Class 21: Outline

Hour 1:

Expt. 9: Faraday's Law

Hour 2:

Faraday's Law

Transformers

Magnetic Materials

Last Time:
Faraday's Law

Faraday's Law of Induction

$$\mathcal{E} = -N \frac{d\Phi_B}{dt}$$

Changing magnetic flux *induces* an EMF

Lenz: Induction ***opposes*** change

What can change?

$$\mathcal{E} = -N\frac{d}{dt}\left(BA\cos\theta\right)$$

Quantities which can vary with time:

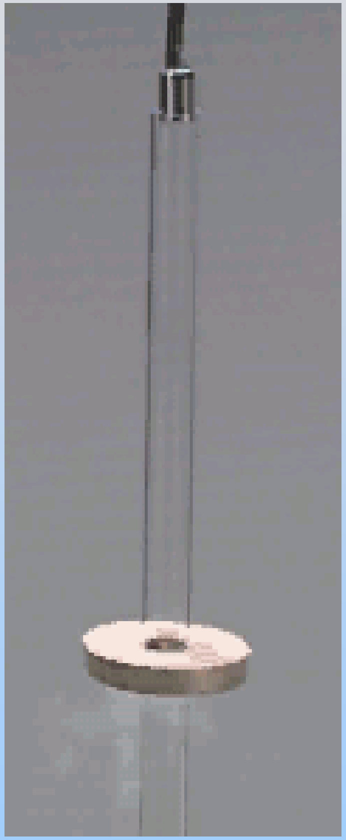
- Magnitude of B
- Area A enclosed by the loop
- Angle θ between B and loop normal

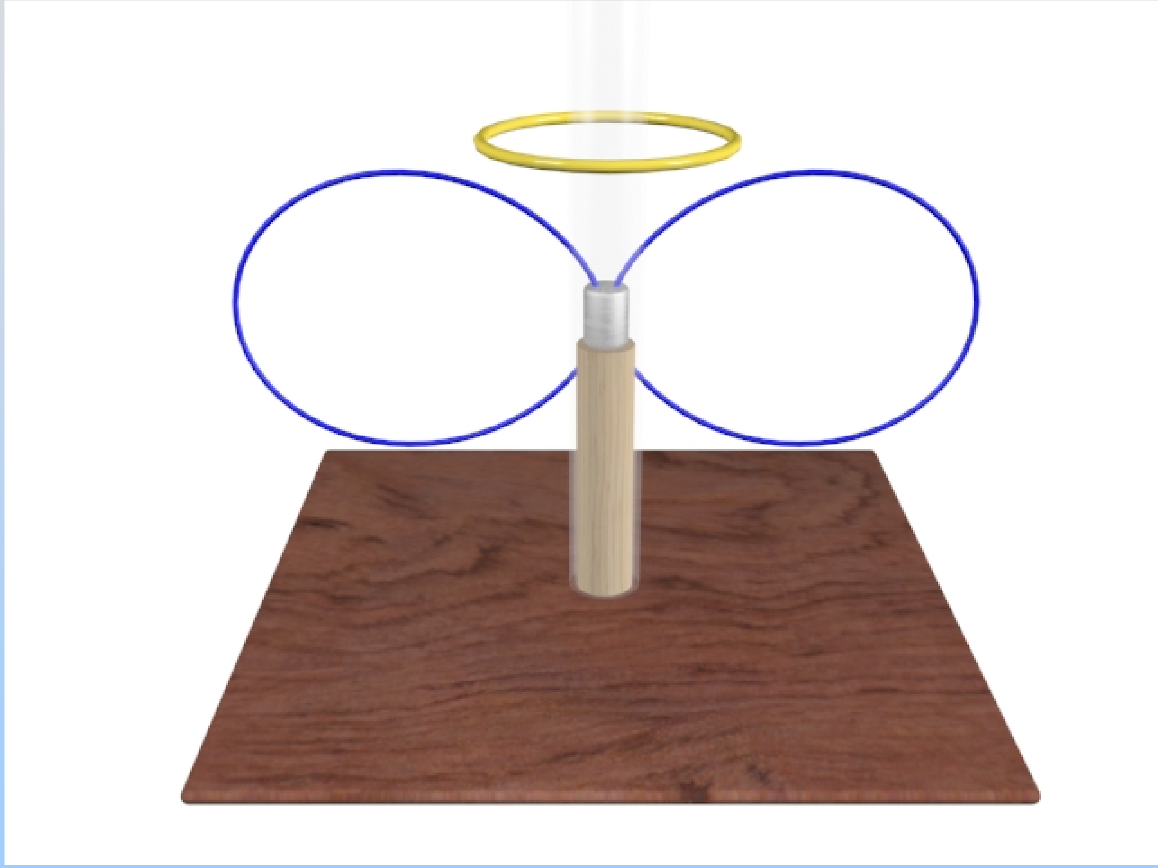
Magnet Falling Through a Ring

http://ocw.mit.edu/ans7870/8/8.02T/f04/visualizations/faraday/07-FallingMagnetResistive/07-FallMAgRes_f54_320.html

Falling magnet slows as it approaches a copper ring which has been immersed in liquid nitrogen.

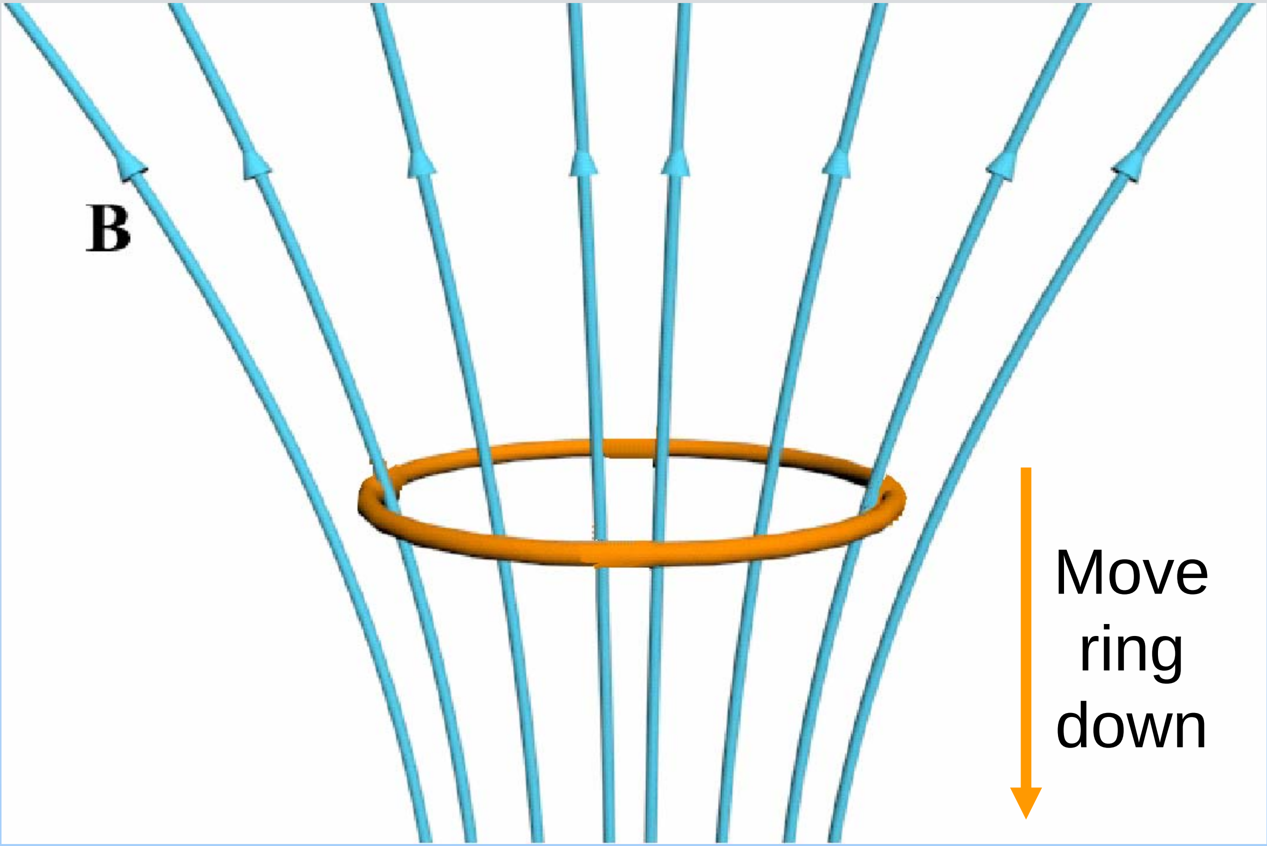
Example: Magnitude of B
Magnet Falling Through a Ring





