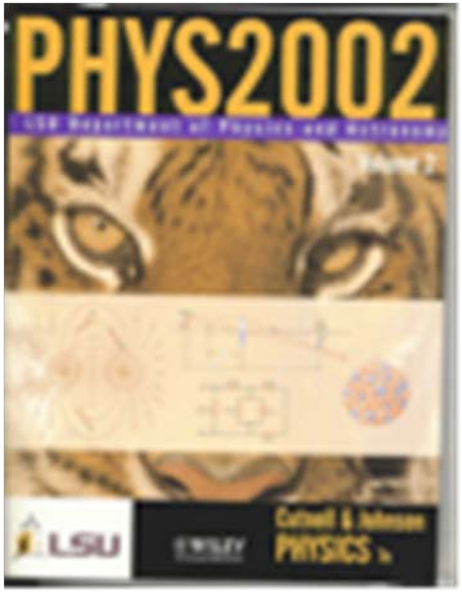
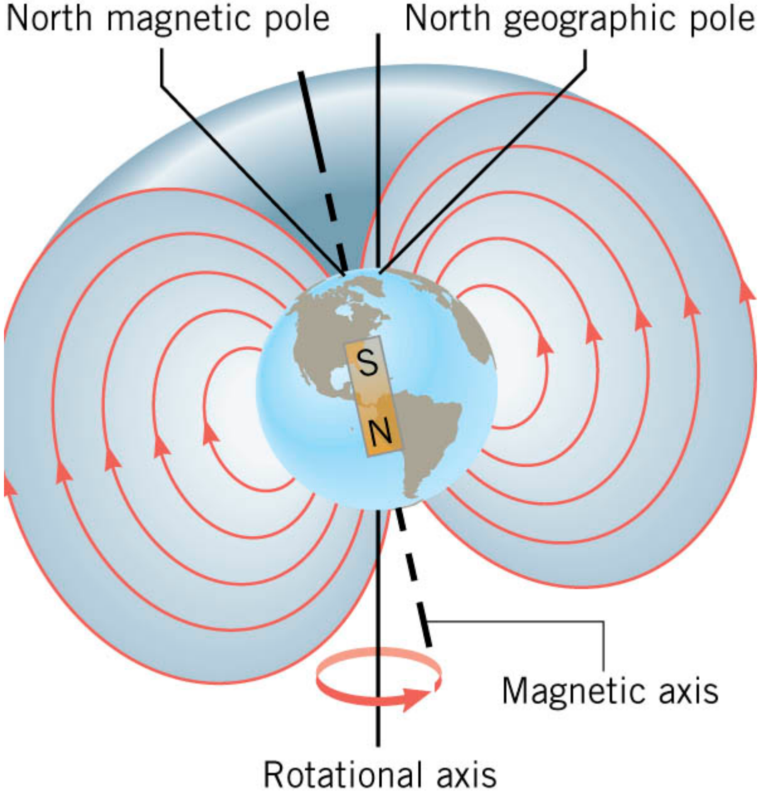
LOUISIANA STATE UNIVERSITY
Department of
Physics & Astronomy

Algebra-based Physics II



Sep.20th, Chap 21.1-3



<u>Class Website</u>:

http://www.phys.lsu.edu/~jzhang/teaching.html

21.1 Magnetic Fields

Magnetism has been observed since roughly 800 B.C.

Certain rocks on the Greek peninsula of Magnesia were noticed to attract and repel one another.

Hence the word: Magnetism.

So just like charged objects, magnetized objects can exert forces on each other – repulsive or attractive.

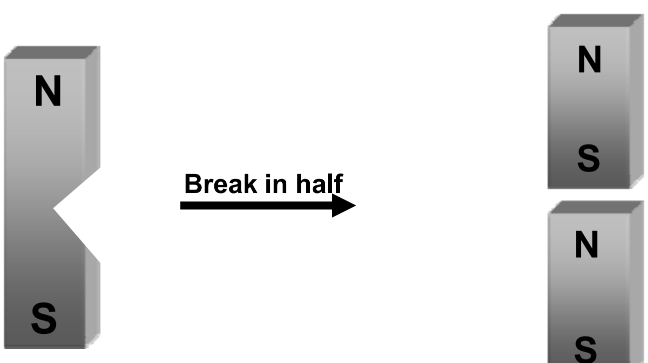
A magnet has two poles, a North and a South:

Like poles repel and opposite poles attract

D

Similar to electric charges, but magnetic poles always come in pairs.

They never exist as a single pole called a magnetic monopole.



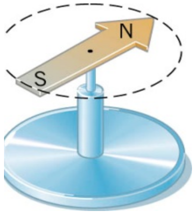
We get two magnets, each with two poles!

Electric charges produce electric fields and magnets produce magnetic fields.

We used a small positive charge (test charge) to determine what the electric field lines looked like around a point charge.

Can we do a similar thing to determine what the magnetic field lines look like around a magnet???

Yes! We can use a small magnet called a compass!

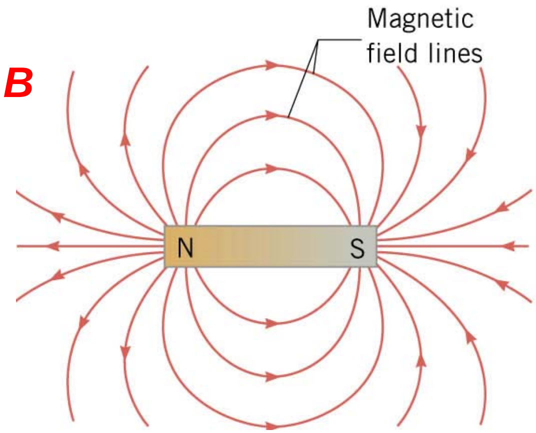


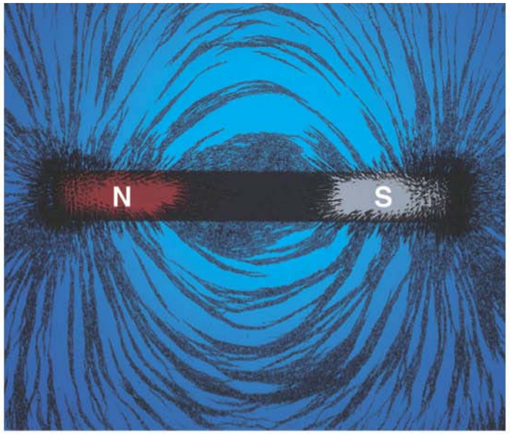
The compass needle is free to pivot, and its tip (the North pole) will point toward the South pole of another magnet.

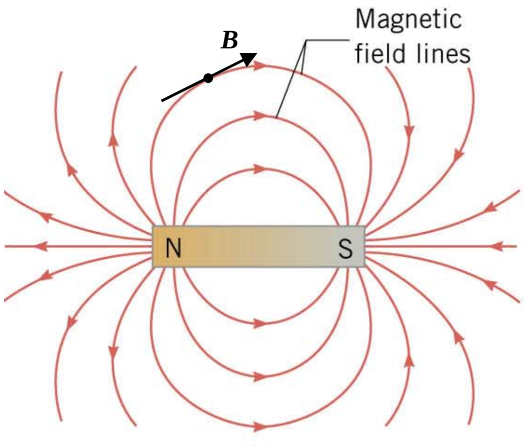
So the field lines around a bar magnet look like this:

B

We represent the Magnetic Field with a capitol B:







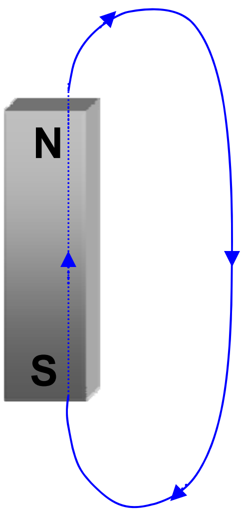
Properties of Magnetic Field Lines:

1. They point away from North poles and point toward South poles. The compass needle will line up in the direction of the field!

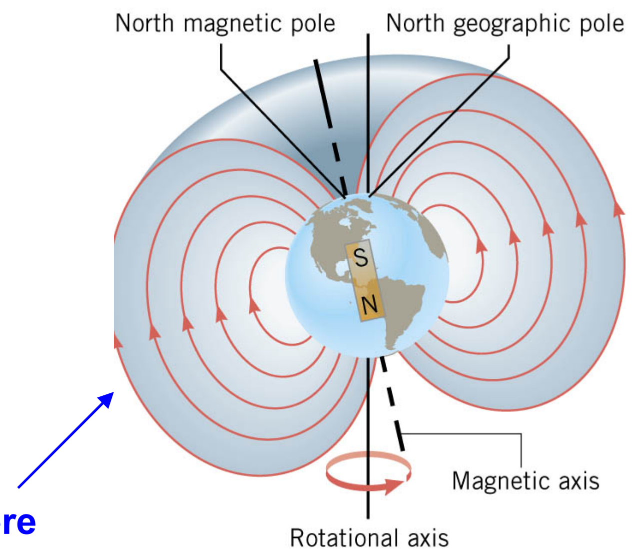
2. The magnetic field at any point in space is tangent to the field line at that point.

3. The higher the density of field lines, the stronger the field. Thus, the strongest field is near the poles!!!

4. The field lines must form closed loops, i.e. they don't start or stop in mid space. There are no magnetic monopoles!



Since a compass needle points North on the surface of the earth, the earth must have a magnetic field, and its South pole, called Magentic North, must be in the northern hemisphere.

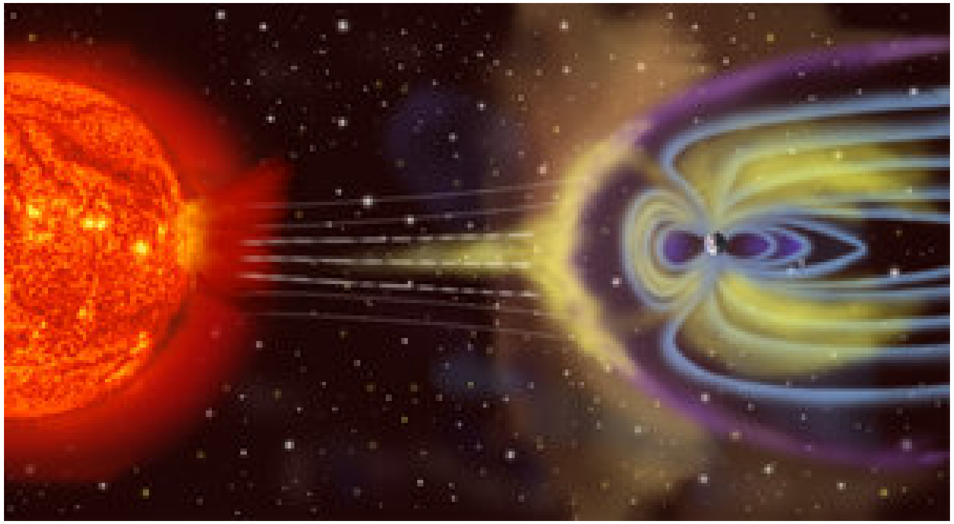


The Magnetosphere

Magnetic north does not coincide with geographic north, and it tends to move around over time.

Earth's magnetic field is not well understood. May be due to the distribution of currents flowing in the liquid nickel core.

