# Announcement: Error in text

At the bottom of page 949, there is a sign error, where it says:

"From this form you can see that the direction of dB/dt
is the same as the direction of $\cancel{-\Delta}$B, ..."

It should read:

"From this form you can see that the direction of dB/dt
is the same as the direction of $+\Delta$B, ..."

http://tinyurl.com/levitating-train

# Last Time

- Faraday's Law:

$$emf = \oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \int \vec{B} \cdot \hat{n} dA = -\frac{d\Phi_{\mathrm{mag}}}{dt}$$

# Today

- Superconductors
- Inductors

# Metals

- Shiny
- Smooth
- Malleable
- Carry current (conduct electricity)

# Metals and Current

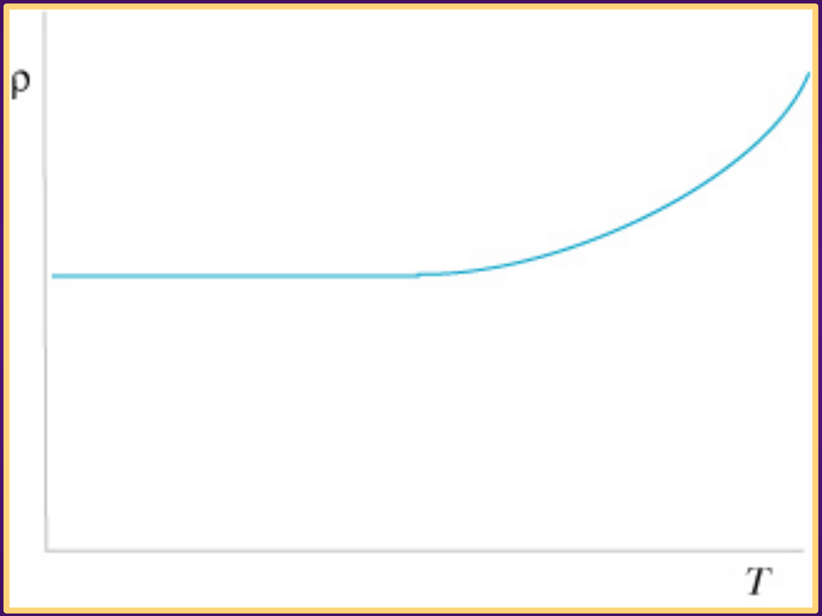
- $P = IV = I^2R$
- Nonzero Resistance
- Wires radiate power away as heat
- You pay for more electricity than you receive!
- Electrons “scatter” off lattice, and lose energy

Can we reduce R?

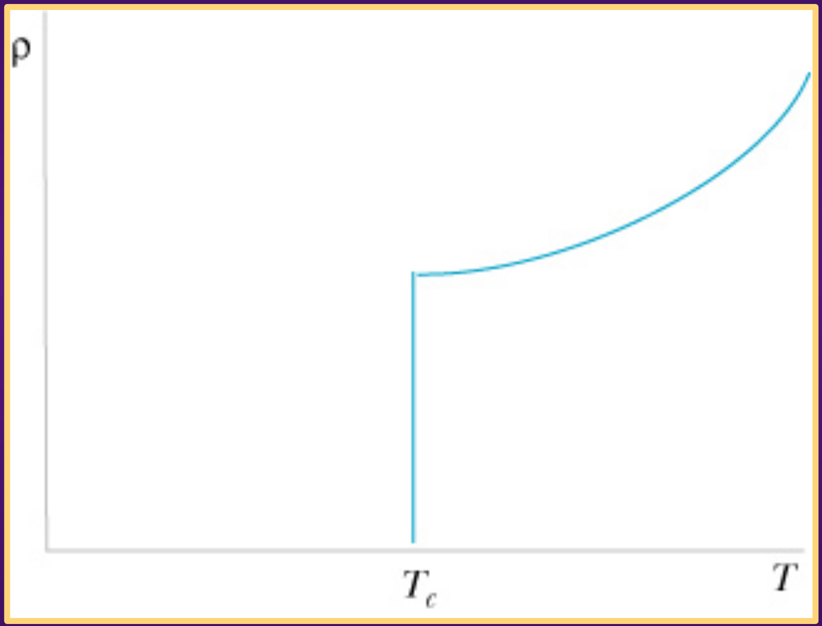
# Can we reduce R?

