Magnetism and Levitation

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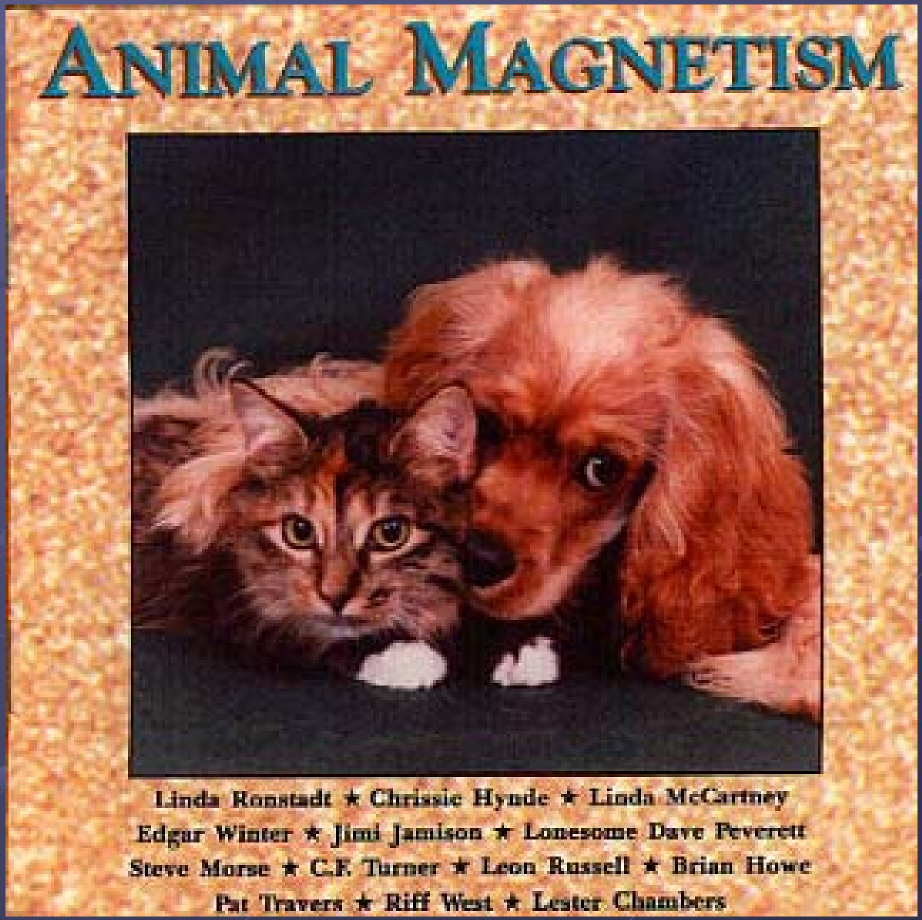
Wednesday, December 11, 2002

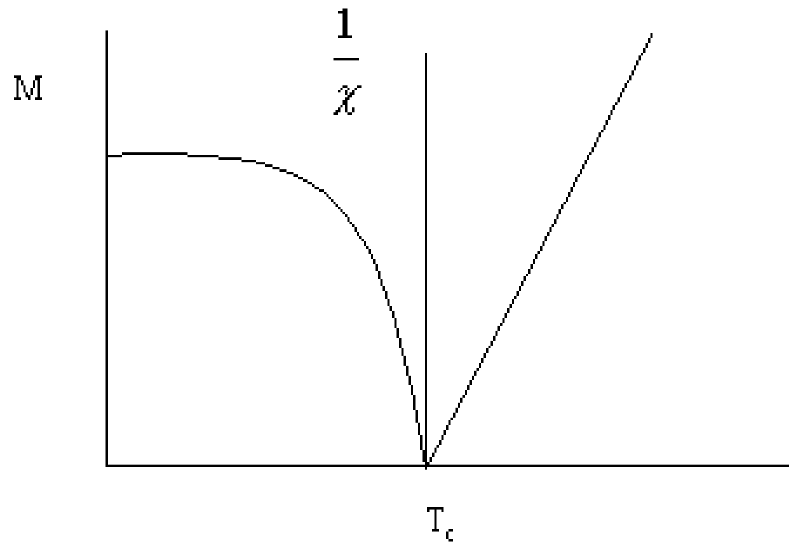
Types of Magnetism

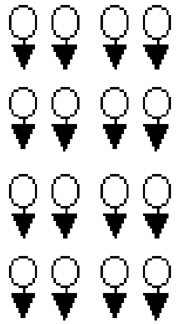
- Ferromagnetism
- Antiferromagnetism
- Ferrimagnetism
- Paramagnetism
- Superparamagnetism
- Diamagnetism



Ferromagnetism

- Refrigerator Magnet
- Unpaired electron
- Spin coupling
  causes large parallel
  dipole domains to form

