



PHYS 1444 – Section 003

Lecture #14

Tuesday October 18, 2013

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- Chapter 27
 - Magnetism
 - Magnetic field
 - Magnetic force
 - Force on a moving charge



Magnetism

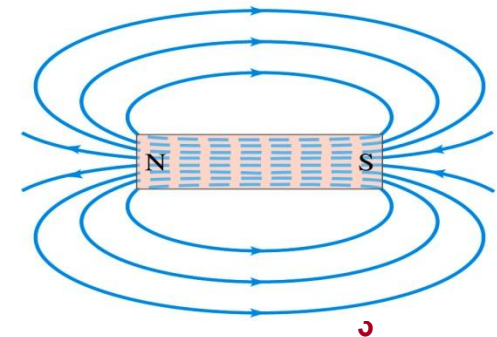
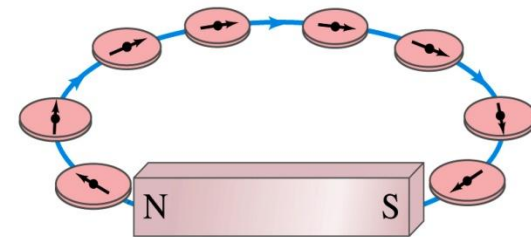
- So are magnet poles analogous to electric charge?
 - No. Why not?
 - While the electric charges (positive and negative) can be isolated, magnet poles cannot.
 - So what happens when a magnet is cut?
 - You get two magnets!
 - The more they get cut, the more magnets are made
 - Single-pole magnets are called “monopoles,” but to date none have been observed...
- Ferromagnetic materials: Materials that show strong magnetic effects
 - Iron, cobalt, nickel, gadolinium and certain alloys
- Other materials show very weak magnetic effects





Magnetic Field

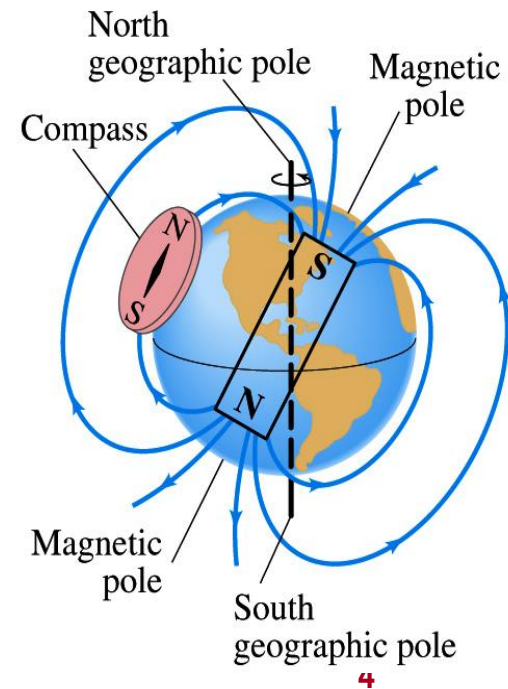
- Just like an electric field surrounds electric charge, a magnetic field surrounds a magnet
- What does this mean?
 - Magnetic force is also a field force
 - The force one magnet exerts on another can be viewed as the interaction between the magnet and the magnetic field produced by the other magnet
 - 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 poles, magnetic field lines form closed loops, unlike electric field lines





Earth's Magnetic Field

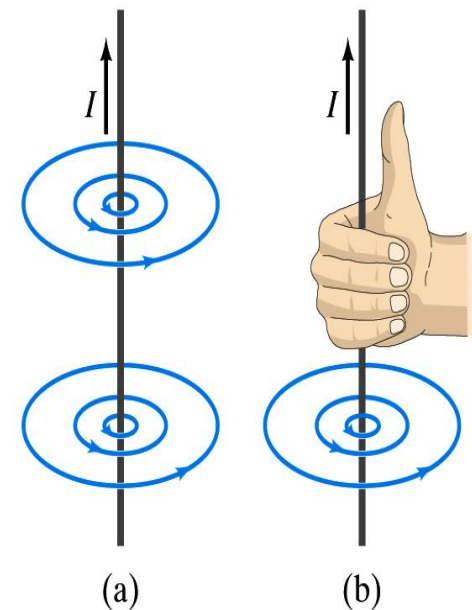
- Which way does a compass point?
- So the magnetic pole of the geographic North pole is ...
 - Yep South!
 - Since the magnetic north pole points to the geographic north, the geographic north must have magnetic south pole
 - The pole in the north is still called geomagnetic north pole just because it is in the north
 - Similarly, south pole has magnetic north pole
- To add confusion: the Earth's magnetic poles do not coincide with the geographic poles → magnetic declination
 - 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 of dip