Falling magnet approaches a copper ring *or* Copper Ring approaches Magnet

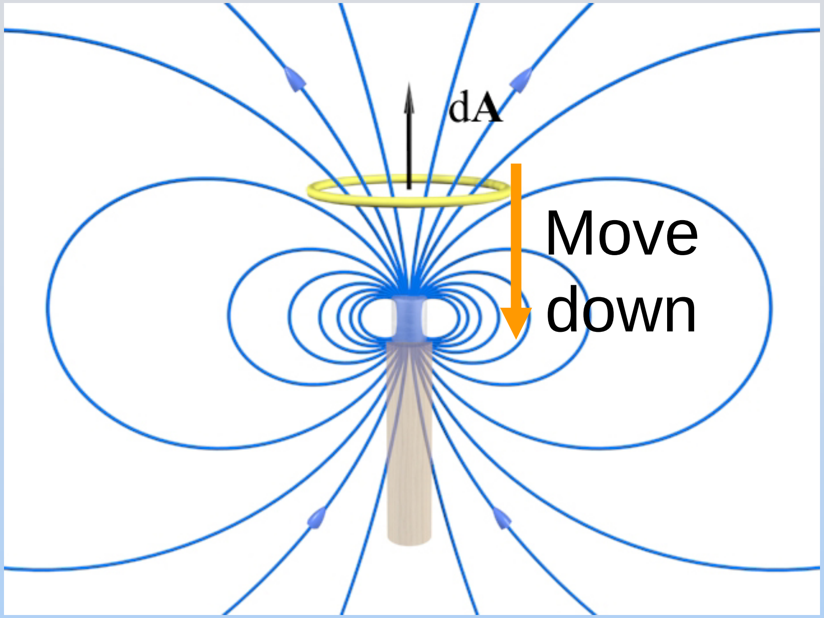
Moving Towards Dipole

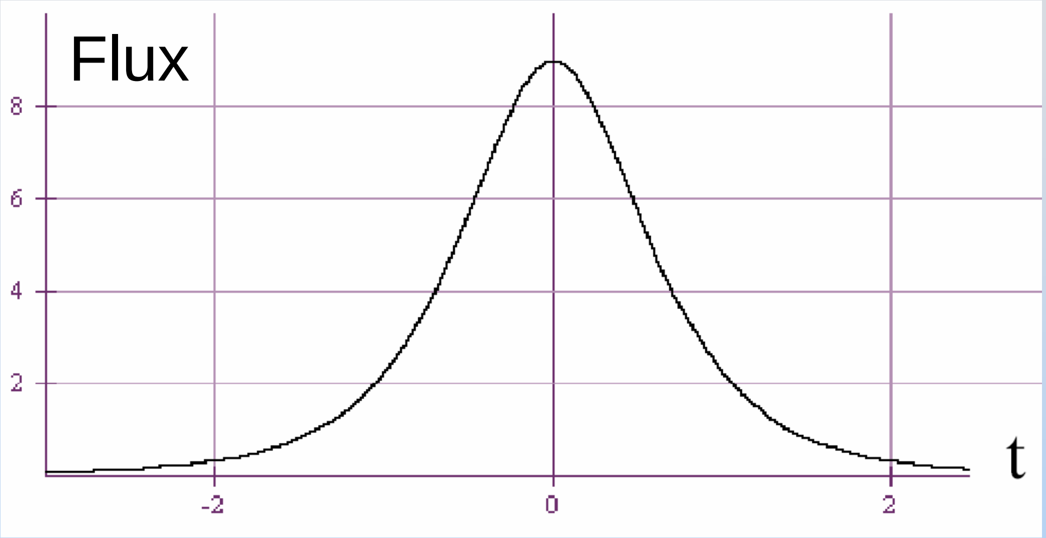


As ring approaches, what happens to flux?

