PHYS 1442 – Section 001
Lecture #9

Wednesday, July 8, 2009

Dr. Jaehoon Yu

- Chapter 20
  - Magnets and Magnetic Field
  - 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

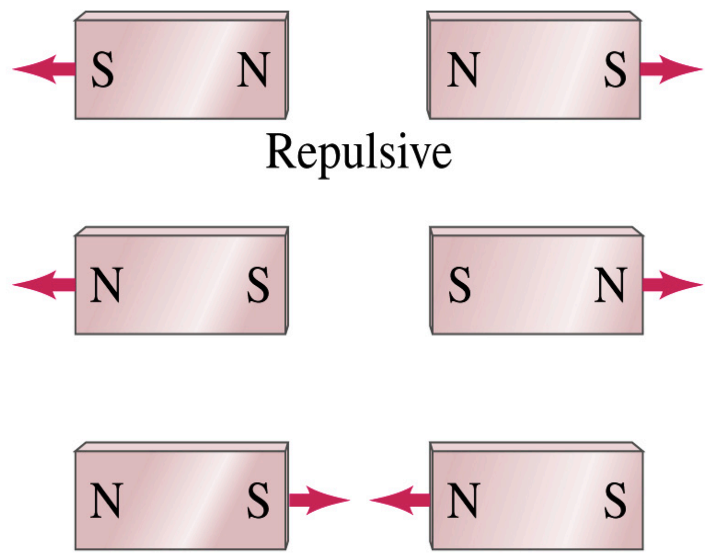
Today's homework is #5, due 9pm, Thursday, July 16!!

Announcements

- Second non-comprehensive exam
  – Date will be moved to Monday, July 27
  – Covers from CH19 – what we finish Monday, July 20
  – There will be a help session Wednesday, July 22, in class
- Evaluation criteria
  – Homework: 30%
  – Final exam: 25%
  – Better of the two term exams: 20%
  – Lab: 15%
  – Quizzes: 10%
  – Extra credit: 10%
- Reading assignments
  – CH20 – 8, 20 – 9, 20 – 10 and 20 – 11

Magnetism

- What are magnets?
  - Objects with two poles, north and south poles
    - The pole that points to geographical north is the north pole and the other is the south pole
      - Principle of compass
  - These are called magnets due to the name of the region, Magnesia, where rocks that attract each other were found
- What happens when two magnets are brought to each other?
  - They exert force onto each other
  - What kind?
  - Both repulsive and attractive forces depending on the configurations
    - Like poles repel each other while the unlike poles attract

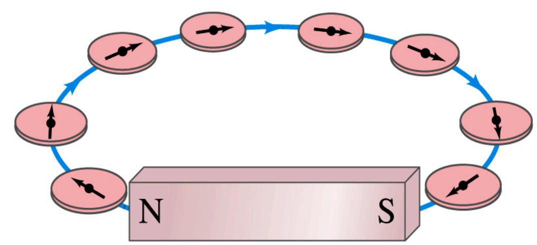


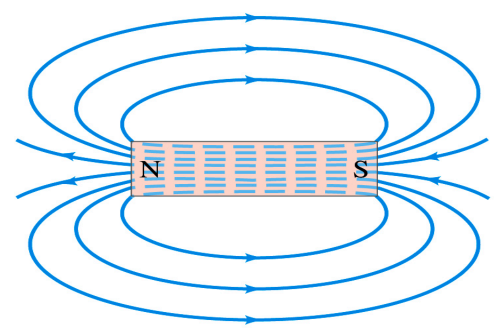
Magnetism

- So the magnet poles are the same as the electric charge?
  - No. Why not?
  - While the electric charges (positive and negative) can be isolated the magnet poles cannot be isolated.
  - So what happens when a magnet is cut?
    - If a magnet is cut, two magnets are made.
    - The more they get cut, the more magnets are made
  - Single pole magnets are called the monopole but it has not been seen yet
- Ferromagnetic materials: Materials that show strong magnetic effects
  - Iron, cobalt, nickel, gadolinium and certain alloys
- Other materials show very weak magnetic effects