Resistivity $\rho = R/A$

METALS



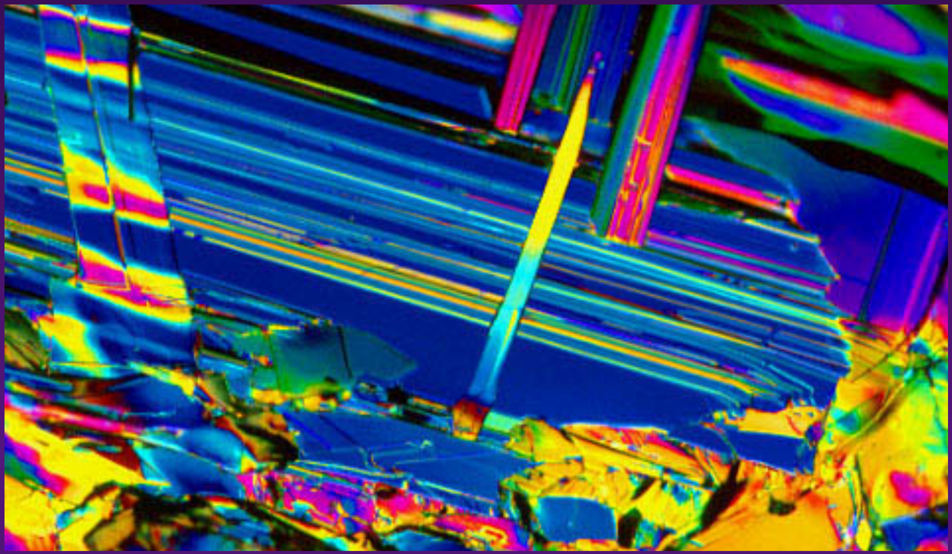

SUPERCONDUCTORS




Low T → Small $\rho$
Low T → Smaller power loss

Superconductors have R = 0

# Superconductors



http://micro.magnet.fsu.edu

- Carry current perfectly
- Do not lose energy
- Current in a loop will run *forever*
- Expel magnetic fields (Meissner effect)


浮いた土佐ノ海
TOSANOUMI
(Sumo Wrestler)
Height of Tosanoumi 186cm
Weight of Tosanoumi 142kg
Weight of disk 60kg
Total weight 202kg
協力：財団法人　日本相撲協会

# How does it happen?

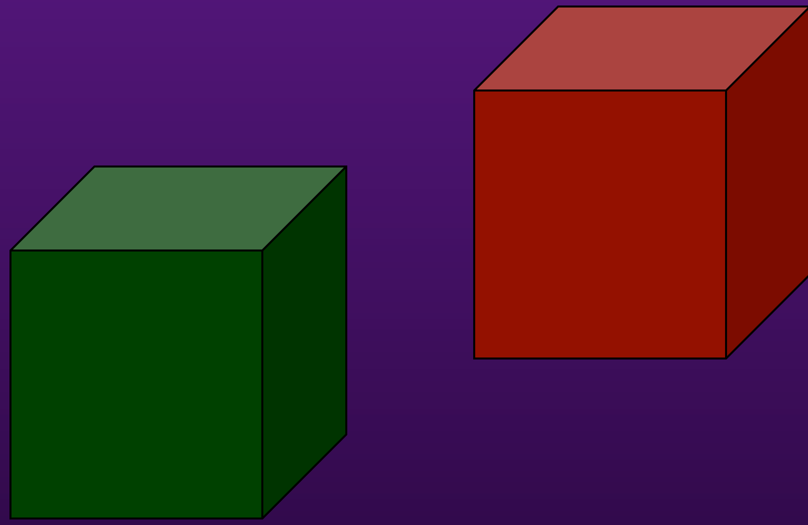
# iClicker Poll

*(participation points only)*

Can two pieces of matter occupy the same space at the same time?

A) YES

B) NO



# Two kinds of particles

## Fermions
(spin 1/2, 3/2, 5/2, etc.)

- Cannot occupy the same space at the same time
- Pauli exclusion principle

Antisocial

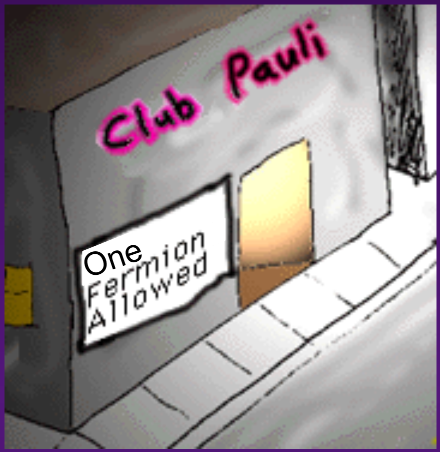
## Bosons
(spin 0, 1, 2, etc.)