The magnetosphere is not perfectly spherical:



It gets defected by the solar wind and protects the earth from the sun's radiation.

21.2 The Magnetic Force

Charges feel forces in electric fields.

Magnets feel forces in magnetic fields.

And,….until 1820, everyone thought electricity and magnetism had absolutely nothing to do with each other.

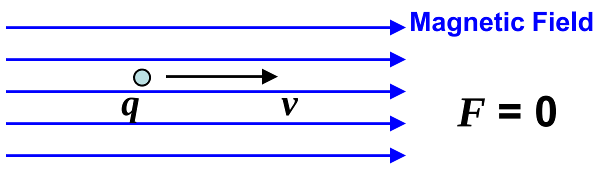
But, it turns out that electrical charges WILL also feel a force in magnetic fields, under certain conditions. First….

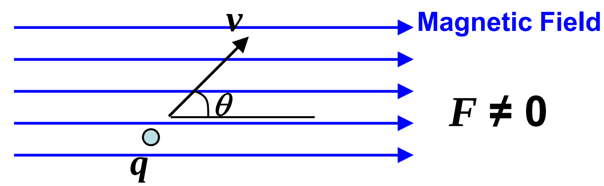
1. The charge must be moving, i.e. it has a nonzero velocity.

There is no magnetic force on a stationary charge! And…

2. The charge's velocity must have a component that is perpendicular to the magnetic field.

Thus, if a charge is moving in a magnetic field, but it moves along the same direction as the field (parallel to it), there is no force.





So, if there is a force on a moving charged particle in a magnetic field, how do we calculate that force?

$$\vec{F} = q\vec{v} \times \vec{B} = qvB\sin\theta$$

$$\boxed{F = qvB\sin\theta}$$

B is the magnetic field.

θ is the angle between B and v.

<u>Units on B?</u>

$$B = \left[\frac{\text{Force}}{\text{Charge} \times \text{Velocity}}\right] = \left[\frac{\text{N} \cdot \text{s}}{\text{C} \cdot \text{m}}\right] = [\text{Tesla}] = [\text{T}]$$

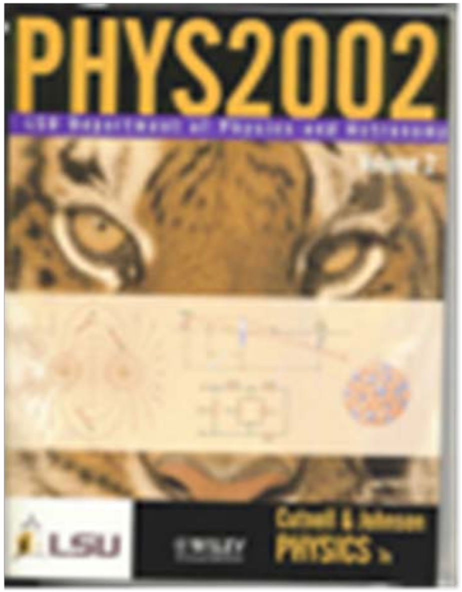
1 T is a pretty big field. We also use another unit of mag. field, the gauss:

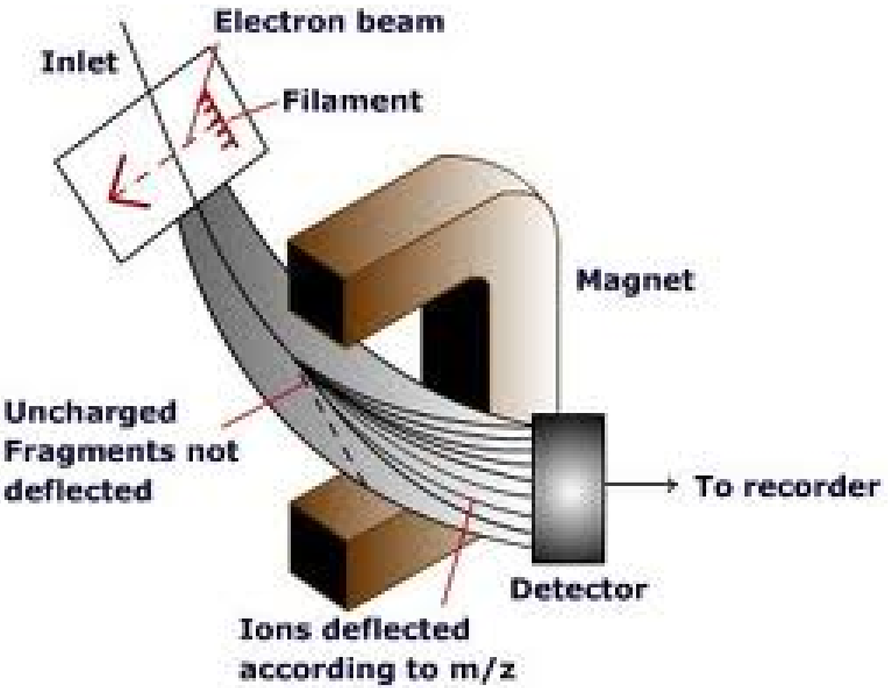
1 gauss = 1 × 10^{-4} T.

Earth's mag. Field is ~0.5 gauss

Algebra-based Physics II

Sep.22th,Chap 21.3-5





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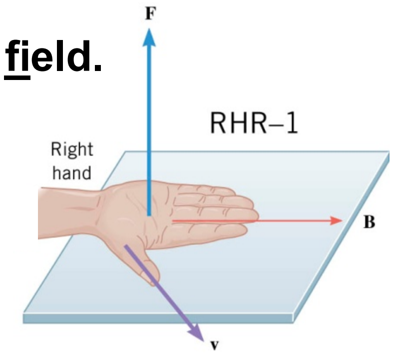
Direction of the force on a charged particle in a mag. field:

$$F = qvB\sin\theta$$

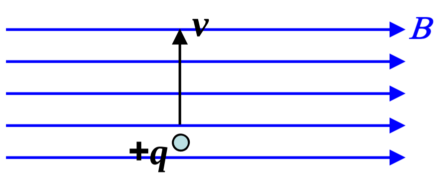
Use Right Hand Rule 1 (RHR-1)

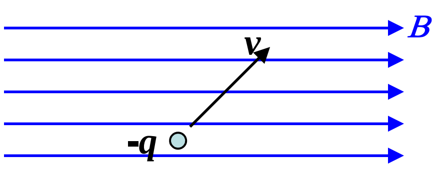
- **Point the fingers of your right hand in the direction of the magnetic field.**



This is the procedure to follow when the charge is positive. If the charge is negative, do everything exactly the same, but then reverse the direction of the force at the end.

Examples





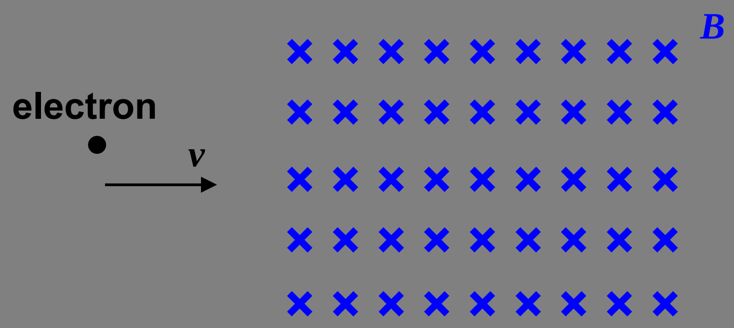
Force? **Force is into the page** $\otimes$

Force? **Force is out of the page** $\odot$

Question

An electron moving with speed v = 1.5 x 10^4 m/s from left to right enters a region of space where a uniform magnetic field of magnitude 7.5 T exists everywhere into the page. What direction is the force on the electron?

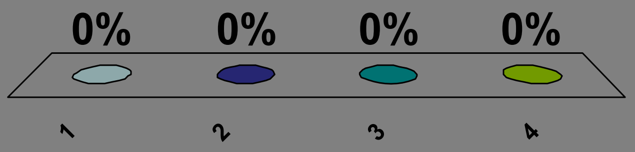
1. Left
2. Right
3. Up
4. $\boxed{\text{Down}}$
5. Into the page
6. Out of the page



Clicker Question 21-1

What is the magnitude of the force that acts on the electron (v = 1.5 x 10^4 m/s, B = 7.5 T) ?

1. 0 N
2. 1.5 N
3. 1.8 x 10^{-14} N
4. 7.02 x 10^{23} N.



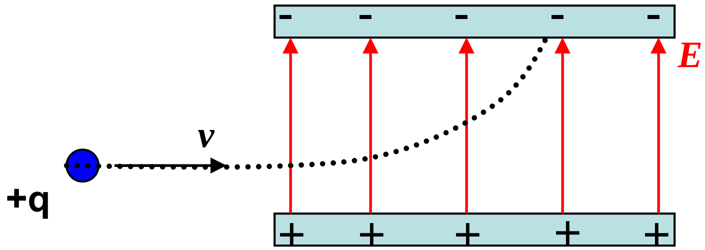
$$F = qvB\cancelto{1}{\sin\theta} = qvB = (1.602\times10^{-19})(1.5\times10^{4})(7.5) = 1.8\times10^{-14}\,N$$

21.3 Motion of a charged particle in electric and magnetic fields

The force on a charged particle in an electric field is directed along the field, either parallel or antiparallel:

$$F = qE$$

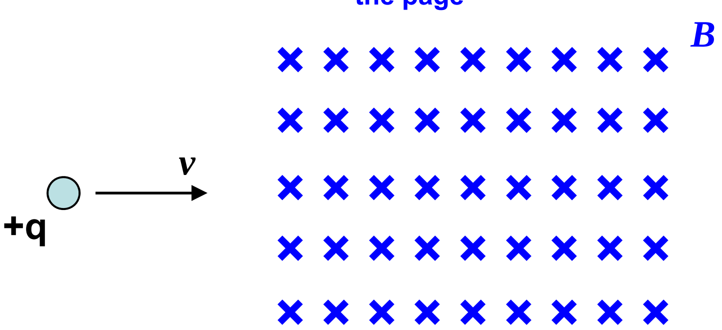
$$\vec{F} \,//\, \vec{E}$$



The positively charged particle feels a force upward due to E.

The force on a charged particle in a magnetic field is always at right angles to the velocity and field:

$$F = qvB\sin\theta$$

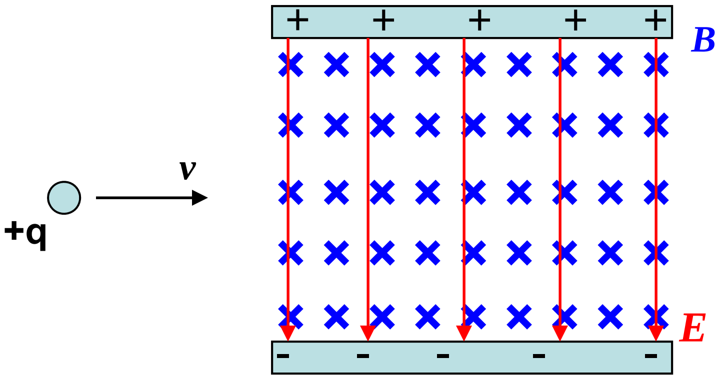


Use RHR-1 to show that the force on the particle is initially upward.

$$\vec{F} \perp \vec{v} \quad \text{and} \quad \vec{F} \perp \vec{B}$$

Now let's use both fields at the same time:

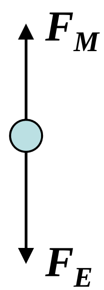
Keep the magnetic field the same, but reverse the direction of the electric field:



The force on the positive charge due to the electric field will now be down, and the force on the charge due to the magnetic field (RHR-1) will be up.