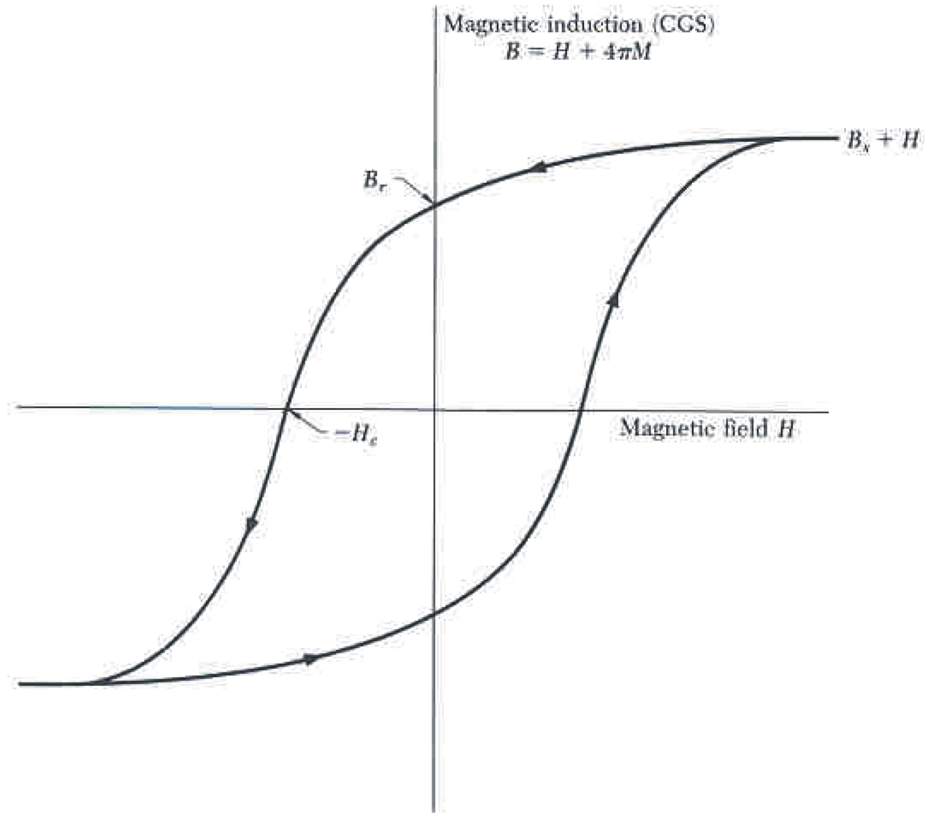




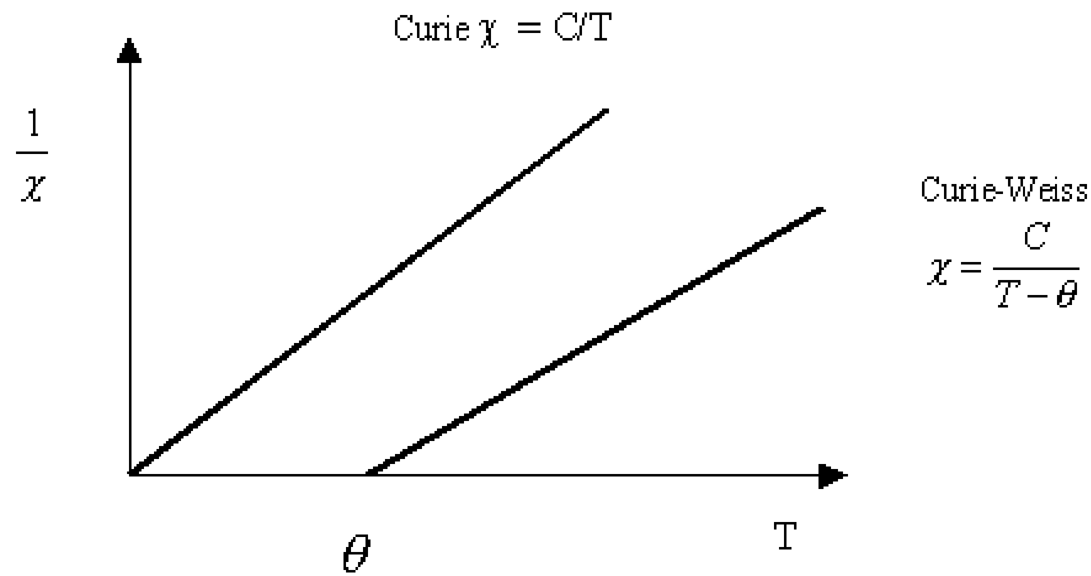
- Domains are randomly oriented until aligned by an external field
- Becomes a paramagnet above the Curie Temperature (Phase Change)

Hysteresis Loops

- Current magnetic state dependent on history
- Found with ferro, ferri, and superpara magnetisms
- Saturation points at tips
- Remanence is the field left over when external B-field is removed