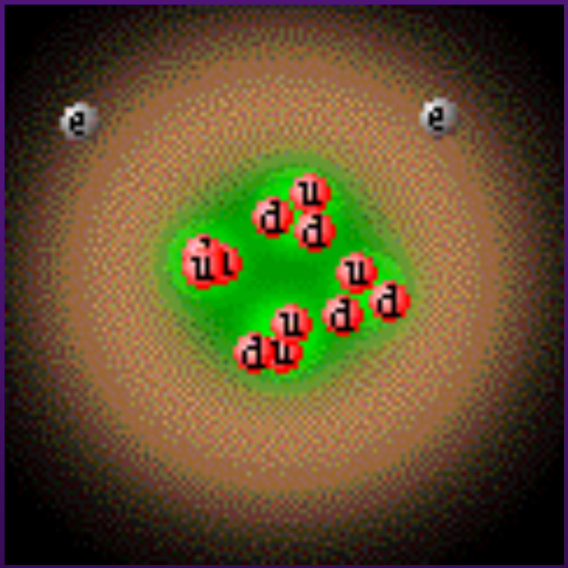
- Can occupy the same space at the same time

All Follow the Crowd

# Electrons are Fermions

Pauli exclusion principle

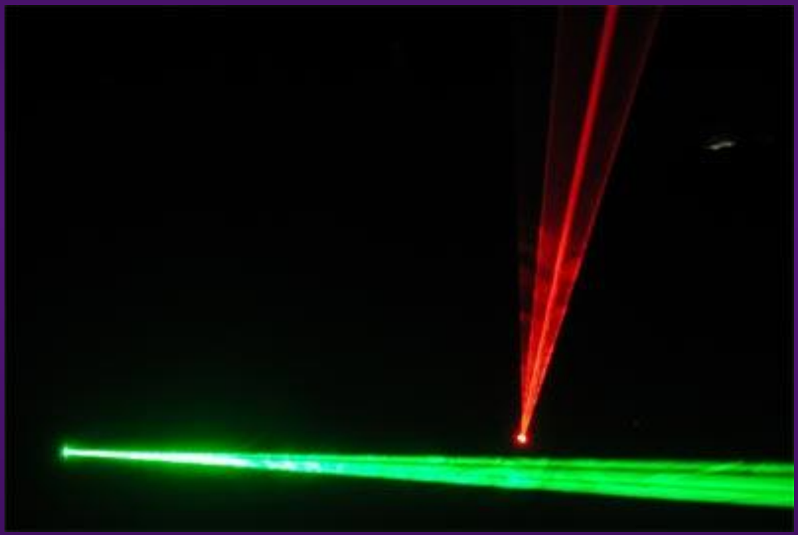


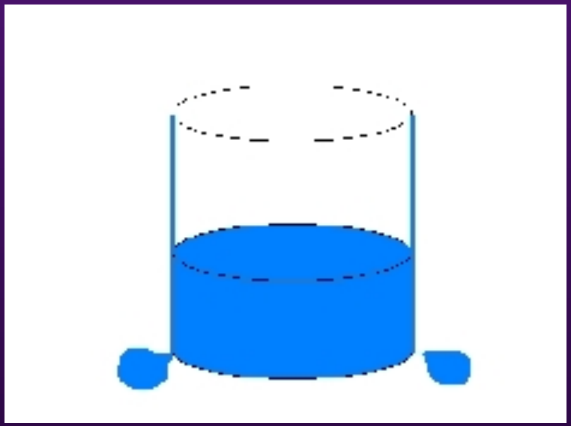

Why most matter cannot occupy the same space at the same time

# Bosons

Can occupy the same space at the same time



Photons are bosons
→ lasers



Helium is a boson
→ superfluidity

# Bose condensation

- At low temperature, bosons flock to the lowest level
- Very stable state!
- Dissipationless flow
- Superfluidity (Helium)
- Superconductivity

(most metals do this at low T)

# Lowest Energy State
# *Cannot* Dissipate Energy

Excited Atom


Releasing a photon decreases the energy

Less Excited Atom


Ground State Atom

Atom in ground state *cannot* lose anymore energy.