Electric Current and Magnetism

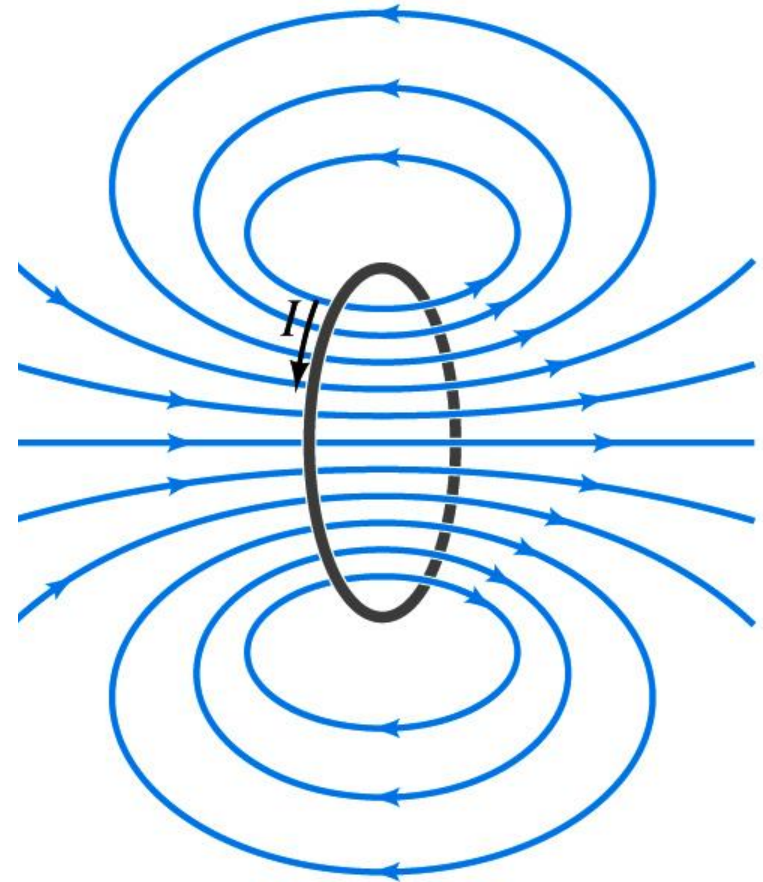
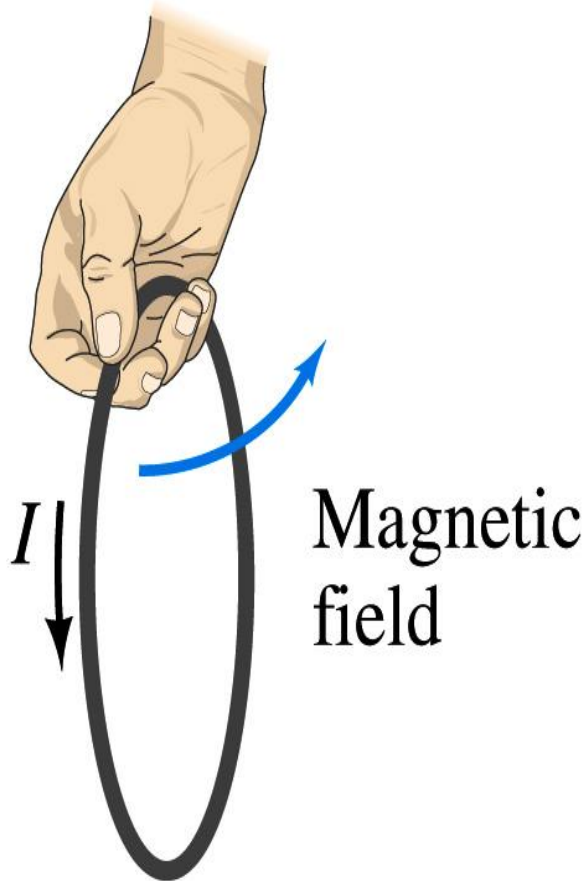
- In 1820, Oersted found that when a compass needle is placed near an electric wire, the needle deflects as soon as the wire is connected to a battery and the current flows
 - Electric current produces a magnetic field
 - The first indication that electricity and magnetism are linked
 - What about a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