Paramagnetism



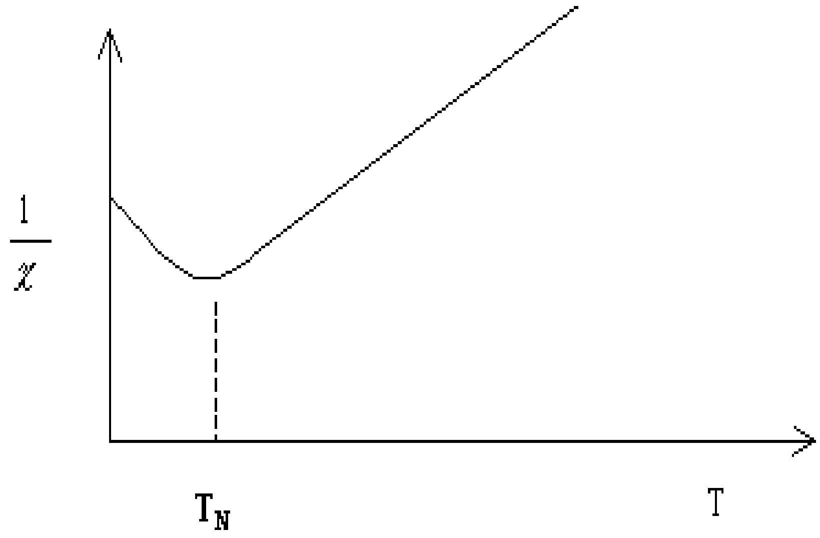
- Unpaired Electron
- Spin coupling small
- Thermal energy tends to destroy any net effect of coupling
- Exhibits other behavior below Curie Temp.
- Extra electron acts as dipole and aligns itself with the field. $\chi>0$

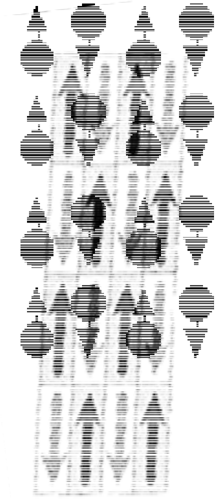
Superparamagnetism

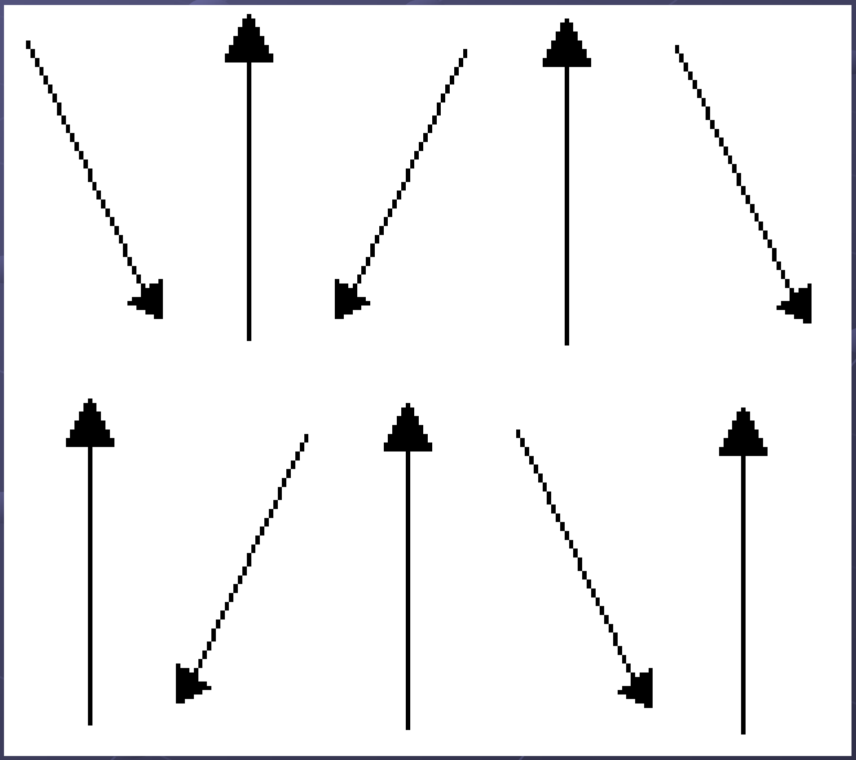
- Works like paramegnetism, but has decay time to return to random polarization
- Yields a hysteresis loop that decays to a curve over time.

Antiferromagnetism

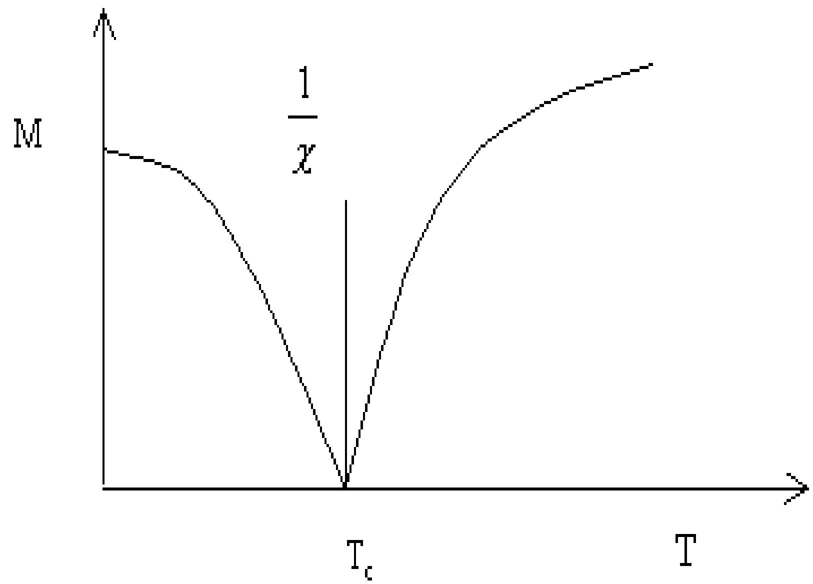
- Unpaired electron
- Antiparallel dipoles cancel
- Spin coupling causes large antiparallel dipole domains to form
- Net magnetization is due to spin canting
- Produces very weak effects