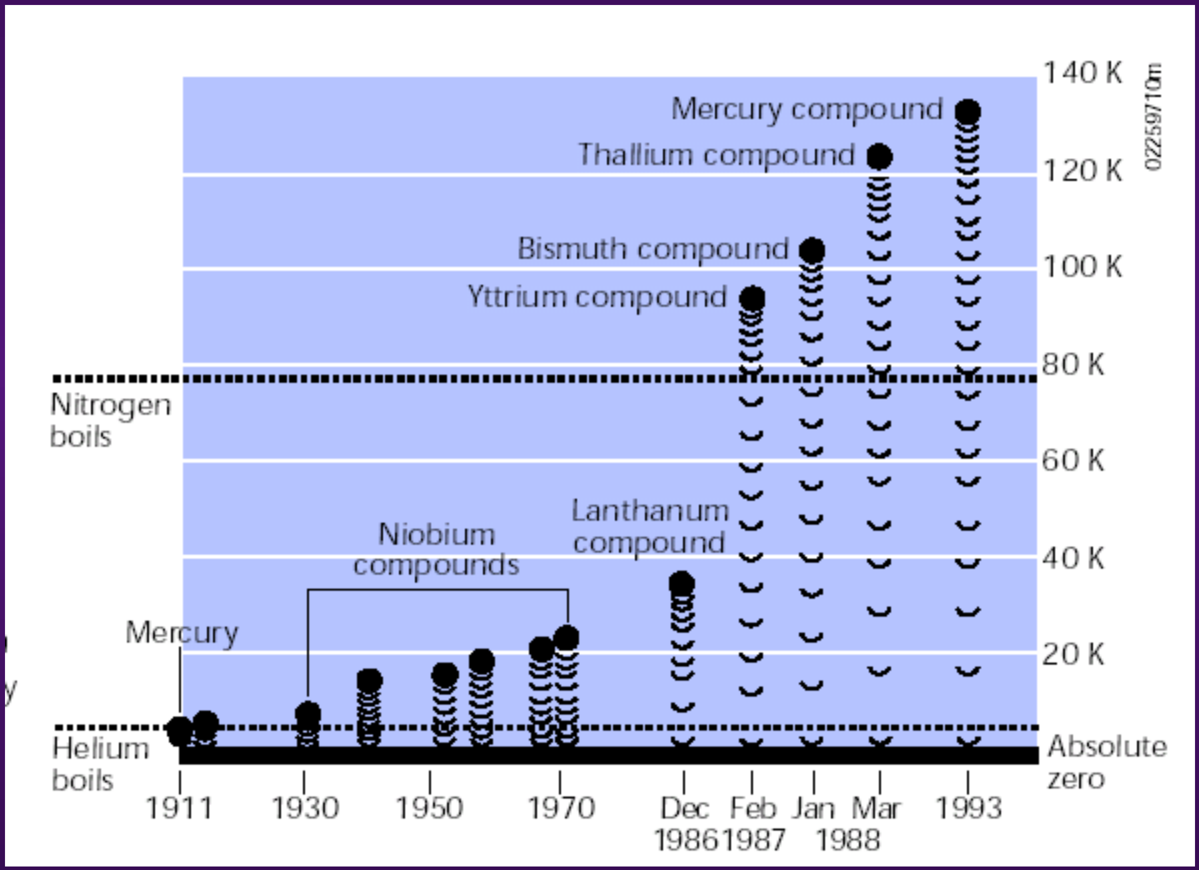
→ Quantum Stability of Ground State

# Superconductivity

- Pair electrons → form *bosons*
- Bosons condense into the lowest energy state
- Lowest energy state *cannot* lose energy →

