Magnetic Materials

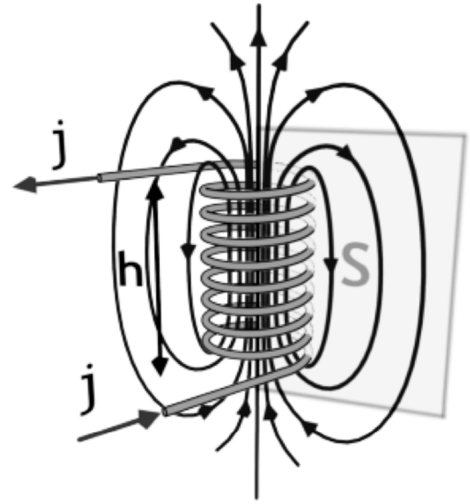
Reading: Chapter 14 in Kong & Shen

Outline

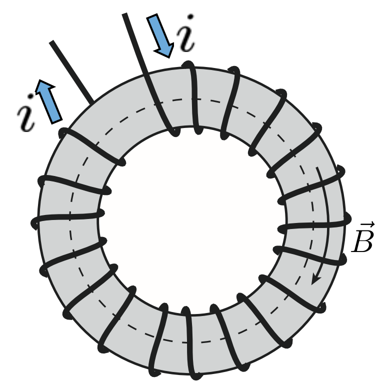
- Magnetization and Magnetic Susceptibility
- Ferromagnetism, Paramagnetism, Diamagnetism
- ‘Magnetic Charges’

True or False?

1. For a solenoid, if we increase the number of loops N by 5% and increase the height h by 5%, then the H-field inside will not change. ______



2. For a toroid, if we increase the number of loops N, but do not increase the radius, then the H-field inside stays the same. ______



3. Lenz's Rule states that the induced E-field drives the current in the direction to try to keep the magnetic flux constant. ______

Maxwell's Equations

Electric Fields

$$\oint_S \epsilon_0 \overline{E} \cdot d\overline{A} = \int_V \rho dV$$

EQS

$$\int_C \overline{E} \cdot d\bar{l} = 0$$

Magnetic Fields

$$\oint_S \overline{B} \cdot d\overline{A} = 0$$

MQS

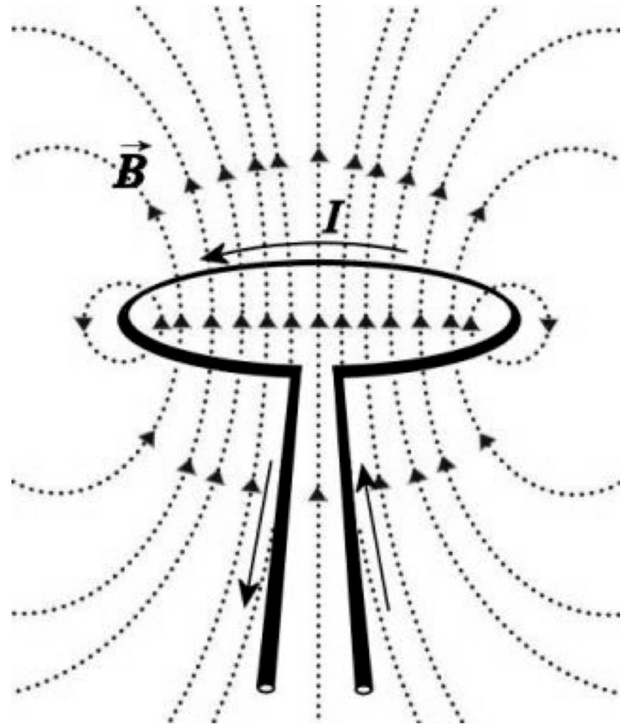
$$\oint_C \overline{H} \cdot d\bar{l} = \int_S \overline{J} \cdot d\overline{A} + \frac{d}{dt} \int_S \epsilon E dA$$

Magnetic Fields

$$\oint \vec{H} \cdot d\vec{l} = \int_S \vec{J} \cdot d\vec{A}$$

$$= I_{enclosed}$$

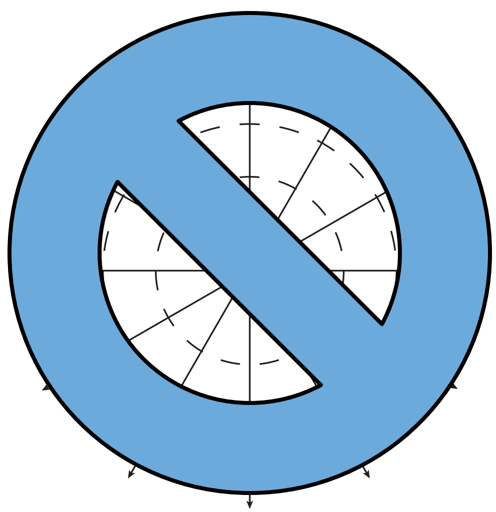
$$\oint \vec{B} \cdot d\vec{A} = 0$$



Magnetic Moment

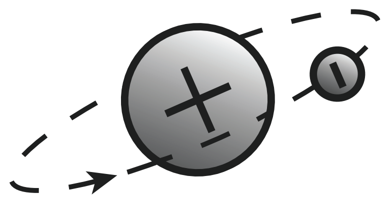
$$\vec{m} = i\,\vec{a}$$

magnetic monopoles do not exist

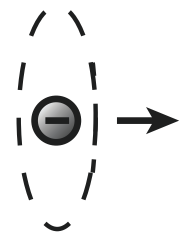


Microscopic Magnets

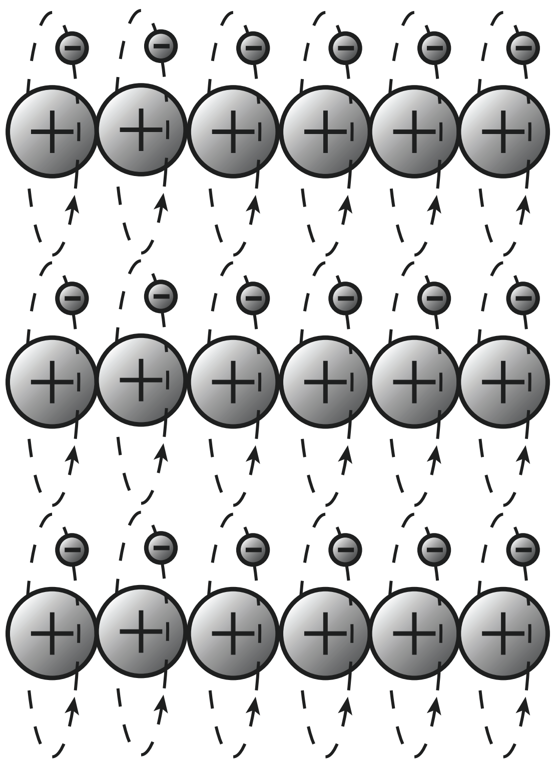
Magnetic moment of an atom due to electron orbit...



