Physics 115
General Physics II

Session 29

Magnetic forces, Coils, Induction

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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

Announcements

- Monday = holiday: no class!
- Exam 3 is next Friday 5/30
  - Same format and procedures as previous exams
    - If you took exams with section B at 2:30, do so again
  - Covers material discussed in class from Chs. 21, 22, and parts of 23 covered by end of class on Tuesday;
    - we will skip section 22-8, magnetism in matter
  - Practice questions will posted next Tuesday evening, we will review them in class Thursday

Example: one long straight wire with current I

Last time

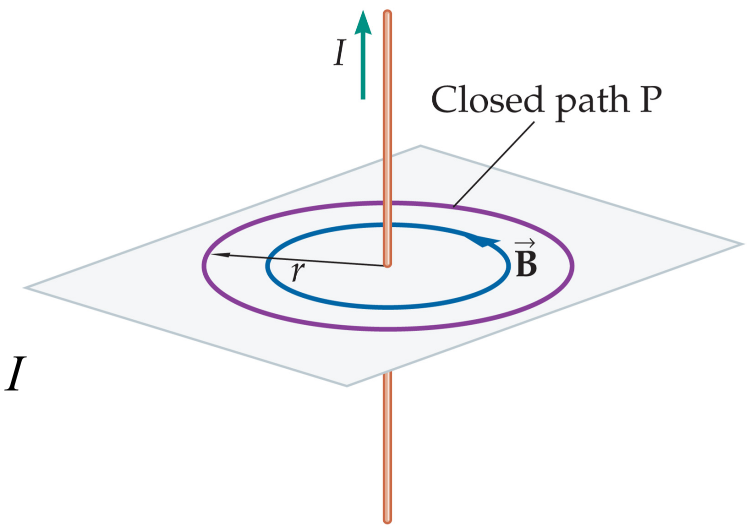
- Choose circular path of radius R centered on wire, in plane perpendicular to wire
  - Symmetry: B must be constant on path (constant r)
  - RHR says it points counterclockwise
  - Sum of BΔL along closed path

    = B (circumference of circle) :

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

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

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



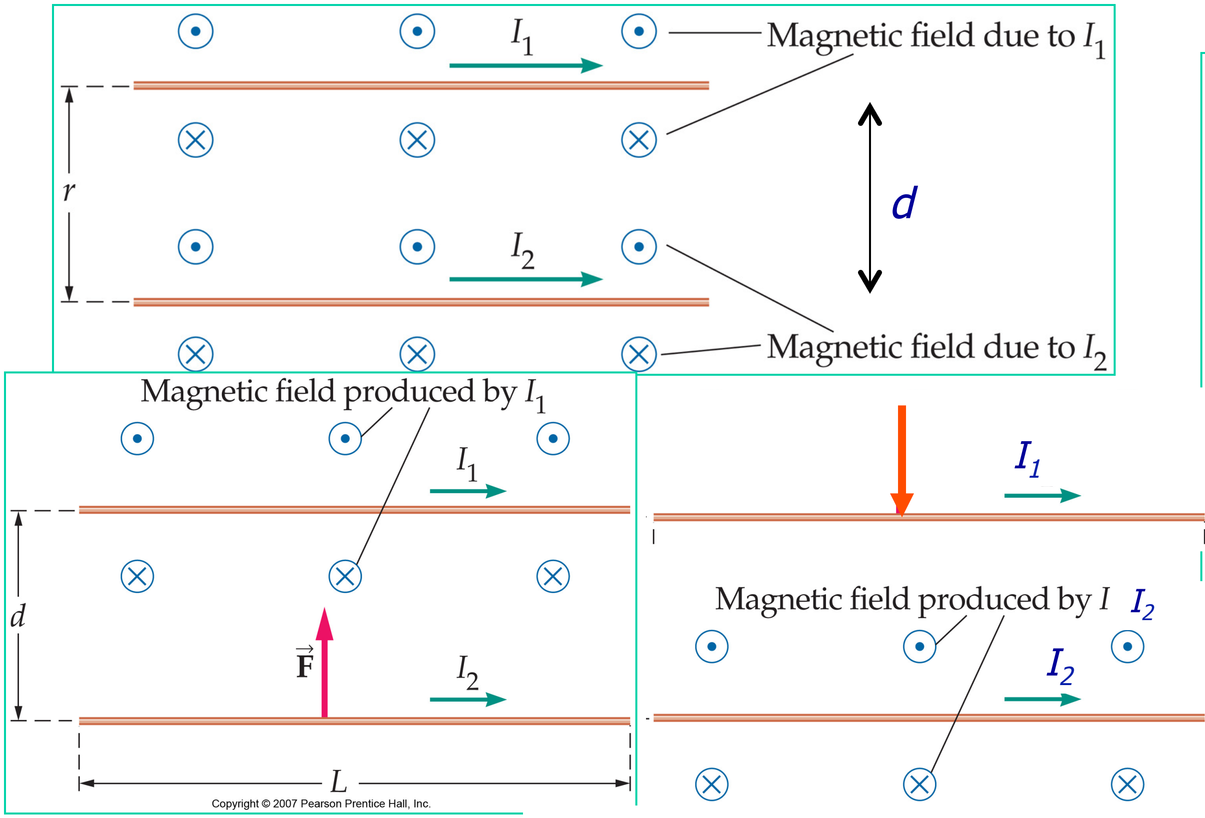
New constant: pronounced "mu-naught" or "mu-zero"