  Electron pairs *cannot* dissipate energy
- Dissipationless current flow

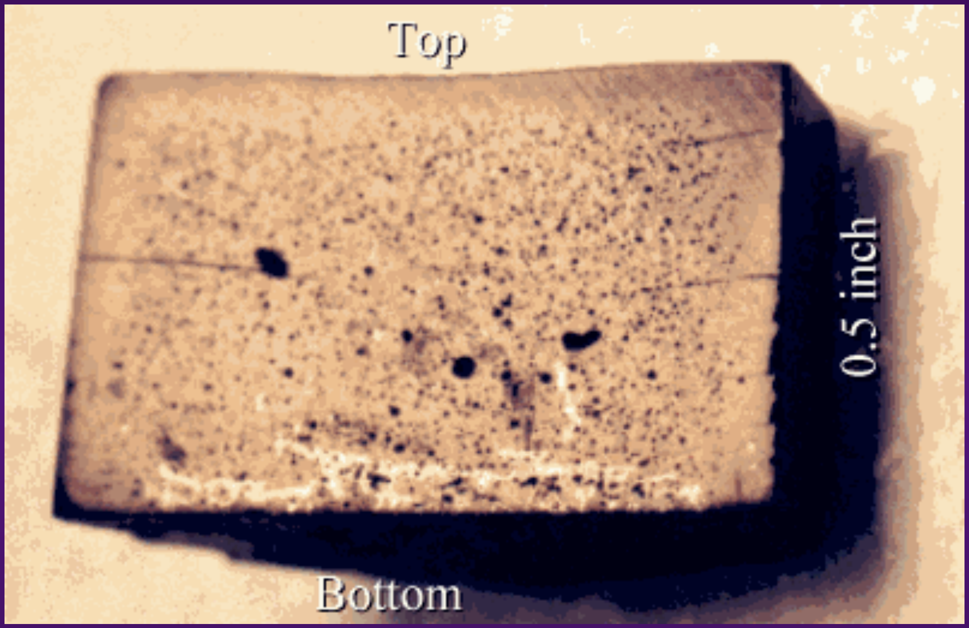
# And then there was 1986




http://www.eere.energy.gov/superconductivity/pdfs/frontiers.pdf

# Mysteries of High Temperature Superconductors

- Brittle
- Ceramic
- Not Shiny
- Not metallic
- Magnetic inside!
- Make your own