Magnetic moment of an atom due to electron/nuclear spin...



$$m_{atom} \approx 10^{-23}\,\frac{\mathrm{A}\cdot\mathrm{m}^2}{\mathrm{atom}}$$



The ***magnetization*** or *net magnetic dipole moment per unit volume* is given by

$$\vec{M} = N\vec{m}$$

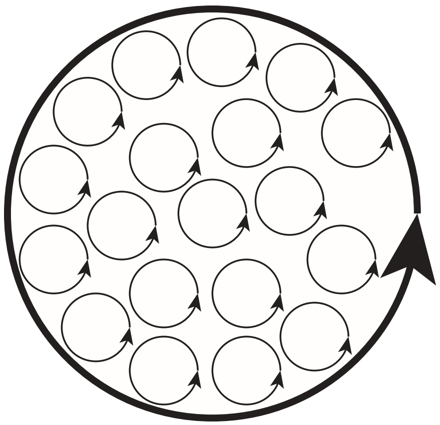
average magnetic dipole moment [A m^2]

[A/m]

Number of dipoles per unit volume [m^{-3}]

Generating Strong Magnetic Fields

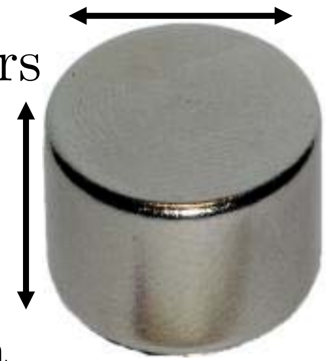
Superposition with current loops...



$$d = 0.012 \text{ meters}$$

$$h = 0.019 \text{ meters}$$

$$B = 0.5 \text{ Tesla}$$



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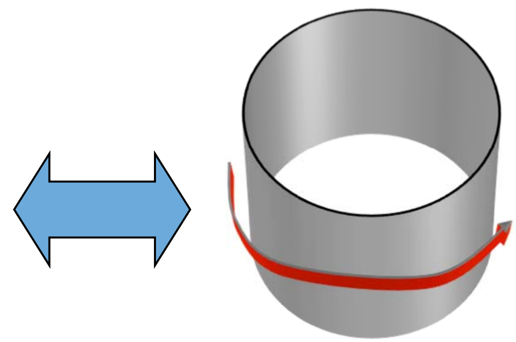


$$\vec{J}_m$$

$$\mu_o = 4\pi \times 10^{-7} \left[\frac{\text{T}}{\text{A/m}}\right]$$

0.5 T Electromagnets

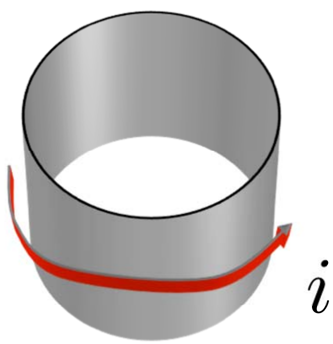
$$h = 0.019\text{meters}$$
$$d = 0.012\text{meters}$$

$$B = \mu_o H = \mu_o n i = 0.5\text{T}$$

$$ni = \frac{Ni}{h} = \frac{0.5}{4\pi \times 10^{-7}} \Rightarrow i = \frac{Bh}{\mu_o N}$$

0.5 Tesla with current loop...

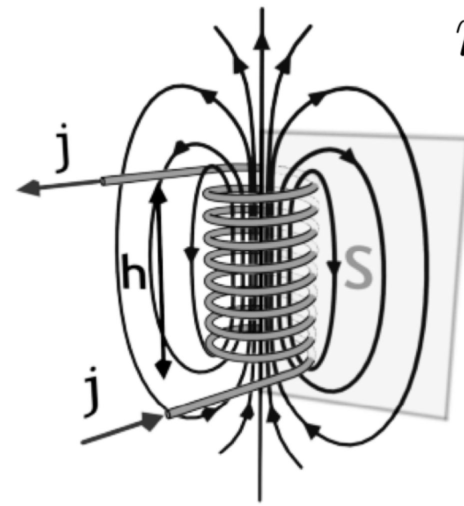
$$n = 1$$



$$i_{0.5\text{ T}} \approx 7600 \text{ Amps}$$

0.5 Tesla with 100 turn solenoid...

$$n = 100$$

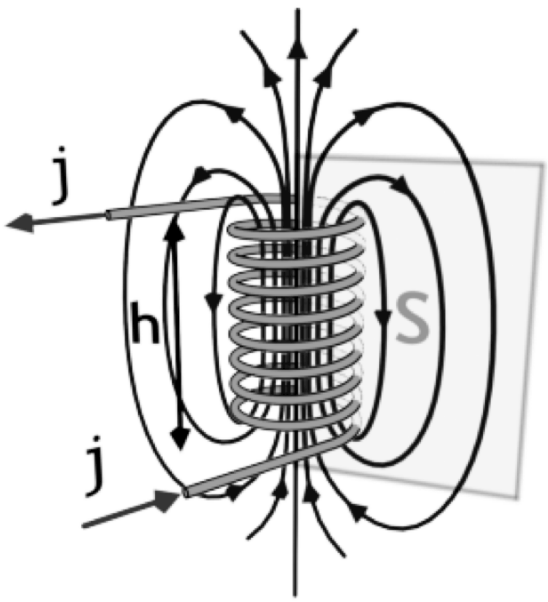


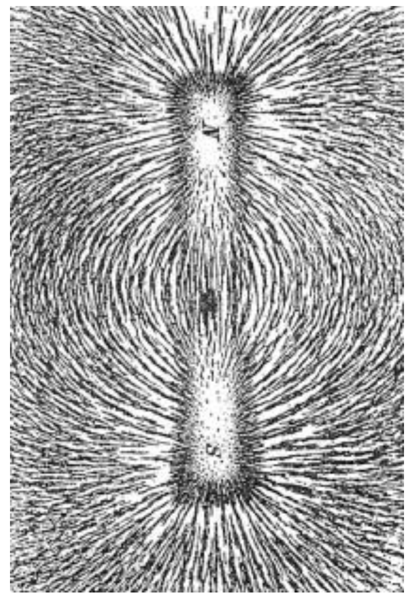
$$i_{0.5\text{T}} \approx 7.6\text{Amps}$$

...but the wires are microscopic !

Generating Strong Magnetic Fields

Will it be "easier" to generate a 0.5-T magnetic flux density with a permanent magnet or an electromagnet ?





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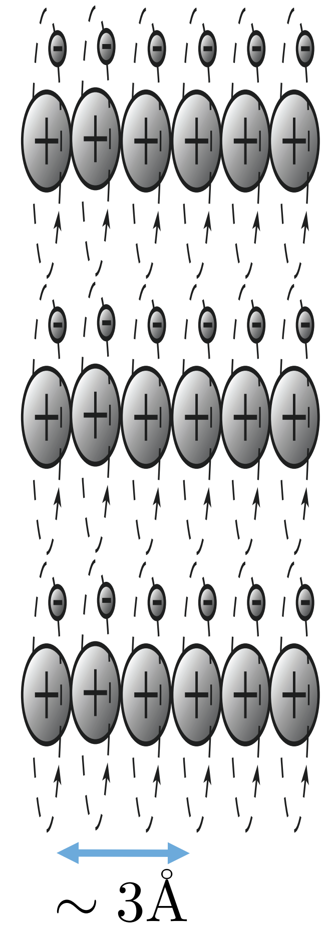
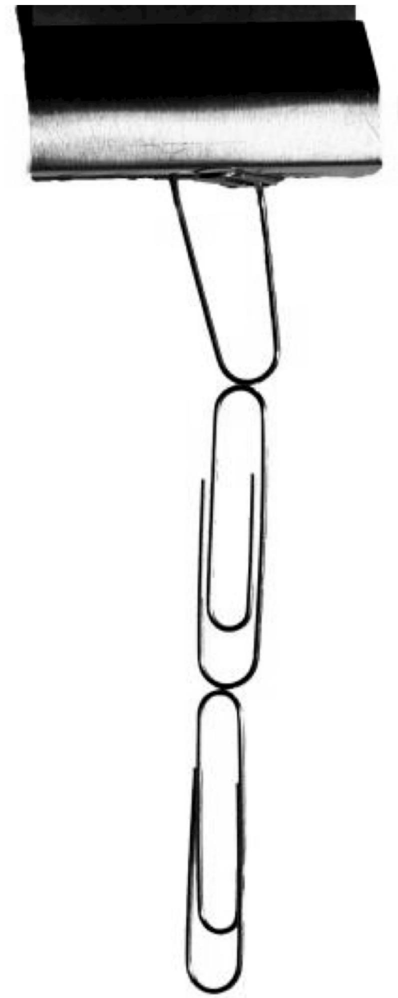


$$m_{atom} \approx 10^{-23}\left[\frac{\text{A}\cdot\text{m}^2}{\text{atom}}\right] \quad \text{and} \quad a_{atom} \approx 9\text{Å}^2 \approx 10^{-19}\text{m}^2$$

$$i_{atom} \approx 10^{-4}\text{A} \quad \text{and} \quad K_{atom} \approx 3000\left[\frac{\text{A}}{\text{cm}}\right]$$