Magnetic Field

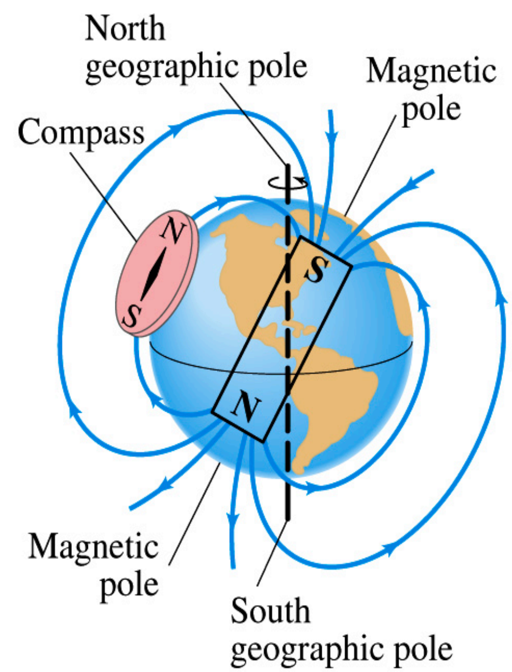
- Just like the electric field that surrounds electric charge, a magnetic field surrounds a magnet
- What does this mean?
  - Magnetic force is also a field force
  - The force one magnet exerts onto another can be viewed as the interaction between the magnet and the magnetic field produced by the other 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

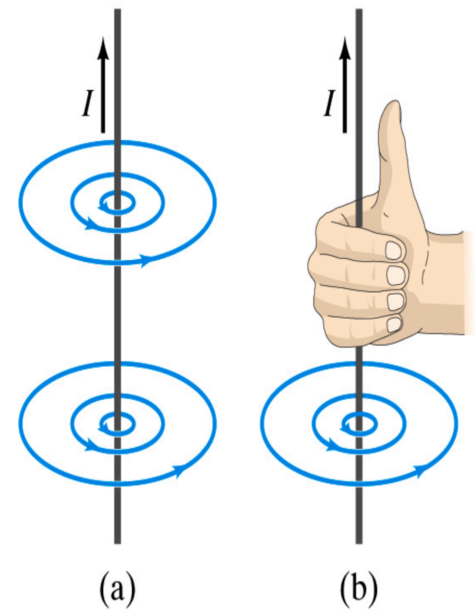
- What magnetic pole does the geographic north pole has to have?
  - W. Gilbert realized in 1600s that the Earth is a giant magnet
  - Magnetic south pole. What? How do you know that?
  - Since the magnetic north pole points to the geographic north, the geographic north must have magnetic south pole
    - The pole in the north is still called geomagnetic north pole just because it is in the north



- The Earth's magnetic poles do not coincide with the geographic poles ➔ magnetic declination (0 – 20^{o} in the US)
  - Geomagnetic 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

