PHYS 1444 – Section 003
Lecture #17

Tuesday, Nov. 1, 2011

Dr. Jaehoon Yu

- Electric Current and Magnetism
- Magnetic Forces on Electric Current
- About Magnetic Field
- Magnetic Forces on a Moving Charge
- Charged Particle Path in a Magnetic Field
- Cyclotron Frequency

Today's homework is #9, due 10pm, Tuesday, Nov. 8!!

Announcements

- Those who have not been able to meet me for grade discussions, please come to my office at 10:30am tomorrow, Wednesday
  - Please bring your exam end of class or to tomorrow's meeting
- Quiz #3
  - Beginning of the class coming Tuesday, Nov. 8
  - Covers: CH26.5 through what we finish Thursday!
- Colloquium at 4pm tomorrow, Wednesday, SH101
  - Department faculty expo part II

Physics Department
The University of Texas at Arlington

COLLOQUIUM

Physics Faculty Research Expo II

Wednesday November 2, 2011
4:00 p.m. Rm. 101SH

SPEAKERS:

Dr. Yue Deng
"Magnetosphere and ionosphere coupling in the polar region"

Dr. Samarendra Mohanty
"Advanced Biophotonics for the future"

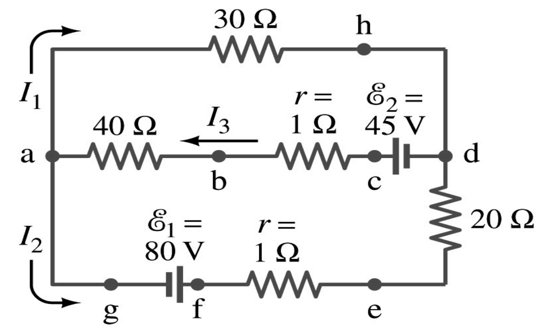
Dr. Zdzislaw Musielak
"Bright and Dark Sides of Our Universe"

Dr. Amir Farbin
"The beginning of time, the scales of the Universe, and Dark Matter"

Refreshments will be served at 3:30 p.m. in the Physics Library

Special Project #5

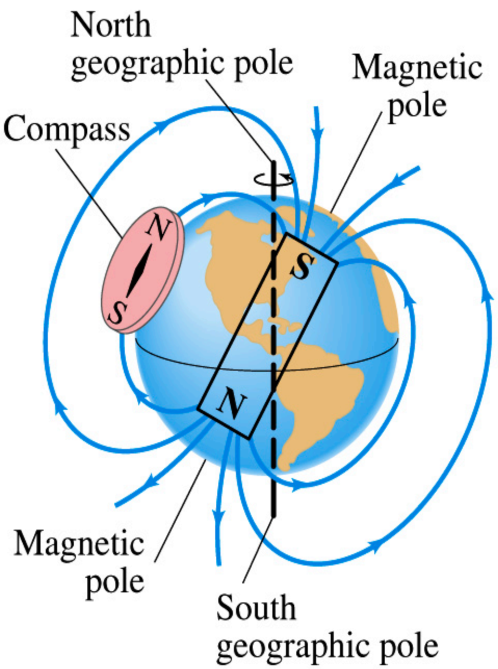
- In the circuit on the right, find out what the currents I_1, I_2 and I_3 are using Kirchhoff's rules in the following two cases:



  - All the directions of the current flows are as shown in the figure. (3points)
  - When the directions of the flow of the current I_1 and I_3 are opposite than what is drawn in the figure but the direction of I_2 is the same. (5 points)
  - When the directions of the flow of the current I_2 and I_3 are opposite than what is drawn in the figure but the direction of I_1 is the same. (5 points)
- Show the details of your OWN work to obtain credit.
- Due is at the beginning of the class Thursday, Nov. 3.