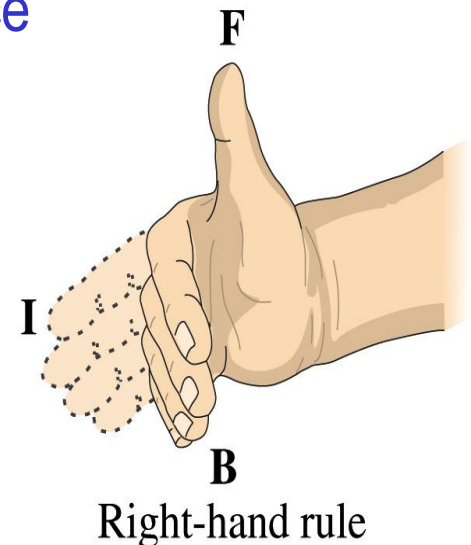
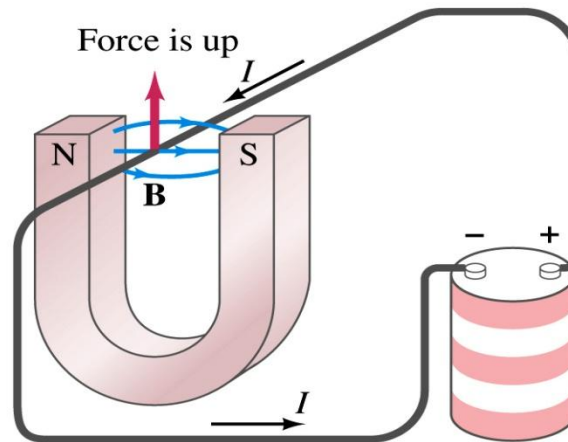
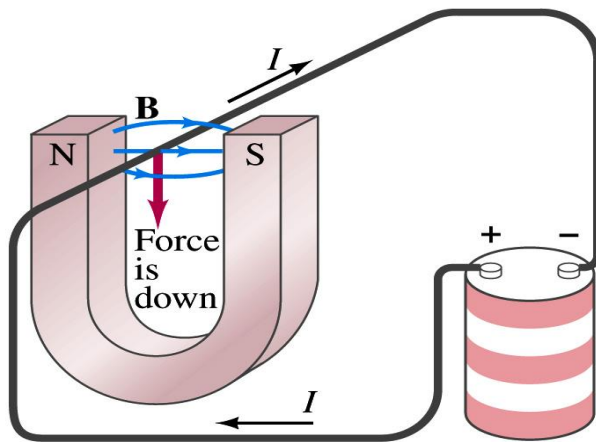
- OK, then what are the directions of the magnetic fields generated by the current flowing through circular loops?





Magnetic Forces on Electric Current

- Since electric current exerts force on a magnet, the magnet should also exert force on the electric current
 - How do we know this?
 - Newton's 3rd law (confirmed in this case by Oerste)
- Direction of the force is always
 - perpendicular to the direction of the current and also
 - perpendicular to the direction of the magnetic field, \mathbf{B}
 - **How is this possible?**
- Experimentally the direction of the force is given by another right-hand rule → When the fingers of the right-hand point in the direction of the current and the finger tips bend in the direction of magnetic field \mathbf{B} , the direction of thumb points to the direction of the force





Another Version of RHR

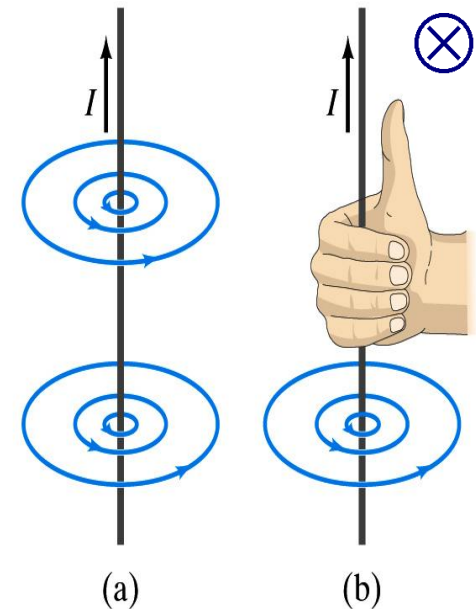
- Suppose we keep thumb in I direction, and fingers in B direction, then the palm will give direction of force!
- Example:

Simply evaluate the force on 2nd wire due to magnetic field in wire 1

The magnetic field at wire 2 from wire 1 is into the page, so the force on wire 2 is to the left.