Induced Magnetization

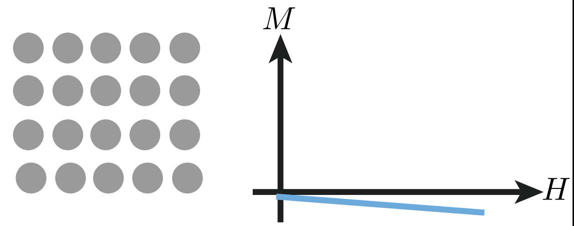
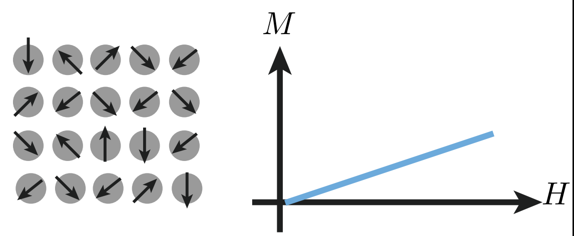
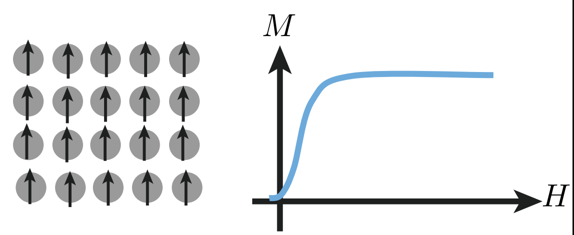
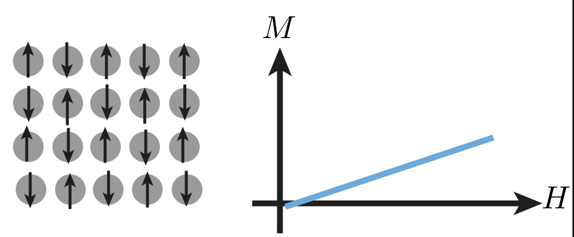
For some materials, the *net magnetic dipole moment per unit volume* is proportional to the *H* field

$$\vec{M} = \chi_m \vec{H}$$

MAGNETIC SUSCEPTIBILITY (dimensionless)

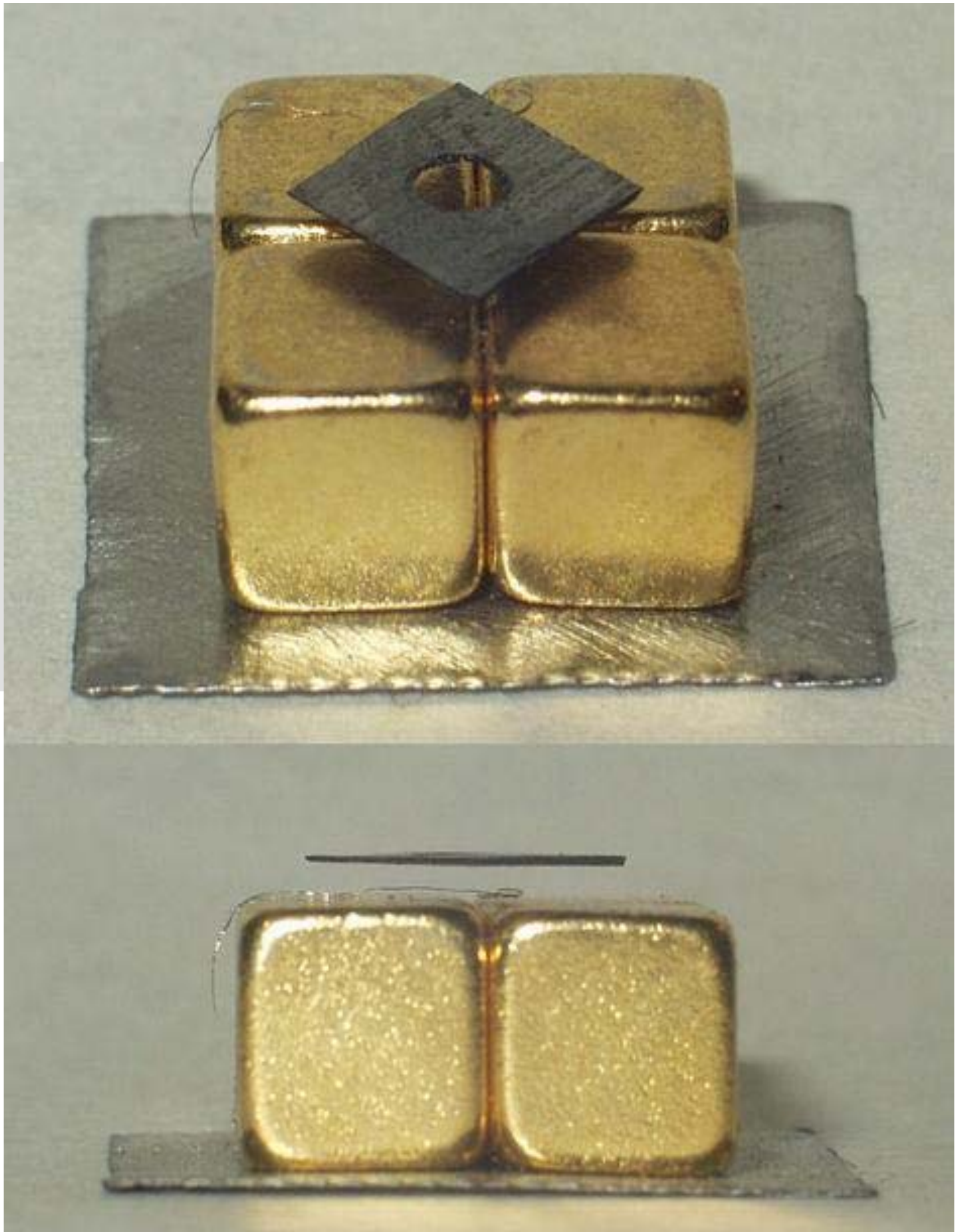
units of both ***M*** and ***H*** are A/m.

The effect of an applied magnetic field on a *magnetic* material is to create a net magnetic dipole moment per unit volume ***M***

Type of Magnetism	*Susceptibility*	*Atomic / Magnetic Behaviour*		*Example / Susceptibility*	
Diamagnetism	Small negative	Atoms have no magnetic moment		Au Cu	-2.74×10^{-6} -0.77×10^{-6}
Paramagnetism	Small positive	Randomly oriented magnetic moments		β-Sn Pt Mn	0.19×10^{-6} 21.04×10^{-6} 66.10×10^{-6}
Ferromagnetism	Large positive	Parallel aligned magnetic moments		Fe	~100,000
Antiferromagnet	Small positive	Parallel and anti-parallel aligned magnetic moments		Cr	3.6×10^{-6}

Diamagnetic Materials

Diamagnetism is the property of an object which causes it to create a magnetic field in opposition of an externally applied magnetic field, thus causing a repulsive effect. It is a form of magnetism that is only exhibited by a substance in the presence of an externally applied magnetic field. Diamagnetism is generally a quite weak effect in most materials, although superconductors exhibit a strong effect.