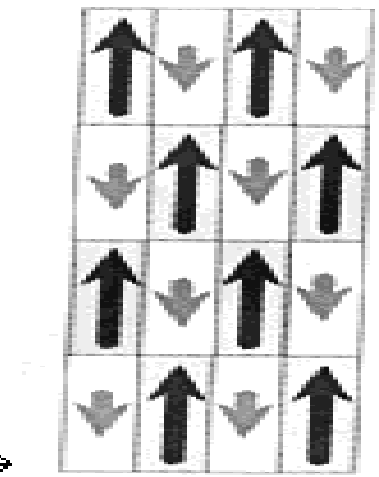






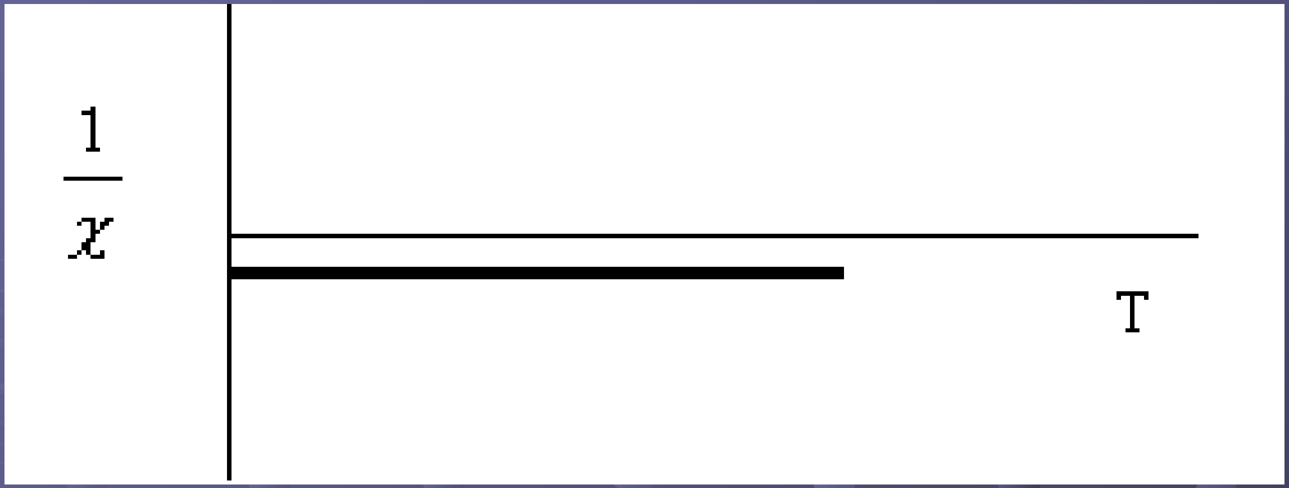
Ferrimagnetism





- Unpaired electron
- Antiparallel dipoles cancel partially
- Spin coupling causes large (anti)parallel dipole domains to form
- Due to crystal structure, dipoles are larger in one direction than the other, netting a field

Diamagnetism



- No unpaired electron
- Magnetic moment due to orbital angular momentum
- Induced Magnetic moments antiparallel to applied field (Lenz's law)
- Superconductors are perfect diamagnets
- Everything is diamagnetic
- Negative χ allows stable equilibrium points => levitation

