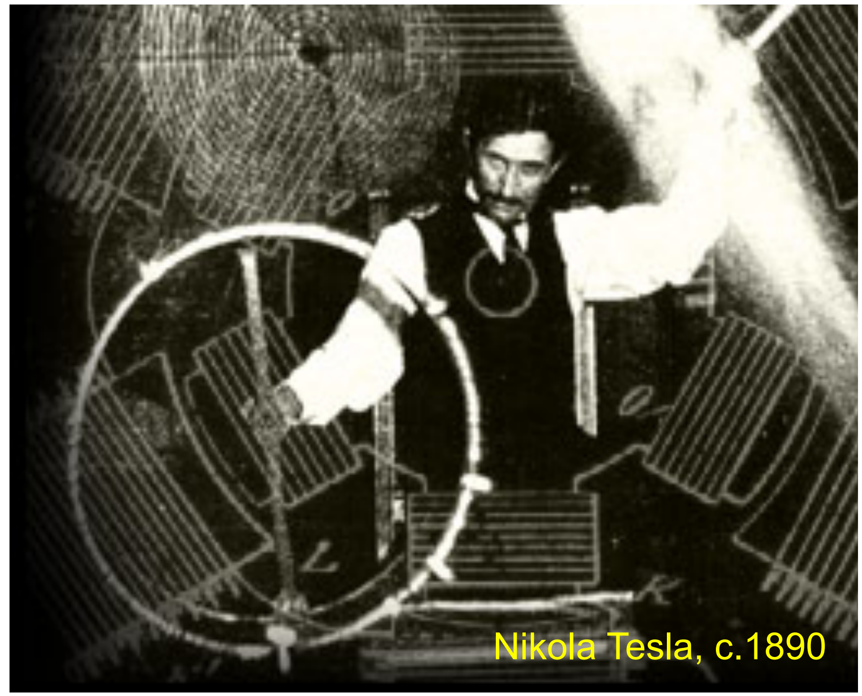
Physics 115
General Physics II

Session 28

Magnetic fields and forces


Nikola Tesla, c.1890

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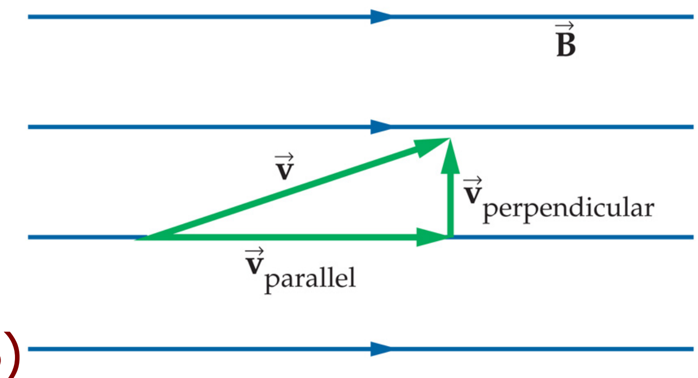
Lecture Schedule

12-May	Mon	23	DC Circuits & Meters	21.5-21.8
13-May	Tues	24	DC Circuits	21.5-21.8
15-May	Thurs	25	RC circuits	21.6-21.7
16-May	Fri	26	Circuits - Neurons	
19-May	Mon	27	Magnetism	22.1
20-May	Tues	28	Magnetic Force	22.2-22.5
22-May	Thurs	29	Magnetic Fields	22.6-22.7
22-May	Fri	30	Induced EMF, Applications	23.1-23.3
26-May	***holiday***		NO CLASS	
27-May	Tues	31	Energy, RL circuits	23.4-23.8
29-May	Thurs	32	Transformer	23.9-23.10
30-May	**Fri**		**EXAM 3 - Chapters 21,22,23**	
2-Jun	Mon	33	AC circuits	24.1-24.3
3-Jun	Tues	34	AC circuits	24.4-24.5
5-Jun	Thurs	35	Resonance, Applications	24.6
6-Jun	Fri	36	Last class - review	
June 9	**FINAL EXAM**		**2:30-4:20 p.m.**	**Comprehensive**
	Mon		**Monday, June 9, 2014**	

Today

General case: motion for **v** at any angle to **B**

- If **v** is neither perpendicular nor parallel to **B**
  - Parallel component will create no force : $a_{par} = 0$
    - → constant v_{par}
  - Perpendicular component will create $F=qv_{par}B$: $a_{perp} = (q/m)v_{par}B$
    - → Motion in a circle with $r=mv/(qB)$
  - Net motion of particle: *helix*
    - Circle around B lines while drifting at constant speed
    - Charged particles are channeled along B field lines