It increases

Moving Over Dipole

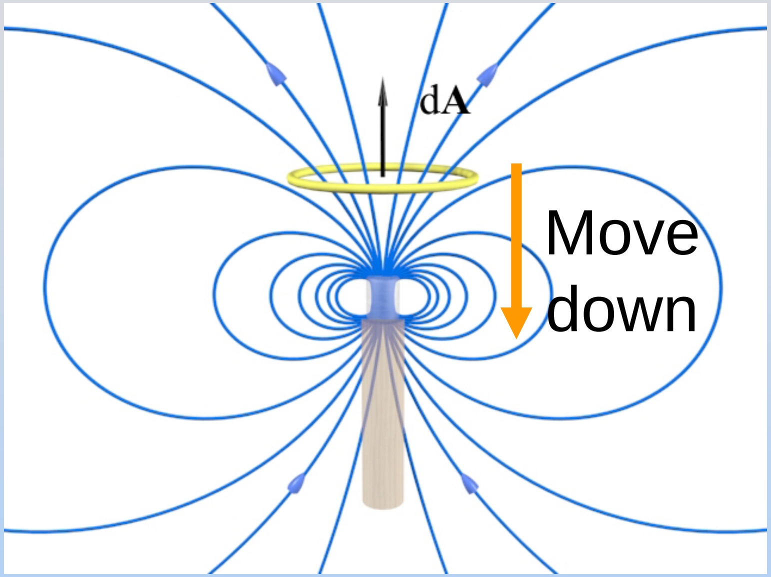


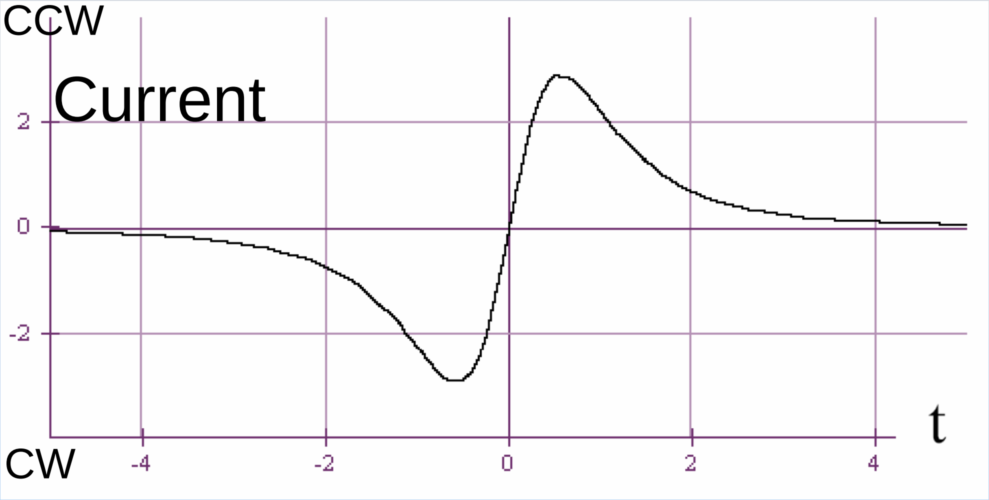


Flux increases then decreases

Note we have arbitrarily assigned dA up

Moving Over Dipole



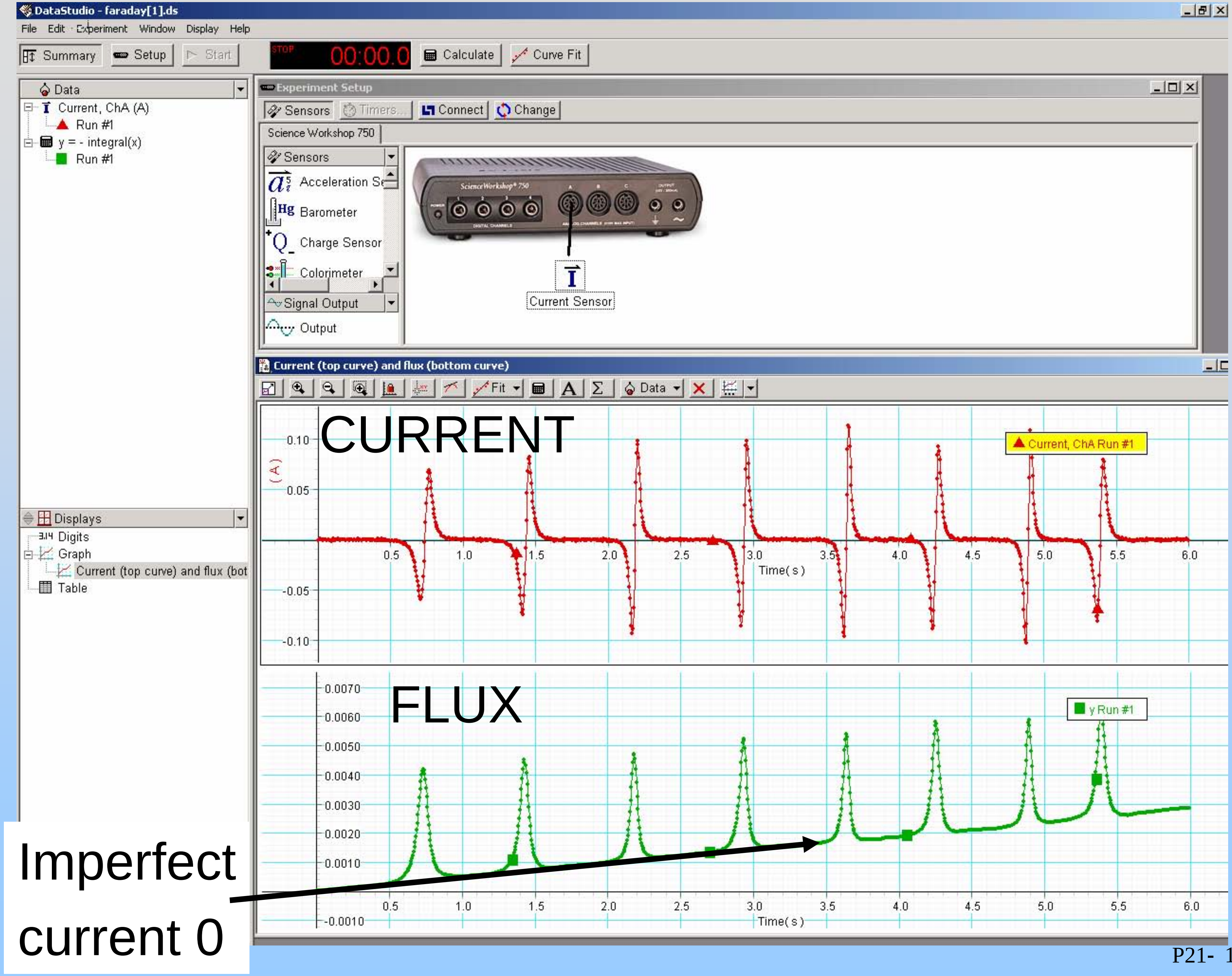


Current first goes in one direction, then other

It ALWAYS opposes the changing flux

Five PRS Questions: Predictions for Experiment 9 Faraday's Law

Experiment 9:
Faraday’s Law of Induction


CURRENT
FLUX
Imperfect
current 0

Four PRS Questions:
Force on A Loop Below Magnet Moving Upward;
Moving Rail;
Moving Rectangle near Wire;
Generator.

Brakes

Magnet Falling Through a Ring

What happened to kinetic energy of magnet?

Eddy Current Braking

http://demoroom.physics.ncsu.edu/html/demos/163.html

What happened to kinetic energy of pendulum?

Eddy Current Braking

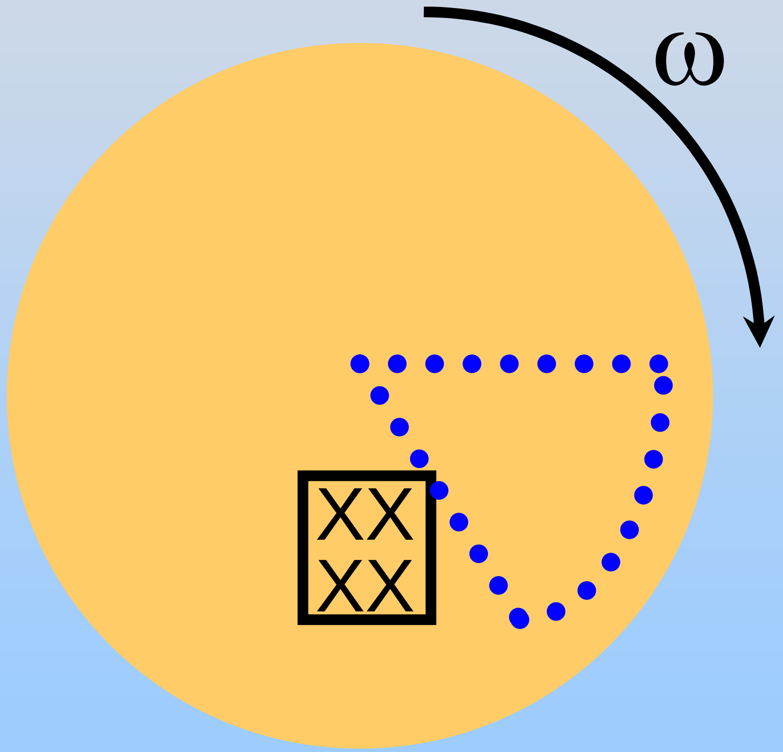
http://demoroom.physics.ncsu.edu/multimedia/video/5K20.22.1.MOV

What happened to kinetic energy of disk?