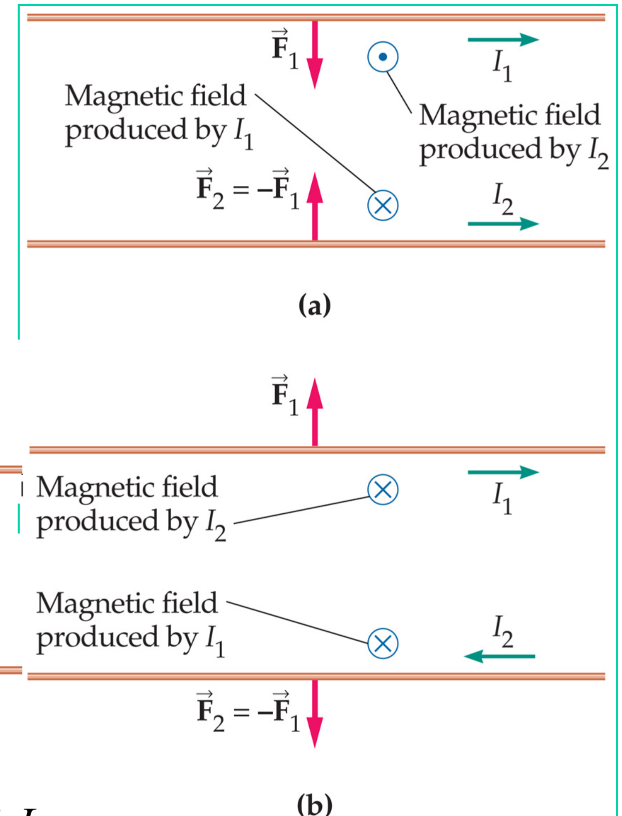
"permeability of free space" (analogous to epsilon-0 for E)

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

Force between parallel wires

- Now we can understand the wire pinch/spread demonstration: each wire sets up a B field that applies a force on the other



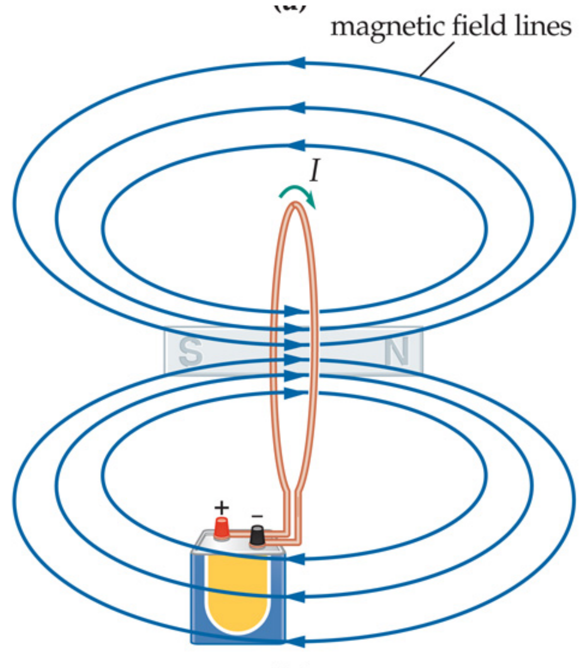


B due to wire 1 at wire 2: $B_1 = \dfrac{\mu_0 I_1}{2\pi d}, \quad F_{ON\,2} = I_2 L\, B_1 = \dfrac{\mu_0 I_1 I_2}{2\pi d} L$

