Lecture 25: MON 16 MAR
Magnetic fields
Ch. 28.1–4

‘I’ll be back....
How Do You Use Magnetic Fields in Your Everyday Life!??
28.2: What Produces Magnetic Field?:

One way that magnetic fields are produced is to use moving electrically charged particles, such as a current in a wire, to make an electromagnet. The current produces a magnetic field that is utilizable.

The other way to produce a magnetic field is by means of elementary particles such as electrons, because these particles have an intrinsic magnetic field around them. The magnetic fields of the electrons in certain materials add together to give a net magnetic field around the material. Such addition is the reason why a permanent magnet, has a permanent magnetic field.

In other materials, the magnetic fields of the electrons cancel out, giving no net magnetic field surrounding the material.
Electric vs. Magnetic Fields

Electric fields are created:
- microscopically, by electric charges (fields) of elementary particles (electrons, protons)
- macroscopically, by adding the field of many elementary charges of the same sign

Magnetic fields are created:
- microscopically, by magnetic “moments” of elementary particles (electrons, protons, neutrons)
- macroscopically, by
  - adding many microscopic magnetic moments (magnetic materials); or by
  - electric charges that move (electric currents)
Magnetic Field Direction

FROM North Poles TO South Poles

Compare to Electric Field Directions
Law of Attraction and Repulsion for Magnets

Opposite Poles Attract

Like Poles Repel
We know that an electric field exists because it accelerates electric charges, with a force independent of the velocity of the charge, proportional to the electric charge: $F_E = qE$

We know that a magnetic field exists because it accelerates electric charges in a direction perpendicular to the velocity of the charge, with a magnitude proportional to the velocity of the charge and to the magnitude of the charge: $F_B = qv \times B$

Magnetic forces are perpendicular to both the velocity of charges and to the magnetic field (electric forces are parallel to the field).

Since magnetic forces are perpendicular to the velocity, they do no work! ($W = F \cdot r = Fr \cos(90^\circ) = 0$)

Speed of particles moving in a magnetic field remains constant in magnitude, ONLY the direction changes. Kinetic energy is constant! (no work).
Magnetic vs. Electric Forces

Electric Force on Charge Parallel to E:

\[ \vec{F}_E = q\vec{E} \]

Magnetic Force on Charge Perpendicular to B and v.

\[ \vec{F}_B = q\vec{v} \times \vec{B} \]
28.3: Finding the Magnetic Force on a Particle:

\[ \vec{F} = \vec{v} \times \vec{B} \]

\( \vec{v} = \text{index = forefinger} \)

\( \vec{B} = \text{"bird" finger} \)

\( \vec{F} = \text{thumb} \)

The force \( \vec{F}_B \) acting on a charged particle moving with velocity \( \vec{v} \) through a magnetic field \( \vec{B} \) is always perpendicular to \( \vec{v} \) and \( \vec{B} \).

Always assume particle is POSITIVELY charged to work Out direction then flip your thumb over if it is NEGATIVE.
CHECKPOINT 1

The figure shows three situations in which a charged particle with velocity $\vec{v}$ travels through a uniform magnetic field $\vec{B}$. In each situation, what is the direction of the magnetic force $\vec{F}_B$ on the particle?

(a) $+ z$

(b) $- x$

(c) $\sin 180^\circ = 0$
Definition of Magnetic Field

\[ B = \frac{F_B}{q|\vec{v}|} \]

Definition of Electric Field:

\[ \vec{E} = \frac{\vec{F}_E}{q} \]

Units:

\[ B = \frac{\text{Newton}}{\text{Coulomb} \cdot (\text{meter/sec})} = \frac{\text{Newton}}{(\text{Coulomb/sec}) \cdot \text{meter}} = \frac{\text{Newton}}{\text{Ampere} \cdot \text{meter}} = \frac{\text{N}}{\text{A} \cdot \text{m}} \]

\[ [T] = \left[ \frac{\text{N}}{\text{A} \cdot \text{m}} \right] = [\text{Tesla}] \]
28.3: The Definition of $B$:

The SI unit for $B$ that follows is newton per coulomb-meter per second. For convenience, this is called the **tesla** ($T$):

$$1 \text{ tesla} = 1 \text{ T} = 1 \frac{\text{newton}}{\text{(coulomb)}(\text{meter/second})}$$

$$= 1 \frac{\text{newton}}{\text{(coulomb/second)}(\text{meter})} = 1 \frac{\text{N}}{\text{A} \cdot \text{m}}$$

An earlier (non-SI) unit for $B$ is the **gauss** ($G$), and

$$1 \text{ tesla} = 10^4 \text{ gauss}.$$
Thompson Experiment & The Discovery of the Electron

Forces Balance: \( v = \frac{E}{B} \)

Cross-section of a velocity selector

While in the magnetic field an electromagnetic force is felt as \( F_B = qvB \). The right hand rule gives us the direction, with fingers into the page (B), thumb to the right (I), gives force in direction of the palm being UP.

The source provides positively charged particles entering the selector at this end.

The ions enter the electric field a force \( F_e = qE \) is created based on the charge of the ion and field strength. This force is directed downward as the positive plate repels the positive particle.

In order to pass undeflected through the crossed fields \( F_B = F_e \) or \( qvB = qE \). Factoring the charge gives us \( vB = E \) or solving for \( v \) gives \( v = \frac{E}{B} \). Thus by controlling \( E \) and \( B \) we allow particles of only a specific velocity to pass through.