Earnshaw's Theorem

- Solutions to Laplace Equation only have saddles

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} = 0$$

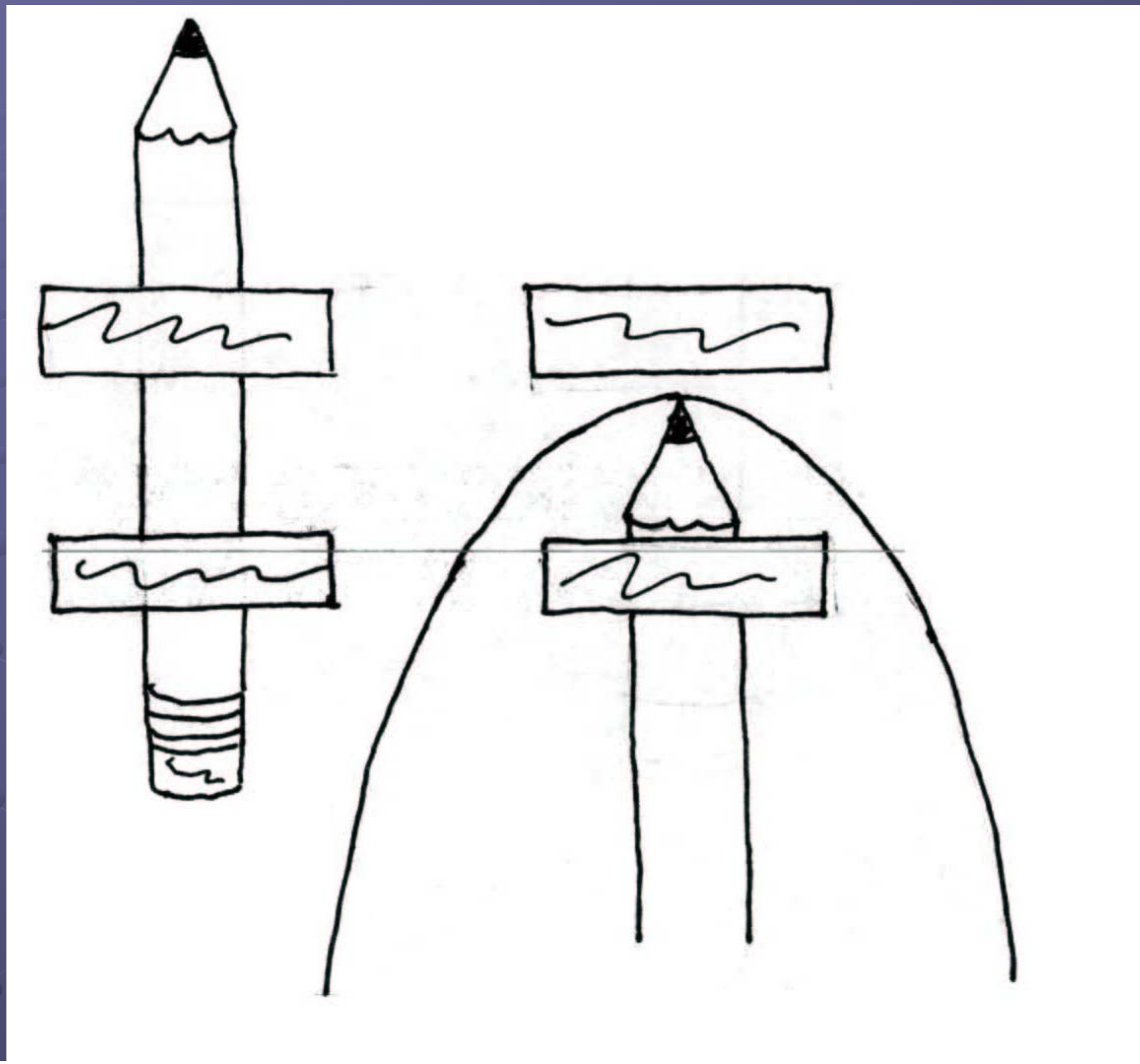
- Laplace's Equation applies to energy of
  - Static mass distributions
  - Static charge distributions
  - Static magnetic dipole distributions
- Equillibrium at energy minimum
  - Energy only has saddles

When Engineers Attack

THUS

- Static distributions of mass, charge, and magnetic dipoles cannot be held in equillibrium by other static distributions of mass, charge, and magnetic dipoles

Levitation possible when constrained
Equilibrium is not stable



- Energy of magnetic and gravitational field in a material

$$E(\boldsymbol{r}) = mgz - \frac{\chi V}{2\mu_0} B^2(\boldsymbol{r})$$

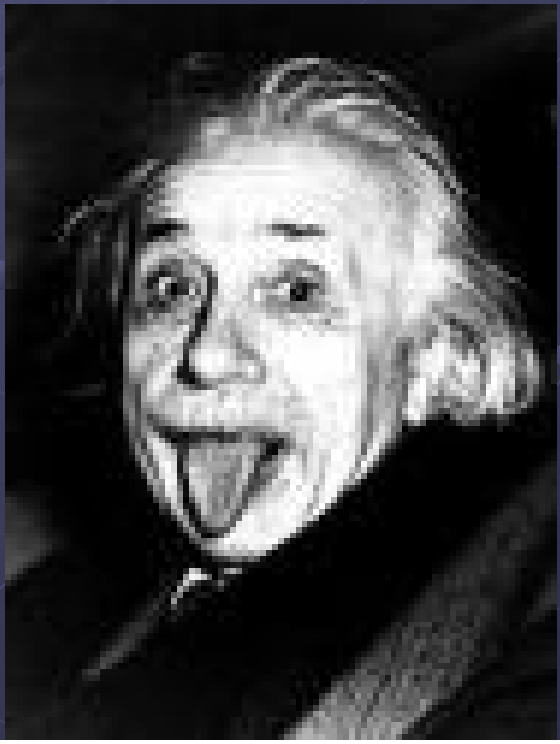
V is Volume
χ is magnetic susceptibility