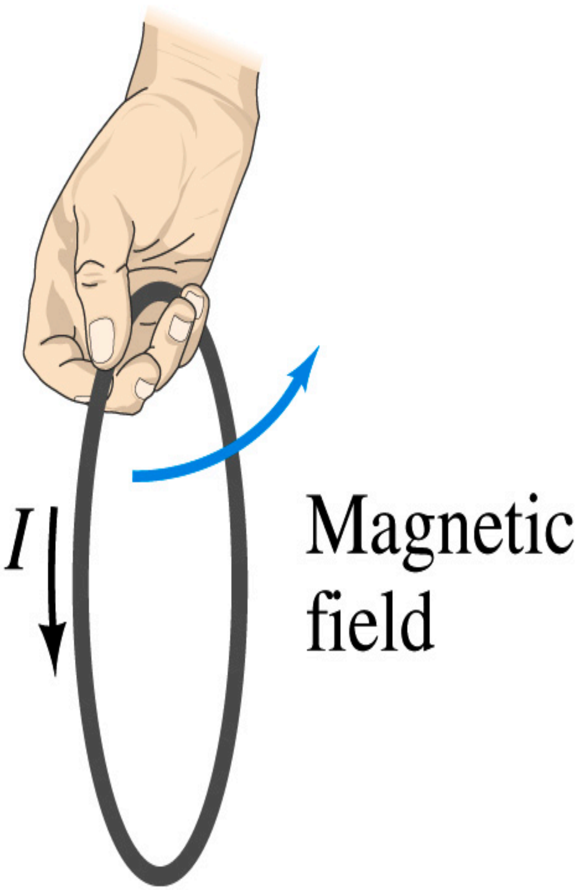
Electric Current and Magnetism

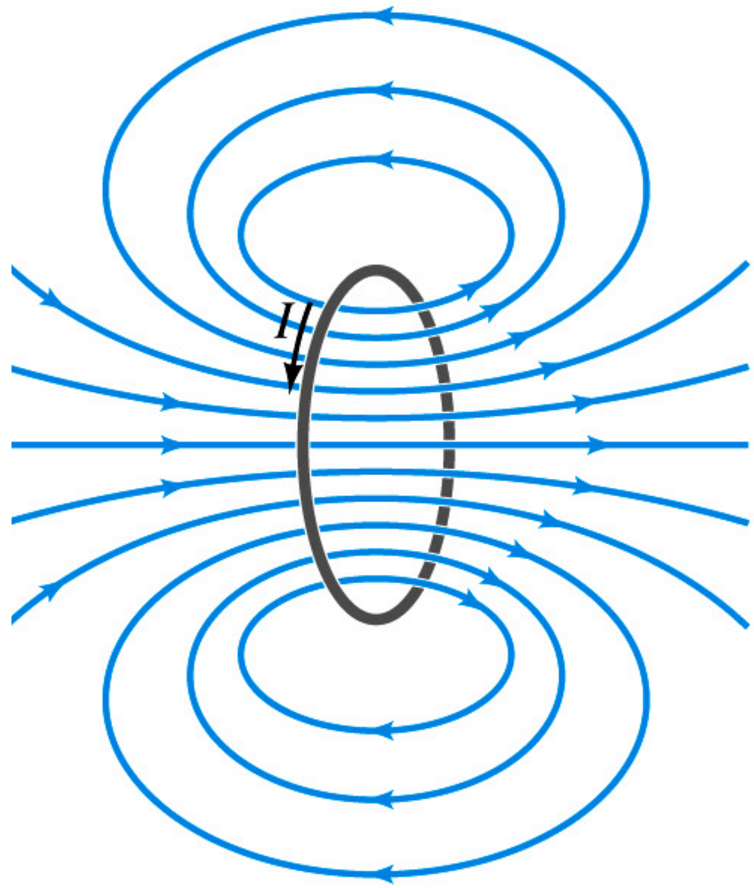
- In 1820, Oersted found that when a compass needle is placed near an electric wire, the needle deflects as soon as the wire is connected to a battery and the current flows
  - Electric current produces a magnetic field
    - The first indication that electricity and magnetism are the same thing
  - 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?

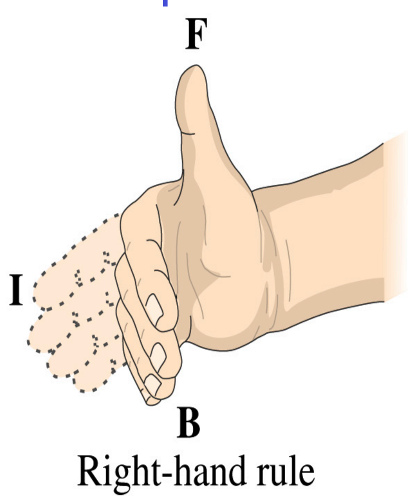
- OK, then what are the directions of the magnetic fields generated by the current flowing through circular loops?

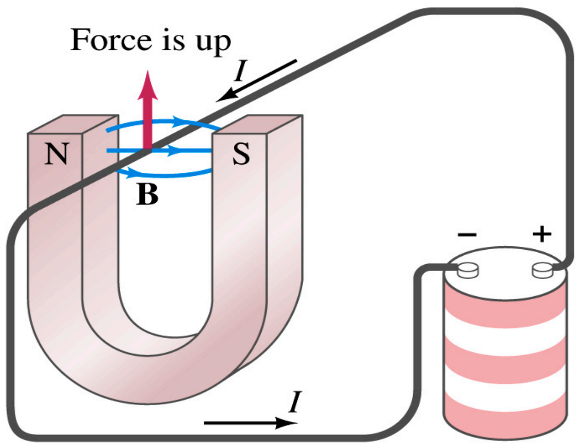


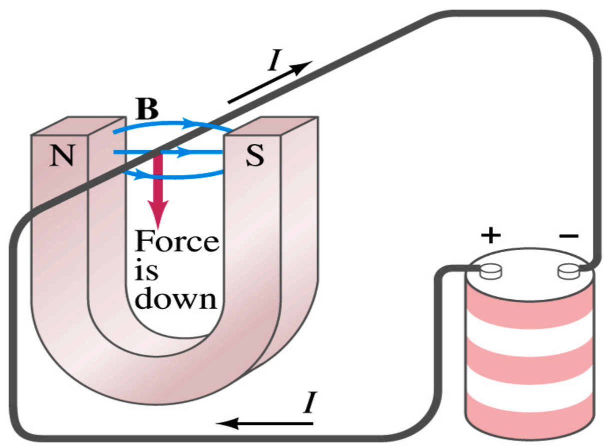


Magnetic Forces on Electric Current

- 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 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







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 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 with the 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 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 wire carrying a 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 $d\vec{F} = Id\vec{l} \times \vec{B}$

About 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.

Properties of Vector Product

Vector Product is Non-commutative

What does this mean?