Demonstration:
Eddy Current Braking

Eddy Current Braking

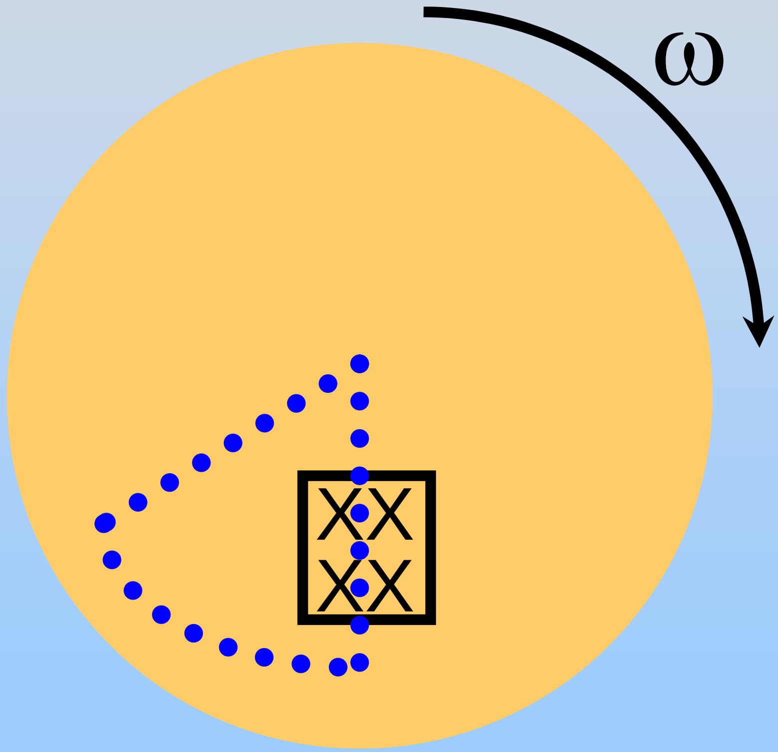
The magnet induces currents in the metal that dissipate the energy through Joule heating:



1. Current is induced counter-clockwise (out from center)
2. Force is opposing motion (creates slowing torque)

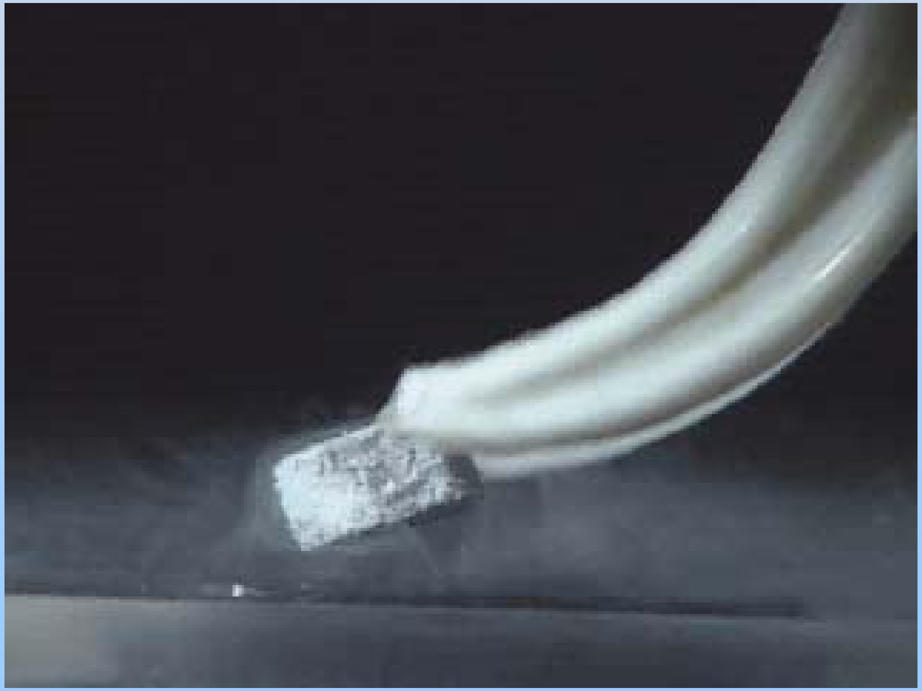
Eddy Current Braking

The magnet induces currents in the metal that dissipate the energy through Joule heating:



1. Current is induced clockwise (out from center)
2. Force is opposing motion (creates slowing torque)
3. EMF proportional to ω
4. $$F \propto \frac{\varepsilon^2}{R}$$

Demonstration: Levitating Magnet Superconductor & Magnet

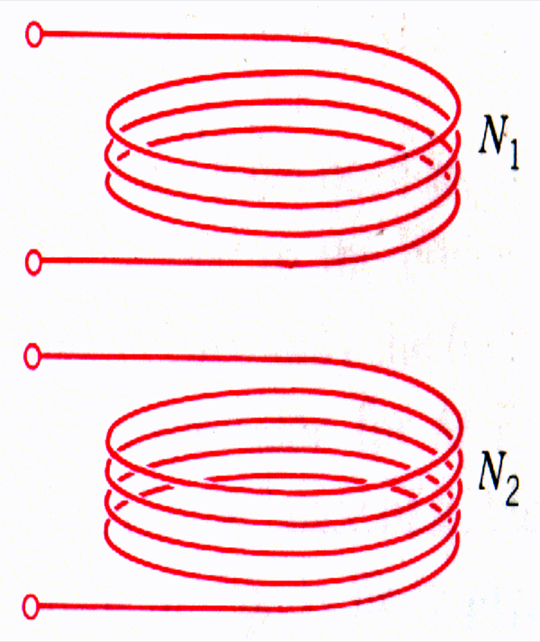


http://ocw.mit.edu/ans7870/8/8.02T/f04/visualizations/faraday/16-superconductor/16-12_wmv320.html