By adjusting the magnitude of E and B, I can find a combination where $F_M = F_E$, such that the net force on the charge is zero: the charge moves through the fields with no deflection at all!

<u>FBD on the charge:</u>



This is called a <u>velocity selector</u>.

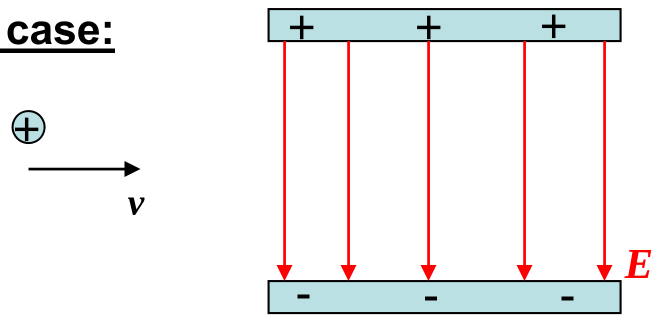
$$F_M = F_E \Rightarrow \cancel{q}vB\,\cancel{\sin\theta}^{\,1} = \cancel{q}E \Rightarrow \boxed{v = E/B}$$

Work done by the fields:

$$W = F \times d,$$

where F is along the direction of motion and it's constant over the displacement.

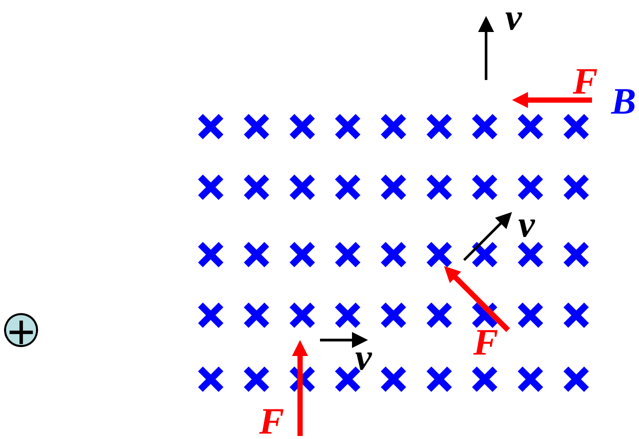
Electric case:



When the positive charge enters the field, the force is downward. The charge accelerates; it's velocity increases.

Thus, positive work is done on the charge!

Magnetic case:

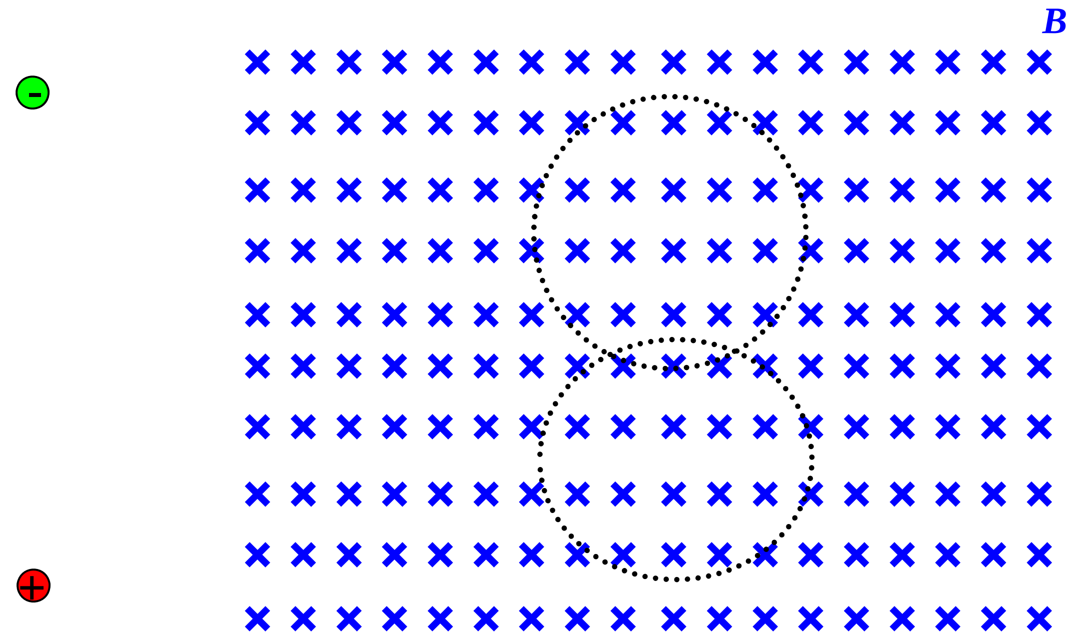


When the positive charge enters the magnetic field, the force is initially up.

This bends the particle upward, but the force changes direction – it must always be perpendicular to v.

This force continues to bend the particle around.

Keep applying the RHR-1 and you see that the particle just keeps bending around into a circular path!!!



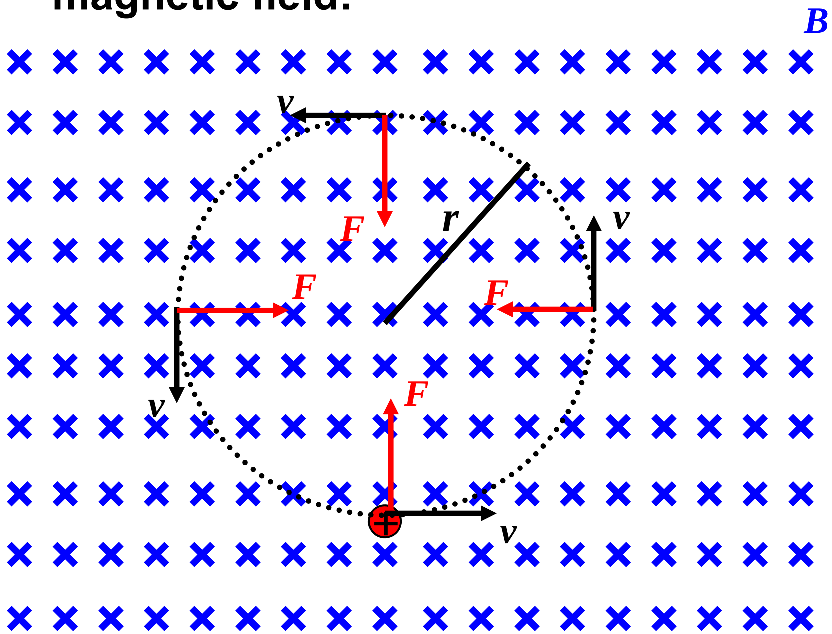
The force is always at right angles to the velocity, so it's never along the direction of motion.

Thus, the magnetic force does <u>no</u> work on the particle.

The particle's speed remains constant, but it's direction changes!

Magnetic fields can <u>not</u> speed up or slow down charged particles, only change their direction.

Consider again our positively charged particle moving at right angles to a magnetic field:



The velocity is always tangent to the particle's trajectory:

By RHR-1, the force is always perpendicular to v and directed in toward the center of motion.

Whenever we have circular motion, we can identify a Centripetal Force.

Remember: The centripetal force is not a new force, but it is the vector sum of the radial forces.

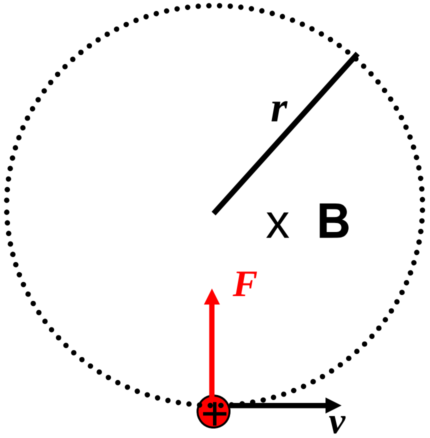
Here, the centripetal force is solely due to the magnetic force, thus,

$$F_C = F_M \Rightarrow F_C = qvB\sin\theta \Rightarrow \frac{mv^{\cancel{2}}}{r} = q\cancel{v}B\cancelto{1}{\sin\theta} \Rightarrow \boxed{r = \frac{mv}{qB}}$$

Thus, the larger B is, the tighter the circular path (smaller r).

Example:

21.13. a beam of proton moves in a circle of radius 0.25 m. The protons moves perpendicular to a 0.3-T magnetic field. (a) What is the speed of each proton? (b) Determine the magnitude of centripetal force that acts on each proton.



$$(a) \qquad r = \frac{mv}{qB}$$

$$v = \frac{qBr}{m} = \frac{eBr}{m_p} = \frac{1.602\times10^{-19}C\cdot0.30T\cdot0.25m}{1.67\times10^{-27}Kg} = 7.19\times10^{6}m/s$$

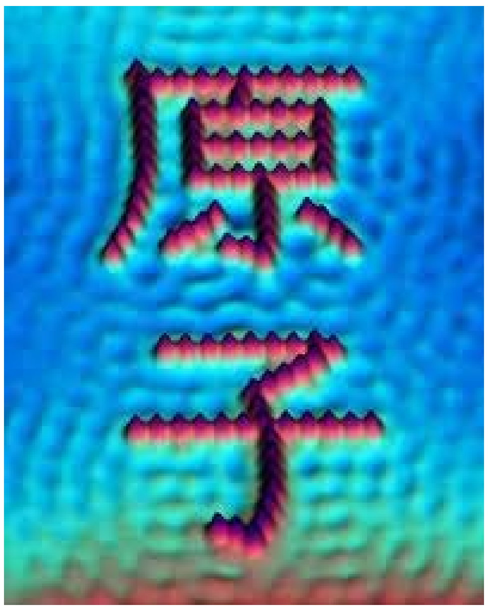
$$(b) \qquad F = qvB\sin\theta \qquad (\theta = 90^\circ)$$

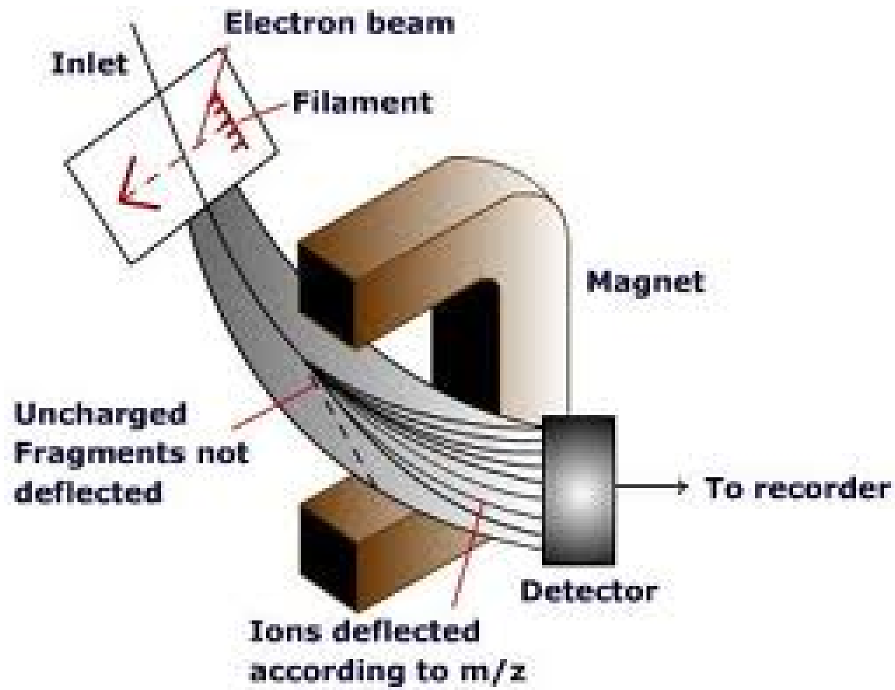
$$F = evB$$

Algebra-based Physics II   Sep.23th, Chap 21.4-6

Announcements:

- HW4 is posted and due on Wed.



