

# PHYS 1444 – Section 003

## Lecture #15

*Monday, Oct. 24, 2005*

*Dr. Jaehoon Yu*

- Magnetic field
- Earth's magnetic field
- Magnetic field by electric current
- Magnetic force on electric current
- Magnetic force on a moving charge

Today's homework is homework #8, due noon, next Tuesday!!



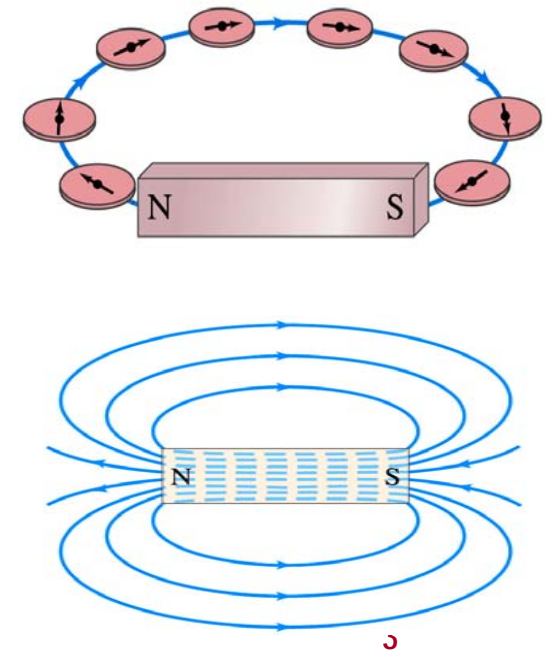
# Announcements

- Reading assignments
  - CH. 27 – 6
  - CH. 27 – 8
  - CH. 27 – 9



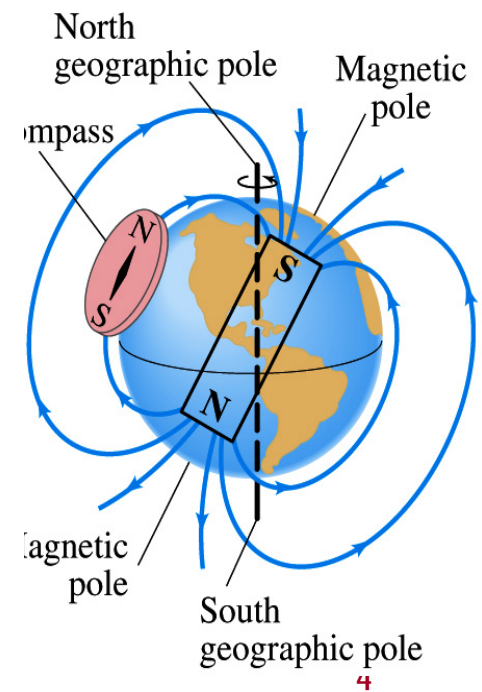
# Magnetic Field

- Just like the electric field that surrounds electric charge, a magnetic field surrounds a magnet
- What does this mean?
  - Magnetic force is also a field force
  - The force one magnet exerts onto another can be viewed as the interaction between the magnet and the magnetic field produced by the other magnet
  - What kind of quantity is the magnetic field? Vector or Scalar? **Vector**
- So one can draw magnetic field lines, too.
  - The direction of the magnetic field is tangent to a line at any point
  - The direction of the field is the direction the north pole of a compass would point to
  - The number of lines per unit area is proportional to the strength of the magnetic field
  - Magnetic field lines continue inside the magnet
  - Since magnets always have both the poles, magnetic field lines form closed loops unlike electric field lines



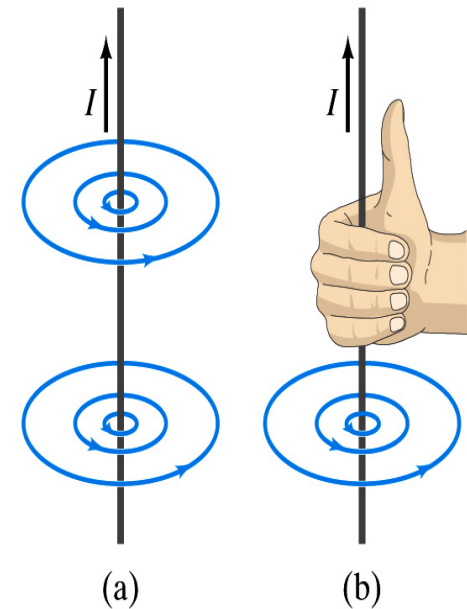
# Earth's Magnetic Field

- Now what magnetic pole does the geographic north pole has to have?
  - Magnetic south pole. What? How do you know that?
  - Since the magnetic north pole points to the geographic north, the geographic north must have magnetic south pole
    - The pole in the north is still called geomagnetic north pole just because it is in the north
  - Similarly, south pole has north magnetic pole
- The Earth's magnetic poles do not coincide with the geographic poles → magnetic declination
  - Magnetic north pole is in northern Canada, some 1300km off the true north pole
- Earth's magnetic field line is not tangent to the earth's surface at all points
  - The angle the Earth's field makes to the horizontal line is called the angle dip