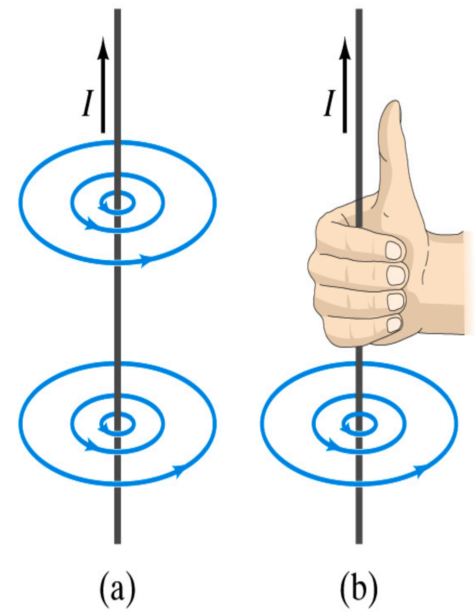
Earth's Magnetic Field

- 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 magnetic north pole
- The Earth's magnetic poles do not coincide with the geographic poles ➔ magnetic declination
  - Geomagnetic north pole is in northern Canada, some 900km 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



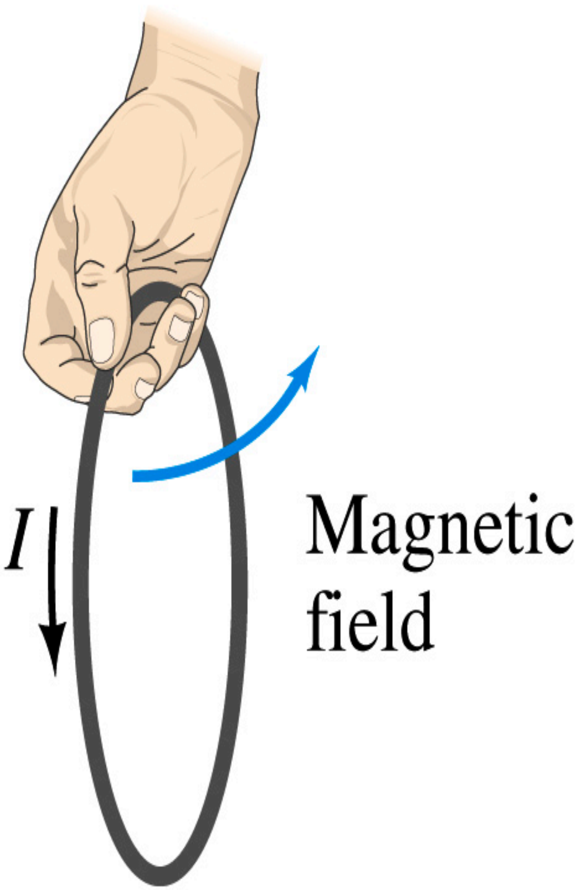
Electric Current and Magnetism

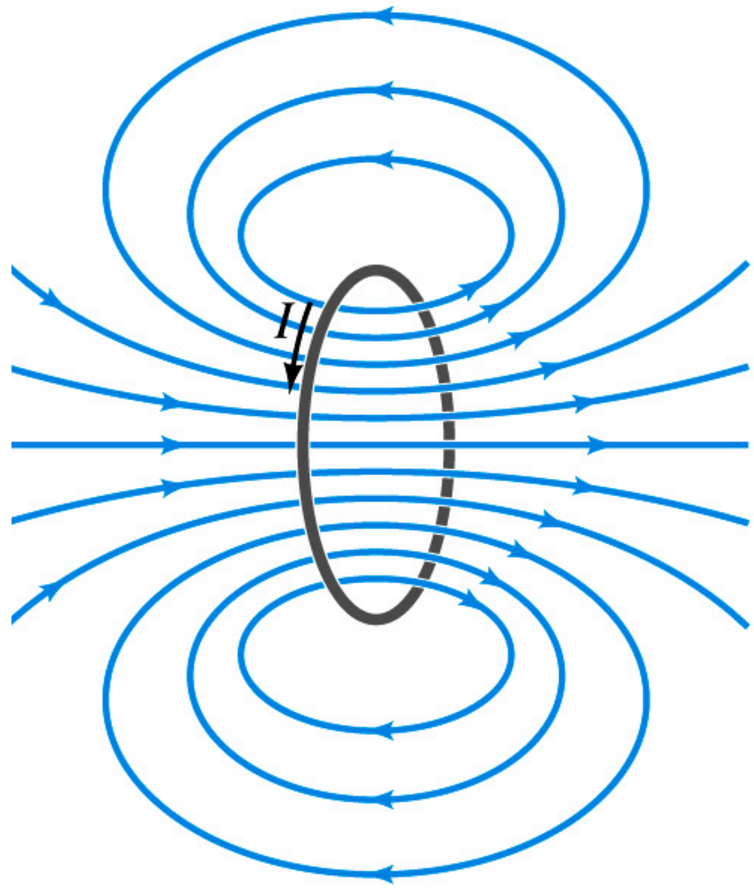
- In 1820, Oersted found that when a compass needle is placed near an electric wire, the needle deflects as soon as the wire is connected to a battery and the current flows
  - Electric current produces a magnetic field
    - The first indication that electricity and magnetism are of the same origin
  - 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 fingers wrapped around the wire when the thumb points to the direction of the electric current