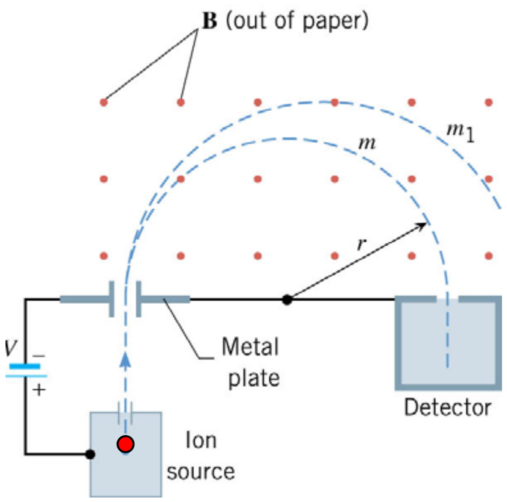


A mass spectrometer

Class Website:

http://www.phys.lsu.edu/~jzhang/teaching.html

21.4 The Mass Spectrometer



Ionized particles are accelerated by a potential difference V.

By conservation of energy, we know that this potential energy goes into the kinetic energy of the particle:

$$\Delta KE = \Delta EPE \Rightarrow \tfrac{1}{2}mv^2 = qV$$

Solve this for the speed, v:

$$v = \sqrt{\frac{2qV}{m}}$$

This is the speed the particle has when it enters the magnetic field. It then gets bent into a circular path whose radius is given by the previous equation:

$$r = \frac{mv}{qB}$$ **rearrange** $$m = \frac{qrB}{v}$$ **Plug in v from here:**

$$\boxed{m = \left(\frac{qr^2}{2V}\right)B^2}$$

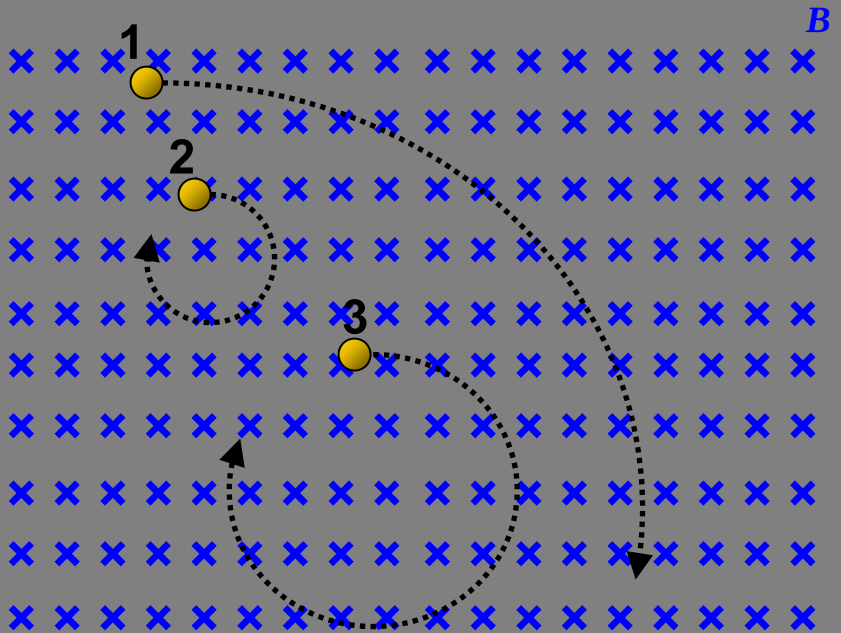
***Thus, the mass of the deflected ion is proportional to B^2.**

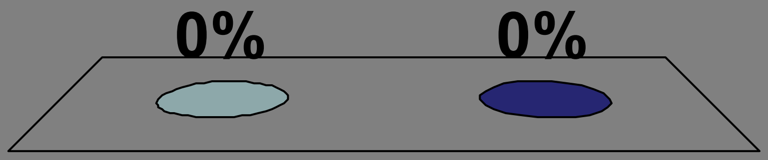
By changing B, we can select a certain mass for a given radius.

Clicker Question 21-3

Three particles have identical charges and are moving at the same speed when they enter a region of space where a uniform magnetic field exists into the screen. What is the sign of the charges?

1. Positive
2. Negative

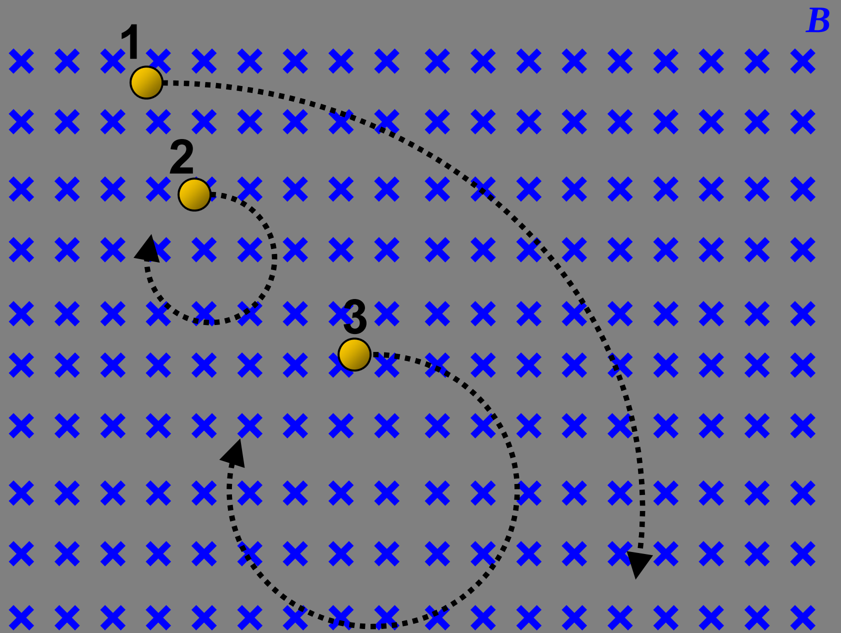


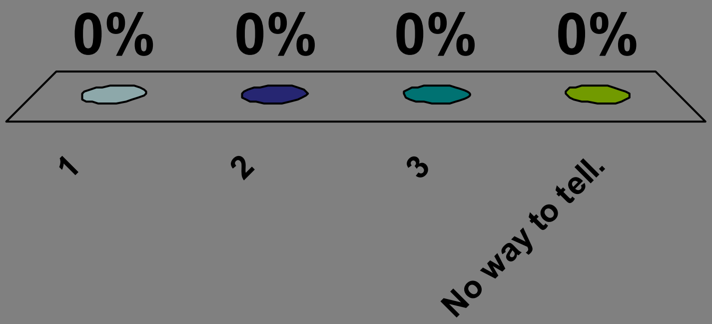


Clicker Question 21-4

Three particles have identical charges and are moving at the same speed when they enter a region of space where a uniform magnetic field exists into the screen. Which charge has the smallest mass?

1. 1
2. 2
3. 3
4. No way to tell.

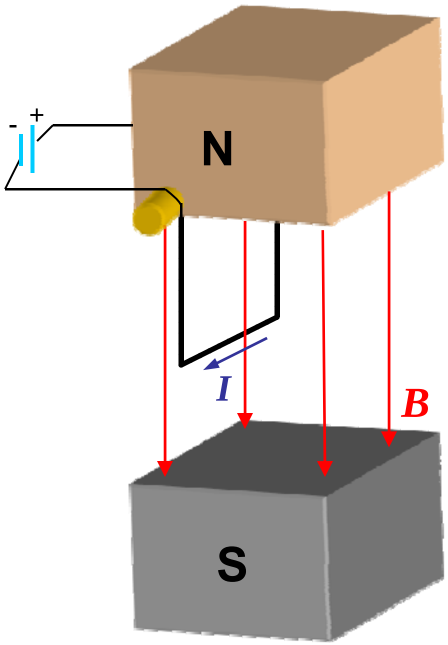


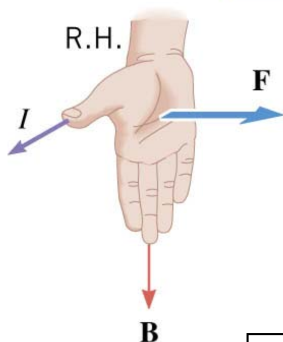


21.5 Force on a Current

Moving charges in a magnetic field experience a force.

A current is just a collection of moving charges, so a current will also feel a force in a magnetic field.



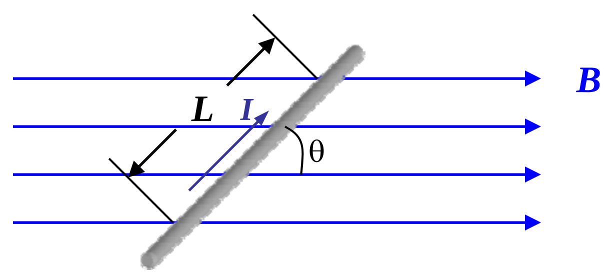


RHR-1 is used to find the direction of the force on a charge moving in a magnetic field, or to find the direction of the force on a current carrying wire in a magnetic field.

$$\boxed{F = ILB\sin\theta}$$

Notice that θ is the angle between the current and the magnetic field.

The force is maximum when the field is perpendicular to the wire!



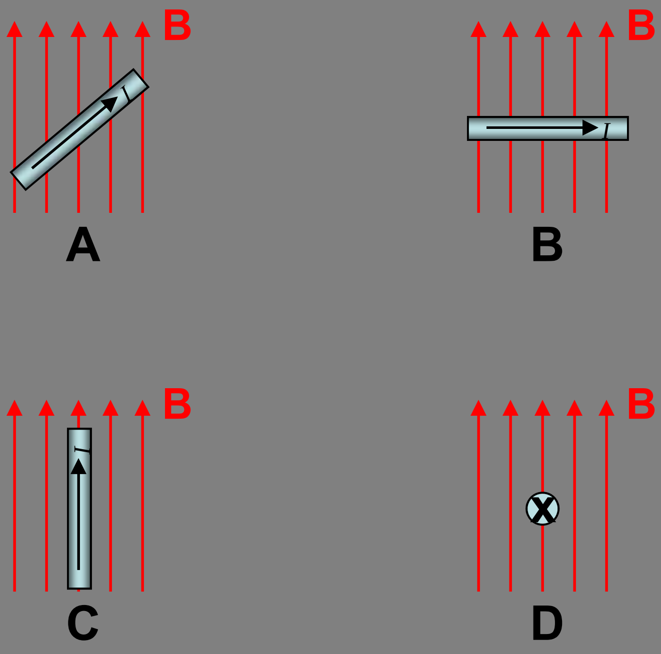
I is the current, and L is the length of the wire that's in the field.