What about the force on wire 1 due to wire 2?

What if I flipped the direction of the current on one wire?





Magnetic Forces on Electric Current

- The right-hand rule gives the direction, but what about magnitude?
- Observations show that the magnitude 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 a wire of length ℓ in a uniform field \mathcal{B} is

$$F \propto I\ell B \sin \theta$$



Magnetic Forces on Electric Current

- Magnetic field strength B can be defined using the previous proportionality relationship with 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 \mathbf{B}

- The relationship between F , B and I can be written in a vector formula: $\vec{F} = I \vec{l} \times \vec{B}$

where l is a vector with magnitude is the length of the wire and the direction is that 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 $d\vec{l}$ is $d\vec{F} = Id\vec{l} \times \vec{B}$



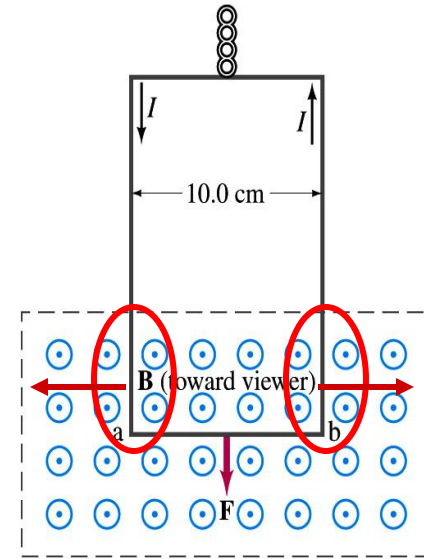
About the Magnetic Field, B

- 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?
 - $1\text{T}=1\text{N}/\text{A}\cdot\text{m}$
 - An older unit: 1 tesla is the same as a weber per meter-squared
 - $1\text{Wb}/\text{m}^2=1\text{T}$
- The cgs unit for B is gauss (G)
 - How many T is one G?
 - $1\text{G}=10^{-4}\text{T}$
 - For computation in SI units , one MUST convert Gauss to Tesla
- 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 out of page and \otimes for field 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 $F = IlB$

What about gravitational force?

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

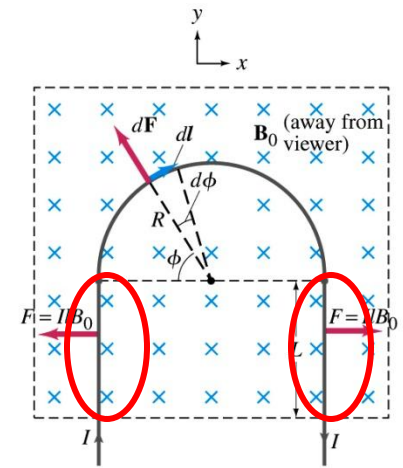
What happened to the forces on the loop on the side?

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 are 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 acting 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 $dF_y = dF \sin \phi = IB_0 R d\phi \sin \phi$

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

$$F = \int_0^\pi dF \sin \phi = IB_0 R \int_0^\pi \sin \phi d\phi = -IB_0 R \cos \phi \Big|_0^\pi = 2RIB_0$$

Which direction? ¹⁸ Vertically upward direction. The wire will be pulled further 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) experiences a 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 \mathbf{B}
 - Then, the length vector ℓ becomes $\vec{\ell} = \vec{v}t$
 - Where \mathbf{v} is the velocity of the particle
- Thus the force on N particles by the field is $\vec{F} = I\vec{\ell} \times \vec{B} = Nq\vec{v} \times \vec{B}$
- 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

- $F = qvB \sin \theta$

- What is θ ?

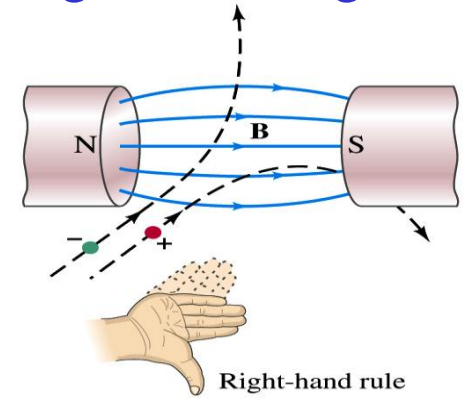
- The angle between the magnetic field and the direction of particle's movement

- 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 – 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 a magnetic field to measure the momentum of a particle.