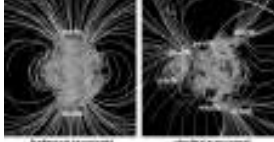
- Earth's magnetic field is similar to that of a bar magnet tilted 11° from Earth's spin axis
- Earth's north geographic pole is actually south magnetic pole

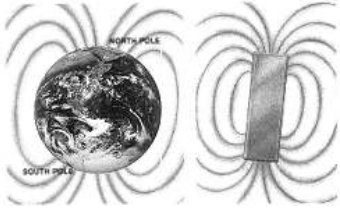
The movement of Earth's north magnetic pole across the Canadian arctic, 1831--2001. Credit: Geological Survey of Canada.

Magnetic Field Reversal

- Evidence for 171 magnetic field reversals during the past 71 million years has been reported.
- Earth's magnetic field is weakening
- interval between reversals of Earth's magnetic field can be as short as 5,000 or as long as 50 million years
- [Simulation of reversal](#)
- [Geodynamo Site](#)

Earth's Inconsistent Magnetic Field



Videos

- [Magnetic Field](#)
- [Magnetic Field of Bar Magnet](#)
- [Magnetic Field of Wire](#)
- [Magnetic Field of a Solenoid](#)
- [Magnetic Field of Toroid](#)
- [Tracking Variations in Earth's Magnetic Field](#)

Magnetic Materials

- Materials can be classified by how they respond to an applied magnetic field, B_{app} .
- Paramagnetic (aluminum, tungsten, oxygen,...)
 - Atomic magnetic dipoles (~atomic bar magnets) tend to line up with the field, *increasing* it. But thermal motion randomizes their directions, so only a small effect persists: $B_{ind} \sim B_{app} \cdot 10^{-5}$
- Diamagnetic (gold, copper, water,...)
 - The applied field induces an *opposing* field; again, this is usually very weak; $B_{ind} \sim -B_{app} \cdot 10^{-5}$ [Exception: Superconductors exhibit perfect diamagnetism \rightarrow they exclude all magnetic fields]
- Ferromagnetic (iron, cobalt, nickel,...)
 - Somewhat like paramagnetic, the dipoles prefer to line up with the applied field. But there is a complicated collective effect due to strong interactions between neighboring dipoles \rightarrow they tend to all line up the same way.
 - Very strong enhancement. $B_{ind} \sim B_{app} \cdot 10^{+5}$

•Which kind of material would you use in a video tape?

- (a) diamagnetic (c) "soft" ferromagnetic
(b) paramagnetic (d) "hard" ferromagnetic

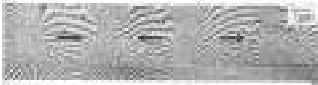
•How does a magnet attract screws, paper clips, refrigerators, etc., when they are not "magnetic"?

Magnetic Materials

•Which kind of material would you use in a video tape?

- (a) diamagnetic
- (b) paramagnetic
- (c) "soft" ferromagnetic
- (d) "hard" ferromagnetic

Diamagnetism and paramagnetism are far too weak to be used for a video tape. Since we want the information to remain on the tape *after* recording it, we need a "hard" ferromagnet. These are the key to the information age—cassette tapes, hard drives, ZIP disks, credit card strips,...



Magnetic Attraction

•How does a magnet attract screws, paper clips, refrigerators, etc., when they are not "magnetic"?

The materials are all "soft" ferromagnets. The external field temporarily aligns the domains so there is a net dipole, which is then attracted to the bar magnet.

- The effect vanishes with no applied B field
- It does *not* matter which pole is used.



IBM introduced the first hard disk in 1957, when data usually was stored on tapes. It consisted of 50 platters, 24 inch diameter, and was twice the size of a refrigerator.



It cost \$35,000 annually in leasing fees (IBM would not sell it outright). Its *total* storage capacity was 5 MB, a huge number for its time!

Magnetic Fields

We know about the existence of magnetic fields by their effect on moving charges. The magnetic field exerts a force on the moving charge.

- What is the "magnetic force"? How is it distinguished from the "electric" force?

experimental observations about the magnetic force:

- magnitude: \propto to velocity of q
- direction: \perp to direction of q 's velocity
- direction: \perp to direction of B

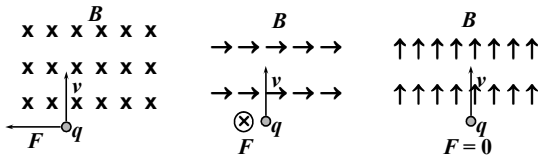


B is the magnetic field vector

Lorentz Force

- The force F on a charge q moving with velocity v through a region of space with electric field E and magnetic field B is given by:

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



Three points are arranged in a uniform magnetic field. The B field points into the screen.




- 1) A positively charged particle is located at point A and is stationary. The direction of the magnetic force on the particle is:

- right
- left
- into the screen
- out of the screen
- zero

- 2) The positive charge moves from point A toward B. The direction of the magnetic force on the particle is:


- right
- left
- into the screen
- out of the screen
- zero



3) The positive charge moves from point A toward C. The direction of the magnetic force on the particle is:

a) up and right **b) up and left** c) down and right
 d) down and left

Magnetic Force: $\vec{F} = q\vec{v} \times \vec{B}$

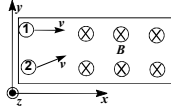


If $v = 0 \Rightarrow F = 0$. If $\vec{v} \perp \vec{B}$ then $F = qvB$

If v is up, and B is into the page, then F is to the left.