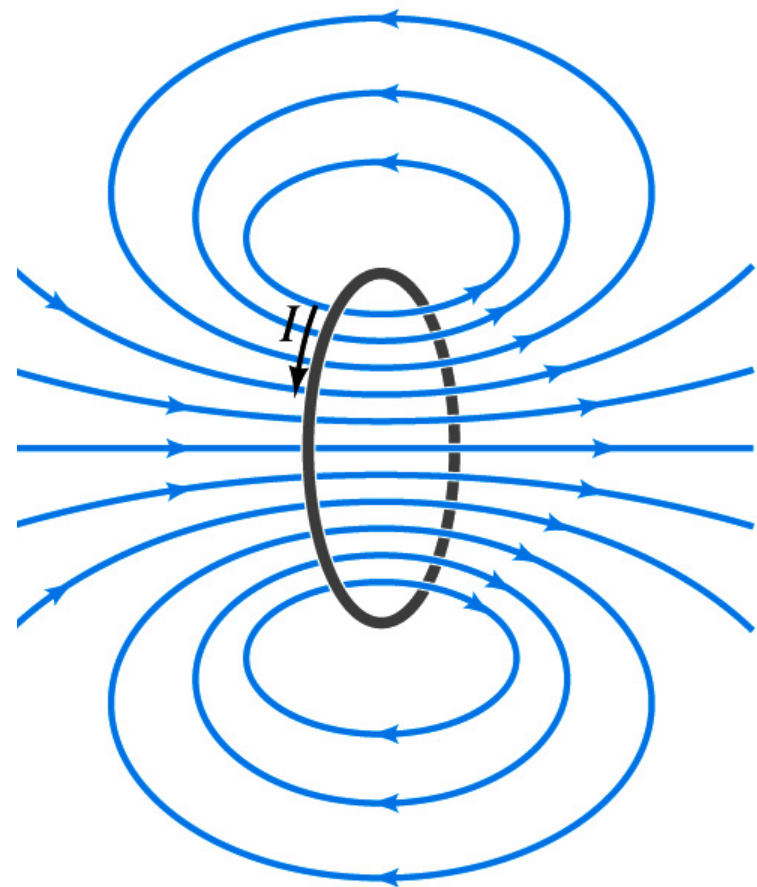
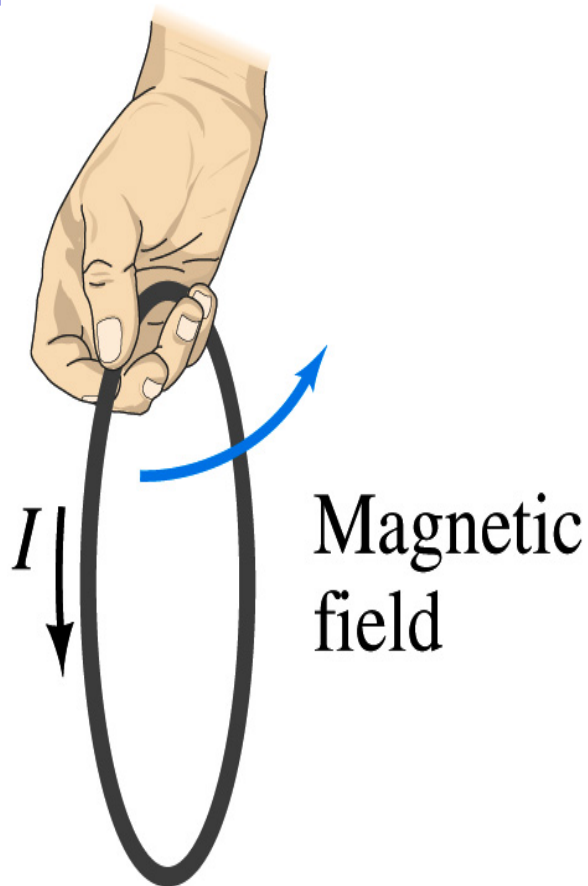
# Electric Current and Magnetism