B due to wire 2 at wire 1: $B_2 = \dfrac{\mu_0 I_2}{2\pi d}, \quad F_{ON\,1} = I_1 L\, B_2 = \dfrac{\mu_0 I_1 I_2}{2\pi d} L$

B field of a current loop

- Field due to a current loop:
  - Apply RHR to small segment of wire loop
  - Near the wire, B lines are circles
  - Farther away, contributions add up
    - Superposition
    - Higher intensity at center of loop
    - Lower intensity outside
      - Contributions from opposite sides of loop oppose each other
  - Looks like bar magnet's field
    - No accident: permanent magnet is array of tiny current loops, at the atomic level
    - Force between separate loops is like interaction between bar magnets



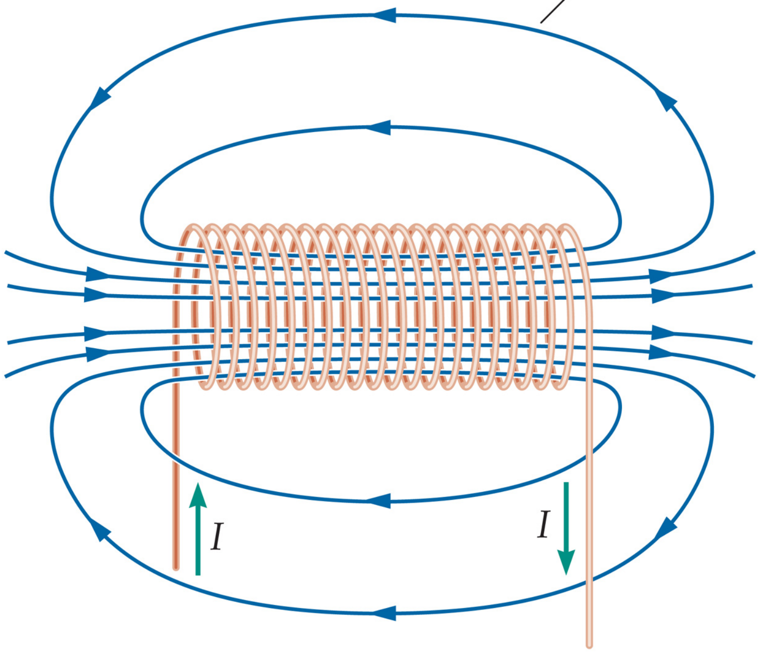
"It can be shown": B at center:

$$B_{CENTER} = \frac{\mu_0 I}{2R}$$

coil of N loops: $$B_{CENTER} = \frac{N\mu_0 I}{2R}$$

Array of loops = “solenoid” coil

- Wind a coil that is a long series of loops
  - Field contributions add up (superposition), same I in all loops
  - Result: **uniform intense** B inside, **weak** B outside
  - Handy device – commonly used to make uniform B field zones

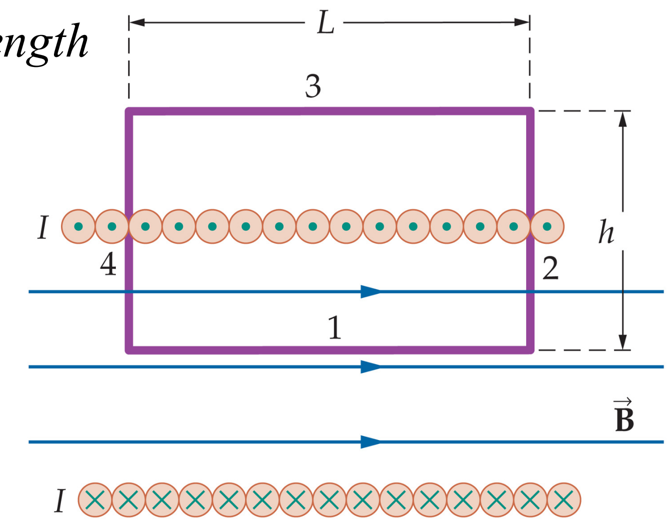


“Long, thin” solenoid: **constant** B inside, **B=0** outside. Apply Ampere’s Law:

$$\sum B_{||}\Delta L = BL_1 + 0L_2 + 0L_3 + 0L_4$$

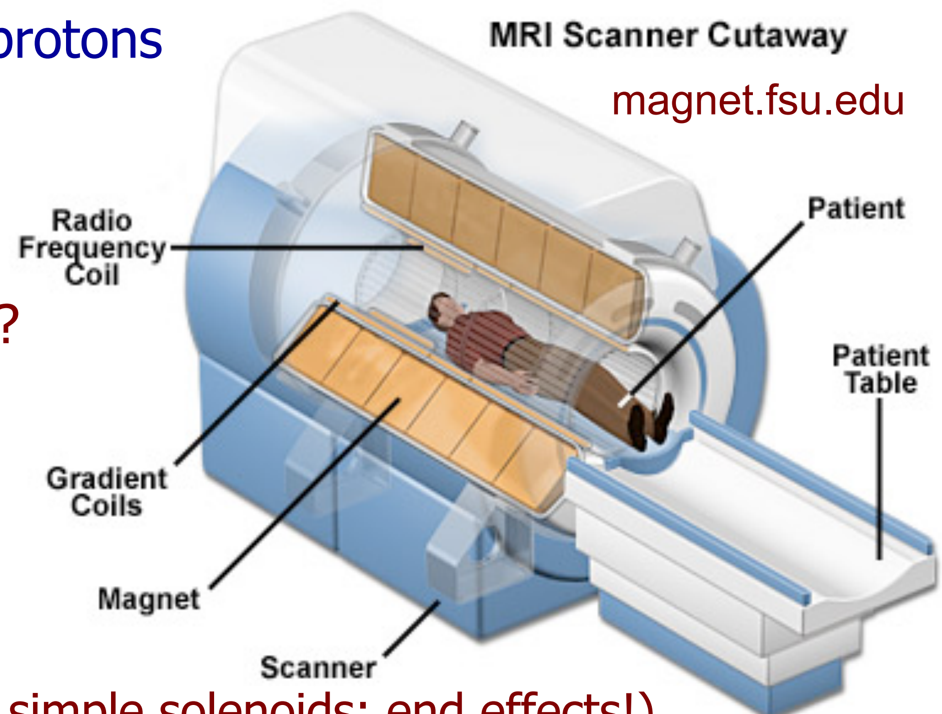
$$BL_1 = \mu_0(I_{ENCLOSED}) = \mu_0(NI) \rightarrow B = \mu_0(\frac{N}{L_1}I) = \mu_0 nI$$

$$n = coils\,/\,unit\ length$$



Solenoids for Magnetic Resonance Imaging (MRI)

- MRI: hydrogen nuclei = protons → magnetic dipoles
  - Put them in a strong uniform B field and they align
    - Just the job for a solenoid coil ("magnet" in diagram below)
  - Then tickle them with radio waves of just the right frequency, and they radiate: easily detected and analyzed
  - Use MRI to image soft tissues (invisible to x-rays)
    - Water = H_2O: many protons



Example:

Superconducting solenoid has n=2000 turns/meter

What I is needed to get B=7 T?

$$B = \mu_0 n I, \quad n = coil\ density, turns/m$$

$$7T = 4\pi \times 10^{-7}\left(T \cdot m/A\right)\left(2000/m\right)I$$

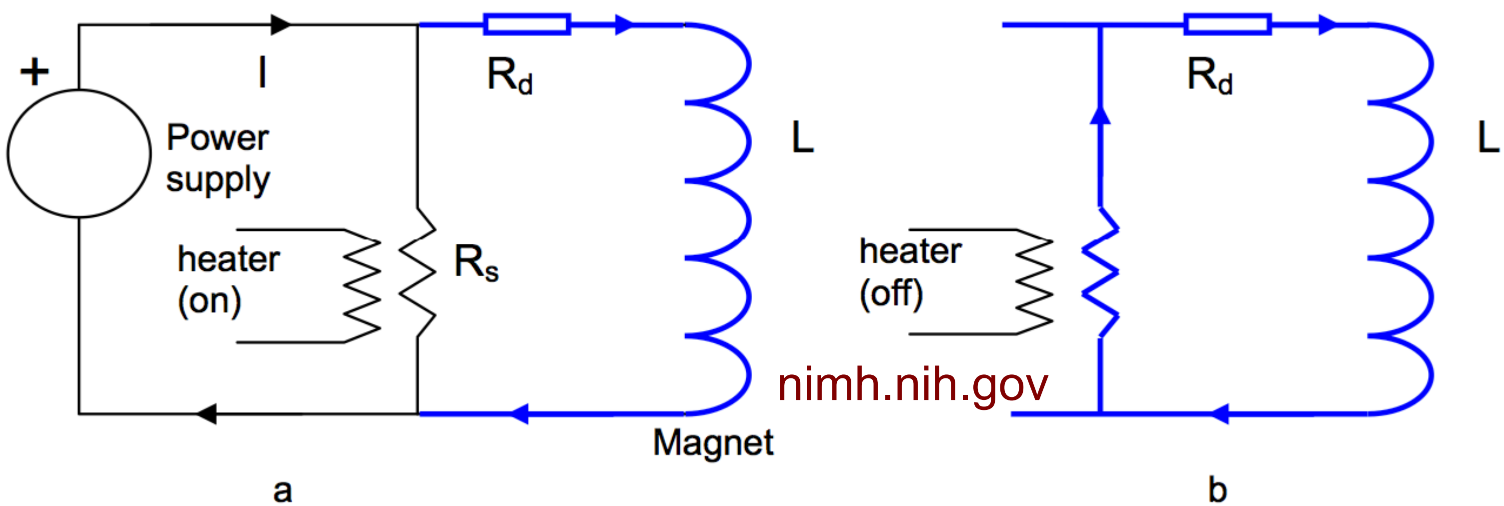
$$I = \frac{7T}{8(3.14)\times 10^{-3}T/A} = 279A$$