- Equillibrium Conditions

$$\nabla^2 E > 0$$

$$-\frac{\chi V}{2\mu_0} \nabla^2 B^2 > 0$$

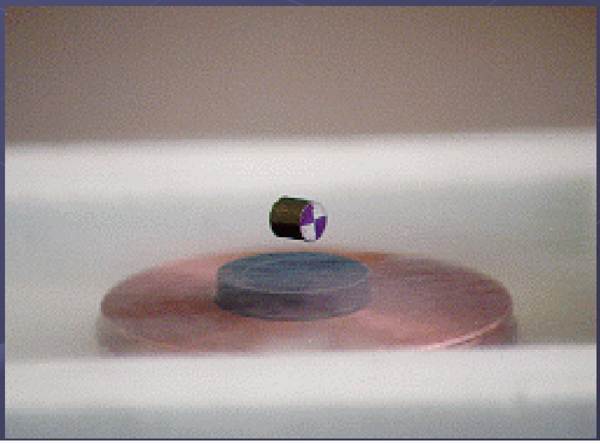
$$\nabla^2 B^2 > 0$$



- So if χ is negative….
 diamagnetic materials
 can levitate!

Internal Feedback

- Basics of Superconductors
  - Form Cooper Pairs – Pairs of Electrons around Fermi Level
  - Energy separation between Cooper Pairs and single electrons
  - Cooper Pairs form Bose-Einstein Condensate (pairs occupy the same space (coherence length) -> many pair interaction)
  - Not enough thermal energy to scatter or destroy pair -> no resistance
  - Type I -> Destroyed above Critical Field
  - Type II -> Destroyed gradually from lower Critical Field to upper



Basics of Superconductors (cont.)