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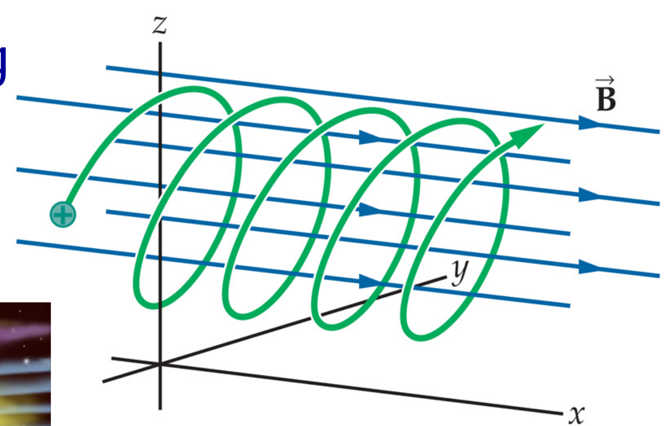

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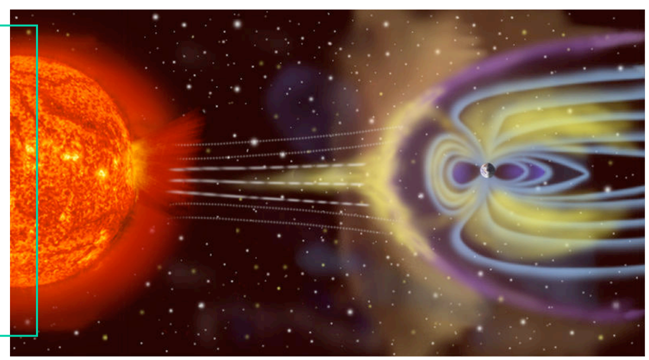
Protons from Sun are channeled to Earth – but geomagnetic B field deflects them around us!

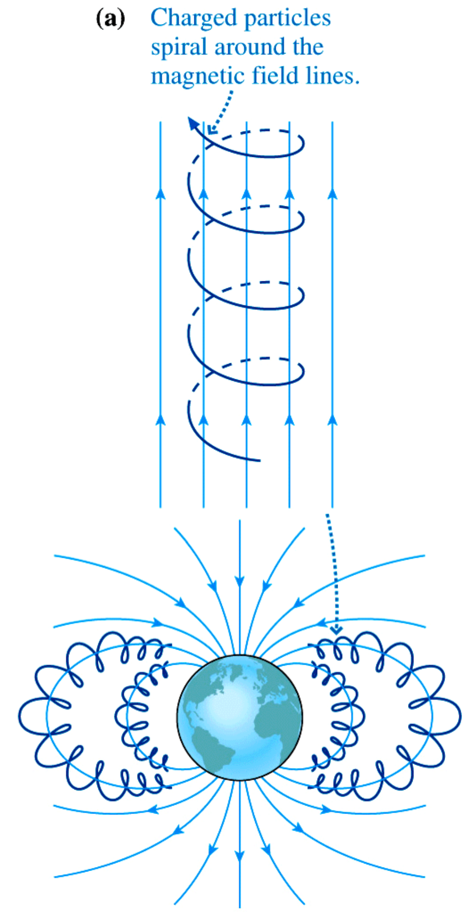


The Earth’s charged particle belts

Charged particles spiral in a magnetic field, moving along field lines in a helical path.
Where field lines “pinch” together (intense B), the particles may get reflected, and reverse direction of their motion. This forms a “trap” that can catch and hold charged particles.

The Earth’s magnetic field forms such traps for electrons and protons emitted by the Sun. These trapped charged particles make the Van Allen radiation belts in the space around the Earth: radiation hazards for astronauts.

Energetic electrons and protons leaking from the trap near the Earth’s magnetic poles (and solar particles arriving along field lines) ionize the air in the upper atmosphere and produce the Auroras in the polar skies.



Force on a wire

- Current I flows in a "long, straight" wire (meaning: "ignore end effects") in a B field
- I = flow of charge – let's assume
  - Charges move at speed v
  - Time for charge to travel a distance L is $\Delta t = L / v$
  - Total q in a wire segment of length L can be found from definition of I:

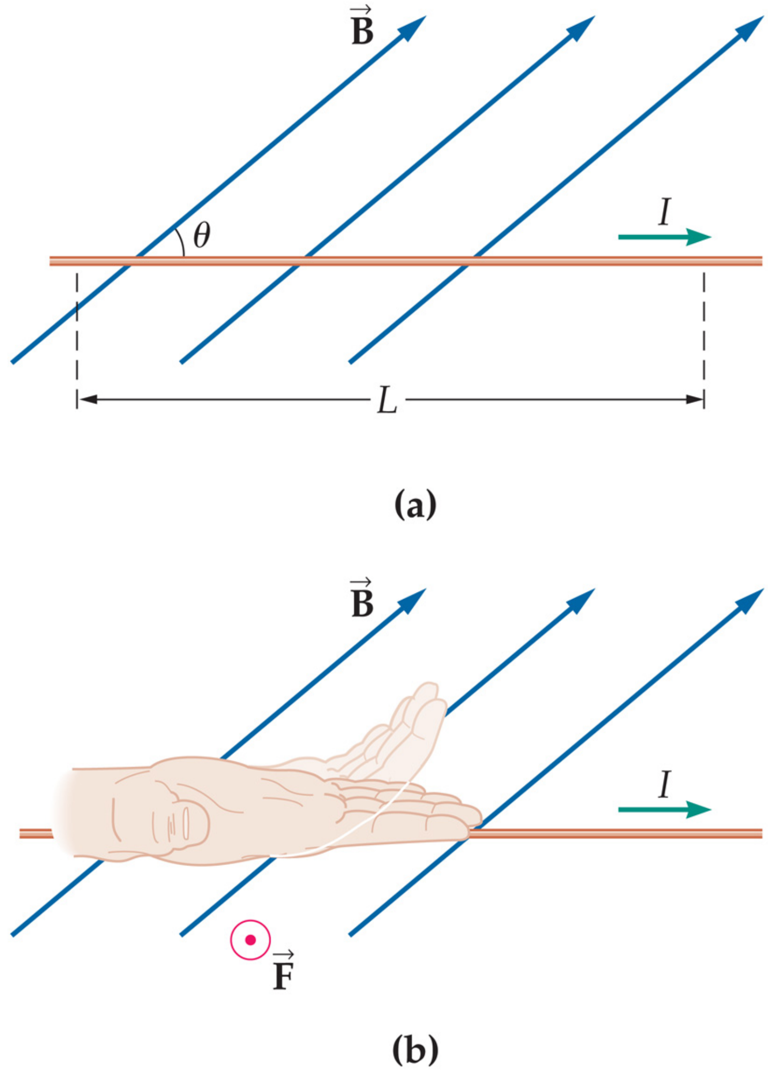
$$I = \frac{q}{\Delta t} \rightarrow q = I \Delta t$$

Then force due to B field on wire segment is

$$F = q v B \sin\theta = \left(\frac{I L}{v}\right) v B \sin\theta = I L B \sin\theta$$

Notice: v drops out: doesn't matter how fast charges move, only need to know I and L

Direction of force is given by right-hand rule



Example

- Wire carrying I=1 A has segment 0.05 m long lying inside magnet with uniform field of 0.5 T
- Force on wire?

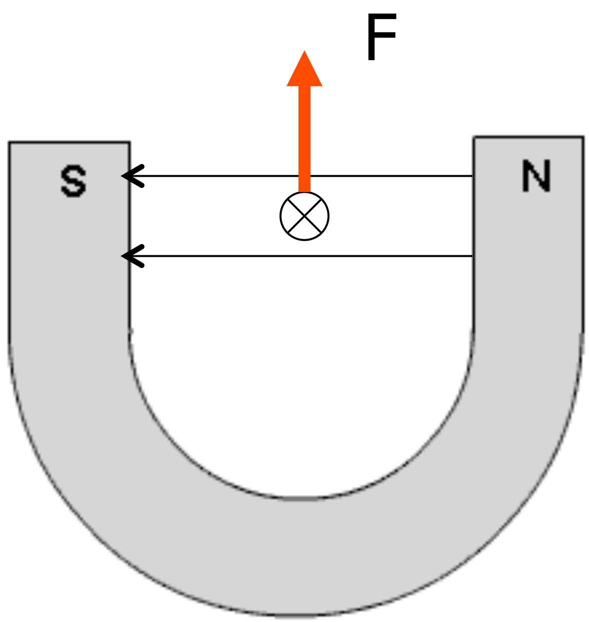
$F = I\,L\,B = (1A)\,(0.05m)\,(0.5T)$

$|\,F\,| = 0.025$ N

Apply the R.H.R.:

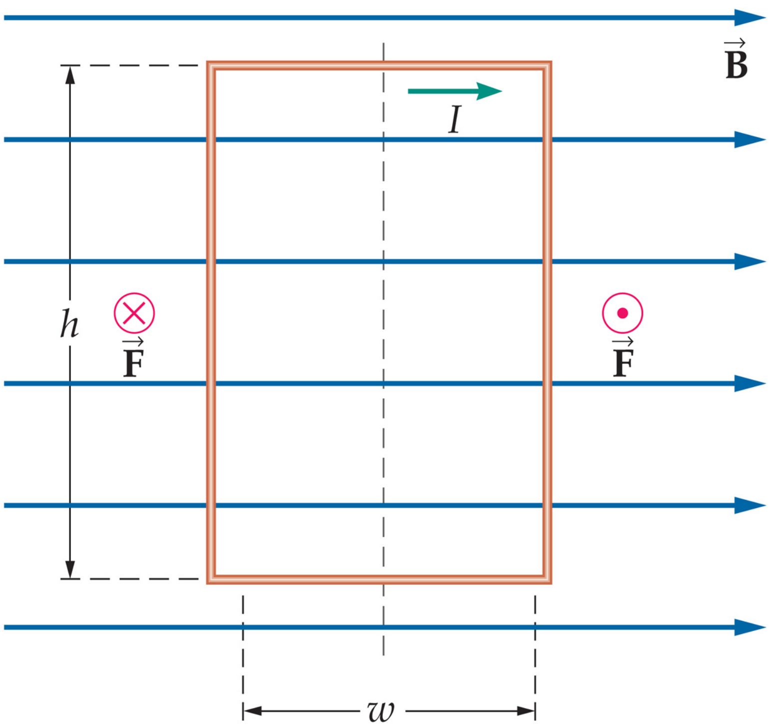
Fingers along I, curl toward B

... So F points up



Forces on rectangular loops of wire

- Coils = loops of wire: important in technology
  - We'll see why soon
- Simplest loop = rectangle of wire
  - Loop of dimensions h x w carries current I
  - Forces on loop?