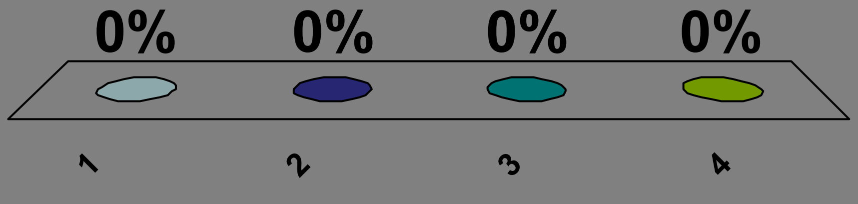
Direction of force? **Into the screen!** $\otimes$

Clicker Question 21-5

The same current carrying wire is placed in the same magnetic field in 4 different orientations. Which wire experiences the maximum force?

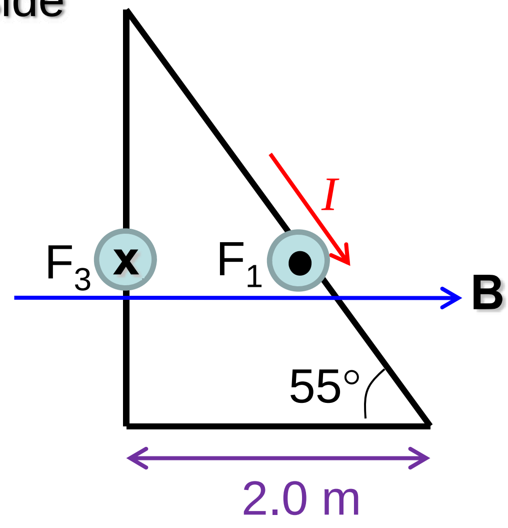
1. A
2. B
3. C
4. D





Example:

A current (I = 5 A) runs through a triangular loop and place in a uniform B-field. (B = 2T). (a) Find the force acting on each side of triangle. (b) Determine the net force.



(a) $$F = ILB\sin\theta$$

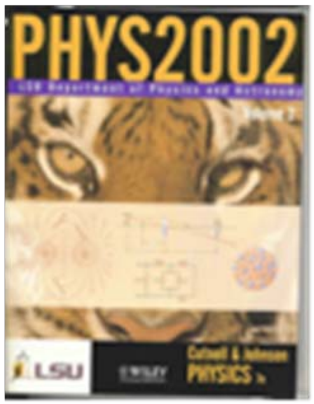
Magnetic forces act on two side only: L_1 and L_3

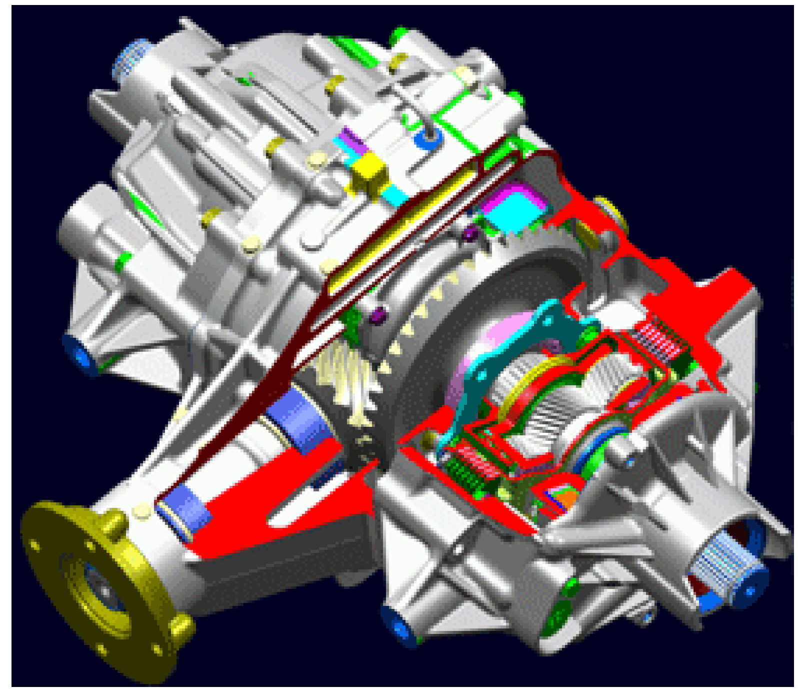
$$F_3 = IL_3B\sin 90° = 5A\cdot 2.0m\tan 55°\cdot 2T = 28.56N$$

$$F_1 = IL_1B\sin 55° = 5A\cdot\frac{2.0m}{\cos 55°}\cdot 2T\sin 55° = 28.56N$$

(b) $$\text{Since } \vec{F}_1 = -\vec{F}_3; \quad \sum\vec{F} = 0$$

Algebra-based Physics II   Sep.27th,Chap 21.4-6





Electromagnetic clutch

Announcements:

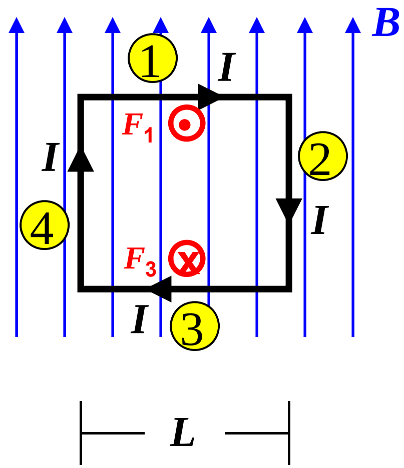
- HW4 is posted and due on Wed 11:59 PM.

Class Website:

http://www.phys.lsu.edu/~jzhang/teaching.html

21.6 Torque on a Wire Loop

Now let's put a closed loop of wire carrying a current in a magnetic field:



Let's label each side of the loop, 1 – 4.

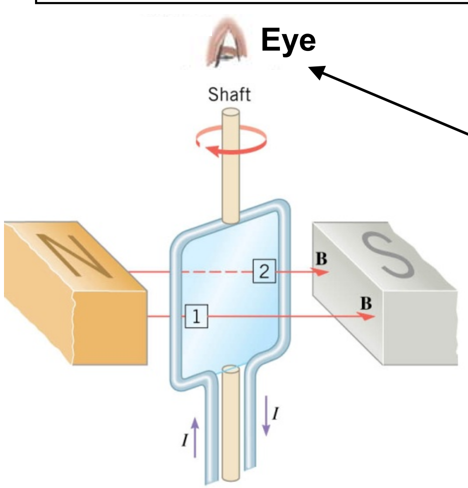
We can use $F = ILB\sin\theta$ **to calculate the force on each segment of the loop.**

Notice: $F_2 = F_4 = 0$, since $\theta = 0$ for those segments!

By RHR-1, F_1 points out of the screen: $\odot$

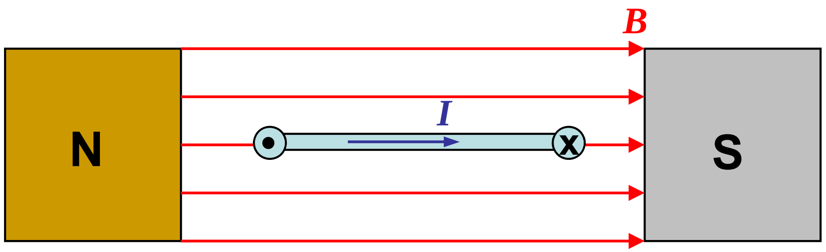
By RHR-1, F_3 points into the screen: $\otimes$

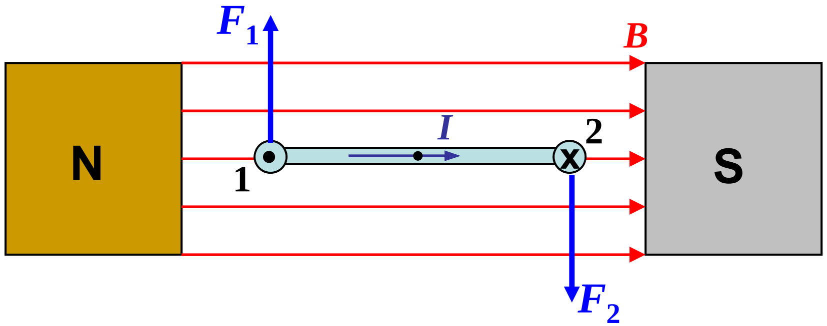
Thus, the loop wants to rotate!



Let's mount the loop vertically on a shaft and place it in a uniform horizontal magnetic field:

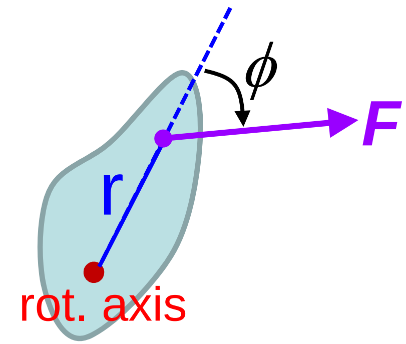
Now look at the loop from above:





By RHR-1, we see that the force on segment 1 is up:

Likewise, we see that the force on segment 2 is down:

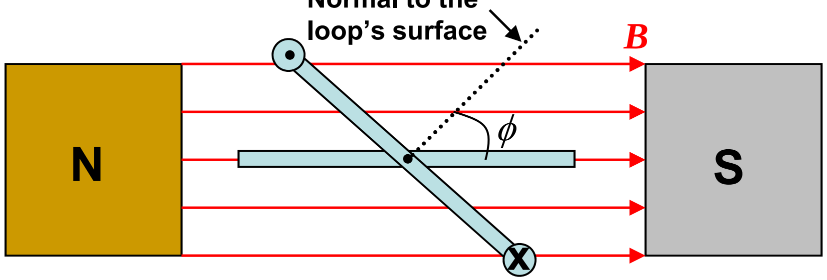


The net force on the loop is zero, since $F_1 = F_2$.