Directions in a Circular Wire?

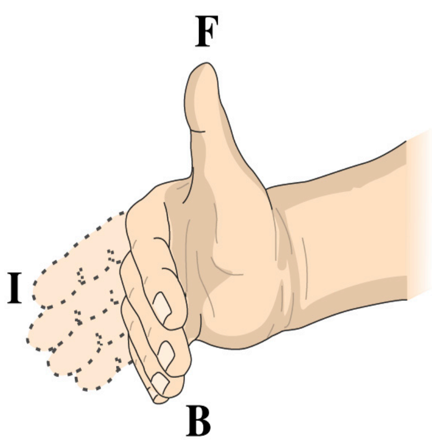
- OK, then what are the directions of the magnetic fields generated by the current flowing through circular loops?



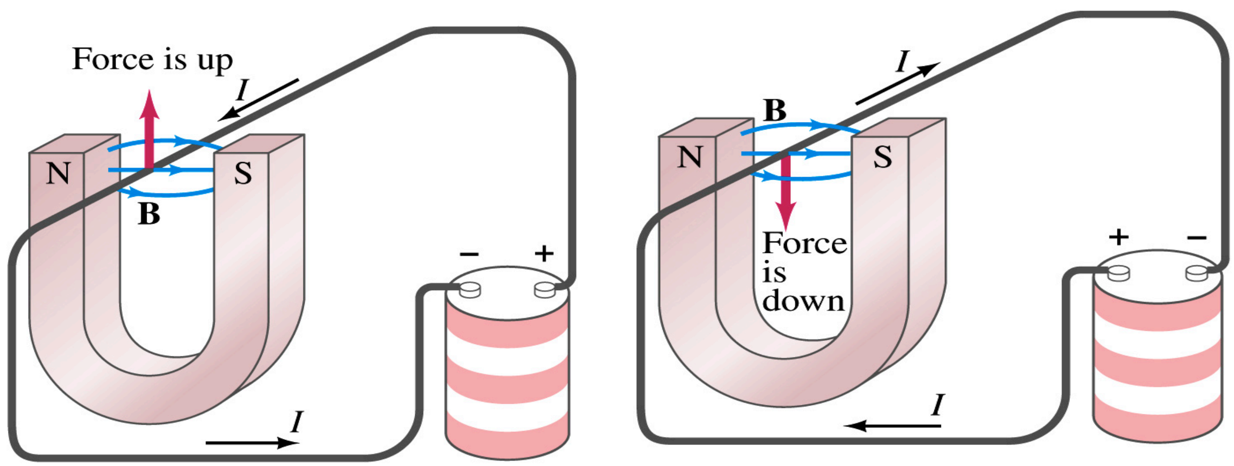


Magnetic Forces on Electric Current

- 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 3rd law
  - This was also discovered 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



Right-hand rule



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
  - To the length of the wire in the magnetic field (if the field is uniform)
  - To the strength of the magnetic field
- The force also depends on the angle θ between the directions of the current and the magnetic field
  - When the wire is perpendicular to the field, the force is the 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 $\mathcal{B}$ is