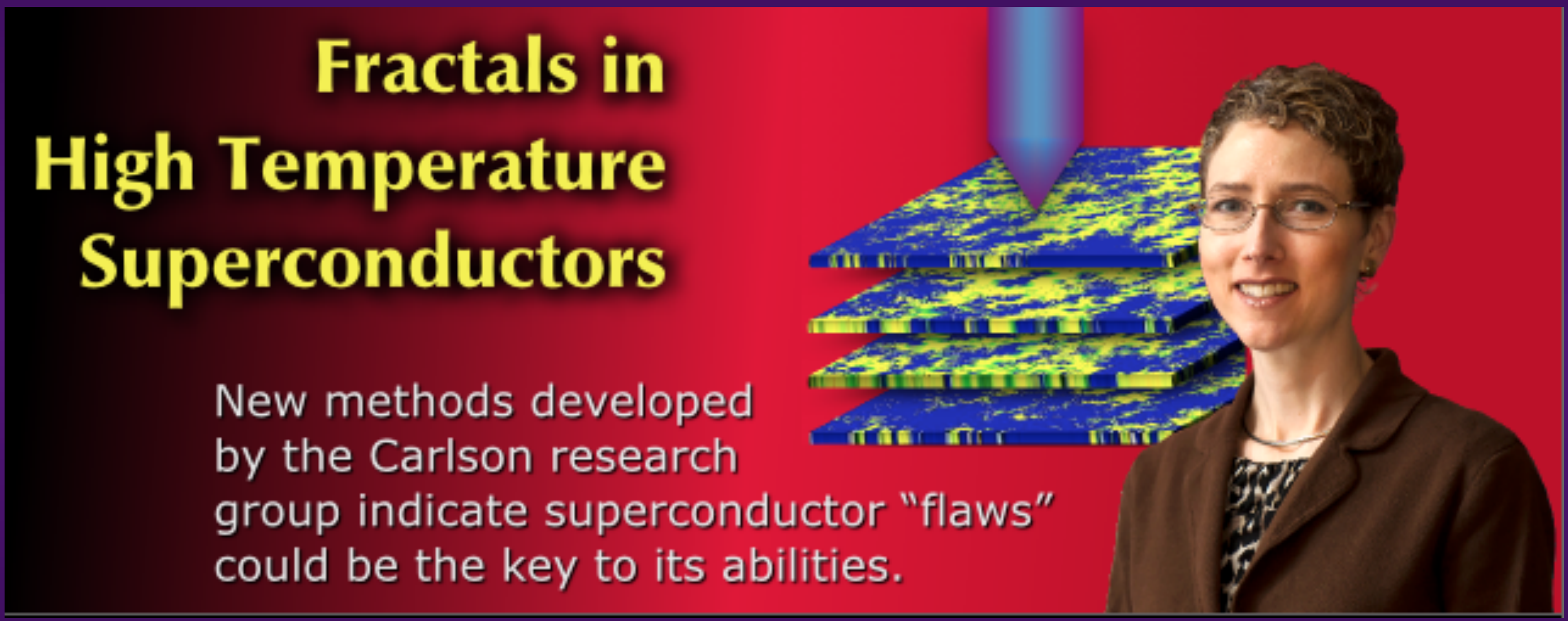



http://www.superconductivecomp.com/

http://www.ornl.gov/reports/m/ornlm3063r1/pt7.html

We don't know how they work!

Prof. Carlson's Research on Superconductors:




Read the story at www.physics.purdue.edu

# Magnetic flux through SC ring *cannot* change

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_{\mathrm{mag}}}{dt}$$ Faraday's Law

***Assume:*** $$\oint \vec{E} \cdot d\vec{l} \neq 0$$

Then we would have: $I = \dfrac{|emf|}{R} \rightarrow \infty$ Impossible!

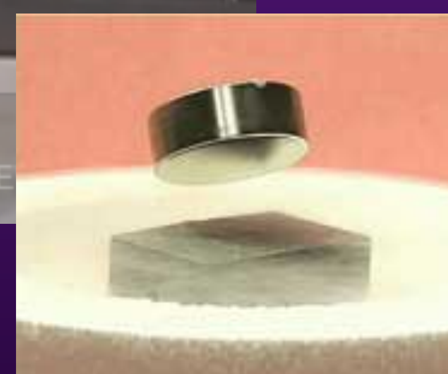
We are forced to conclude that $\dfrac{d\Phi_{\mathrm{mag}}}{dt} = 0$ must always be true for the flux through a superconducting ring.

# Meissner Effect

Even more extreme!
Superconductors *expel* magnetic fields.

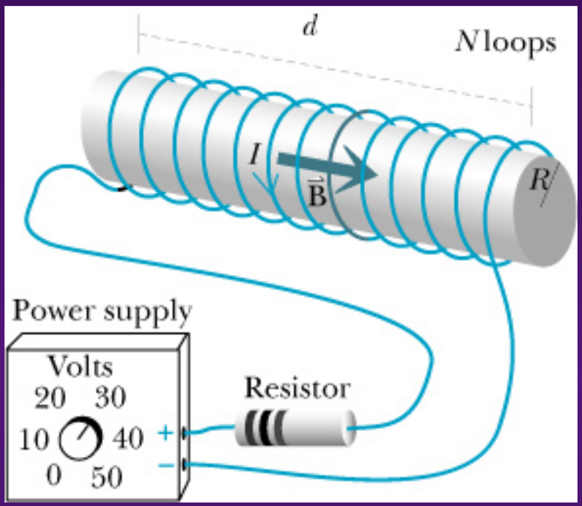
**http://tinyurl.com/levitating-train**





# Inductance

*Basic idea: Because of Faraday's Law,*
*coils of wire take awhile to reach steady state.*




Think about a solenoid in steady state: $B = \dfrac{\mu_o N I}{d}$

Now let the current change.
→ Induces emf in *every loop:*

$$emf_{\text{loop}} = \left|\frac{d\Phi_{\text{mag}}}{dt}\right| = \frac{d}{dt}\left[\frac{mu_o N I}{d}\pi R^2\right]$$

$$= \frac{mu_o N \pi R^2}{d}\frac{dI}{dt} \qquad \textit{each loop}$$

N turns in the solenoid →

$$emf_{\text{tot}} = N(emf_{\text{loop}}) = \frac{mu_o N^2 \pi R^2}{d}\frac{dI}{dt}$$

Induced emf
*opposes* the change

$$|emf_{\text{tot}}| \equiv L\left|\frac{dI}{dt}\right|$$

**Definition of Inductance L**

$$\boxed{L = \frac{mu_o N^2}{d}\pi R^2}$$

**INDUCTANCE OF SOLENOID**

# Energy Stored in Inductor

$P = IV$ Power

$|emf_{\text{tot}}| \equiv L\left|\frac{dI}{dt}\right|$ Inductor

As inductor reaches steady state, Power going into it is: $P = I(emf_{\text{tot}}) = LI\frac{dI}{dt}$