(real MRIs cannot use simple solenoids: end effects!)

BTW: how to get I into a superconducting loop?

- Superconducting magnets are closed loops
  - SuperC: "R=0" so I flows "forever" (actually: R ~ 10^{-9} Ω)
  - First you have to get I circulating in the loop
  - Trick: have a heater that makes part of the SC wire "normal"
    - Acts like a resistor – large R compared to cold SC wire!
    - Attach DC power supply
    - Turn on heater: I goes through L
    - Turn off heat: $R_s \rightarrow 0$: closed loop

L=magnet coil
R_s = R of SC wire when warm
R_d = cold R of SC wire: 10^{-9} Ω



Quiz 19

- An electron beam in a vacuum tube goes **into** the screen, as shown (that is the **electrons** are moving into the screen)
- What is the direction of the B field due to the electron beam, at point P?

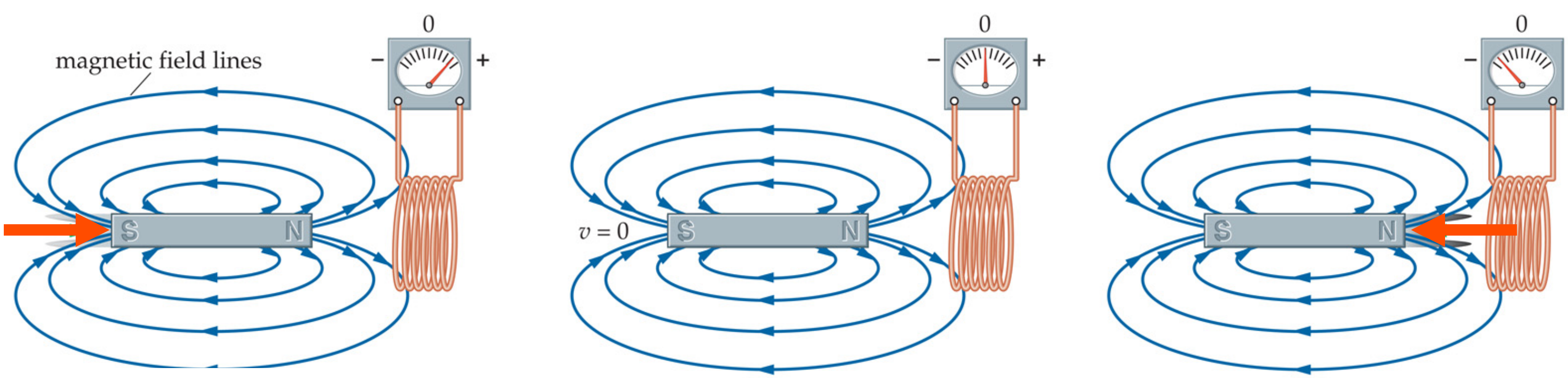
electron beam

A. Up
B. Down
C. Right
D. Left
E. Insufficient info to tell

RHR says clockwise, so B points up at P for conventional current - but the electrons have **negative** q, so opposite: down