PRS Questions: Loop in Uniform Field

Mutual Inductance

Mutual Inductance



A current I_2 in coil 2, induces some magnetic flux Φ_{12} in coil 1. We define the flux in terms of a "mutual inductance" M_{12}:

$$N_1 \Phi_{12} \equiv M_{12} I_2$$

$$\rightarrow M_{12} = \frac{N_1 \Phi_{12}}{I_2}$$

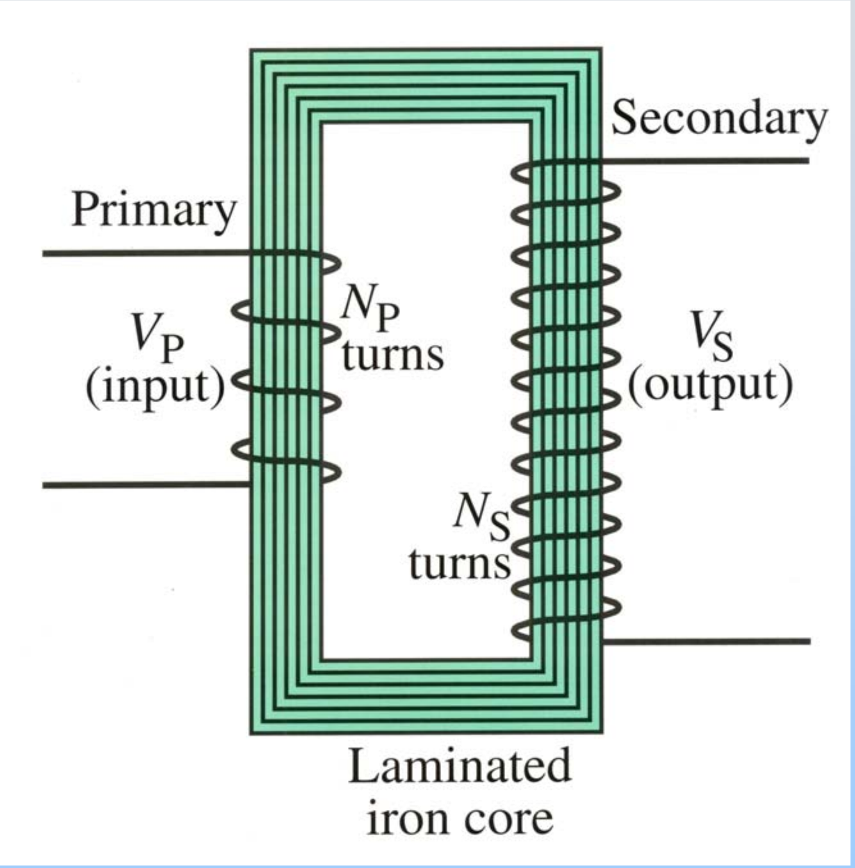
$$M_{12} = M_{21} = M$$

$$\varepsilon_{12} \equiv -M_{12} \frac{dI_2}{dt}$$

Demonstration: Remote Speaker

Transformer

Step-up transformer



$$\varepsilon_p = N_p \frac{d\Phi_B}{dt}$$

$$\varepsilon_s = N_s \frac{d\Phi_B}{dt}$$

$$\frac{\varepsilon_s}{\varepsilon_p} = \frac{N_s}{N_p}$$

$N_s > N_p$: step-up transformer

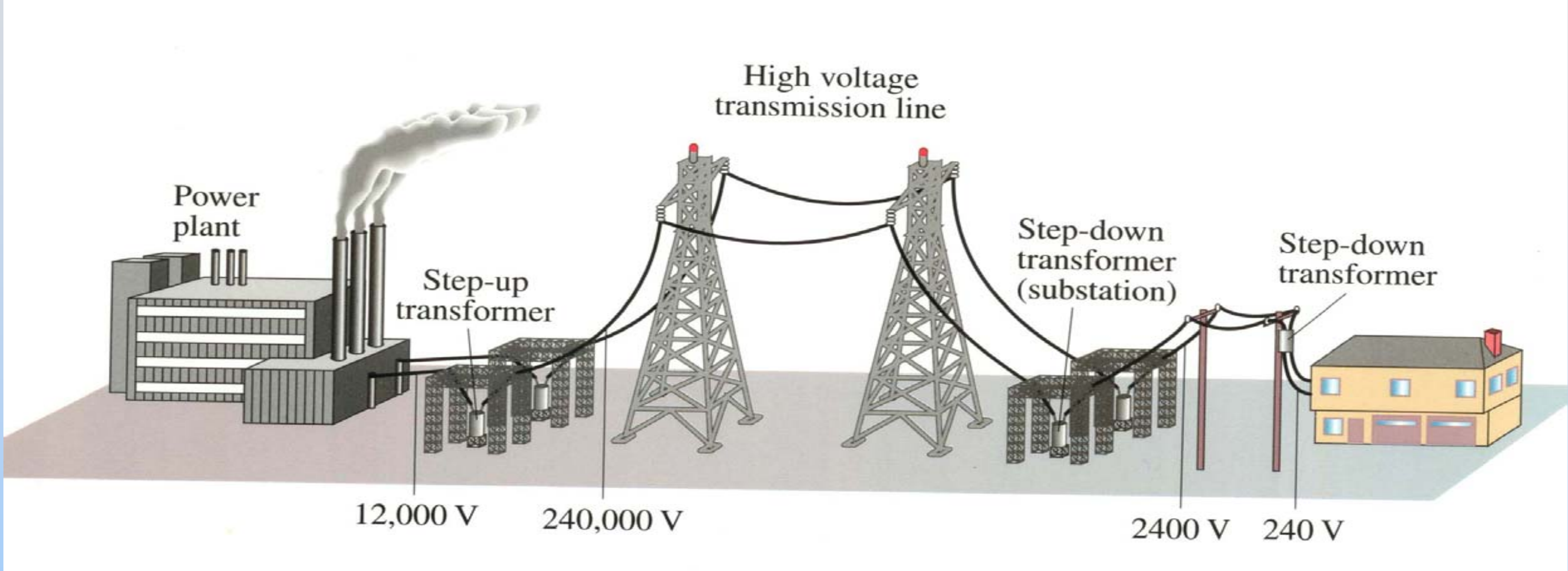
$N_s < N_p$: step-down transformer

Demonstrations:

One Turn Secondary: Nail

Many Turn Secondary: Jacob's Ladder

Transmission of Electric Power



Power loss can be greatly reduced if transmitted at high voltage

Example: Transmission lines

An average of 120 kW of electric power is sent from a power plant. The transmission lines have a total resistance of 0.40 Ω. Calculate the power loss if the power is sent at (a) 240 V, and (b) 24,000 V.