To find the total energy in the inductor in steady state, integrate P:

$$E_{\text{tot}} \equiv \int P dt = L\int I\frac{dI}{dt}dt$$

Cancel the dt's

$$= L\int IdI = L\left[\frac{1}{2}I^2\right]_{I_i=0}^{I_f=I} = \boxed{\frac{1}{2}LI^2 = E_{\text{tot}}}$$

Energy stored in INDUCTOR

# Energy Stored in Solenoid

$E_{\text{tot}} = \frac{1}{2}LI^2$ Inductor $\quad B = \frac{\mu_o N I}{d}$ Solenoid $\quad L = \frac{mu_o N^2}{d}\pi R^2$ Inductance of Solenoid

$$I = \frac{Bd}{\mu_o N} \qquad \Rightarrow E = \frac{1}{2}L\left(\frac{Bd}{\mu_o N}\right)^2 = \frac{1}{2}\left(\frac{mu_o N^2}{d}\pi R^2\right)\left(\frac{Bd}{\mu_o N}\right)^2$$

$$= \frac{1}{2}\frac{1}{\mu_o}(\pi R^2 d)B^2 \quad = \frac{1}{2}\frac{1}{\mu_o}(\text{Volume})B^2$$

$$\boxed{\frac{E}{\text{Volume}} = \frac{1}{2}\frac{1}{\mu_o}B^2}$$

Energy Density of Magnetic Field

(Result is more general than solenoid)

# Electromagnetic Energy Density

$$\frac{E}{\text{Volume}} = \frac{1}{2}\frac{1}{\mu_o}B^2$$

$$\frac{E}{\text{Volume}} = \frac{1}{2}\epsilon_o E^2$$ (Ch. 17)

$$\boxed{\frac{E_{\text{tot}}}{\text{Volume}} = \frac{1}{2}\epsilon_o E^2 + \frac{1}{2}\frac{1}{\mu_o}B^2}$$

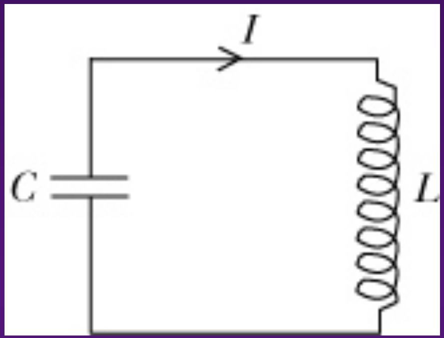
Total Energy in any Electromagnetic Field

S

# LC Circuit

$E_{\text{tot}} = \frac{1}{2}LI^2$ Inductor

$E = \frac{1}{2}CV^2$ Capacitor (Ch. 17)



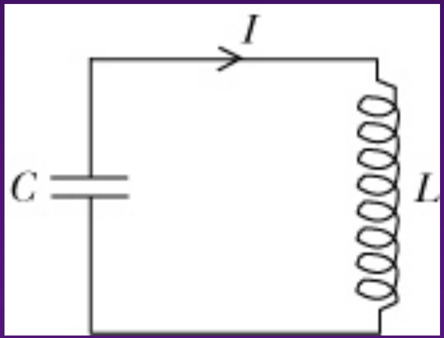

$$E_{\text{tot}} = \frac{1}{2}CV^2 + \frac{1}{2}LI^2$$

Which term is most like KE?
Which term is most like PE?

# LC Circuit is a Harmonic Oscillator

$E_{\text{tot}} = \frac{1}{2}LI^2$ Inductor

$E = \frac{1}{2}CV^2$ Capacitor (Ch. 17)




Kinetic Energy in Inductor

$$E_{\text{tot}} = \frac{1}{2}CV^2 + \frac{1}{2}LI^2$$

Potential Energy in Capacitor

When C is fully charged, I → 0.
When C is fully discharged, I → max, and inductor's reluctance to change "swings" the electrons the other way fully charging the capacitor with the opposite polarity.

KE and PE trade back and forth, just like any Harmonic Oscillator.

$T = 2\pi\sqrt{LC}$ Period of LC circuit

# Today

- Superconductors
- Inductors