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

Magnetic Forces on Electric Current

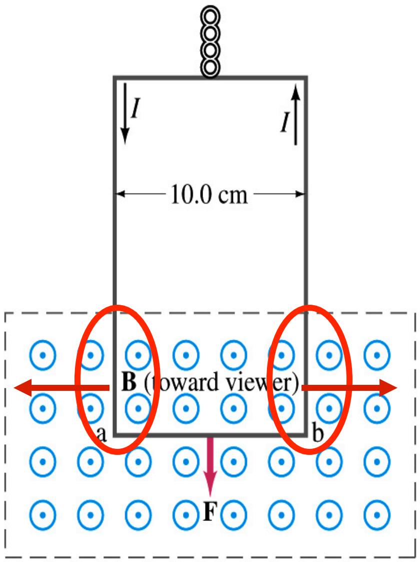
- Magnetic field strength B can be defined using the previous proportionality relationship w/ the constant 1: $F = IlB\sin\theta$
- if θ=90°, $F_{\max} = IlB$ and if θ=0° $F_{\min} = 0$
- So the magnitude of the magnetic field B can be defined as
  - $B = F_{\max}/Il$ where F_{max} is the magnitude of the force on a straight length l of the wire carrying the current I when the wire is perpendicular to **B**
- The relationship between F, B and I can be written in a 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 form the same angle with B everywhere, the infinitesimal force acting on a differential length dl is $d\vec{F} = Id\vec{l} \times \vec{B}$

Fundamentals on the Magnetic Field, B

- The magnetic field 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?
  - 1T=1N/Am
  - In older names, tesla is the same as weber per meter-squared
    - $1Wb/m^2=1T$
- The cgs unit for B is gauss (G)
  - How many T is one G?
    - $1G=10^{-4}$ T
  - For computation, one MUST convert G to T at all times
- Magnetic field on the Earth's surface is about $0.5G=0.5\times10^{-4}T$
- On a diagram, $\odot$ for field coming out and $\otimes$ for going in.

Example 27 – 2

Measuring a magnetic field. A rectangular loop of wire hangs vertically as shown in the figure. A magnetic field **B** is directed horizontally perpendicular to the wire, and points out of the page. The magnetic field **B** is very nearly uniform along the horizontal portion of wire *ab* (length l=10.0cm) 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=3.48x10^{-2}N when the wire carries a current I=0.245A. 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 $\vec{F} = I\vec{l} \times \vec{B}$

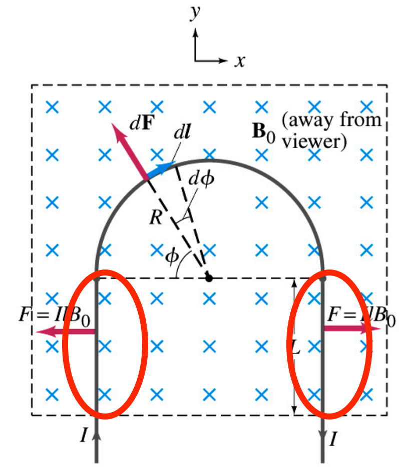
Since $\vec{B} \perp \vec{l}$ Magnitude of the force is $F = IlB$

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

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 – 3



Magnetic force on a semi-circular wire. A rigid wire, carrying the 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 **B₀**. The straight portions each have length ℓ within the field. Determine the net force on the wire due to the magnetic field **B₀**.

As in the previous example, the forces on the straight sections of the wire is equal and in 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 $dF_y = d\left(F \sin\phi\right) = IRB_0\, d\phi$

Integrating over φ=0 - π

$$F = \int_0^\pi d\left(F\sin\phi\right) = IB_0 R\int_0^\pi \sin\phi\, d\phi = -IB_0 R\left[\cos\phi\right]_0^\pi = 2RIB_0$$

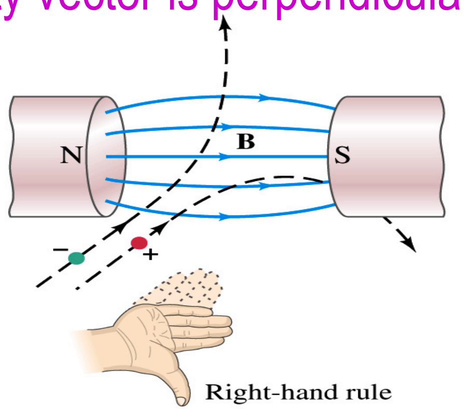
Which direction? Vertically upward direction. The wire will be pulled deeper into the field.