Force due to B field on wire segments at top and bottom = 0

there, I is parallel to B

Left and right sides are perpendicular to B, so | F |= I L B

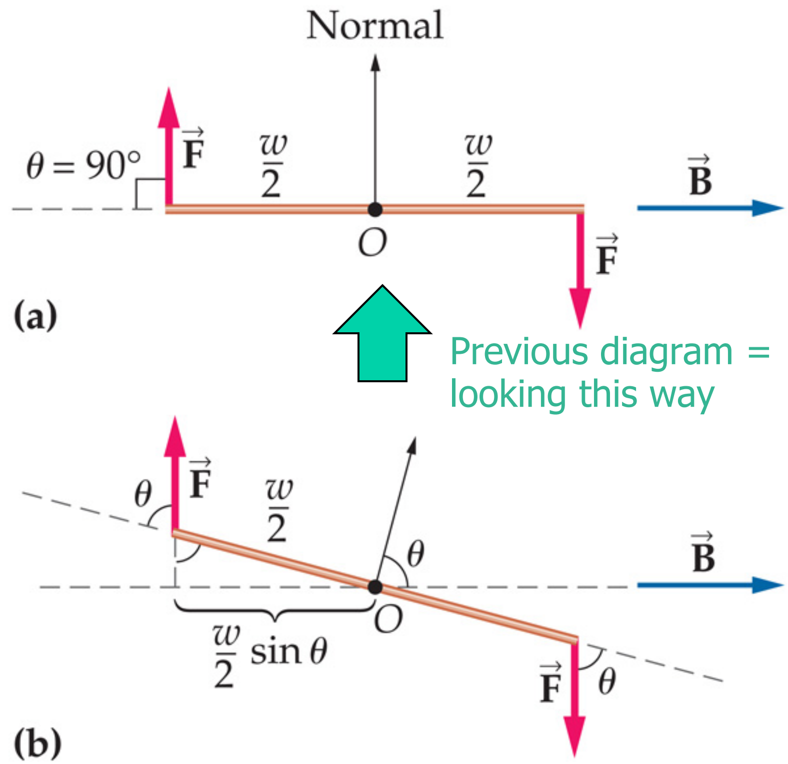
Direction of force is given by right-hand rule:

Left segment: into screen

Right segment: out of screen

Torque on rectangular loop

- Recall from 114:
  - Torque = twist, caused by forces with lines of action separated from axis of rotation by distance r
  - Here: equal and opposite forces are separated by width of loop w
  - Symmetry: assume rotation axis is at centerline of loop, distance w/2 from each side
  - Net torque = sum of torques due to force on each side:



$$F = ILB\sin\theta = IhB\sin\theta$$

θ= angle between I and B= angle of normal to loop

$$\tau = F(w/2) + F(w/2)$$

$$= 2IhB\sin\theta(w/2) = IhwB\sin\theta$$

$$= IAB\sin\theta$$

Units for torque = N m

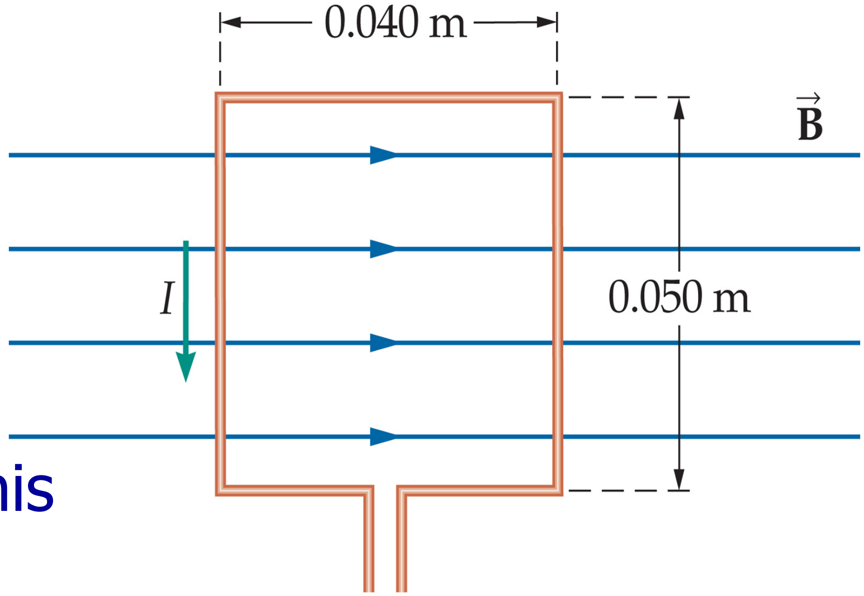
h w = A = *area* of loop

So torque is maximum when B lies in plane of loop, zero when B cuts through open area of loop