But the net torgue $\sum \tau$ is not zero! This leads to a rotation!

$$\tau = rF\sin\phi$$

Thus, the loop rotates clockwise as viewed from above:



What is the magnitude of the net torque on the loop?

$$\boxed{\tau_{Net} = NIAB\sin\phi}$$

N = the number of loops of wire

I = the current

A = cross-sectional area of the loop

B = magnetic field

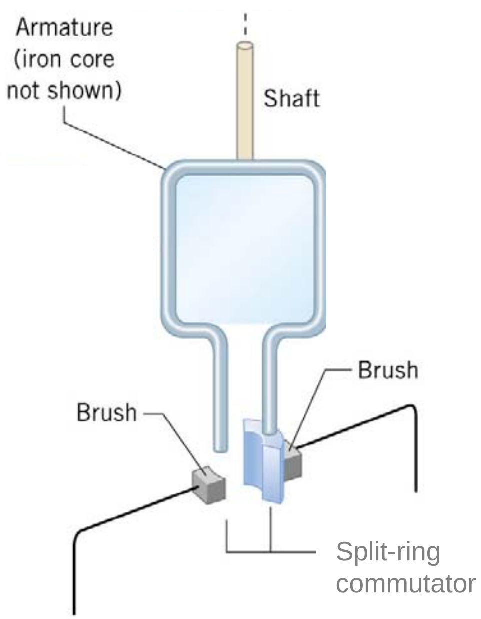
ϕ = the angle between the magnetic field and the normal to the loop's surface

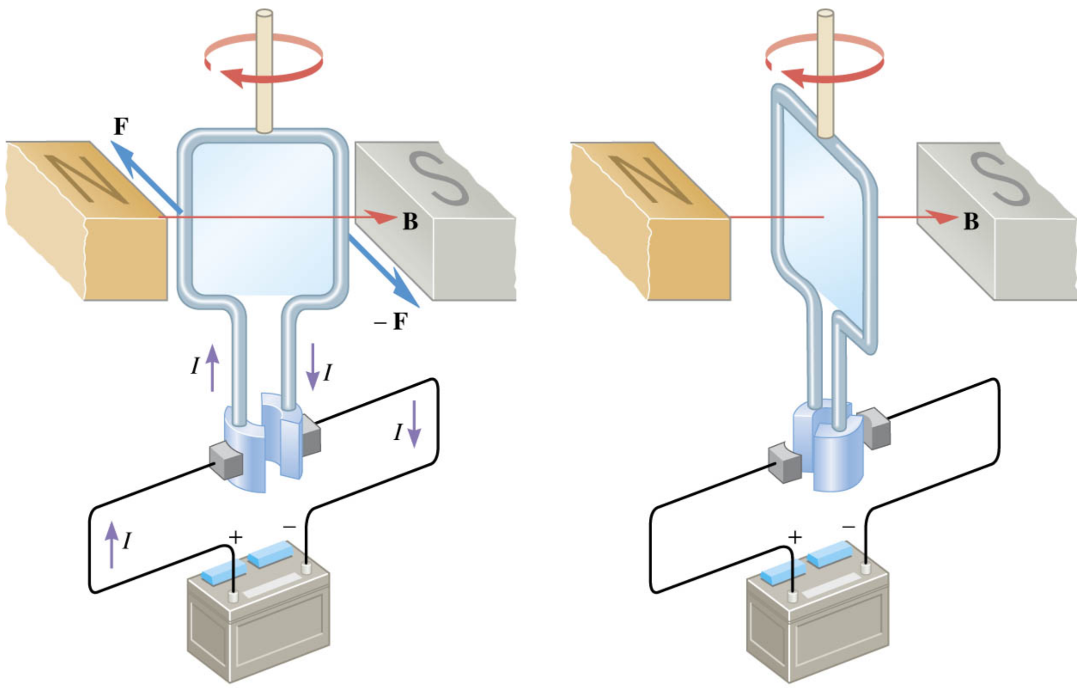
The net torque depends on the quantity *NIA*, which is called the magnetic moment of the loop:

$$\tau_{Net} = NIAB\sin\phi = \mu B\sin\phi,$$ **where** $\boxed{\mu = NIA}$ **is the magnetic moment.**

Units? $[\text{Current} \times \text{Area}] = [\text{A} \cdot \text{m}^2]$

DC Electric Motors



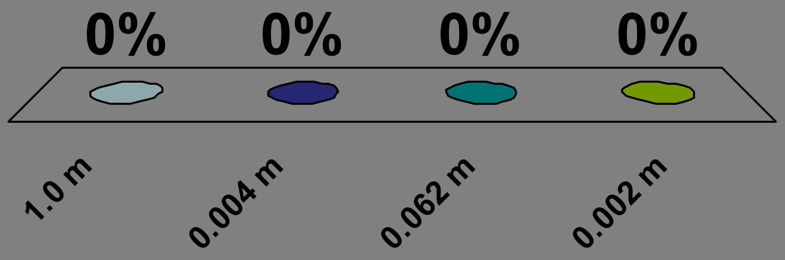


(a) (b)

Clicker Question 21-6

The maximum torque experienced by a coil in a 0.75-T magnetic field is 8.4×10^{-4} N·m. The coil is circular and consists of only one turn. The current in the coil is 3.7 A. What is the length of wire in the coil?

1. 1.0 m
2. 0.004 m
3. 0.062 m
4. 0.002 m



21.7 Magnetic Fields Produced by Currents

Moving charges experience a force in magnetic fields. $F = qvB\sin\theta$

Currents also feel a force in a magnetic field. $F = ILB\sin\theta$

Until 1820 everyone thought electricity and magnetism were completely separate entities.

Then Hans Christian Oersted discovered the following:

Electric currents create magnetic fields!

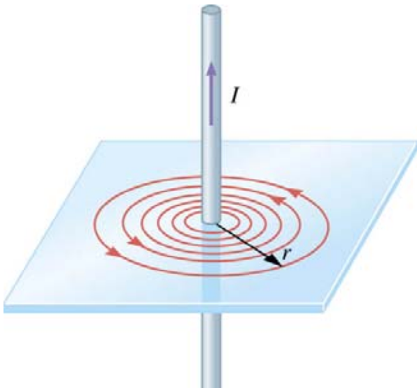
A more general statement is that moving charges create magnetic fields.

Stationary charges create Electric Fields

Moving charges (constant v) create Magnetic Fields.

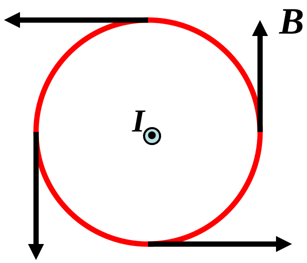
This discovery helped create the field of Electromagnetism.

What do the magnetic field lines look like around a long, straight, current-carrying wire?



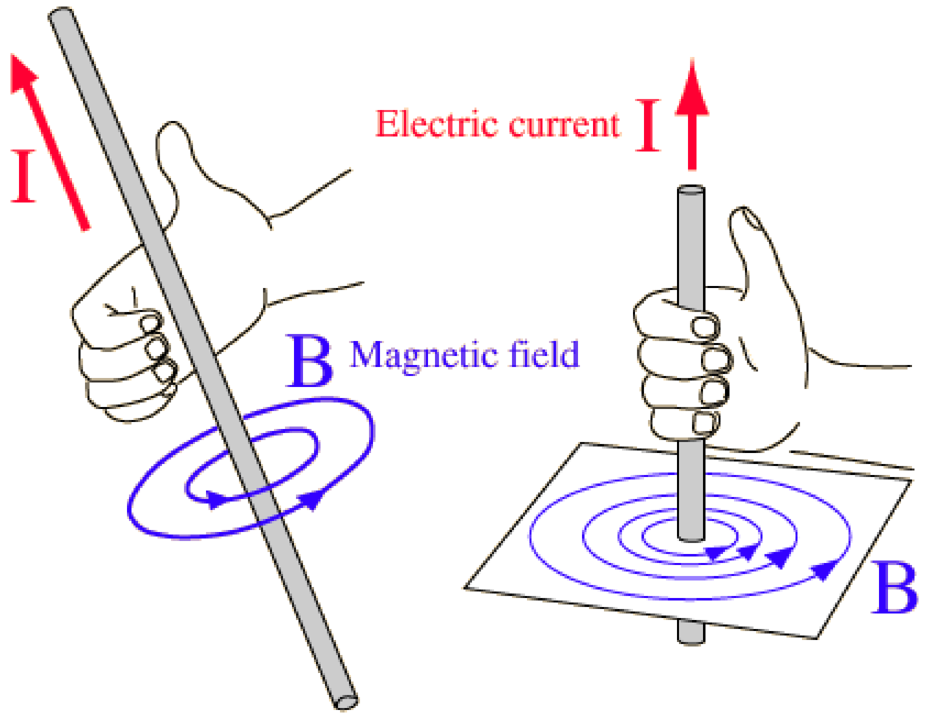
The current produces concentric circular loops of magnetic field around the wire.

Remember, the magnetic field vector at any point is always tangent to the field line!



The current I is coming out at you.

We determine the direction of the magnetic field around a long current carrying wire by using RHR-2.



RHR-2: Point the thumb of your right hand in the direction of the current, and your fingers curl around the wire showing the direction of the field lines.

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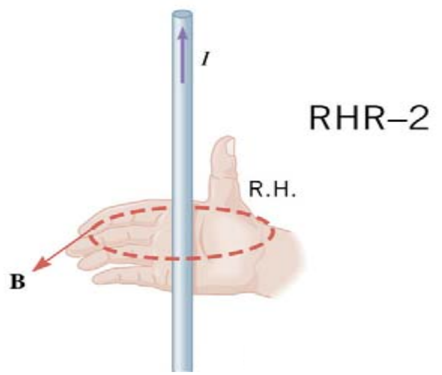
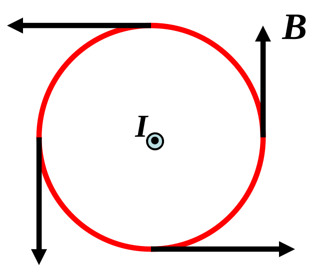
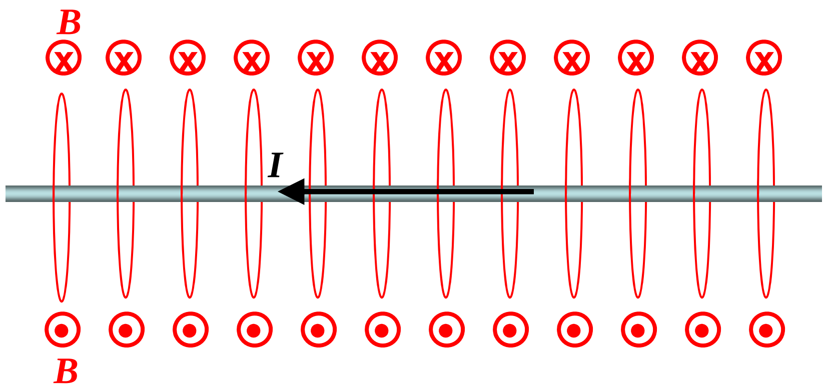






Experimentally, it is found that $B \propto I$ and $B \propto {}^{1}\!/_{r}$.

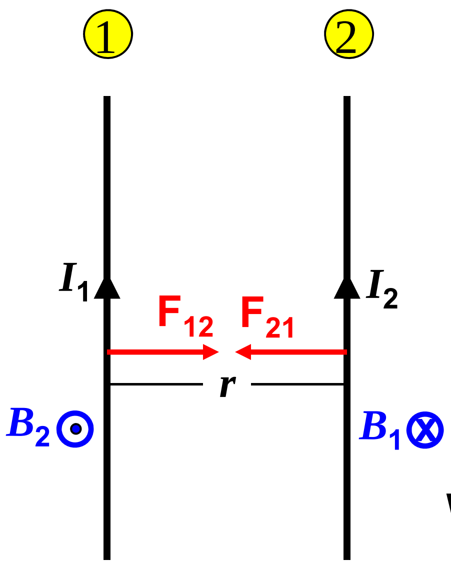
The magnetic field created by a long straight wire is: $\boxed{B = \dfrac{\mu_o I}{2\pi r}}$

μ_o is the permeability of free space: $\boxed{\mu_o = 4\pi \times 10^{-7}\ \dfrac{\mathrm{T \cdot m}}{\mathrm{A}}}$

So electrical currents create magnetic fields of their own.

