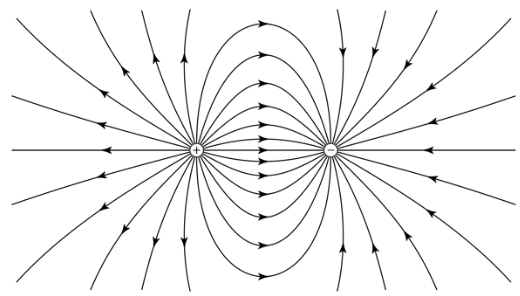
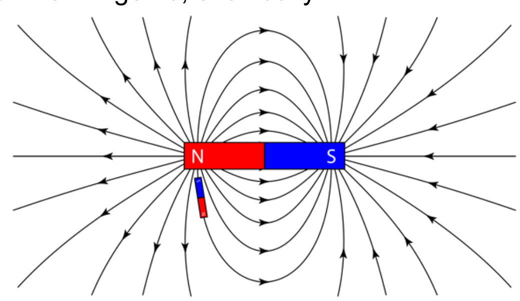
Flipping Physics Lecture Notes:
Magnetic Fields
Review for AP Physics C: Electricity and Magnetism
http://www.flippingphysics.com/apcem-magnetic-fields.html

Magnetic fields (or "B" fields) are be created by magnetic dipoles:

- Just like electric charges are described as positive and negative charges, magnetic poles are described as north and south poles.
    - A magnetic monopole has never been found.
        - This does not mean magnetic monopoles do not exist.
            - We cannot prove magnetic monopoles do not exist.
                - We can only say we have no evidence that they exist.
    - If a magnetic dipole is broken in half, it becomes two new magnetic dipoles.
- Like poles repel and unlike poles attract.
    - Just like the Law of Charges



- The magnetic field caused by a magnetic dipole looks remarkably like the electric field caused by an electric dipole.
    - B field lines external to the magnet, point from north pole to south pole.
        - Just like E field points from positive charge to negative charge.
    - Magnetic field lines must be closed loops.
        - Due to Gauss' law for magnetism which we will get to, eventually.
        - This means B fields inside the magnet point from the south pole to the north pole, to complete the closed loop.
    - A magnetic dipole placed in a magnetic field will align itself with the magnetic field.
        - Think *compass!*



- For planet Earth:
    - The location of the geographic north pole is close to that of the magnetic south pole.
    - The location of the geographic south pole is close to that of the magnetic north pole.
        - The north pole of a compass points north because it is attracted to the magnetic south pole of the Earth.
            - (unlike poles attract)
    - The magnetic field of the Earth can be approximated as a magnetic dipole.

Magnetic dipoles are the result of electric charges moving in circles.

- We will cover electric charges moving in circles creating magnetic fields extensively later. At this point, just know that electric charges moving in circles create magnetic fields.
- The magnetism of magnets is most often the motion of electrons moving in circles inside them.
- Permanent magnetic dipoles and induced (temporary) magnetic dipoles are a property of the object which results from the alignment of magnetic dipoles within the object.

The material composition of a magnet affects its magnetic behavior when it is placed in an external magnetic field:

- *Ferromagnetic* materials can be *permanently* magnetized by an external magnetic field.
    - The alignment of the magnetic domains or atomic magnetic dipoles is *permanent*.
    - Example materials: nickel, iron, cobalt
- *Paramagnetic* materials are only *temporarily* magnetized by an external magnetic field.
    - The alignment of the magnetic domains or atomic magnetic dipoles is *temporary*.
    - Example materials: aluminum, magnesium, titanium

Just like materials have an electric permittivity, ε, materials also have a magnetic permeability, μ:

- Magnetic permeability: the measurement of the amount of magnetization a material has in response to an external magnetic field.
  - Ferromagnetic materials have high magnetic permeabilities that increase in the presence of an external magnetic field.
  - Paramagnetic materials have low magnetic permeabilities.
  - The magnetic permeability of materials is not constant. It changes depending on various factors such as temperature, orientation, and the strength of the external magnetic field.
- The magnetic permeability of free space has a constant value, μ_0: $\mu_0 = 4\pi \times 10^{-7} \frac{T \cdot m}{A}$

A magnetic field is defined by the fact that a moving electric charge in a B field can experience a magnetic force, F_B.

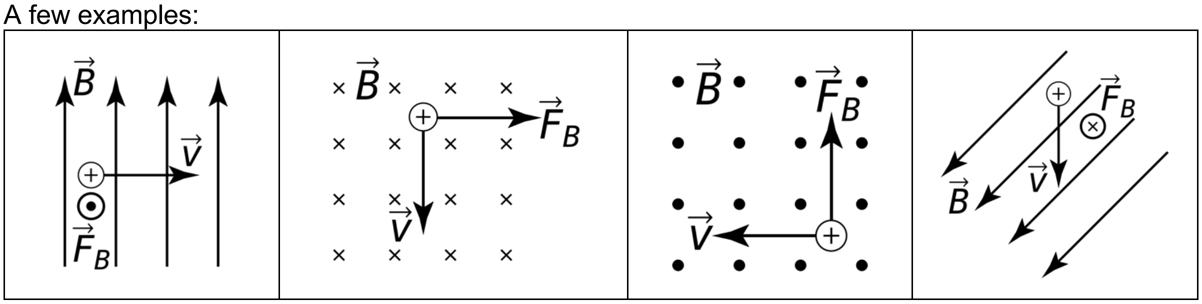
- $\vec{F}_B = q\vec{v} \times \vec{B} \Rightarrow \|F_B\| = qvB\sin\theta$
  - This equation is an experimentally determined equation. In other words, there is no way to mathematically derive it! We know it is true because we have repeatedly measured it.
  - Notice the similarities to the torque equations: $\vec{\tau} = \vec{r} \times \vec{F} \Rightarrow \|\tau\| = rF\sin\theta$
- $\Rightarrow B = \frac{F_B}{qv\sin\theta} \Rightarrow \frac{N}{C\left(\frac{m}{s}\right)} = \frac{N}{\left(\frac{C}{s}\right)m} = \frac{N}{A \cdot m} = \text{tesla}, T$
  - $1 \text{ tesla}, T = 10{,}000 \text{ gauss}, G$