Example

- Single loop has h=4 cm, w=5 cm, I = 1.6 A, in field with B = 0.35 T
  - Maximum torque?

$$\tau = I\,A\,B\sin\theta$$
$$\tau_{MAX} = I\,A\,B$$
$$= (1.6A)(0.002m^2)(0.35T)$$
$$= 0.00112\ N\,m$$



- Coil has 200 turns like this
  - Max torque now?

$$\tau = I\,A\,B\sin\theta$$
$$\tau_{MAX} = N\,I\,A\,B$$
$$= 200\,(0.0011\ N\,m)$$
$$= 0.22\ N\,m$$

What if loops are **not** rectangles?
Torque is still given by τ = IAB sinθ

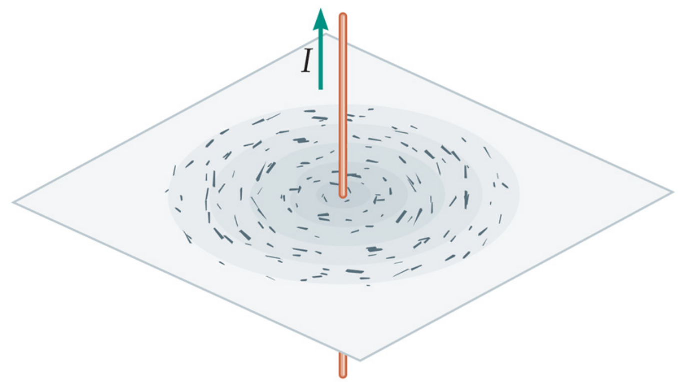
Example: circular loop of area 0.002m^2 has same max torque as rectangle: its radius is

$$A = \pi r^2 \rightarrow r = \sqrt{A/\pi} = \sqrt{0.002m^2/3.14} = 0.025m$$

B fields from currents: Ampere's Law

- Experimental facts:
  - Current in a wire causes a B field (Oersted)
  - We see that I in a long straight wire creates circular field lines
  - B is proportional to I
  - Field is more intense near the wire, drops off ~ 1/r:

$$B \propto I, \quad B \propto \frac{1}{r} \Rightarrow B \propto \frac{I}{r} \rightarrow B = (const)\frac{I}{r}$$



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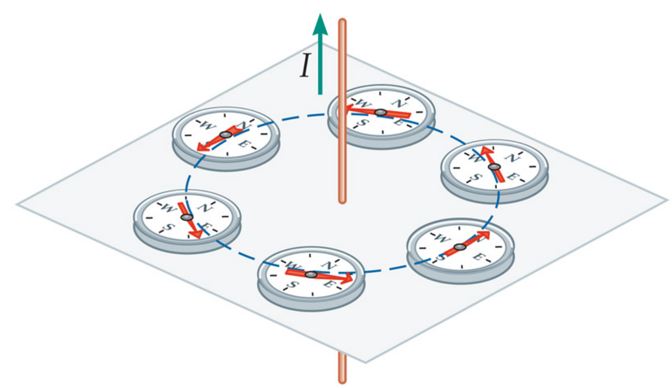
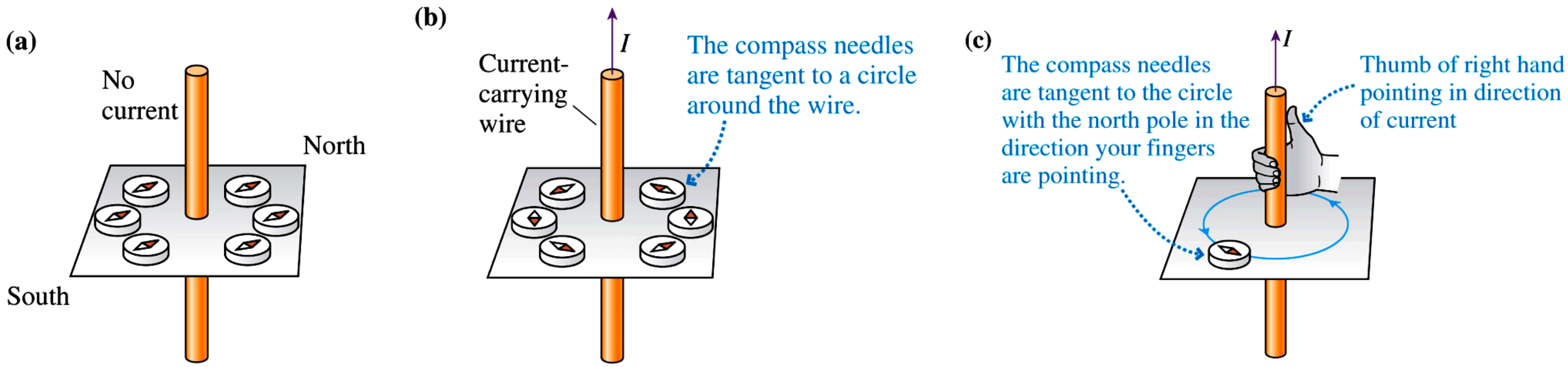