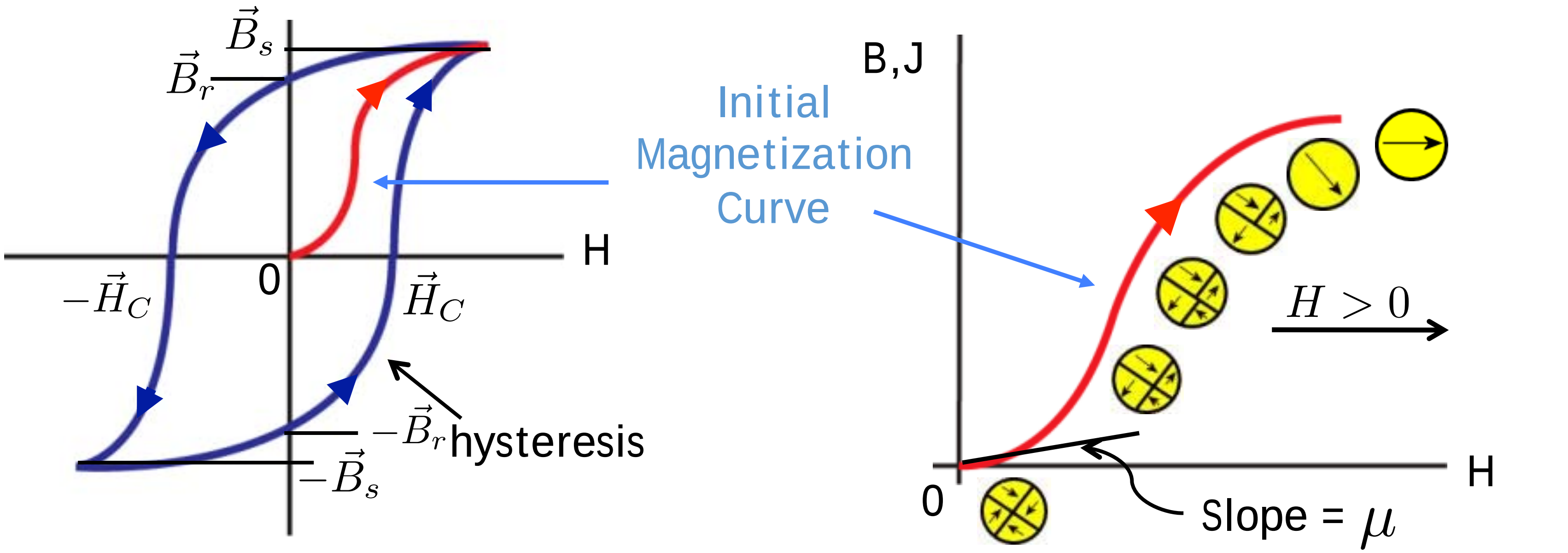


On Right: A small (~6mm) piece of pyrolytic graphite levitating over a permanent neodymium magnet array (5mm cubes on a piece of steel). Note that the poles of the magnets are aligned vertically and alternate (two with north facing up, and two with south facing up, diagonally)

from Wikipedia

Ferromagnetic Materials

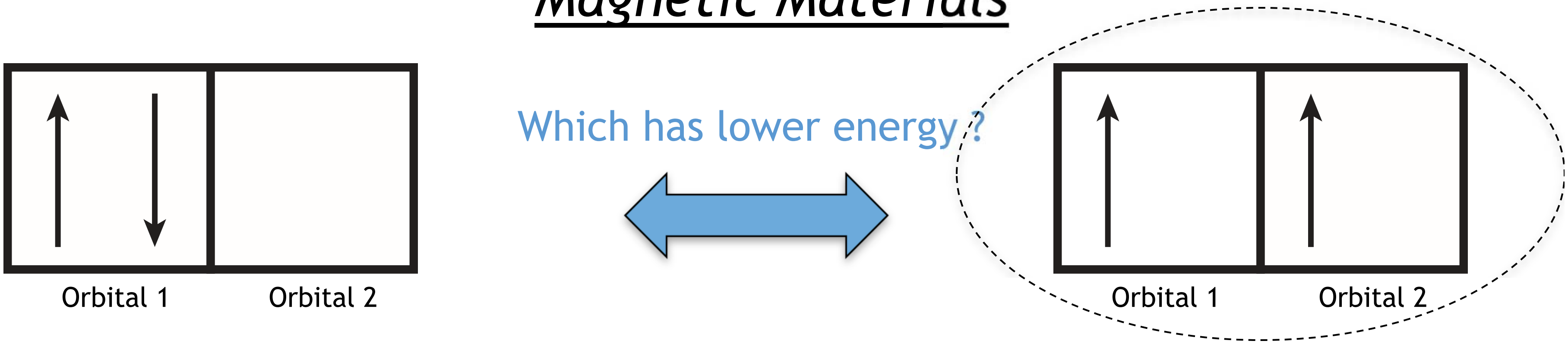
Impact that the imposition of a magnetic field *H* on a ferromagnetic material has on the resulting magnetic flux density *B*. The field causes the magnetic moments in each of the domains to begin to align. When the magnetizing force *H* is eliminated, the domains relax, but don't return to their original random orientation, leaving a remanent flux B_r ; that is, the material becomes a "permanent magnet." One way to demagnetize the material is to heat it to a high enough temperature (called the *Curie temperature*) that the domains once again take on their random orientation. For iron, the Curie temperature is 770ºC.

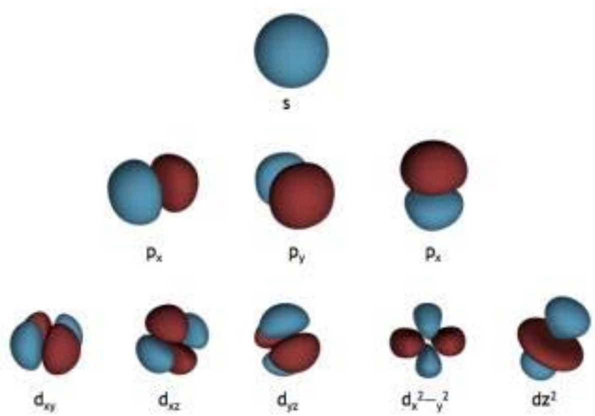


BEHAVIOR OF AN INITIALLY UNMAGNETIZED MATERIAL
Domain configuration during several stages of magnetization

- Why is there a B even when H is zero ??
- Why doesn't the magnetization change sign until H_C ??

Magnetic Materials





Atomic Number	Element	Electronic Structure of 3*d*					Moment (μ_B)
21	Sc	↑					1
22	Ti	↑	↑				2
23	V	↑	↑	↑			3
24	Cr	↑	↑	↑	↑	↑	5
25	Mn	↑↓	↑	↑	↑	↑	5
26	Fe	↑↓	↑↓	↑	↑	↑	4
27	Co	↑↓	↑↓	↑↓	↑	↑	3
28	Ni	↑↓	↑↓	↑↓	↑↓	↑	2
29	Cu	↑↓	↑↓	↑↓	↑↓	↑↓	0

↑ = electron spin orientation

Magnetic Materials

magnetic susceptibility χ_m

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H (-2,5)																	He (-1,1)
	Be -23											B -19	C -22	N (-6,3)		F	Ne (-4,0)
												Al 21	Si -3,4	P -23	S -12	Cl (-22)	Ar (-11)
										Cu -9,7	Zn -12	Ga -23	Ge -7,3	As -5,4	Se -18	Br -16	Kr (-16)
										Ag -25	Cd -19	In -8,2		Sb -67	Te -24	I -22	Xe (-24)
										Au -34	Hg -28	Tl -36	Pb -16	Bi -153	Po	At	Rn