A superconductor repels all magnetic fields

(the Meissner Effect) → Perfect Diamagnet

$$\nabla^2 B = \frac{B}{\lambda_L^2}$$

$$\nabla^2 B = 0$$

$$\lambda_L = \sqrt{\frac{\varepsilon_0 m c^2}{n e^2}}$$

λ_L = London penetration depth

n = superconducting electron density

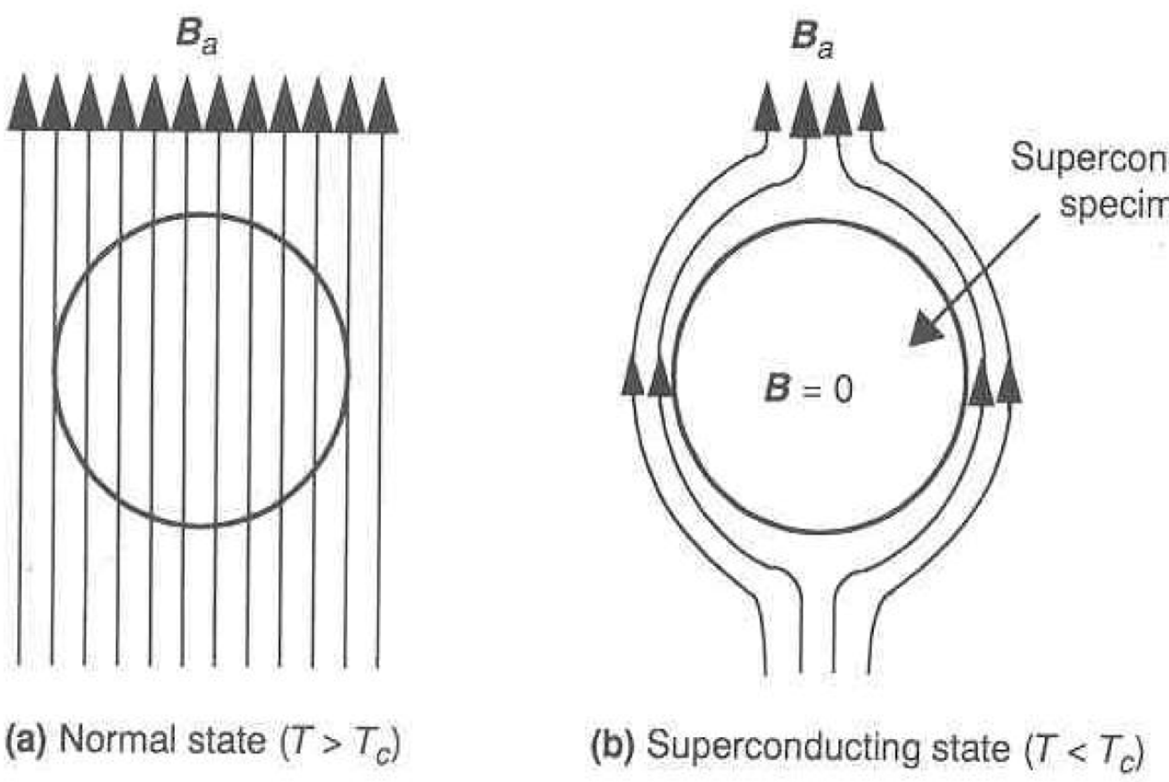
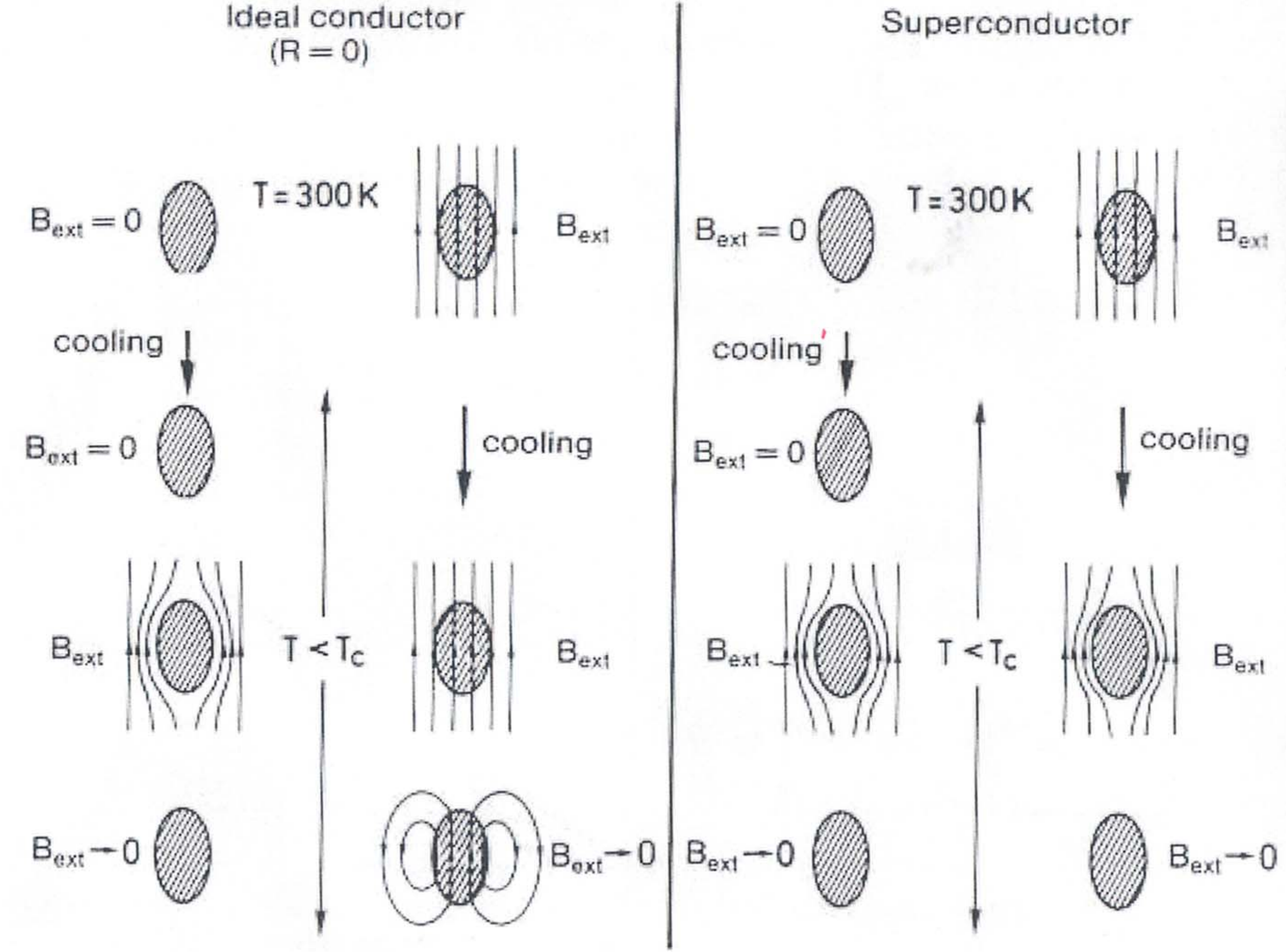