- In 1820, Oersted found that when a compass needle is placed near an electric wire, the needle deflects as soon as the wire is connected to a battery and a current flows
  - Electric current produces a magnetic field
    - The first indication that electricity and magnetism are the same thing
  - What about a stationary electric charge and magnet?
    - They don't affect each other.
- The magnetic field lines produced by a current in a straight wire is in the form of circles following the “right-hand” rule
  - The field lines follow right-hand's fingers wrapped around the wire when the thumb points to the direction of the electric current



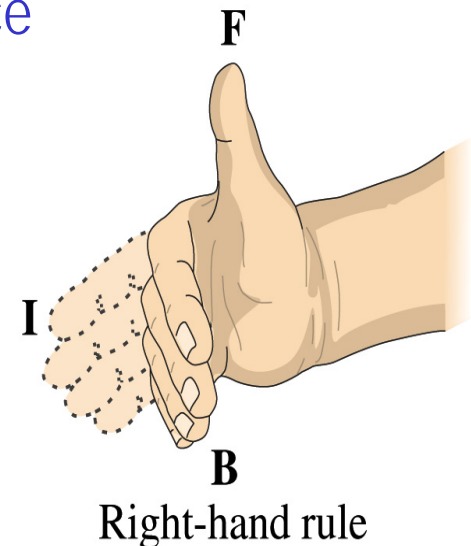
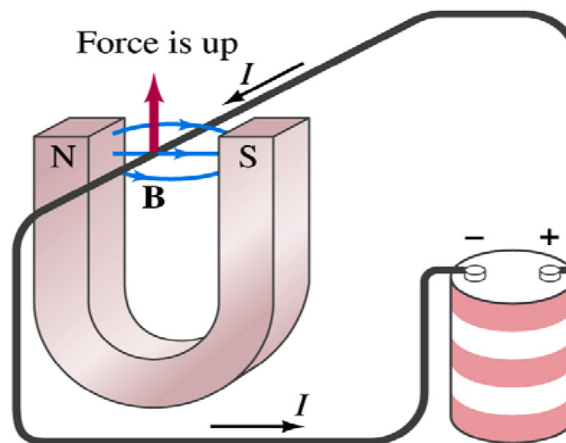
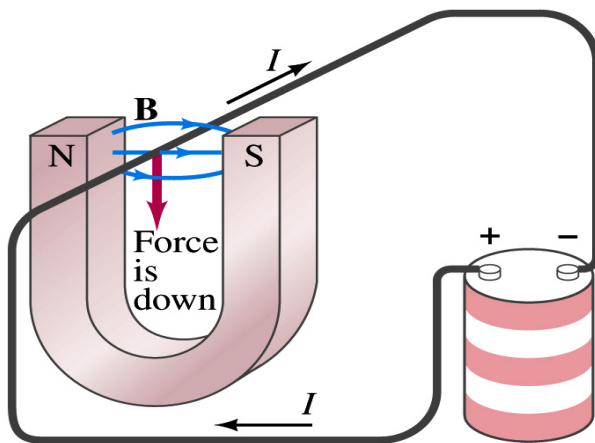
# Directions in a Circular Wire?

- OK, then what are the directions of the magnetic fields generated by the current flowing through circular loops?



# Magnetic Forces on Electric Current

- Since the electric current exerts force on a magnet, the magnet should also exert force on the electric current
  - Which law justifies this?
    - Newton's 3<sup>rd</sup> law
  - This also was found by Oersted
- Direction of the force is always
  - perpendicular to the direction of the current and also
  - perpendicular to the direction of the magnetic field,  $B$
- Experimentally the direction of the force is given by another right-hand rule → When the fingers of the right-hand points to the direction of the current and the finger tips bent to the direction of magnetic field  $B$ , the direction of thumb points to the direction of the force