Diamagnetic

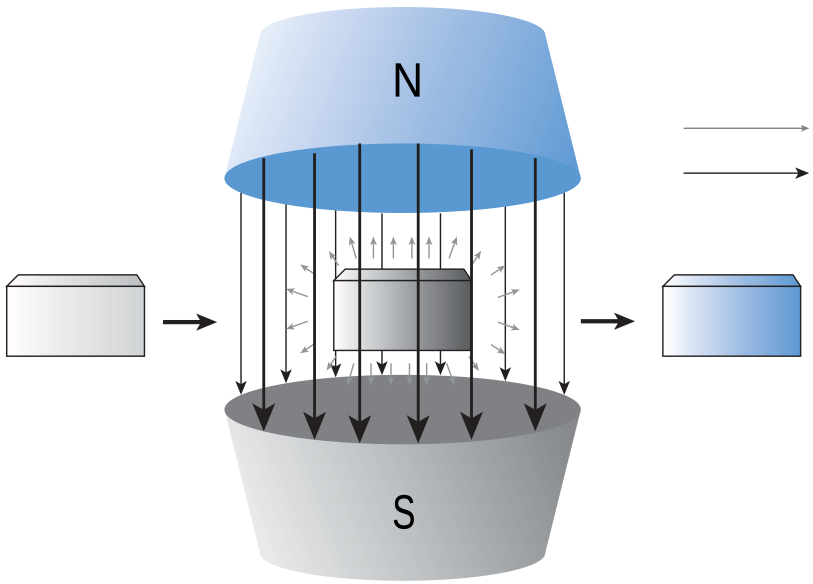
Paramagnetic

Ferromagnetic

All values given for a temperature of 300 K
In case of ferromagnetic materials: saturation polarization

numbers without (): $\cdot 10^{-6}$
numbers with(): $\cdot 10^{-9}$

Magnetic refrigeration



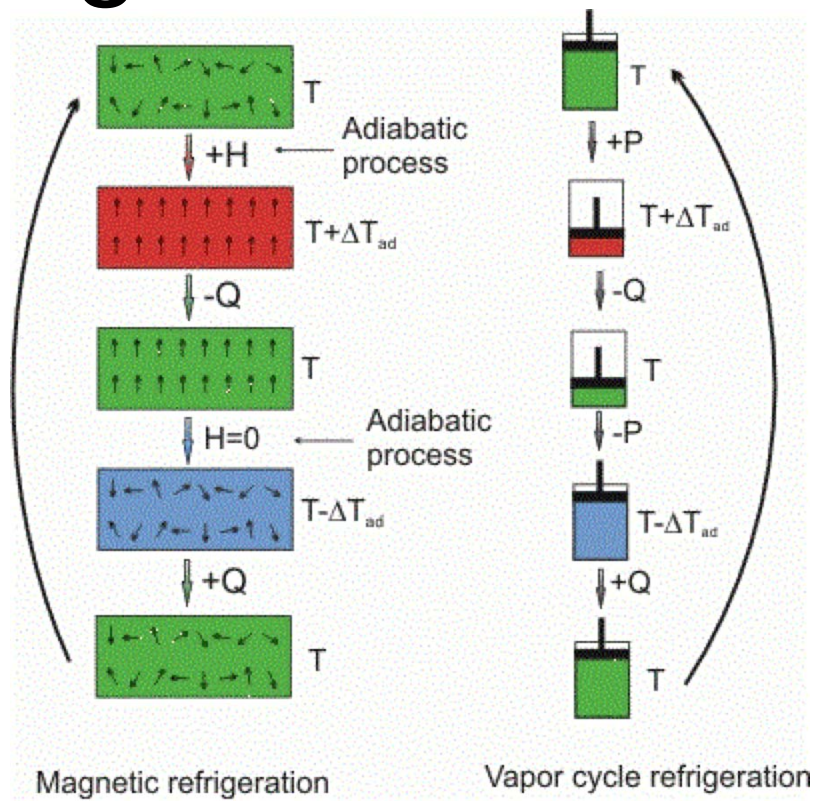


Image in the Public Domain

One of the most notable examples of the magnetocaloric effect is in the chemical element gadolinium and some of its alloys. Gadolinium's temperature is observed to increase when it enters certain magnetic fields. When it leaves the magnetic field, the temperature drops. Praseodymium alloyed with nickel (PrNi5) has such a strong magnetocaloric effect that it has allowed scientists to approach within one thousandth of a degree of absolute zero.

Source: Wikipedia

Gadolinium

Gd

3 to 4 K per Tesla

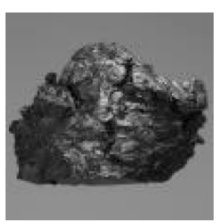
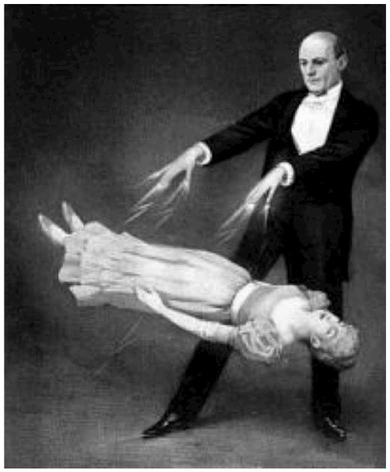


Image by Jurii http://commons.wikimedia.org/wiki/File:Gadolinium-2.jpg on Wikimedia Commons

Today's Culture Moment



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Magnetic Levitation

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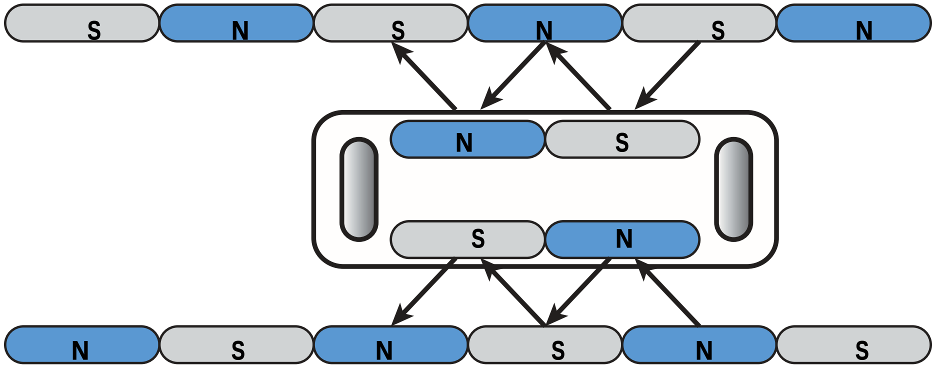
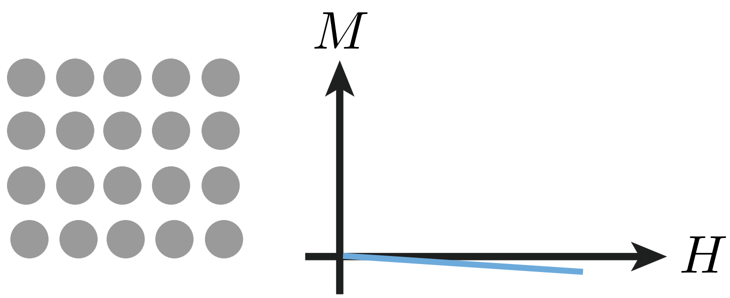
Shanghai Maglev Train goes up to 431 km/h

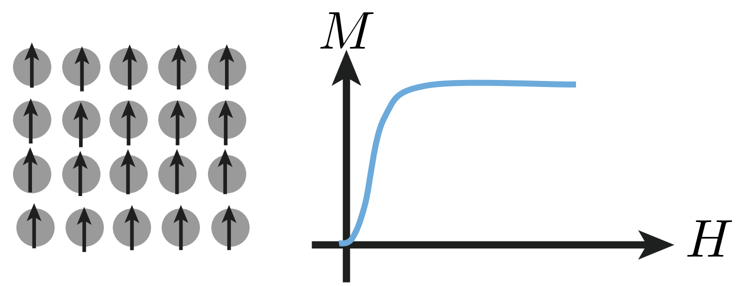


Maglev Propulsion

Magnetic Materials

weak magnetism	strong magnetism
diamagnetism Induced magnetic dipoles directed reverse to the external magnetic field.	**ferromagnetism** Spontaneous alignment of all permanent magnetic dipoles within a domain in the crystal lattice (only metals)





What kind of Magnetism is present in these materials ?