(b)

Electric Current and B: the Right Hand Rule again



Demonstration showed:

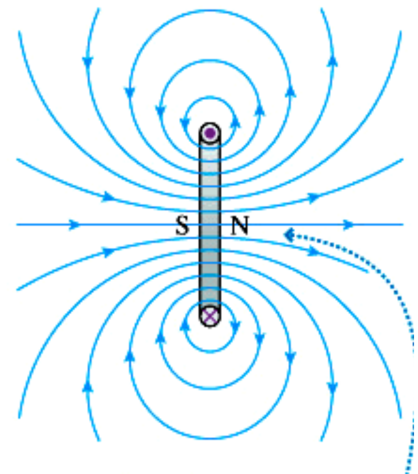
- When we place compasses around a wire, if no current is flowing in the wire, all compasses point north.
- When current flows in the wire, the compasses point in a ring around the wire.

The Right-Hand Rule for B due to I: Hold the wire so that the thumb of your right hand points in the direction of the current. (+ !!) Then your fingers will curl in the direction of the magnetic field created by the current flow.

Notice: B is always **perpendicular** to I; B field lines are **closed** (circles)

Q: Are there two kinds of magnetism?

(a) Current loop

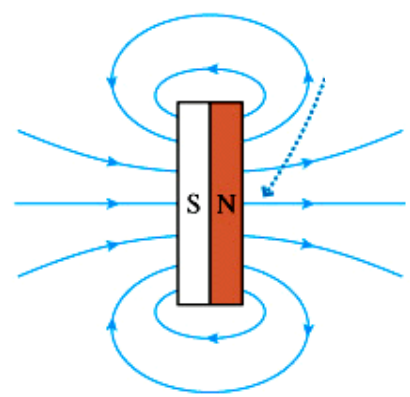


We know about the magnetic effects of permanent magnets and the magnetic fields they create.

We now find that B fields are produced by current-carrying wires. A loop of wire produces a field similar to a bar magnet's

Are these two distinct kinds of magnetism?

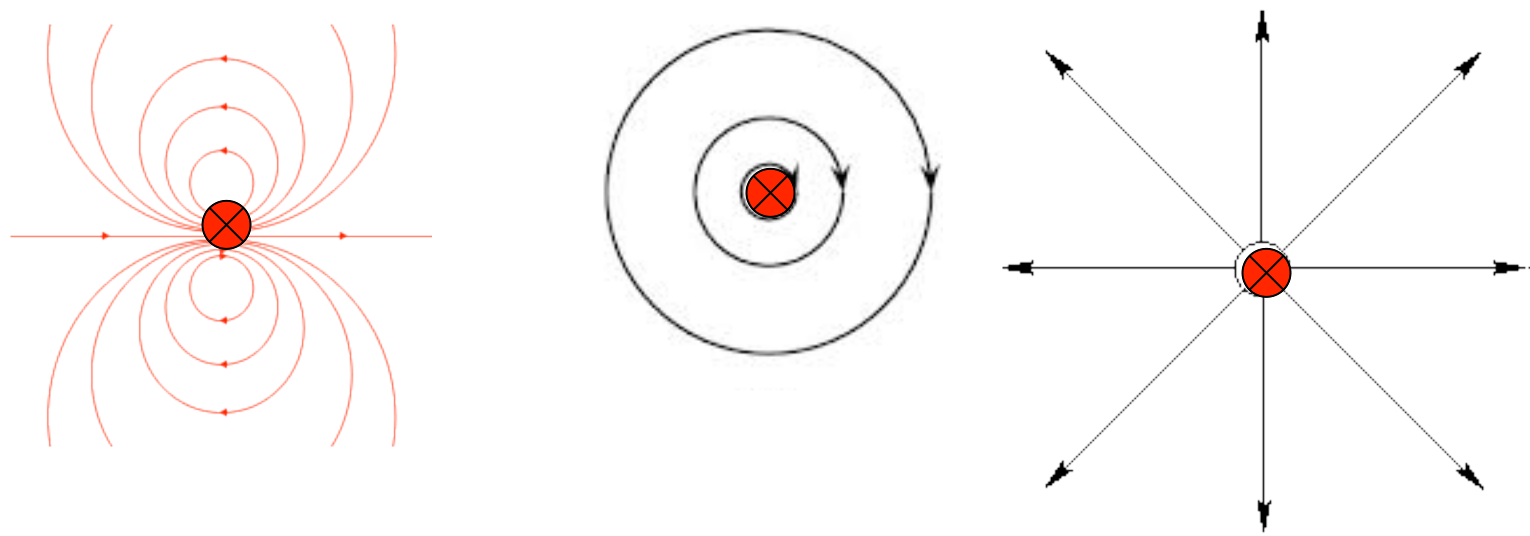
(b) Permanent magnet



No. The two manifestations of magnetism are just two aspects of the same fundamental ***electro-magnetic force***.