These fields can effect the motion of other moving charges or currents.

As an example, let's look at two long parallel wires each carrying a current in the same direction:



Wire 1 creates a magnetic field that affects wire 2, and wire 2 creates a magnetic field that affects wire 1.

Thus, there will be a force on each wire due to the magnetic field that the other produces.

$$F_{12} = I_1 L B_2 \sin\theta_{12}$$ **Force on 1 from 2.**

$$F_{21} = I_2 L B_1 \sin\theta_{21}$$ **Force on 2 from 1.**

What is the value of the magnetic field (B_1) where I_2 is? $$B_1 = \frac{\mu_o I_1}{2\pi r}$$

Likewise, $$B_2 = \frac{\mu_o I_2}{2\pi r}$$

How about directions???

By using RHR-2, we see that where I_2 sits, the magnetic field B_1 points everywhere into the page.

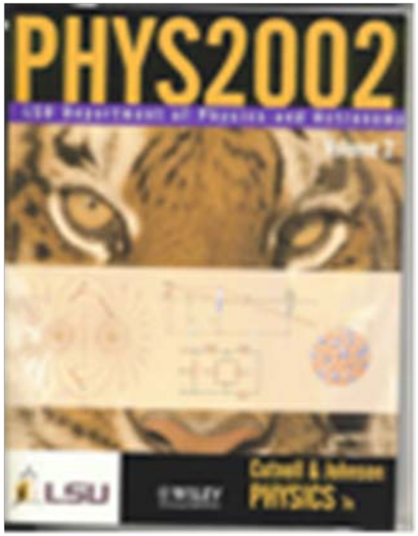
Thus, by RHR-1 the force on wire 2 would be to the left.

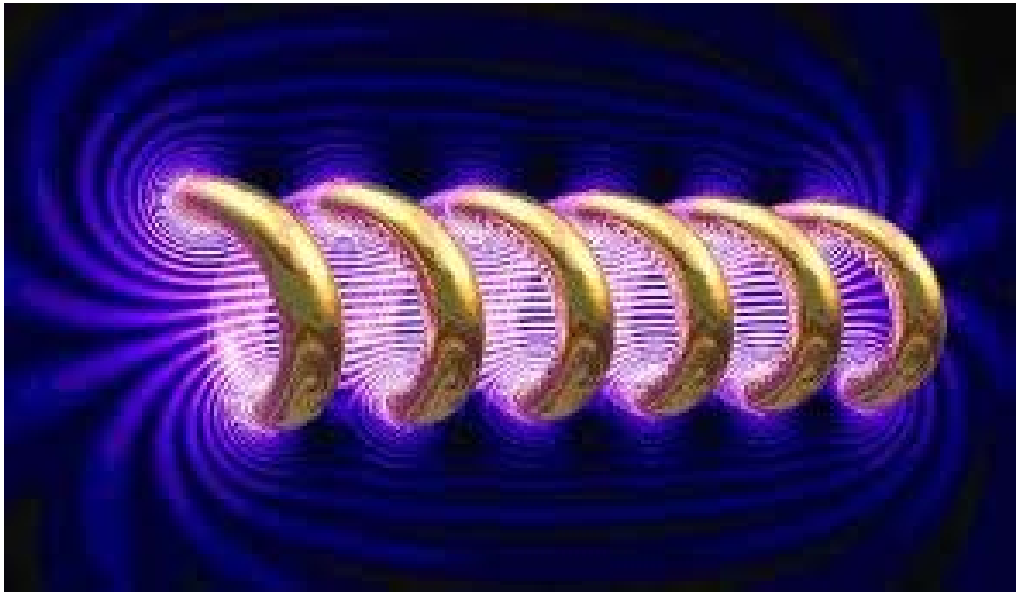
Likewise, the mag. field that I_1 feels from I_2 points out of the page.

Thus, by RHR-1 the force on wire 1 would be to the right.

Thus, the two wires attract each other!

Algebra-based Physics II   Sep.29th, Chap 21.6





B-field created by a current solenoid

Announcements:

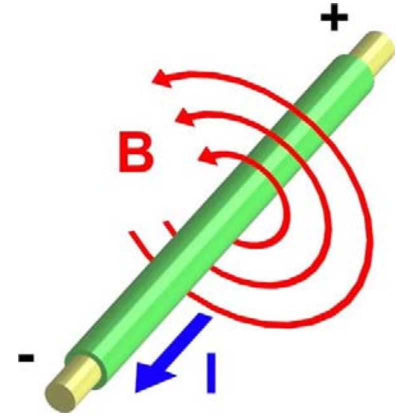
- **HW4 is posted and due on Wed 11:59 PM.**

Class Website:

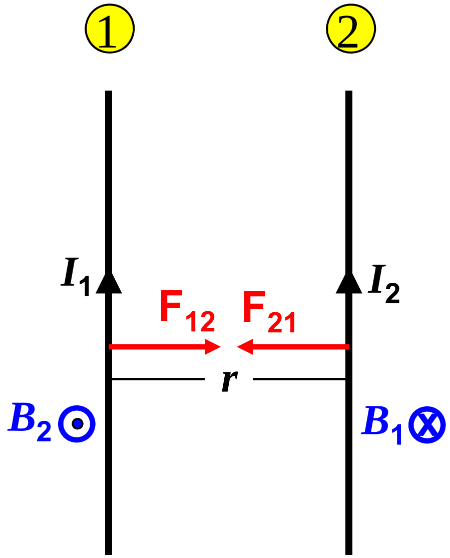
http://www.phys.lsu.edu/~jzhang/teaching.html

Magnetic field created by a straight current:

$$B = \frac{\mu_o I}{2\pi r}$$



Magnetic force between two straight currents:



$$B_1 = \frac{\mu_o I_1}{2\pi r}$$

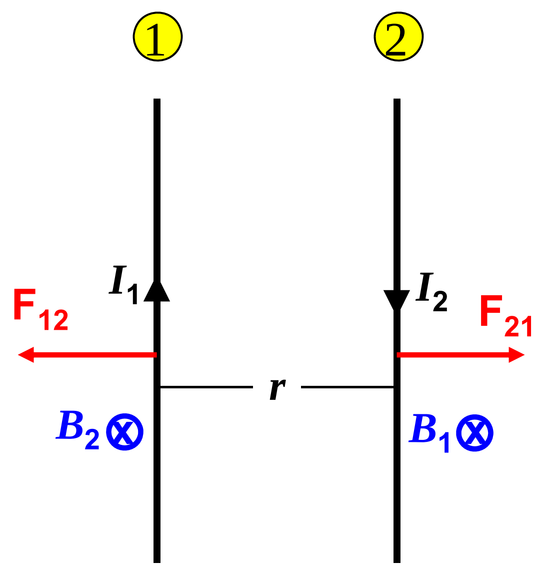
$$B_2 = \frac{\mu_o I_2}{2\pi r}$$

Force acting on I_1 by I_2 :

$$F_{12} = I_1 L_1 B_2 \sin\theta_{12} = I_1 L_1 \frac{\mu_0 I_2}{2\pi r}$$

Force acting on I_1 by I_2 :

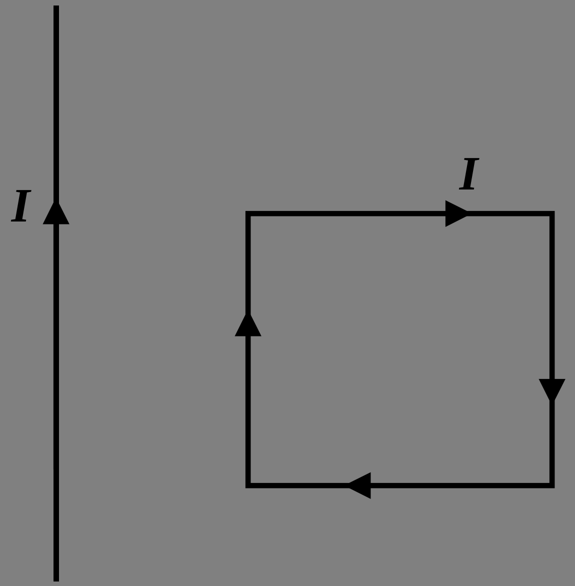
$$F_{21} = I_2 L_2 B_1 \sin\theta_{21} = I_2 L_2 \frac{\mu_0 I_1}{2\pi r}$$

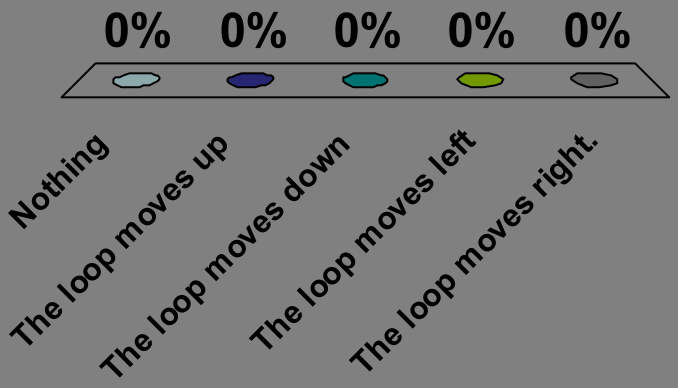


Clicker Question 21-7

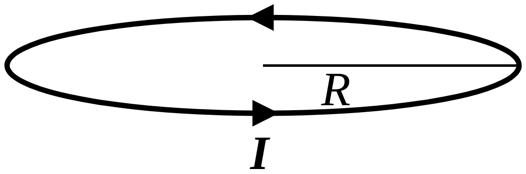
A long straight wire carrying a current I is held fixed. A square loop of wire also carrying a current I is held near the straight wire and then released. What happens?