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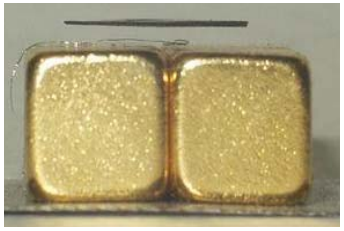

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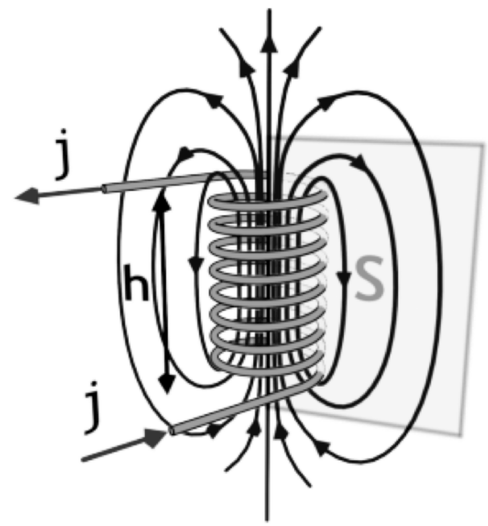
Maxwell's Equations for Magnetic Materials

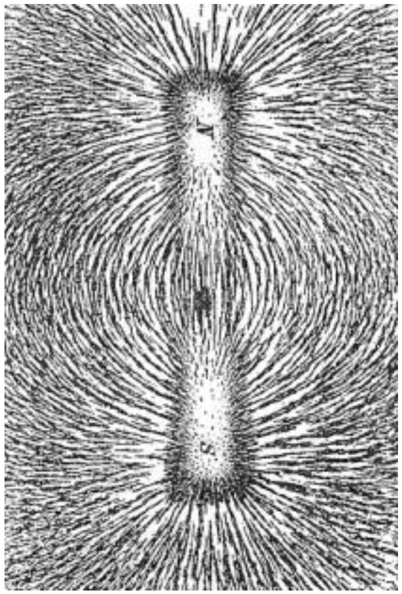
Magnetic Fields

$$\oint \vec{H} \cdot d\vec{l} = \int_S \vec{J} \cdot d\vec{A}$$

$$= I_{enclosed}$$

$$\oint \vec{B} \cdot d\vec{A} = 0$$





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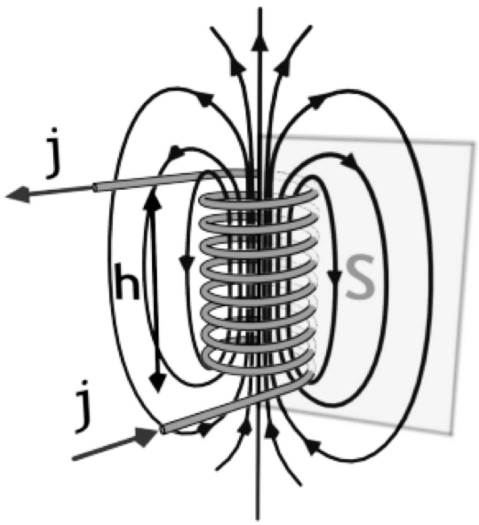
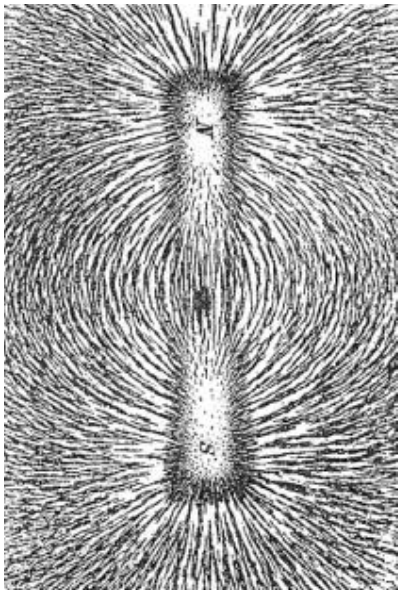
How do we incorporate magnetic materials in Maxwell's Equation ?

Analogy Between Magnetic and Electric Dipoles

Magnetic Fields





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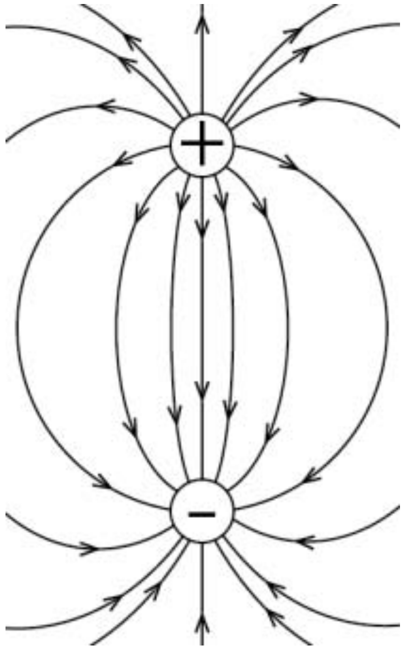
Magnetic Moment