Electromagnetic induction: induced EMF

- Oersted observed: current affects compass: I causes B
- Michael Faraday (Britain, 1791-1867) asked
  - Does the opposite happen? Can magnetic field **cause** a current?
  - Observation: yes, current flows – but only while B is changing
    - Bar magnet + coil: I=0 when stationary, I > 0 when moving
      - Moving magnet → field in coil is increasing or decreasing
      - Direction of change → direction of current in loop
  - Induced current →must be an induced EMF to make charges flow



Move magnet toward coil
Increasing B in coil

(b) Stop
B = constant

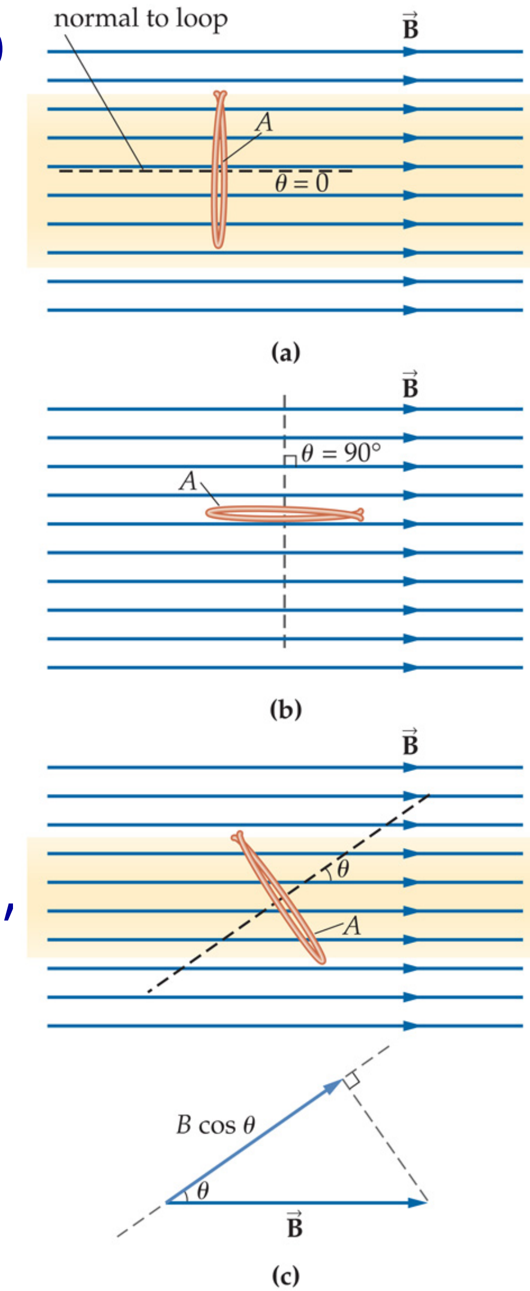
(c) Move away
Decreasing B

Magnetic flux through a wire loop

- Faraday's conclusions:
  - EMF is induced in wire loop only when magnetic flux through loop changes
    - Same idea as electric flux: how many field lines pass through loop
    - Change in flux can be due to changing B intensity and/or direction
  - As with electric flux:
    - Φ is max when loop's area is perpendicular to B, 0 when parallel
    - Define **A** vector as normal to loop area, angle θ between **A** and **B**