- Two protons each move at speed v (as shown in the diagram) in a region of space which contains a constant B field in the $-z$ -direction. Ignore the interaction between the two protons.

← What is the relation between the magnitudes of the forces on the two protons?



(a) $F_1 < F_2$ (b) $F_1 = F_2$ (c) $F_1 > F_2$

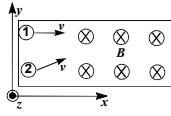
– What is F_{2x} , the x -component of the force on the second proton?

(a) $F_{2x} < 0$ (b) $F_{2x} = 0$ (c) $F_{2x} > 0$

– Inside the B field, the speed of each proton:

(a) decreases (b) increases (c) stays the same

- Two independent protons each move at speed v (as shown in the diagram) in a region of space which contains a constant B field in the $-z$ -direction. Ignore the interaction between the two protons.
 ◀ What is the relation between the magnitudes of the forces on the two protons?

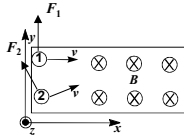


(a) $F_1 < F_2$ (b) $F_1 = F_2$ (c) $F_1 > F_2$

- The magnetic force is given by:

$$\vec{F} = q\vec{v} \times \vec{B} \Rightarrow |F| = qvB \sin \theta$$
- In both cases the angle between v and B is 90° !!
 Therefore $F_1 = F_2$.

- Two independent protons each move at speed v (as shown in the diagram) in a region of space which contains a constant B field in the $-z$ -direction. Ignore the interaction between the two protons.
 ◀ What is F_{2x} , the x -component of the force on the second proton?

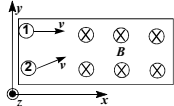


(a) $F_{2x} < 0$ (b) $F_{2x} = 0$ (c) $F_{2x} > 0$

- To determine the direction of the force, we use the right-hand rule.

$$\vec{F} = q\vec{v} \times \vec{B}$$
- As shown in the diagram, $F_{2x} < 0$.

- Two protons each move at speed v (as shown in the diagram) in a region of space which contains a constant B field in the $-z$ -direction. Ignore the interaction between the two protons.
 ◀ Inside the B field, the speed of each proton:



(a) decreases (b) increases (c) stays the same

Although the proton does experience a force (which deflects it), this is *always* \perp to \vec{v} .
 Therefore, there is *no possibility to do work*, so kinetic energy is constant and $|\vec{v}|$ is constant.

Trajectory in Constant B Field

- Suppose charge q enters B -field with velocity v as shown below. What will be the path q follows?

- Force is always \perp to velocity and B . What is path?
- Path will be circle. F will be the centripetal force needed to keep the charge in its circular orbit. Calculate R :

Radius of Circular Orbit

- Lorentz force:**
 $F = qvB$
- centripetal acc:**
 $a = \frac{v^2}{R}$
- Newton's 2nd Law:**
 $F = ma \Rightarrow qvB = m \frac{v^2}{R}$
 $\Rightarrow R = \frac{mv}{qB}$

This is an important result, with useful experimental consequences !

The drawing below shows the top view of two interconnected chambers. Each chamber has a unique magnetic field. A positively charged particle is fired into chamber 1, and observed to follow the dashed path shown in the figure.

5) What is the direction of the magnetic field in chamber 1?

a) Up b) Down c) Left
d) Right e) Into page f) Out of page

6) What is the direction of the magnetic field in chamber 2?

a) Up b) Down c) Left
 d) Right e) Into page f) Out of page

In chamber 1, the velocity is initially up. Since the particle's path curves to the right, the force is to the right as the particle enters the chamber.

Three ways to figure out the direction of B from this:

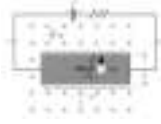
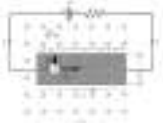
- 1) Put your thumb in the direction of the F (right) and your fingers in the direction of v (up). The way that your fingers curl is the direction of B .
- 2) Put your palm in the direction of F (right), and your thumb in the direction of v (up), your fingers (keep them straight) point in the direction of B .
- 3) Keep your thumb, index and middle fingers at right angles from each other. Your thumb points in the direction of v (up), middle finger points towards F (right), then the index finger gives the the direction of B (out of page)

8) Compare the magnitude of the magnetic field in chamber 1 to the magnitude of the magnetic field in chamber 2.

a) $B_1 > B_2$
 b) $B_1 = B_2$
 c) $B_1 < B_2$

The Hall Effect

- Which charges carry current?



- Positive charges moving counterclockwise experience upward force
- Upper plate at *higher* potential
- Negative charges moving clockwise experience upward force
- Upper plate at *lower* potential

Equilibrium between electrostatic & magnetic forces:

$$F_{\text{up}} = qv_{\text{drift}}B \quad F_{\text{down}} = qE_{\text{induced}} = q\frac{V_{\text{H}}}{w} \quad V_{\text{H}} = v_{\text{drift}}Bw = \text{"Hall Voltage"}$$

• This type of experiment led to the discovery (E. Hall, 1879) that current in conductors is carried by negative charges (not always so in semiconductors).

• Can be used as a B-sensor; used in some ABS to detect shaft rotation speed - ferromagnetic rotating blades interrupt the magnetic field → oscillating voltage