(a) $$I = \frac{P}{V} = \frac{1.2\times 10^5 W}{2.4\times 10^2 V} = 500A$$

83% loss!!

$$P_L = I^2 R = (500A)^2 (0.40\Omega) = 100kW$$

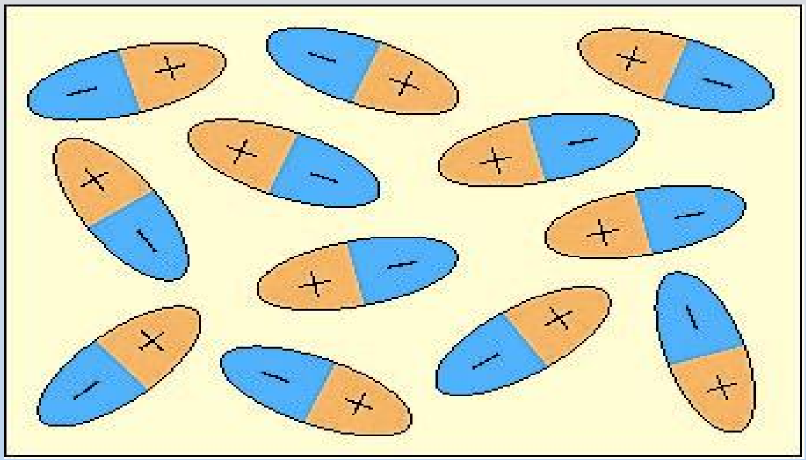
(b) $$I = \frac{P}{V} = \frac{1.2\times 10^5 W}{2.4\times 10^4 V} = 5.0A$$

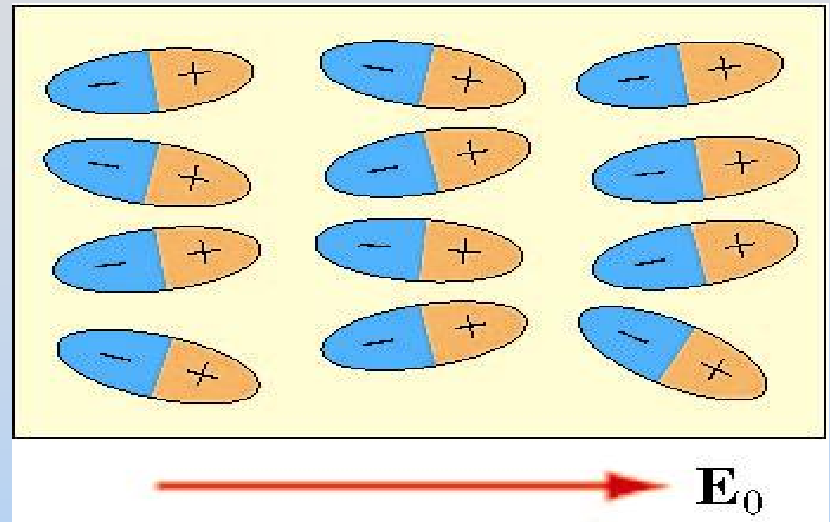
0.0083% loss

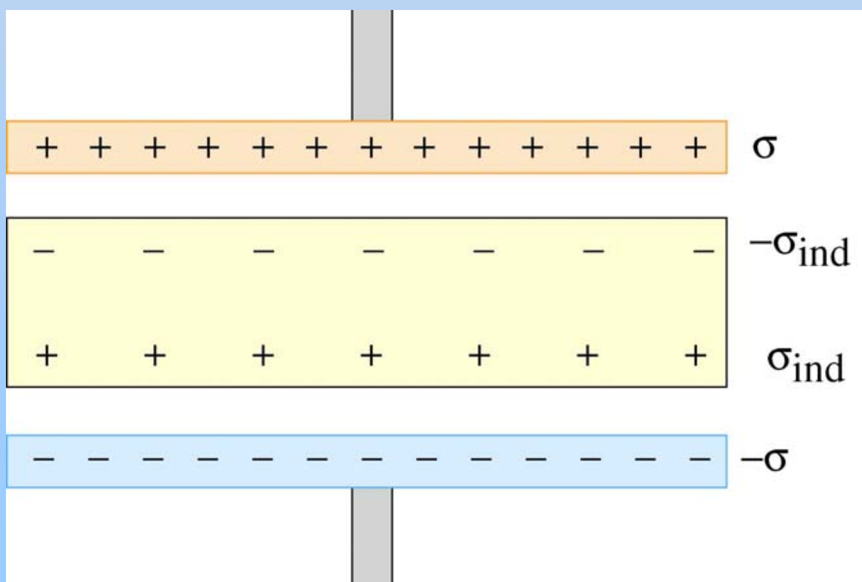
$$P_L = I^2 R = (5.0A)^2 (0.40\Omega) = 10W$$

Magnetic Materials

Recall Polar Dielectrics

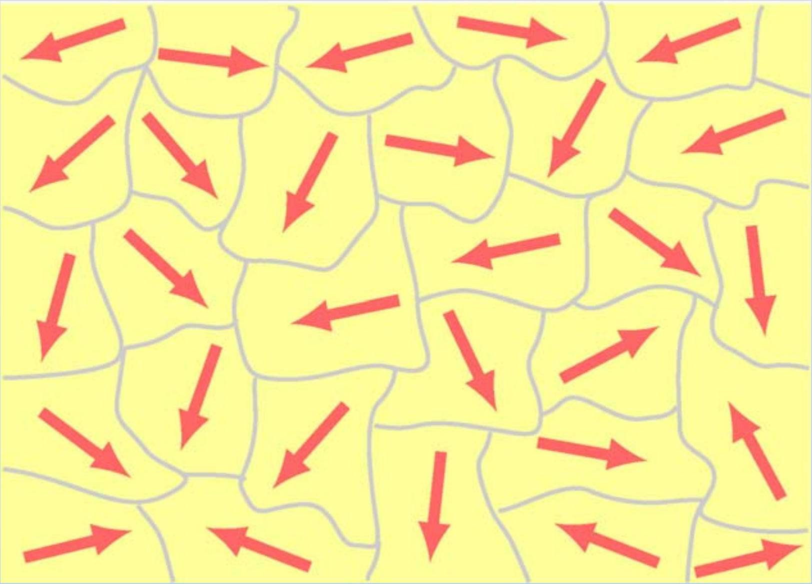


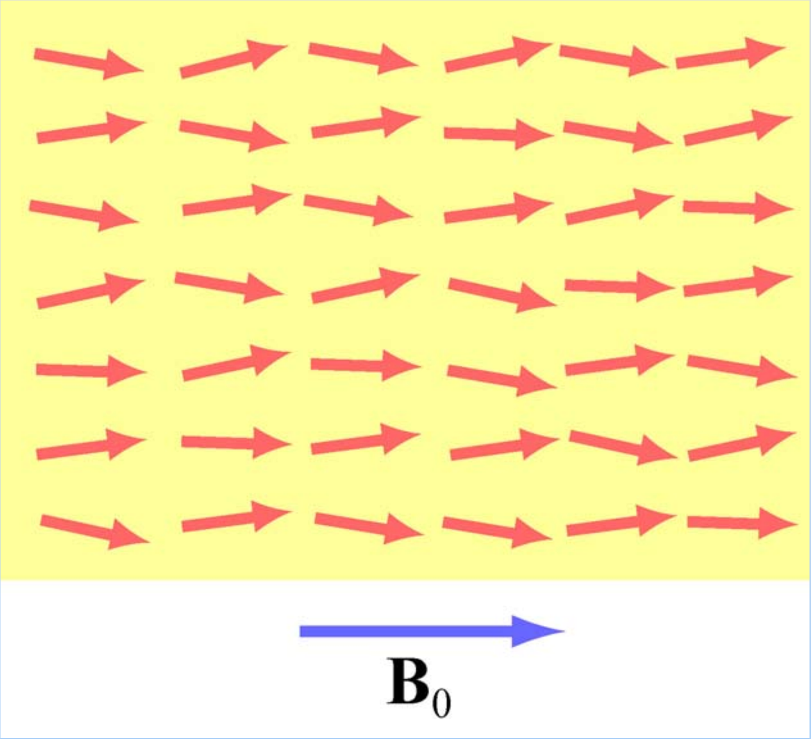




Dielectric polarization ***decreases*** Electric Field!