$$\Phi_B = \vec{B} \cdot \vec{A} = BA\cos\theta$$

$$Units : \Phi_B = [T][m^2] \equiv 1\, weber\ (Wb)$$



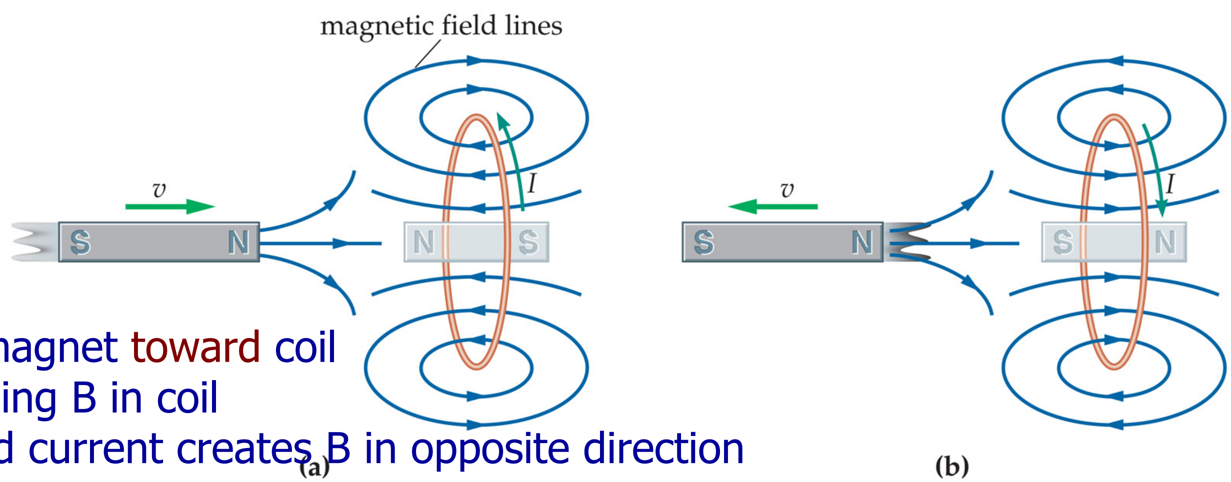
Faraday's Law of Induction

- Induced EMF is related to **rate of change** of flux

$$\mathcal{E} = -\frac{\Delta\Phi_B}{\Delta t} = -\frac{\Phi_{FINAL} - \Phi_{INITIAL}}{\Delta t} \text{ for 1 loop}$$

$$\mathcal{E} = -N\frac{\Phi_{FINAL} - \Phi_{INITIAL}}{\Delta t} \text{ for coil of N loops}$$

  - The minus sign is important:
    - Lenz's Law: induced current flows in the direction that makes its B field oppose the flux change that induced it



Move magnet away from coil.
Decreasing B.
Induced current creates B that adds to external B

Move magnet toward coil
Increasing B in coil
Induced current creates B in opposite direction

Direction of $I_{INDUCED}$: Lenz's Law

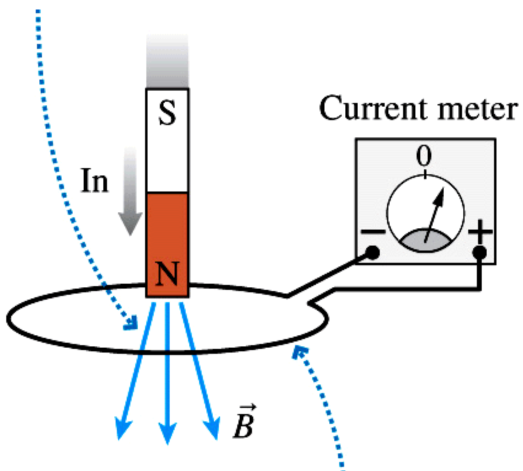
*Faraday:Induced current in a closed conducting loop only if the magnetic flux through the loop is **changing**, and emf is proportional to the **rate of change**.*

Lenz's Law (1834):
The direction of the induced current is such that its magnetic field opposes the change in flux.

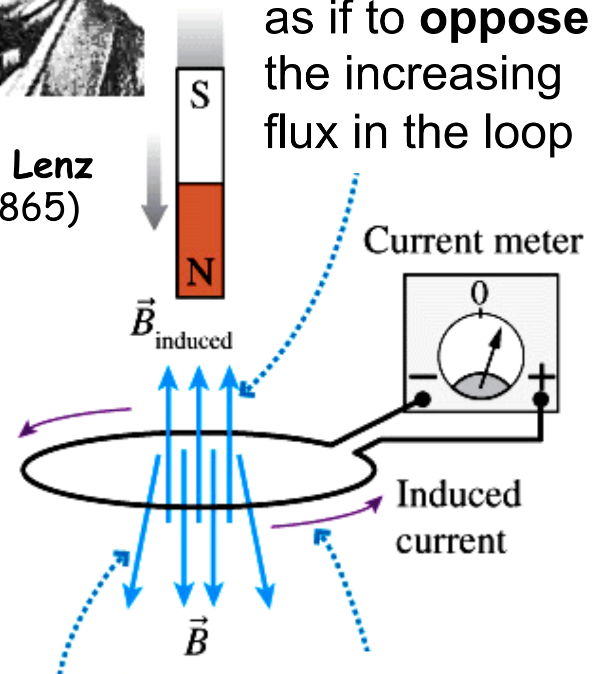
Heinrich Lenz
(1804-1865)

Induced I in the loop must make a B field that points **upward,** as if to **oppose** the increasing flux in the loop

Example: push N-seeking end of a bar magnet into a loop of wire:



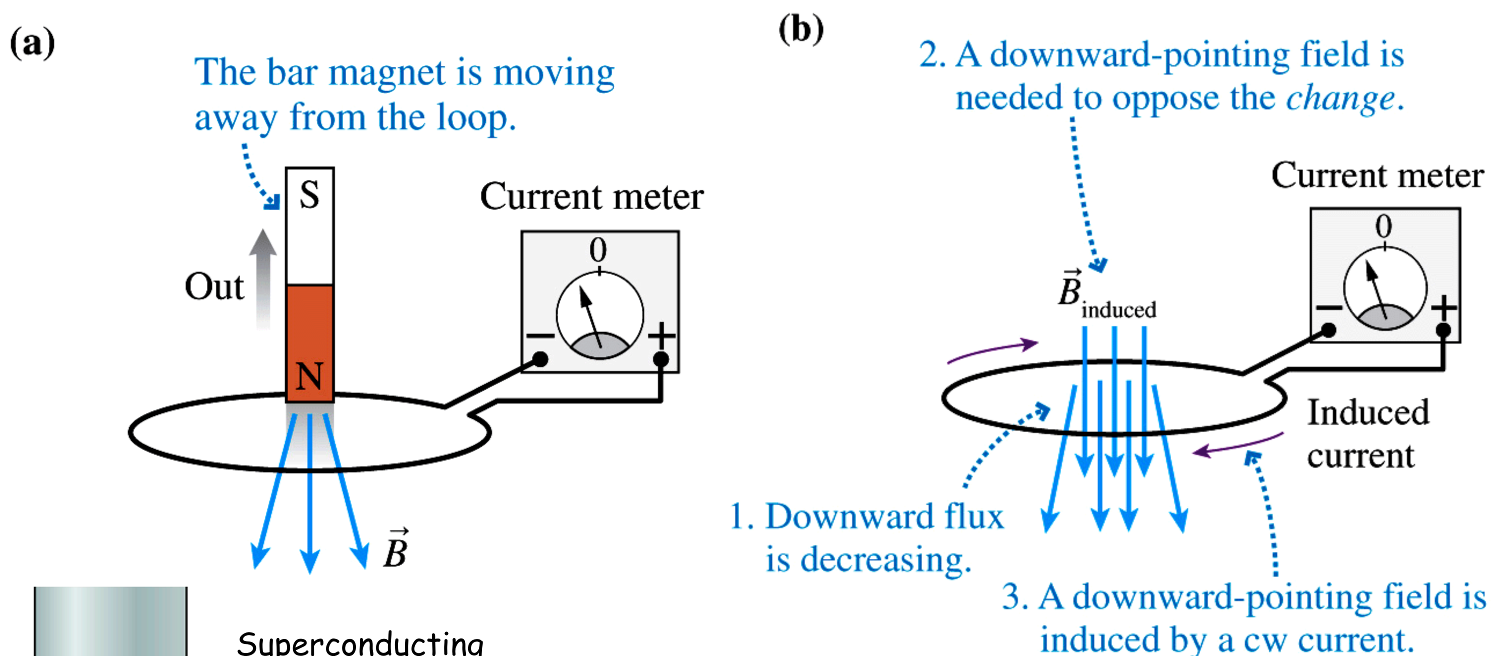
B flux through the loop points **downward** and is **increasing**

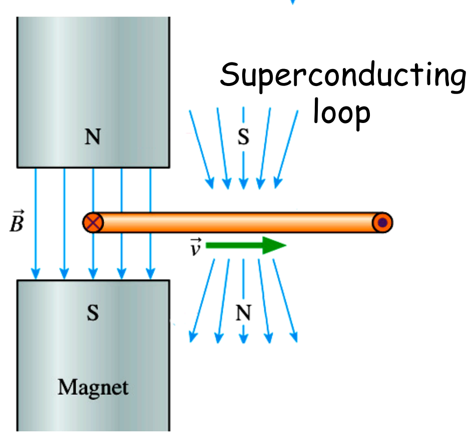


To make a B field that points **upward** the induced current must be counter-clockwise (by RHR)

Lenz's Law : reverse the previous process?

Suppose the bar magnet's N end is at first inside the loop and then is removed. The B field in the loop is now **decreasing**, so induced current is in the **opposite direction**, trying to keep the field constant (**adds** to the decreased external field)





BTW: In normal conductors, the induced current **dies out quickly** when B stops changing, due to R.

But: If the loop is a ***superconductor***, R~0, so a **persistent current** is induced in the loop – the loop's B field remains constant even after it is removed from the changing flux area.