If the order of operation changes the result changes $\vec{A}\times\vec{B}\neq\vec{B}\times\vec{A}$

Following the right-hand rule, the direction changes $\vec{A}\times\vec{B}=-\vec{B}\times\vec{A}$

Vector Product of two parallel vectors is 0.

$$\left|\vec{C}\right|=\left|\vec{A}\times\vec{B}\right|=\left|\vec{A}\right|\left|\vec{B}\right|\sin\theta=\left|\vec{A}\right|\left|\vec{B}\right|\sin 0=0$$

Thus, $\vec{A}\times\vec{A}=0$

If two vectors are perpendicular to each other

$$\left|\vec{A}\times\vec{B}\right|=\left|\vec{A}\right|\left|\vec{B}\right|\sin\theta=\left|\vec{A}\right|\left|\vec{B}\right|\sin 90^\circ=\left|\vec{A}\right|\left|\vec{B}\right|=AB$$

Vector product follows distribution law

$$\vec{A}\times\left(\vec{B}+\vec{C}\right)=\vec{A}\times\vec{B}+\vec{A}\times\vec{C}$$

The derivative of a Vector product with respect to a scalar variable is

$$\frac{d\left(\vec{A}\times\vec{B}\right)}{dt}=\frac{d\vec{A}}{dt}\times\vec{B}+\vec{A}\times\frac{d\vec{B}}{dt}$$

More Properties of Vector Product

The relationship between unit vectors, $\vec{i}, \vec{j}$ and $\vec{k}$

$$\vec{i}\times\vec{i}=\vec{j}\times\vec{j}=\vec{k}\times\vec{k}=0$$

$$\vec{i}\times\vec{j}=-\vec{j}\times\vec{i}=\vec{k}$$

$$\vec{j}\times\vec{k}=-\vec{k}\times\vec{j}=\vec{i}$$

$$\vec{k}\times\vec{i}=-\vec{i}\times\vec{k}=\vec{j}$$

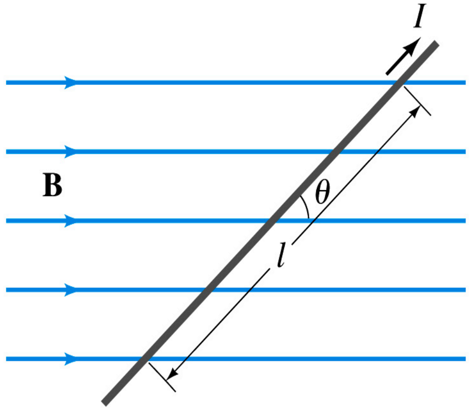
Vector product of two vectors can be expressed in the following determinant form

$$\vec{A}\times\vec{B}=\begin{vmatrix}\vec{i} & \vec{j} & \vec{k}\\ A_x & A_y & A_z\\ B_x & B_y & B_z\end{vmatrix}=\vec{i}\begin{vmatrix}A_y & A_z\\ B_y & B_z\end{vmatrix}-\vec{j}\begin{vmatrix}A_x & A_z\\ B_x & B_z\end{vmatrix}+\vec{k}\begin{vmatrix}A_x & A_y\\ B_x & B_y\end{vmatrix}$$

$$=\left(A_yB_z-A_zB_y\right)\vec{i}-\left(A_xB_z-A_zB_x\right)\vec{j}+\left(A_xB_y-A_yB_x\right)\vec{k}$$

Example 20 – 1

Magnetic force on a current carrying wire. A wire carrying a 30 A current I, has a length l= 12cm between the pole faces of a magnet at an angle θ=60° as in the figure. The magnetic field is approximately uniform at 0.9T. We ignore the field beyond the pole pieces. What is the magnitude of the force on the wire?



Which formula should we use for this problem?

$$\vec{F} = I\left(\vec{l} \times \vec{B}\right)$$

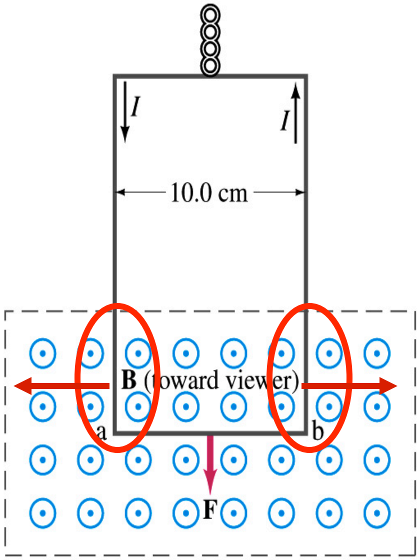
The magnitude of the magnitude of the magnetic force is

$$\left|\vec{F}\right| = I\left|\left(\vec{l} \times \vec{B}\right)\right| = IlB\sin\theta_{lB}$$

$$\left|\vec{F}\right| = IlB\sin\theta_{lB} = 30 \cdot 0.12 \cdot 0.9 \cdot \sin 60^\circ = 2.8N$$

Example 20 – 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

$$B = \frac{F}{Il} = \frac{3.48\times10^{-2}\,N}{0.245A \cdot 0.10m} = 1.42T$$

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.