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 **B**
    - Then, the length vector *ℓ* becomes $\vec{l} = \vec{v}t$
    - Where **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 θ?
      - 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 – 5

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

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

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.

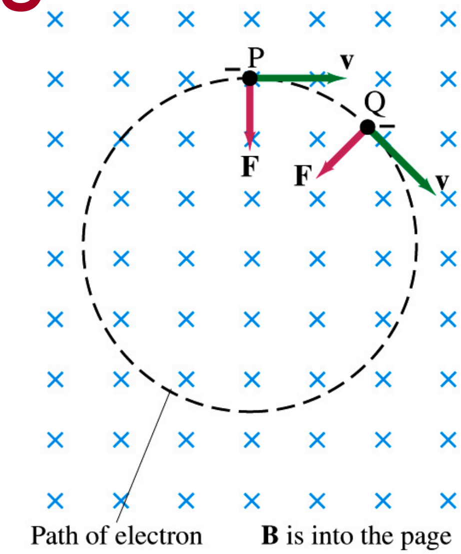
Since the particle feels force toward West, the field should be pointing to …. North

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

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

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

Charged Particle's Path in Magnetic Field



- What shape do you think is the path of a charged particle on a plane perpendicular to a uniform magnetic field?
  - Circle!! Why?
  - An electron moving to right at the point P in the figure will be pulled downward
  - At a later time, the force is still perpendicular to the velocity
  - Since the force is always perpendicular to the velocity, the magnitude of the velocity is constant
  - The direction of the force follows the right-hand-rule and is perpendicular to the direction of the magnetic field
  - Thus, the electron moves on a circular path with a centripetal force F.

Example 27 – 7

Electron's path in a uniform magnetic field. An electron travels at a speed of 2.0×10^7m/s in a plane perpendicular to a 0.010-T magnetic field. Describe its path.

What is formula for the centripetal force? $F = ma = m\frac{v^2}{r}$

Since the magnetic field is perpendicular to the motion of the electron, the magnitude of the magnetic force is $F = evB$

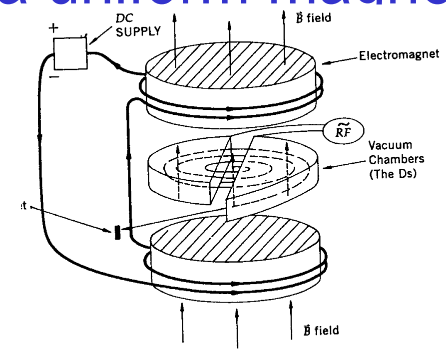
Since the magnetic force provides the centripetal force, we can establish an equation with the two forces $F = evB = m\frac{v^2}{r}$

Solving for r

$$r = \frac{mv}{eB} = \frac{\left(9.1\times10^{-31}kg\right)\cdot\left(2.0\times10^{7}\ m/s\right)}{\left(1.6\times10^{-19}C\right)\cdot\left(0.010T\right)} = 1.1\times10^{-2}m$$

Cyclotron Frequency

- The time required for a particle of charge q moving w/ constant speed v to make one circular revolution in a uniform magnetic field, $\vec{B} \perp \vec{v}$, is



$$T = \frac{2\pi r}{v} = \frac{2\pi}{v}\frac{mv}{qB} = \frac{2\pi m}{qB}$$

- Since T is the period of rotation, the frequency of the rotation is

$$f = \frac{1}{T} = \frac{qB}{2\pi m}$$

- This is the cyclotron frequency, the frequency of a particle with charge q in a cyclotron accelerator
  - While r depends on v, the frequency is independent of v and r.