Quiz

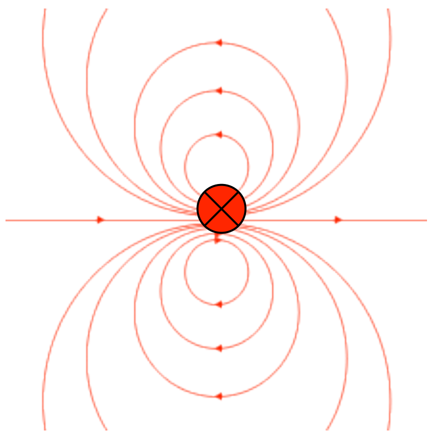
- Which picture best represents B field around a wire with current going into the screen?



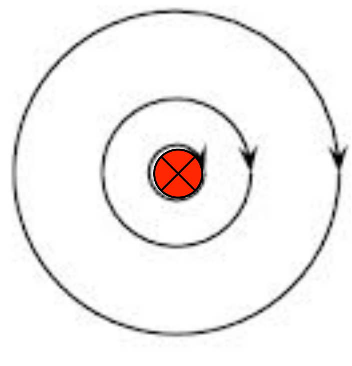
A B C

Quiz

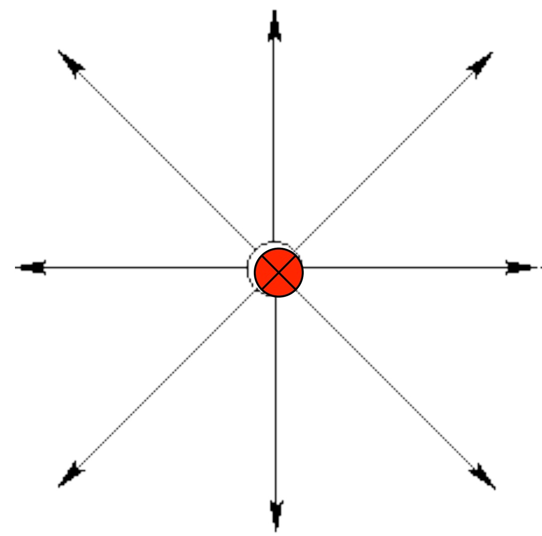
- Which picture best represents B field around a wire with current going into the screen?



A



B



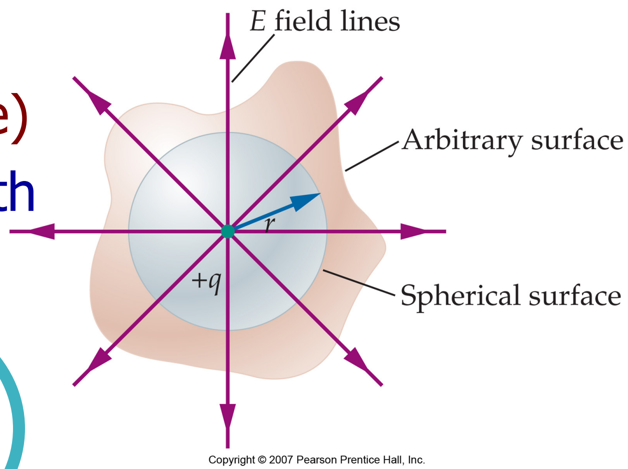
C

Ampere's Law

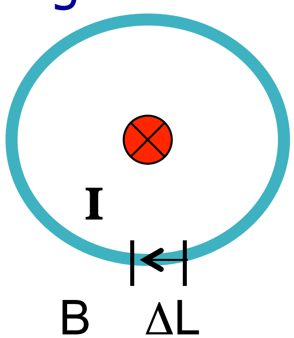
- Mathematical relation between I and B : Ampere's Law
  - Geometry of relation is complicated and 3-dimensional (RHR !)
- Analogy to Gauss's Law for q and E:
  - Recall

$$\Phi_E = \frac{Q_{ENCLOSED}}{\varepsilon_0}, \quad \Phi_E = \vec{E}\cdot\vec{A} = EA\cos\theta$$

    - Magnitude of E on a Gaussian surface depends on dot product of **E** and area patch's normal vector **A**
- Ampere's law relates
  - B along a **closed** path (circle, for example)
  - **Net current enclosed** by that closed path
  - Add up contributions for small segments



$$\sum_{PATH} B_{||}\Delta L = const(I_{ENCLOSED})$$



Ampere's law in general (This is not easy!)