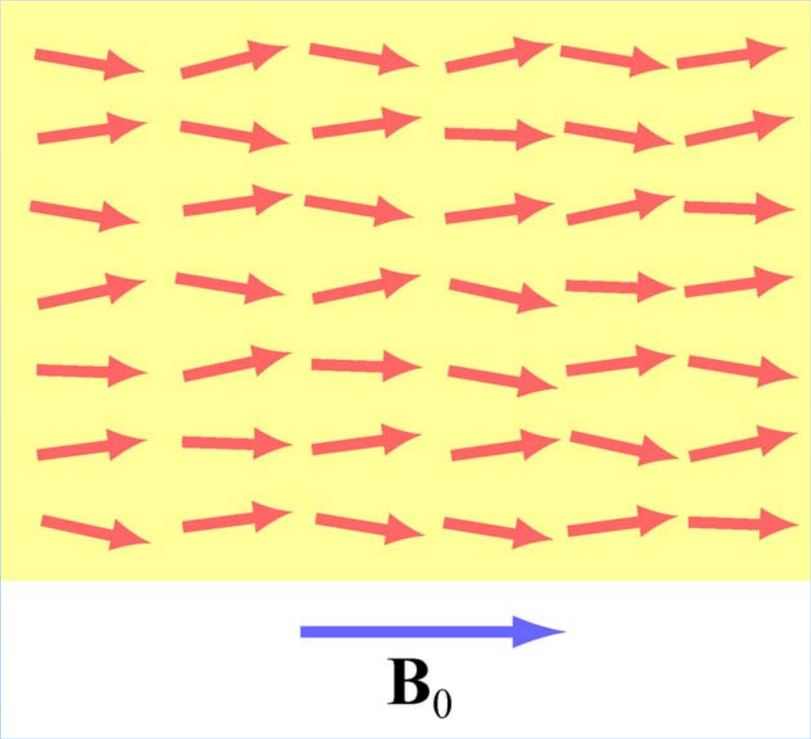
Para/Ferromagnetism

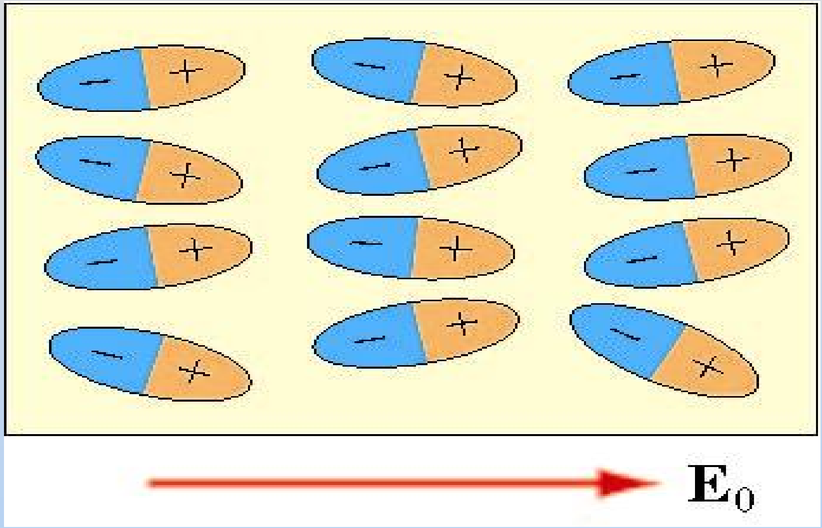




Applied external field B_0 tends to align the atomic magnetic moments

Para/Ferromagnetism



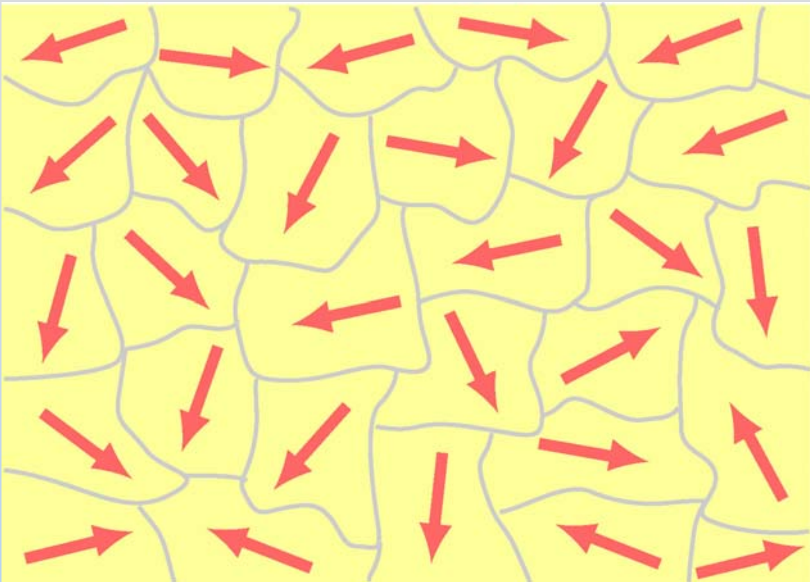


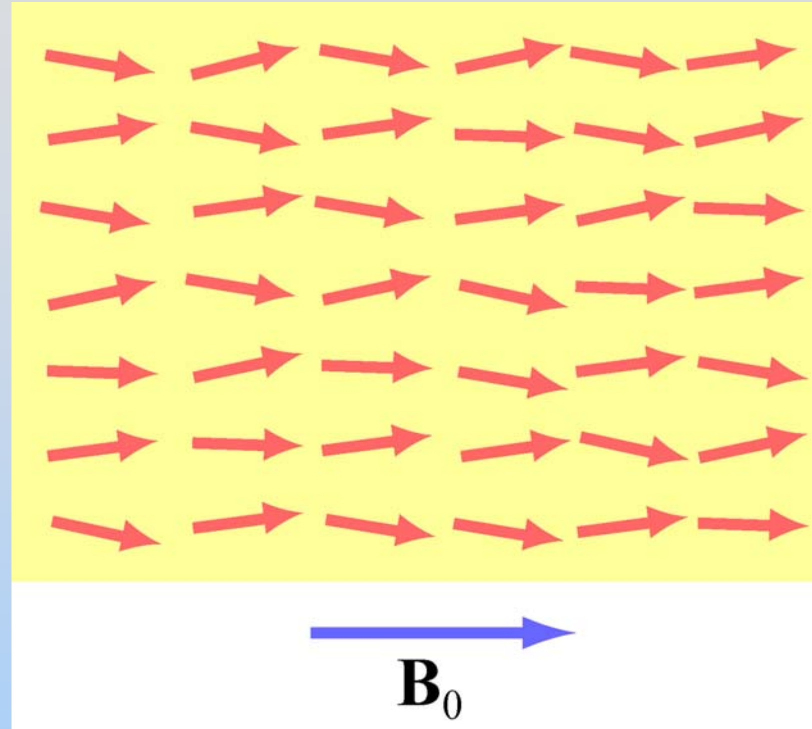
The aligned moments tend to ***increase*** the B field