1. Nothing
2. The loop moves up
3. The loop moves down
4. ✓ The loop moves left
5. The loop moves right.



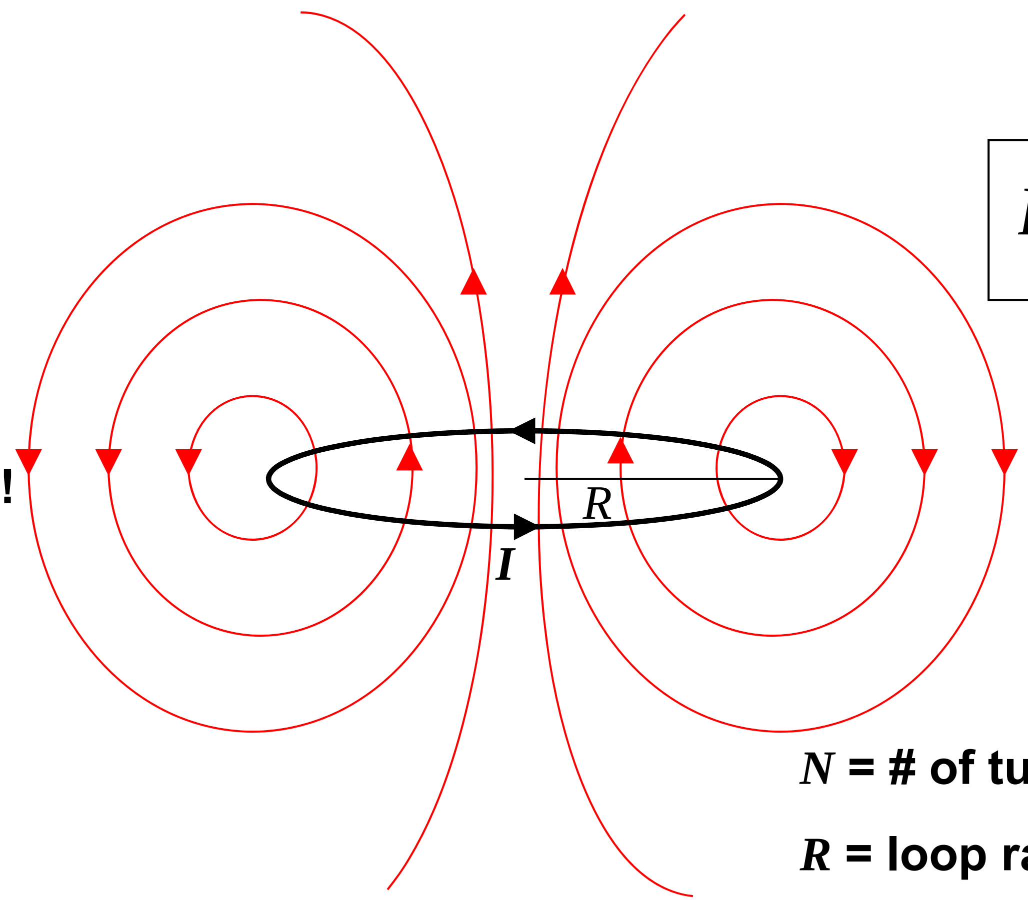


Now let’s bend our long straight wire into a loop:



What would the magnetic field lines look like around a closed loop of wire carrying a current I?

They come out of the center of the loop and bend around the edges!



$$B = N\frac{\mu_o I}{2R}$$

What is the value of the field at the center of the loop?

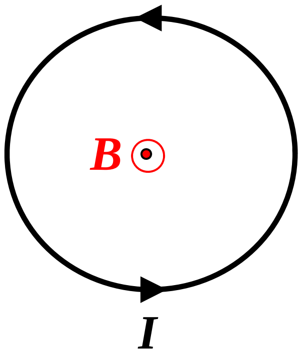
N = # of turns in the loop

R = loop radius

How do you calculate the direction of the magnetic field for loops?

Use RHR-3: **Curl the fingers of your right hand along the direction of the current, and your thumb points in the direction of the magnetic field.**

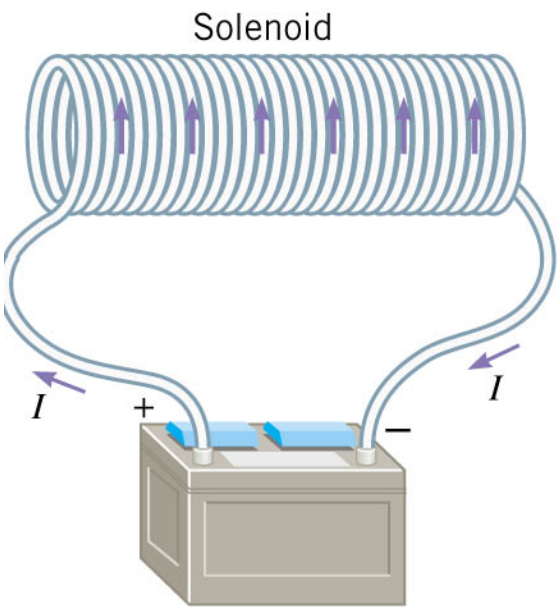
Example: Let's look at the loop from above:



Field direction would be: Out of the page

Now let's form many loops by bending the wire into a helix (coil):

This is called a Solenoid.



What would the field lines look like inside the solenoid?

Use RHR-3 to find the direction of the field.

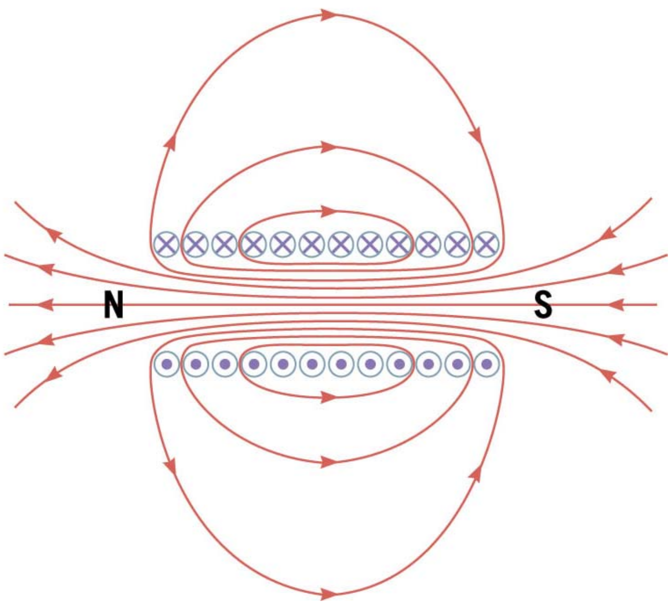
$$\boxed{B = \mu_o I n}$$

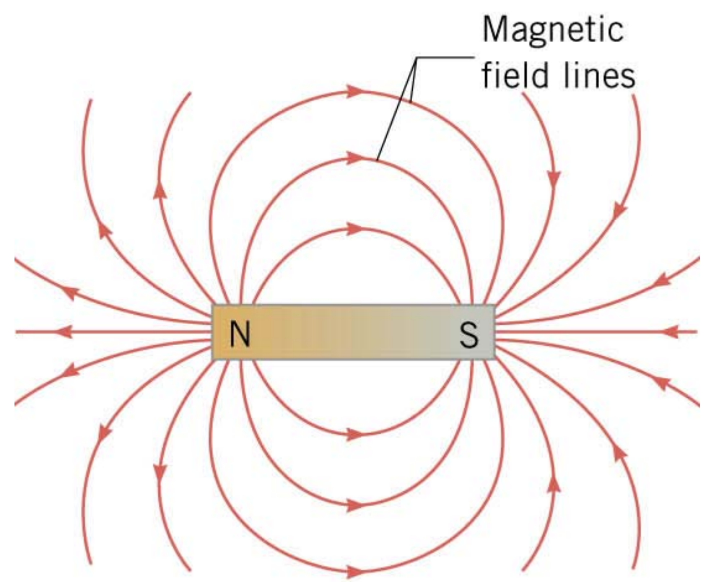
What about the magnitude of the field?

Here, $n \equiv N/L$ (turn density)

# of turns per unit length.

Notice: The field lines from a solenoid look just like the field lines created by a bar magnet.



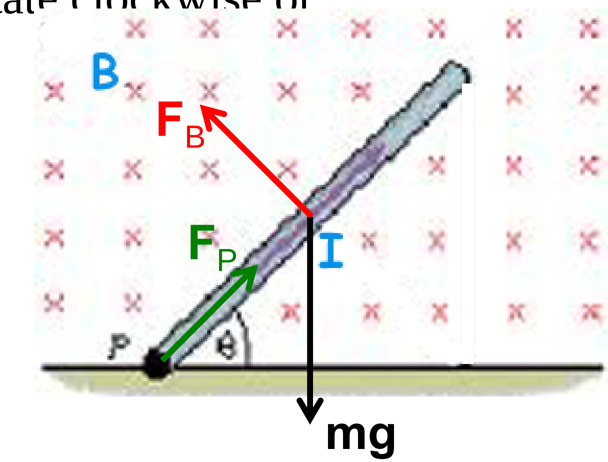


Field lines emerge from a North pole and converge on a South pole.

This is called an electromagnet.

We can switch the direction of the field in the electromagnet just by switching the direction of the current!

Example (Problem 21.34): The drawing shows a thin, uniform rod, which has a length of 0.45 m and a mass of 0.094Kg. This rod lies in the plane of the paper and is attached to the floor by a hinge at point *P*. A uniform B-field of 0.36T is directed perpendicularly into the plane of the paper. There is a current I = 0.41 A in the rod, which does not rotate clockwise or counterclockwise. Find the angle *θ*.



Three Forces acting on the rod:

$$F_B = ILB; \qquad mg; \qquad F_p$$

Condition of equilibrium (NO rotation):

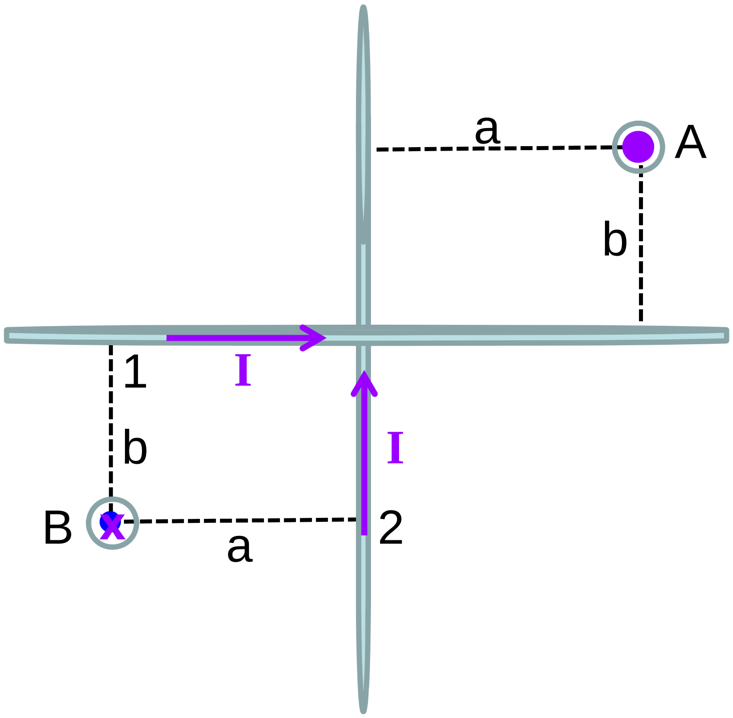
$$\sum \tau = 0$$

$$F_B \cdot \frac{L}{2} = mg \cdot \frac{L}{2} \cdot \cos\theta$$

$$ILB \cdot \frac{L}{2} = mg \cdot \frac{L}{2} \cdot \cos\theta$$

$$\frac{ILB}{mg} = \cos\theta \Rightarrow \theta = \cos^{-1}\left(\frac{ILB}{mg}\right)$$

Example : The drawing shows two perpendicular, long, straight wire, both of which lie in the plane of the paper and have the same current of *I*. What are the magnetic field of point A and B, respectively ? Assume a > b.



Use: $B = \dfrac{\mu_o I}{2\pi r}$ Identify directions of field

Point A: **B** points out of the paper

$$B_A = B_1 - B_2 = \frac{\mu_o I}{2\pi b} - \frac{\mu_o I}{2\pi a} = \frac{\mu_o I}{2\pi}\left(\frac{1}{b} - \frac{1}{a}\right)$$

Point A: **B** points into the paper

$$B_B = B_1 - B_2 = \frac{\mu_o I}{2\pi b} - \frac{\mu_o I}{2\pi a} = \frac{\mu_o I}{2\pi}\left(\frac{1}{b} - \frac{1}{a}\right)$$