If the velocity of the particle is too high, then \( F_B > F_e \) and the particle curves up hitting the plate at the end of the selector. If the velocity is too low, \( F_B < F_e \) and the particle curves down hitting the lower portion of the same plate.
\[ E \neq 0, \ B = 0; \quad qE = F_E = ma \]
\[ a = F_E / m = qE / m \]
\[ L = vt; \quad y = \frac{1}{2} at^2; \quad \text{Solve:} \quad y = \frac{qEL^2}{2mv^2} \]

\[ \frac{m}{q} = \frac{L^2B^2}{2yE} \]

\[ v = E / B; \quad y = \frac{qEL^2}{2mv^2} \]
\[ y = \frac{qEL^2B^2}{2mE^2} = \frac{qL^2B^2}{2mE} \]
CHECKPOINT 2

The figure shows four directions for the velocity vector $\vec{v}$ of a positively charged particle moving through a uniform electric field $\vec{E}$ (directed out of the page and represented with an encircled dot) and a uniform magnetic field $\vec{B}$. (a) Rank directions 1, 2, and 3 according to the magnitude of the net force on the particle, greatest first. (b) Of all four directions, which might result in a net force of zero?

\[ F_1 = 0_B + \bigodot_E \]
\[ F_2 = \bigodot_B + \bigodot_E \]
\[ F_3 = 0_B + \bigodot_E \]
\[ F_4 = -\bigodot_B + \bigodot_E \]

(a) $F_2 > F_1 = F_3$

(b) $F_4 = 0$
28.4: Crossed Fields, Discovery of an Electron:

When the two fields in Fig. 28-7 are adjusted so that the two deflecting forces acting on the charged particle cancel, we have

\[ |q|E = |q|vB \sin(90^\circ) = |q|vB \quad \Rightarrow \quad v = \frac{E}{B}. \]

Thus, the crossed fields allow us to measure the speed of the charged particles passing through them.

The deflection of a charged particle, moving through an electric field, \( E \), between two plates, at the far end of the plates (in the previous problem) is

\[ y = \frac{|q|EL^2}{2mv^2} \quad \Rightarrow \quad \frac{m}{|q|} = \frac{B^2L^2}{2vE}. \]

Here, \( v \) is the particle’s speed, \( m \) its mass, \( q \) its charge, and \( L \) is the length of the plates.

**Experiment measured electrons mass to charge ratio \( m/q \).**
Magnetic Deflection of a TV Image

MIT Department of Physics Technical Services Group
Example, Magnetic Force on a Moving Charged Particle:

A uniform magnetic field $\vec{B}$, with magnitude 1.2 mT, is directed vertically upward throughout the volume of a laboratory chamber. A proton with kinetic energy 5.3 MeV enters the chamber, moving horizontally from south to north. What magnetic deflecting force acts on the proton as it enters the chamber? The proton mass is $1.67 \times 10^{-27}$ kg. (Neglect Earth’s magnetic field.)

$$a = \frac{F_B}{m} = \frac{6.1 \times 10^{-15} \text{ N}}{1.67 \times 10^{-27} \text{ kg}} = 3.7 \times 10^{12} \text{ m/s}^2.$$  

**Direction:** To find the direction of $\vec{F}_B$, we use the fact that $\vec{F}_B$ has the direction of the cross product $q \vec{v} \times \vec{B}$. Because the charge $q$ is positive, $\vec{F}_B$ must have the same direction as $\vec{v} \times \vec{B}$, which can be determined with the right-hand rule for cross products (as in Fig. 28-2d). We know that $\vec{v}$ is directed horizontally from south to north and $\vec{B}$ is directed vertically up. The right-hand rule shows us that the deflecting force $\vec{F}_B$ must be directed horizontally from west to east, as Fig. 28-6 shows. (The array of dots in the figure represents a magnetic field directed out of the plane of the figure. An array of Xs would have represented a magnetic field directed into that plane.)

If the charge of the particle were negative, the magnetic deflecting force would be directed in the opposite direction—that is, horizontally from east to west. This is predicted automatically by Eq. 28-2 if we substitute a negative value for $q$.

**KEY IDEAS**

Because the proton is charged and moving through a magnetic field, a magnetic force $\vec{F}_B$ can act on it. Because the initial direction of the proton’s velocity is not along a magnetic field line, $\vec{F}_B$ is not simply zero.

**Magnitude:** To find the magnitude of $\vec{F}_B$, we can use Eq. 28-3 ($F_B = |q|vB \sin \phi$) provided we first find the proton’s speed $v$. We can find $v$ from the given kinetic energy because $K = \frac{1}{2}mv^2$. Solving for $v$, we obtain

$$v = \sqrt{\frac{2K}{m}} = \sqrt{\frac{(2)(5.3 \text{ MeV})(1.60 \times 10^{-13} \text{ J/MeV})}{1.67 \times 10^{-27} \text{ kg}}} = 3.2 \times 10^7 \text{ m/s}.$$  

Equation 28-3 then yields

$$F_B = |q|vB \sin \phi$$

$$= (1.60 \times 10^{-19} \text{ C})(3.2 \times 10^7 \text{ m/s})$$

$$\times (1.2 \times 10^{-3} \text{ T})(\sin 90^\circ)$$

$$= 6.1 \times 10^{-15} \text{ N}. \quad \text{(Answer)}$$

This may seem like a small force, but it acts on a particle of small mass, producing a large acceleration; namely,
Fred brings home one too many cute refrigerator magnets.