$$m = i\,\mathbf{a}$$

Electric Field

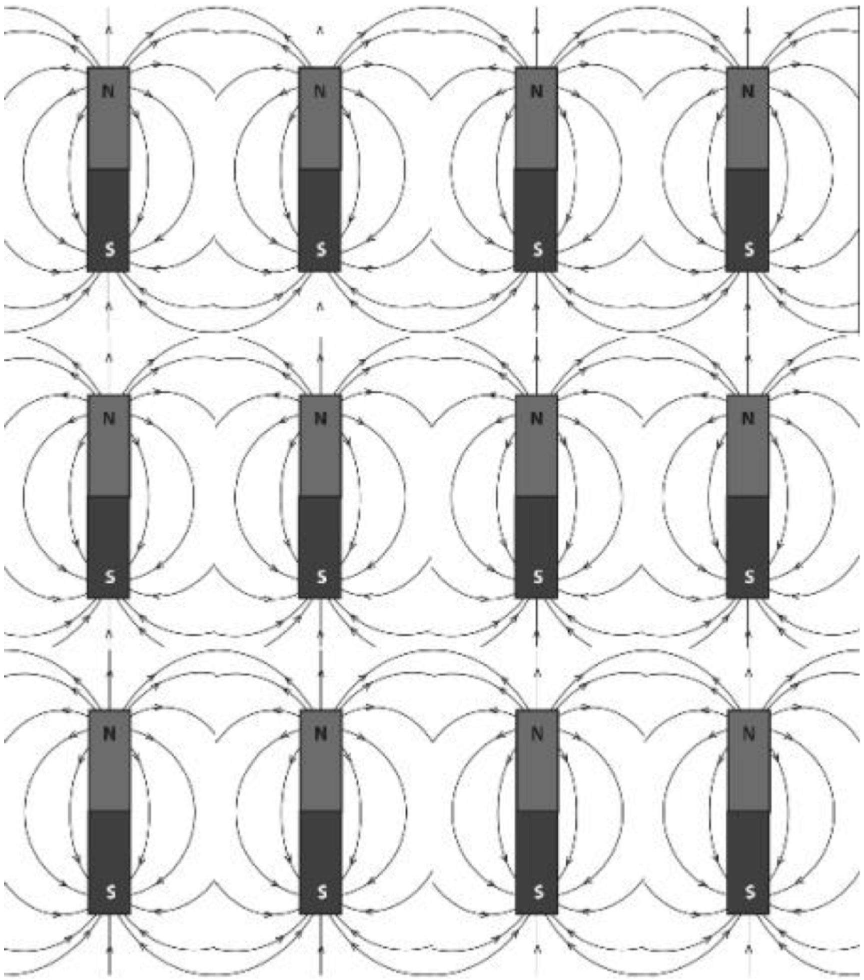


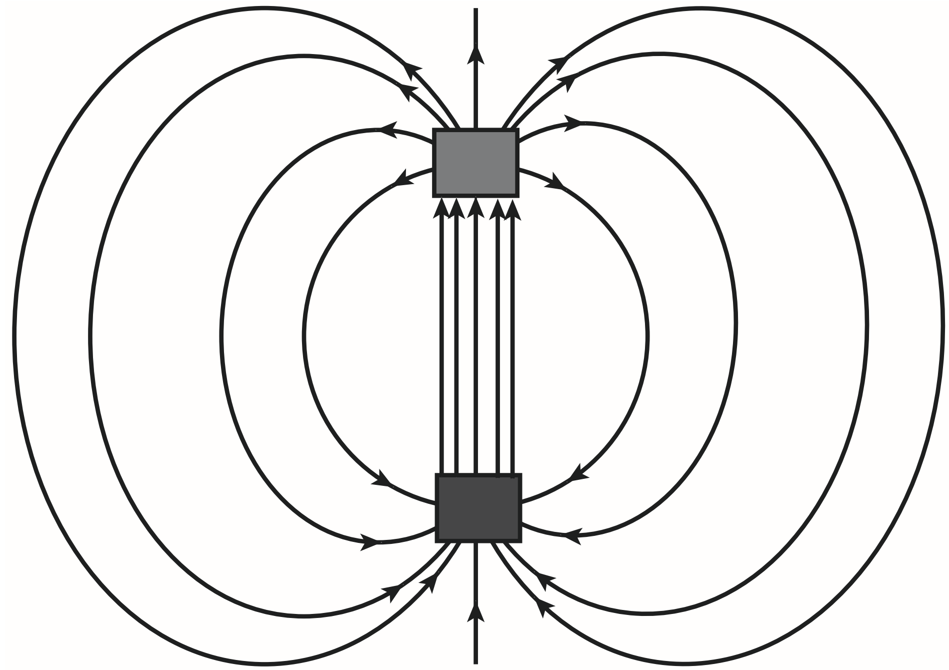
Electric Dipole Moment

$$m = q\,\mathbf{d}$$

The H-field lines for a magnet looks like the E-field lines for a electric dipole!

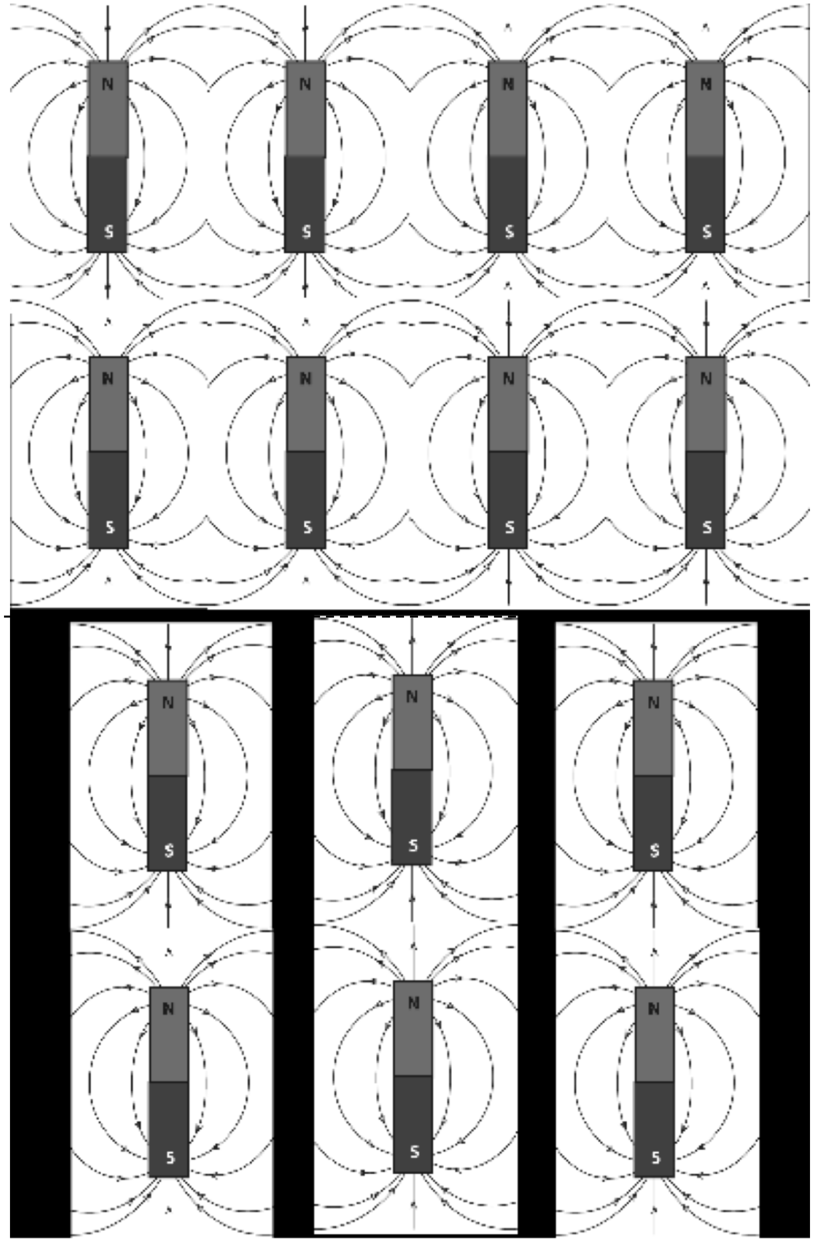
Superposition of Magnetic Moments





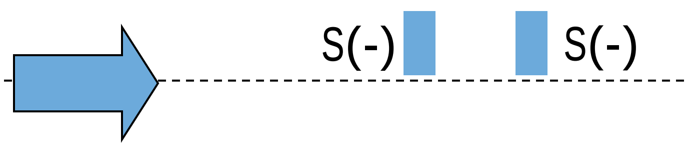
The field outside looks the same as a ‘magnetic charge’ dipole ρ_M

Equivalent Magnetic Charges



Going from region of high magnetization to low magnetization it appears as if there are ‘magnetic charges (monopoles)’ within the material !!

$$\rho_M = -\vec{\nabla}\left(\mu_o \vec{M}\right)$$



These ‘magnetic charges’ obey a Gauss Law…

$$\int_S \mu_o \vec{H} \cdot d\vec{A} = \int_V \rho_M dV$$

$$\int_S \mu_o \vec{H} \cdot d\vec{A} = -\int_S \mu_o \vec{M} \cdot d\vec{A}$$

$$\int_S \mu_o \left(\vec{H} + \vec{M}\right) \cdot d\vec{A} = 0$$

Magnetic Flux Φ [Wb] (Webers)

Magnetic Flux Density B [Wb/m^2] = T (Teslas)

Magnetic Field Intensity H [Amp-turn/m]

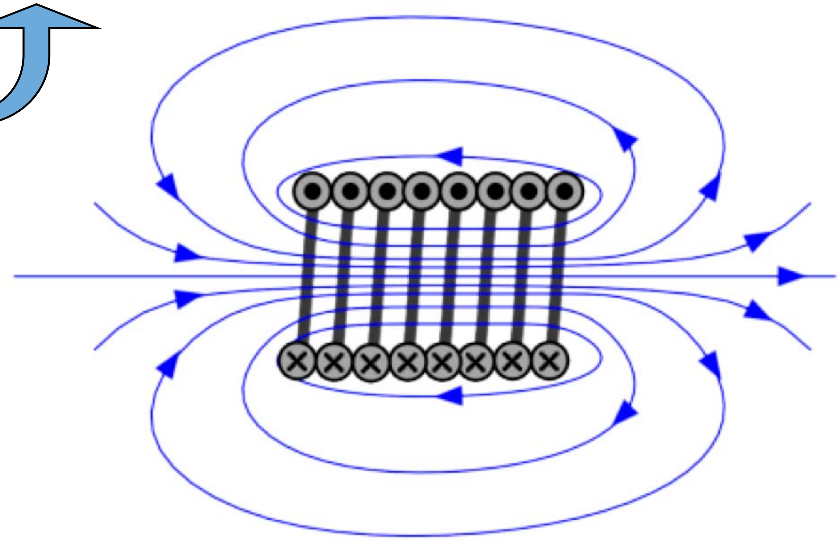
due to <u>macro</u>scopic & <u>micro</u>scopic

due to macroscopic currents

$$\Phi = \int \vec{B} \cdot d\vec{A}$$

$$\vec{B} = \mu_o \left(\vec{H} + \vec{M} \right) = \mu_o \left(\vec{H} + \chi_m \vec{H} \right) = \mu_o \mu_r \vec{H}$$

Magnetization **M** is due to material's <u>micro</u>scopic response to magnetic field **H**



Magnetic Susceptibility and Permeability

$$\vec{B} = \mu_o\left(\vec{H} + \vec{M}\right) = \mu_o\left(\vec{H} + \chi_m\vec{H}\right) = \mu_o\mu_r\vec{H}$$