Please recognize that the magnetic field is a vector. To that end, we need to know the direction of the magnetic force acting on an electric charge moving in a magnetic field. For that we use …

The Right-Hand Rule: [Don't be too cool. Limber up. Find your right hand.]

- Fingers point in the direction of the electric charge velocity.
- Fingers curl in the direction of the magnetic field.
  - It's a good rule of thumb[1] to start at 90°.
- Thumb points in the direction of the magnetic force on a positive charge.
  - For a negative charge, the thumb points 180° from the direction of the magnetic force.
  - Make sure your thumb points normal to the plane created by the velocity of the electric charge and the magnetic field.
    - In other words, realize the direction of the magnetic force is always normal to the plane created by the velocity of the electric charge and the magnetic field.
- Realize, the cross-product version of the magnetic force equation also gives you the direction of the magnetic force in terms of unit vectors.
- Since examples of this concept require vectors in all three dimensions, we introduce two symbols to indicate direction perpendicular to the page. A dot for out of the page, and an X for into the page, like the pointed tip and fletching (feathers) of a flying arrow respectively.

A few examples:

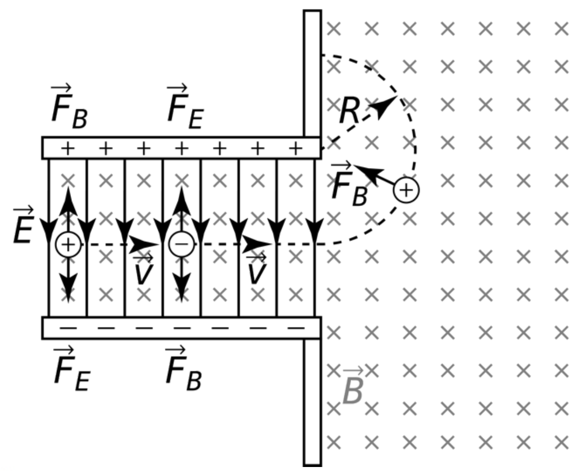


[1] Ha ha ha!

What if we have a series of charges all moving in the same direction? Like a current carrying wire?

- We already derived the equation for the current in a wire: $I = nAv_dq$
- And we know the magnetic force acting on *each individual charge* moving in the wire:
  $\vec{F}_B = q\vec{v} \times \vec{B}$
- However, what we want to know is the net magnetic force acting on all the charges moving in the wire. So, we need to use charge carrier density, n:
  - $$n = \frac{\#\text{ of charges}}{V} \Rightarrow \#\text{ of charges} = nV = nAL$$
- Which we can use to get the magnetic force acting on *all the charges* moving in the wire:
  $$\vec{F}_B = \left(q\vec{v} \times \vec{B}\right) nAL = nAvq\vec{L} \times \vec{B}$$
- And we have derived the general equations for the magnetic force on a current carrying wire both for a straight wire and, using an integral, a wire that does not follow a straight path.
  $$\Rightarrow \vec{F}_B = I\vec{L} \times \vec{B} \Rightarrow \vec{F}_B = \int I\left(d\vec{L} \times \vec{B}\right) \quad \& \quad \|F_B\| = ILB\sin\theta$$
- You use the same wonderful right-hand rule to determine the direction of this force.

Because it involves many concepts that are likely to come up on the AP exam, let's take a moment to analyze a mass spectrometer:



The magnetic field is uniform into the page throughout, and in the velocity selector, the electric field uniform and down.

Velocity Selector:

- For a positive charge the magnetic force is up and the Coulomb force is down.
- For a negative charge the magnetic force is down and the Coulomb force is up.
- Regardless of whether the charge is positive or negative, the free body diagrams result in the same Newton's Second Law equation:

$$\sum F_y = F_B - F_E = ma_y = 0 \Rightarrow F_B = F_E$$

$$\Rightarrow qvB\sin\theta = qE \Rightarrow vB\sin(90°) = E \Rightarrow v = \frac{E}{B}$$

- So, all charged objects with the same constant velocity will all move in a straight horizontal line in the velocity selector. Regardless of mass, charge sign, and charge magnitude.

Deflection Chamber:

- The uniform magnetic field is the only field present in the deflection chamber.
- The only force acting on the charged particle is the magnetic force which acts inward.
  - The charged particles will move along a circular path with radius, R.
  - Positive charges will be deflected upward.
  - Negative charges will be deflected downward.
- Again, we use Newton's Second Law:

$$\sum F_{\text{in}} = F_B = ma_c \Rightarrow qvB\sin\theta = qvB\sin(90^\circ) = qvB = m\left(\frac{v_t^2}{R}\right)$$

$$\Rightarrow qB = \frac{mv_t}{R} \Rightarrow qB = \frac{m\left(\frac{E}{B}\right)}{R} \Rightarrow mE = qRB^2 \Rightarrow \frac{m}{q} = \frac{RB^2}{E}$$

The mass spectrometer is a tool for determining velocities and mass-to-charge ratios of electric charges. Imagine how useful this could be for learning information about new particles!