- Choose a circular path surrounding wires
- RHR tells us **B** will point generally counterclockwise on this path
  - NOT necessarily constant magnitude!
  - NOT necessarily pointing along circle!
- Contribution to sum from a short segment of path ΔL is

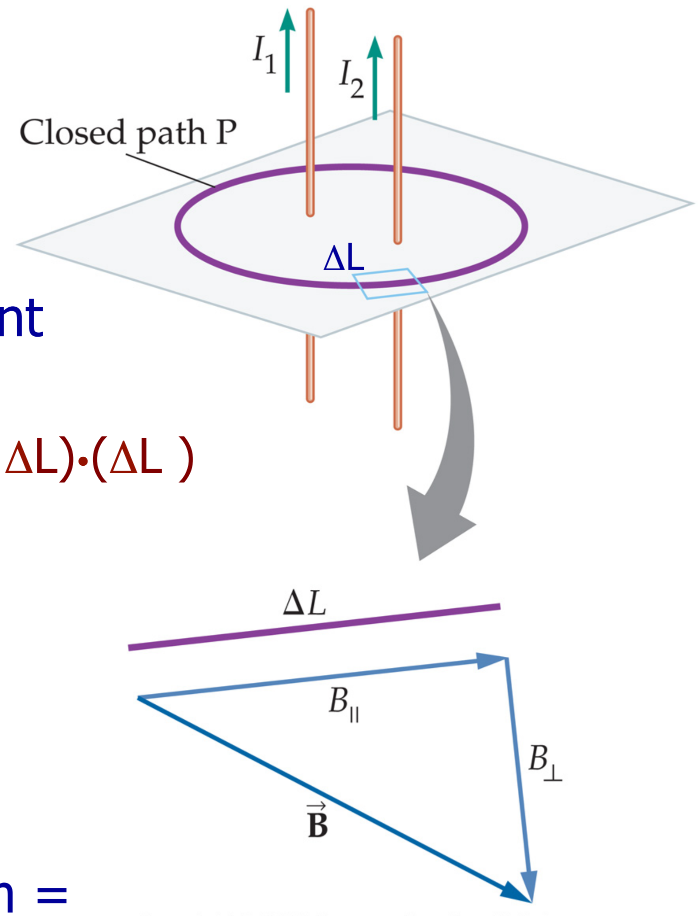
(magnitude of component of B there, **parallel** to ΔL)$\cdot$(ΔL)

- Sum up contributions from all segments around the closed path:

Ampere's Law tells us:

Sum = net current passing through surface enclosed by path = $I_1 + I_2$

Note: just as for charge in Gauss's law, sum = NET current: if I_2 pointed in opposite direction, sum would be $= I_1 - I_2$



$$\vec{B} = \vec{B}_1 + \vec{B}_2$$

Example: one long straight wire with current I

(We can only apply Ampere's law in a few cases with simple geometry)

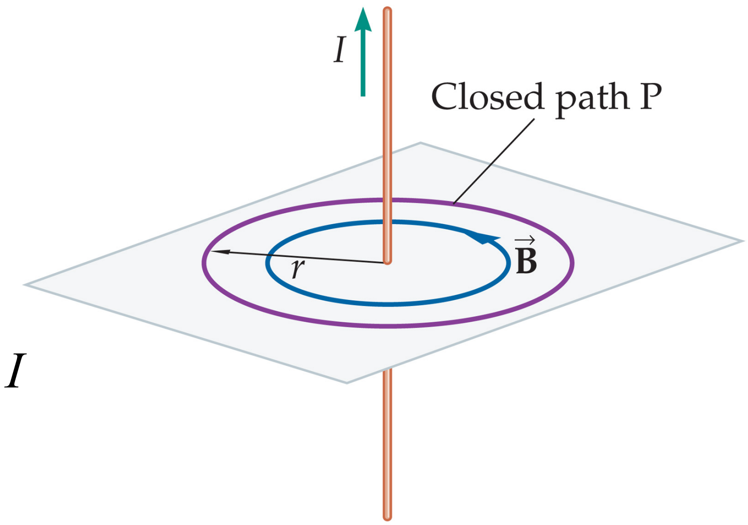
- Choose circular path of radius R centered on wire, in plane perpendicular to wire
  - Symmetry: B must be constant on path (constant r)
  - RHR says it points counterclockwise
  - Sum of B ΔL along closed path

    = B (circumference of circle) :

$$\sum_{CIRCLE} B_{||}\Delta L = B \sum_{CIRCLE} \Delta L = 2\pi r\, B$$

$$\sum_{PATH} B_{||}\Delta L = 2\pi r\, B = const(I_{ENCLOSED}) = \mu_0\, I$$

$$B = \frac{\mu_0\, I}{2\pi r}$$



New constant: μ_0 , pronounced "mu-naught" or "mu-zero"

"permeability of free space" (analogous to epsilon-0 for E)

$$\boxed{\mu_0 = 4\pi \times 10^{-7}\left(T \cdot m/A\right)}$$