# Magnetic Forces on Electric Current

- OK, we are set for the direction but what about the magnitude?
- It is found that the magnitude of the force is directly proportional to
  - the current in the wire
  - The length of the wire in the magnetic field (if the field is uniform)
  - The strength of the magnetic field
- The force also depends on the angle  $\theta$  between the directions of the current and the magnetic field
  - When the wire is perpendicular to the field, the force is strongest
  - When the wire is parallel to the field, there is no force at all
- Thus the force on current  $I$  in the wire w/ length  $l$  in a uniform field  $B$  is

$$F \propto IlB \sin \theta$$





# Magnetic Forces on Electric Current

- Magnetic field strength  $B$  can be defined using the previous proportionality relationship w/ the constant 1:  $F = IlB \sin \theta$
- if  $\theta=90^\circ$ ,  $F_{\max} = IlB$  and if  $\theta=0^\circ$   $F_{\min} = 0$
- So the magnitude of the magnetic field  $B$  can be defined as
  - $B = F_{\max} / Il$  where  $F_{\max}$  is the magnitude of the force on a straight length  $l$  of wire carrying a current  $I$  when the wire is perpendicular to  $B$
- The relationship between  $F$ ,  $B$  and  $I$  can be written in vector formula:  $\vec{F} = I\vec{l} \times \vec{B}$ 
  - $l$  is the vector whose magnitude is the length of the wire and its direction is along the wire in the direction of the conventional current
  - This formula works if  $B$  is uniform.
- If  $B$  is not uniform or  $l$  does not make the same angle everywhere, the infinitesimal force acting on a differential length  $d\vec{l}$  is  $d\vec{F} = Id\vec{l} \times \vec{B}$

Monday, Oct 10, 2005



PHYS 1444-003, Fall 2005  
Dr. Jaehoon Yu

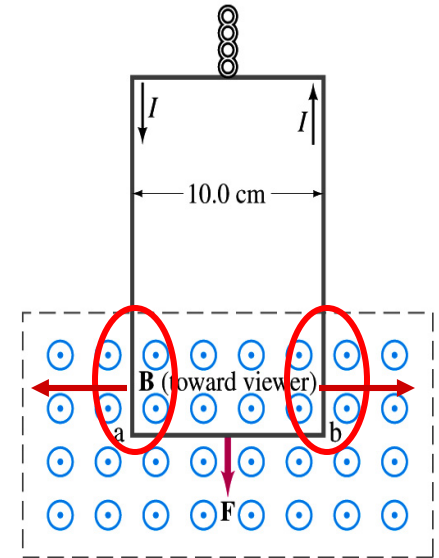
# About the Magnetic Field, B

- It is a vector quantity
- The SI unit for B is tesla (T)
  - What is the definition of 1 Tesla in terms of other known units?
  - $1\text{T}=1\text{N/Am}$
  - In older names tesla is weber per meter-squared
    - $1\text{Wb/m}^2=1\text{T}$
- The cgs unit for B is gauss (G)
  - How many T is one G?
    - $1\text{G}=10^{-4}\text{T}$
  - For computation, one MUST convert G to T at all times
- Magnetic field on the Earth's surface is about  $0.5\text{G}=0.5\times 10^{-4}\text{T}$
- On a diagram,  $\odot$  for field coming out and  $\otimes$  for going in.



# Example 27 – 1

**Measuring a magnetic field.** A rectangular loop of wire hangs vertically as shown in the figure. A magnetic field  $\mathbf{B}$  is directed horizontally perpendicular to the wire, and points out of the page. The magnetic field  $\mathbf{B}$  is very nearly uniform along the horizontal portion of wire ab (length  $l=10.0\text{cm}$ ) which is near the center of a large magnet producing the field. The top portion of the wire loop is free of the field. The loop hangs from a balance which measures a downward force (in addition to the gravitational force) of  $F=3.48\times 10^{-2}\text{N}$  when the wire carries a current  $I=0.245\text{A}$ . What is the magnitude of the magnetic field  $B$  at the center of the magnet?



Magnetic force exerted on the wire due to the uniform field is

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

Since  $\vec{B} \perp \vec{l}$  Magnitude of the force is  $F = IlB$

Solving for B

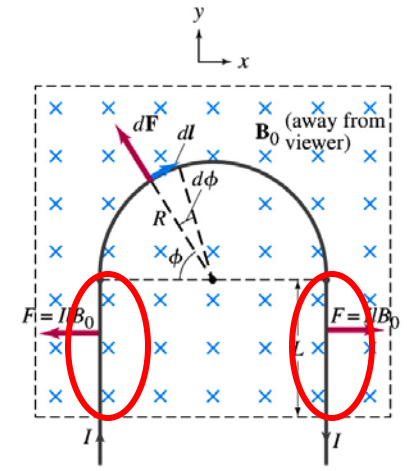
$$B = \frac{F}{Il} = \frac{3.48 \times 10^{-2} \text{ N}}{0.245 \text{ A} \cdot 0.10 \text{ m}} = 1.42 \text{ T}$$

Something is not right! What happened to the forces on the loop on the side?

The two forces cancel out since they are in opposite direction with the same magnitude.