$$\vec{\mathbf{B}} = \kappa_m \vec{\mathbf{B}}_0$$

Compare to: $\vec{\mathbf{E}} = \dfrac{\vec{\mathbf{E}}_0}{\kappa_E}$

Para/Ferromagnetism



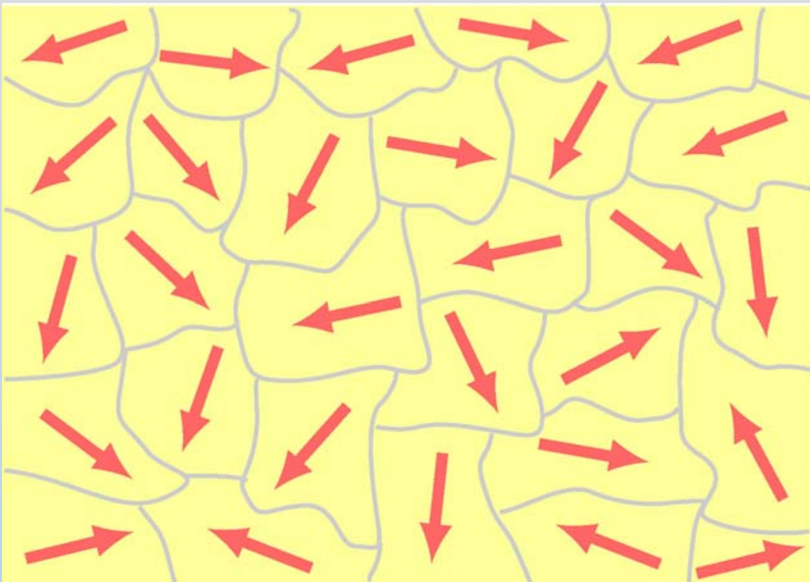


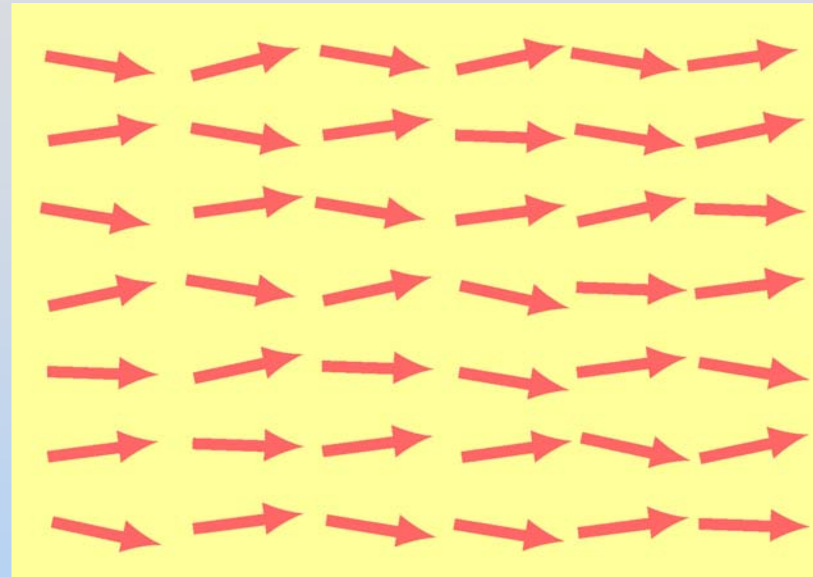
Paramagnet: Turn off B_0, everything disorders

Ferromagnet: Turn off B_0, remains (partially) ordered

This is why some items you can pick up with a magnet even though they don't pick up other items

Magnetization Vector


M=0


M>0

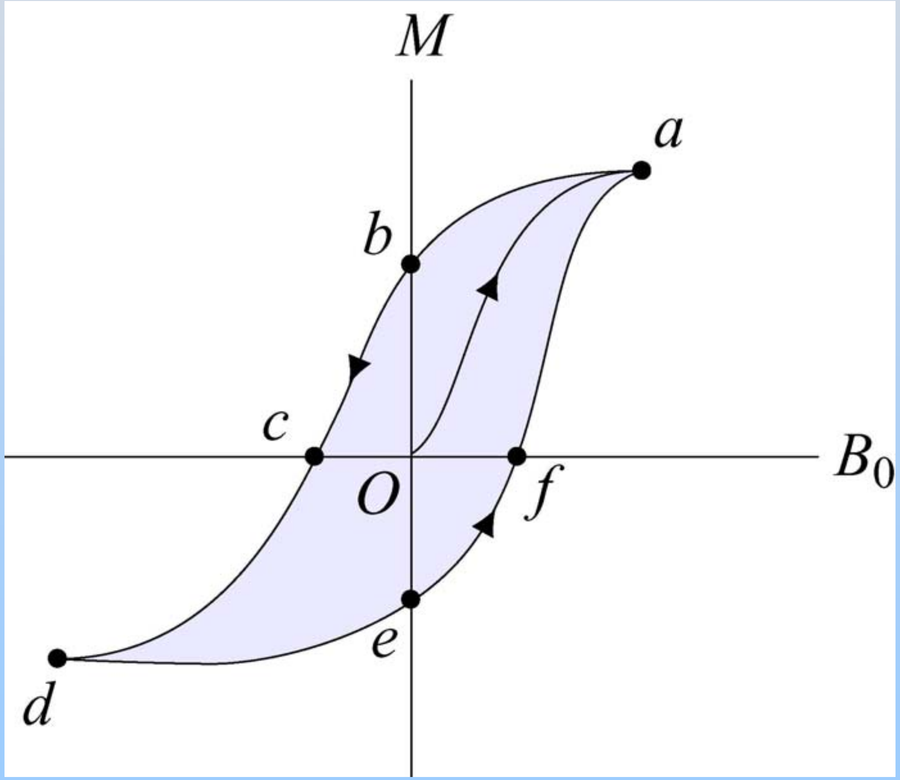
Useful to define "Magnetization" of material:

$$\vec{\mathbf{M}} = \frac{1}{V}\sum_{i=1}^{N}\vec{\boldsymbol{\mu}}_i = \frac{\vec{\boldsymbol{\mu}}}{V}$$

$$\vec{\mathbf{B}} = \vec{\mathbf{B}}_0 + \mu_0\vec{\mathbf{M}}$$

Hysteresis in Ferromagnets

The magnetization *M* of a ferromagnetic material depends on the *history* of the substance



Magnetization remains even with B_0 off !!!