Figure 3: The Meissner effect of a superconductor

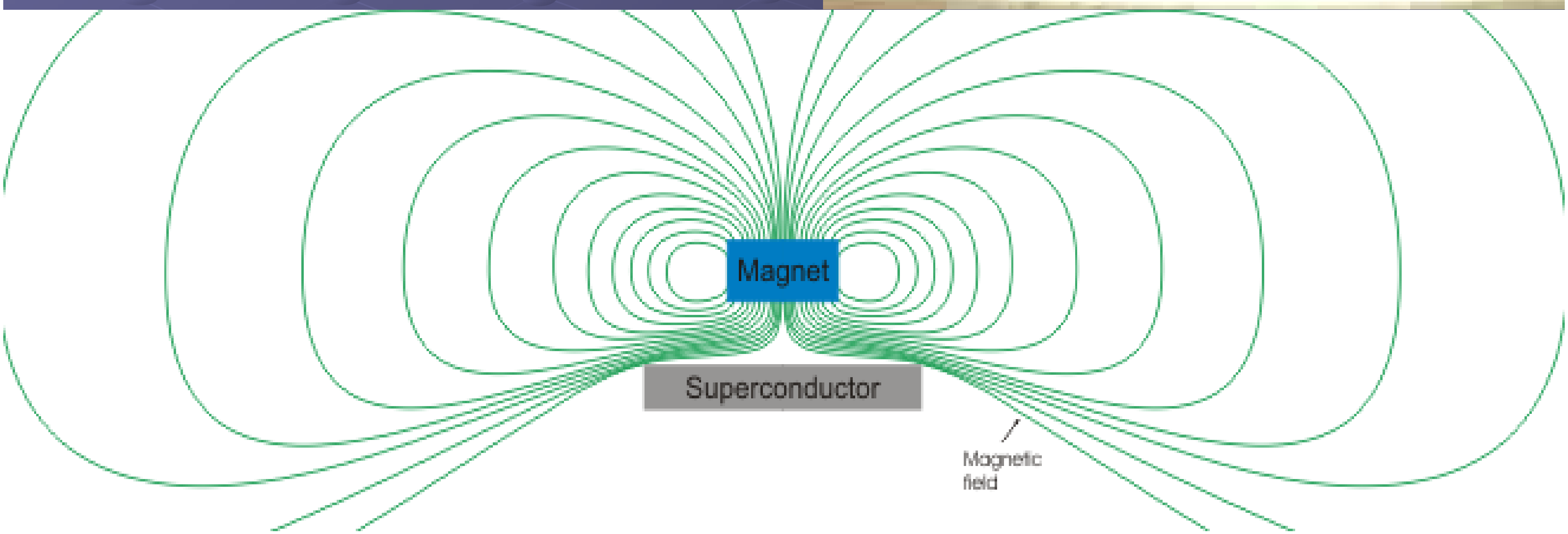
Ideal Conductor ≠ Superconductor



Superconducting Effects!!!

Superconducting Levitation

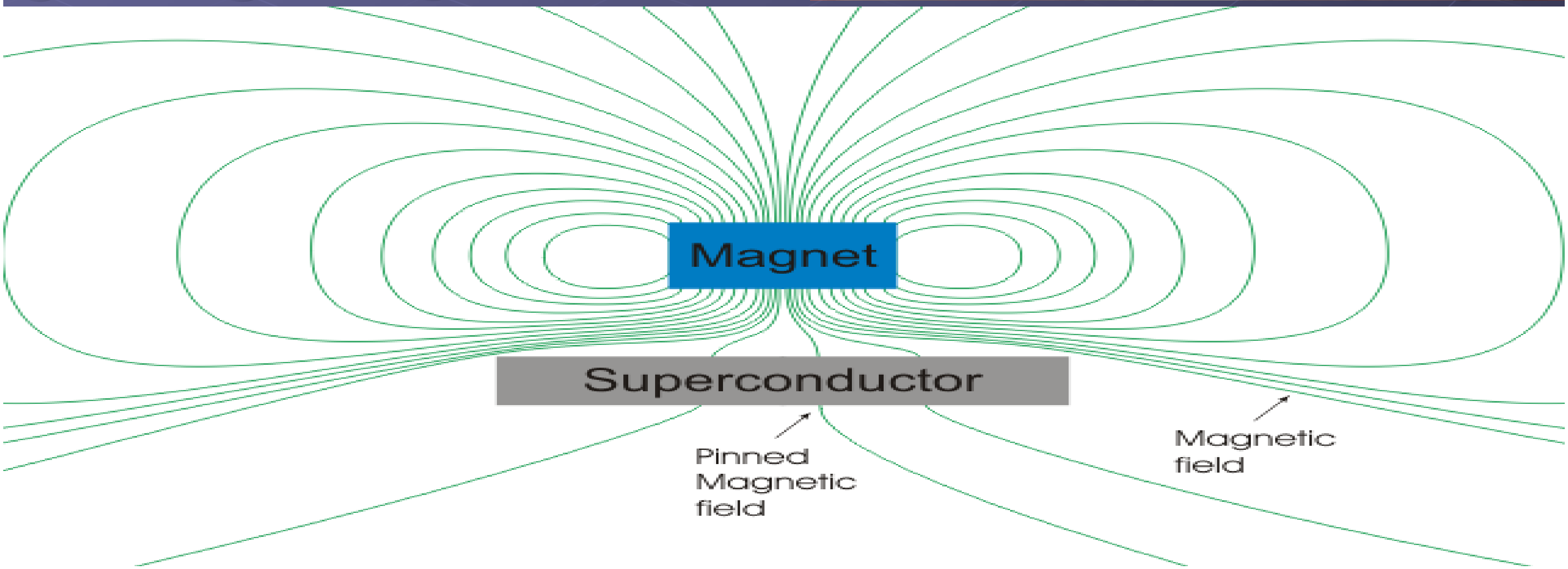
- Changing magnetic field induces a current
- Current induces magnetic field (Remember Meissner Effect!)
- Perfectly cancels gravity
- Stable Equilibrium



Superconducting Effects!!!

Magnetic Pinning

- Outside B-field introduced above T_C → permeates impurities
- Stays pinned within impurities (vortices) as T lowers < T_C
- B-field cannot separate from Superconductor
- B-field can be broken



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