# Example 27 – 2

**Magnetic force on a semi-circular wire.** A rigid wire, carrying a current  $I$ , consists of a semicircle of radius  $R$  and two straight portions as shown in the figure. The wire lies in a plane perpendicular to the uniform magnetic field  $\mathbf{B}_0$ . The straight portions each have length  $l$  within the field. Determine the net force on the wire due to the magnetic field  $\mathbf{B}_0$ .



As in the previous example, the forces on the straight sections of the wire is equal and opposite direction. Thus they cancel.

What do we use to figure out the net force on the semicircle?

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

We divide the semicircle into infinitesimal straight sections.

$$dl = R d\phi$$

What is the net x component of the force exerting on the circular section? **0** Why?

Because the forces on left and the right-hand sides of the semicircle balance.

Since  $\vec{B}_0 \perp d\vec{l}$  Y-component of the force  $dF$  is  $dF = d(F \sin \phi) = IRB_0 d\phi$

Integrating over  $\phi=0 \rightarrow \pi$

$$F = \int_0^\pi d(F \sin \phi) = IB_0 R \int_0^\pi \sin \phi d\phi = -IB_0 R [\cos \phi]_0^\pi = 2IB_0 R$$

Which direction? <sup>2c</sup> Vertically upward direction. The wire will be pulled deeper into the field.

# Magnetic Forces on a Moving Charge

- Will moving charge in a magnetic field experience force?
  - Yes
  - Why?
  - Since the wire carrying a current (moving charge) experience force in a magnetic field, a free moving charge must feel the same kind of force...☺
- OK, then how much force would it experience?
  - Let's consider N moving particles with charge q each, and they pass by a given point in time interval t.
    - What is the current?  $I = Nq/t$
  - Let t be the time for a charge q to travel a distance L in a magnetic field  $\vec{B}$ 
    - Then, the length vector l becomes  $\vec{l} = \vec{v}t$
    - Where  $\vec{v}$  is the velocity of the particle
- Thus the force on N particles by the field is  $\vec{F} = I\vec{l} \times \vec{B} = Nq\vec{v} \times \vec{B}$
- The force on one particle with charge q,  $\vec{F} = q\vec{v} \times \vec{B}$



# Magnetic Forces on a Moving Charge

- This can be an alternative way of defining the magnetic field.

- How?

- The magnitude of the force on a particle with charge  $q$  moving with a velocity  $v$  in the field is

- $F = qvB \sin \theta$

- What is  $\theta$ ?

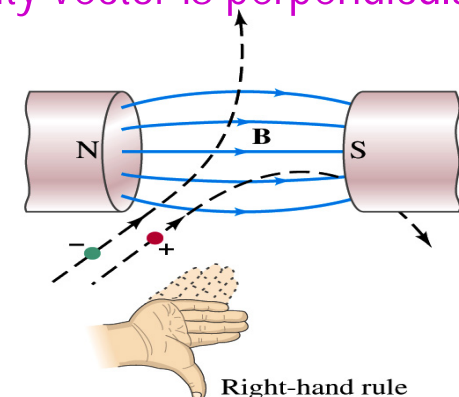
- The angle between the magnetic field and the direction of particle's movement

- When is the force maximum?

- When the angle between the field and the velocity vector is perpendicular.

- $F_{\max} = qvB \rightarrow B = \frac{F_{\max}}{qv}$

- The direction of the force follows the right-hand-rule and is perpendicular to the direction of the magnetic field



## Example 27 – 3

**Magnetic force on a proton.** A proton having a speed of  $5 \times 10^6 \text{ m/s}$  in a magnetic field feels a force of  $F = 8.0 \times 10^{-14} \text{ N}$  toward the west when it moves vertically upward. When moving horizontally in a northerly direction, it feels zero force. What is the magnitude and direction of the magnetic field in this region?

What is the charge of a proton?  $q_p = +e = 1.6 \times 10^{-19} \text{ C}$

What does the fact that the proton does not feel any force in a northerly direction tell you about the magnetic field?

The field is along the north-south direction. Why?

Because the particle does not feel any magnetic force when it is moving along the direction of the field.

Since the particle feels force toward the west, the field should be pointing to .... North

Using the formula for the magnitude of the field  $B$ , we obtain

$$B = \frac{F}{qv} = \frac{8.0 \times 10^{-14} \text{ N}}{1.6 \times 10^{-19} \text{ C} \cdot 5.0 \times 10^6 \text{ m/s}} = 0.10 \text{ T}$$

We can use magnetic field to measure the momentum of a particle. How?