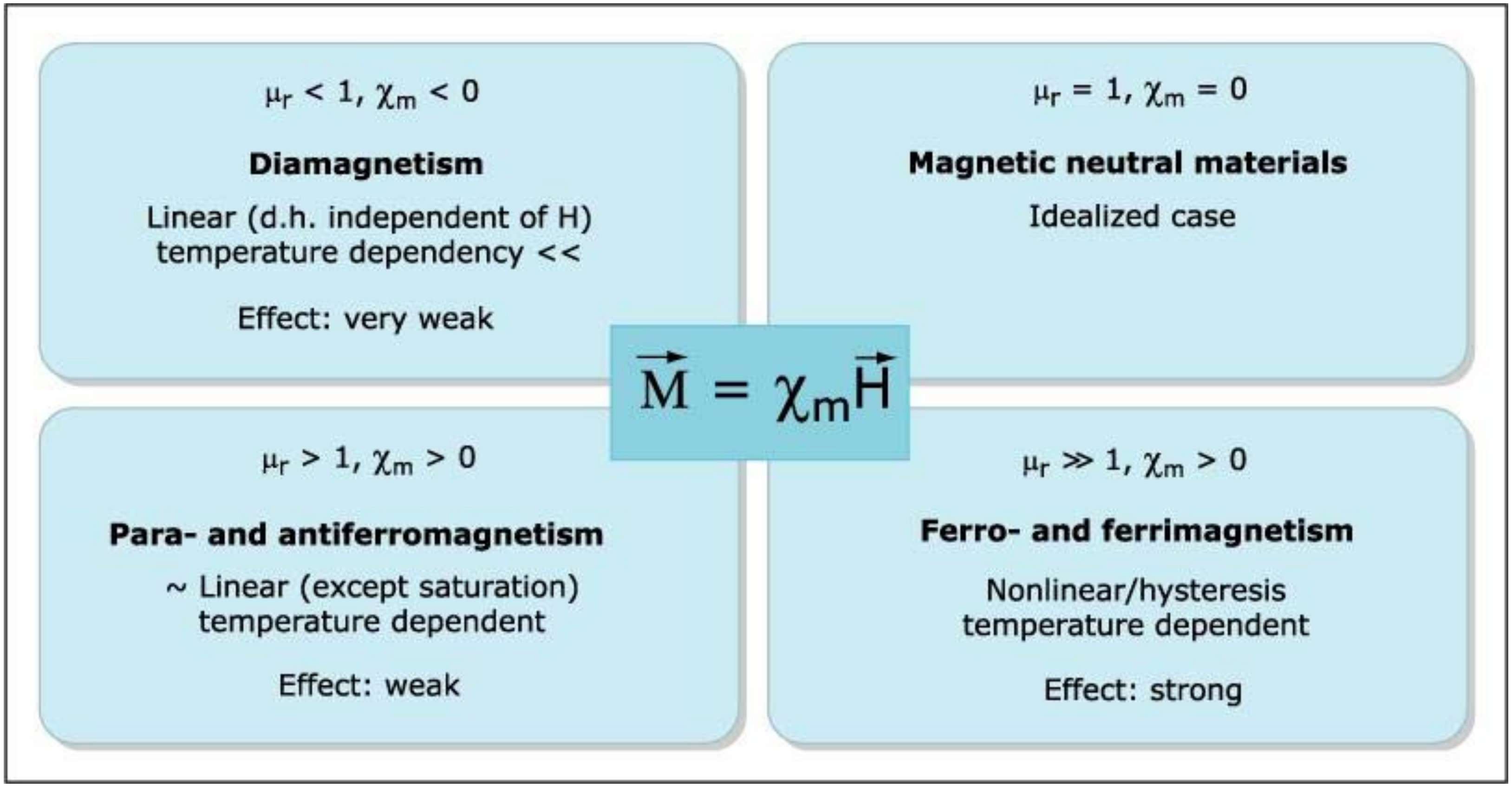
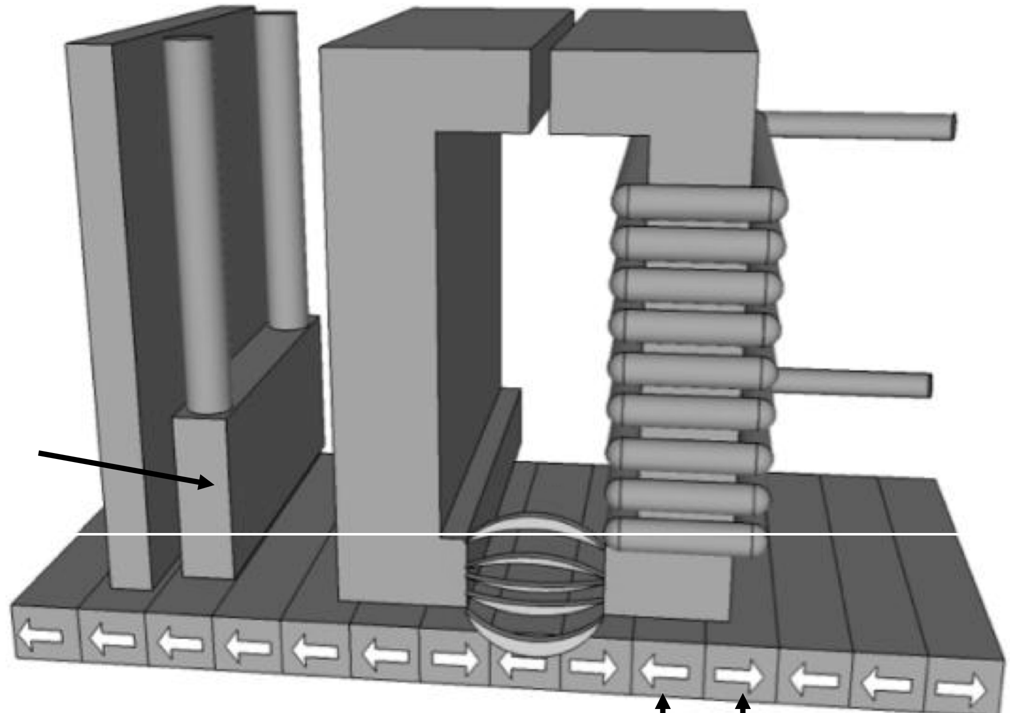


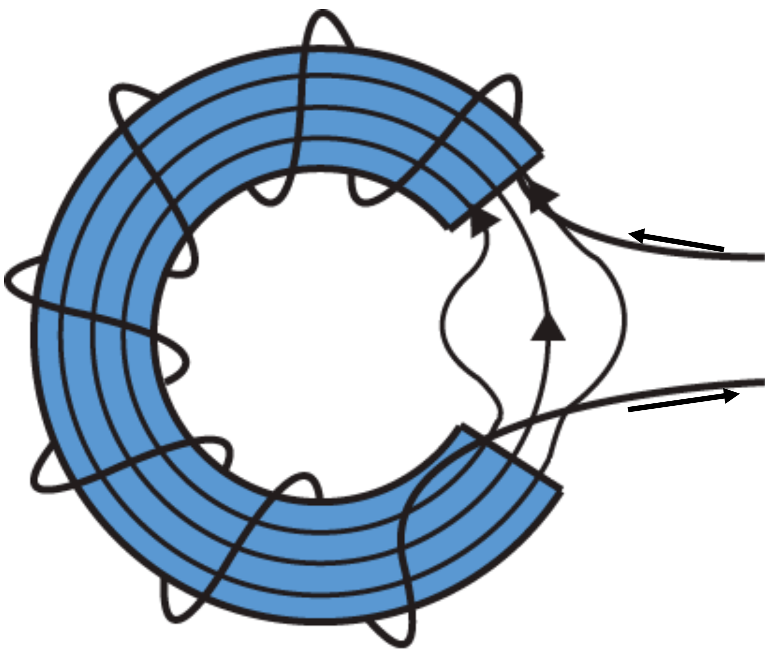
Image by MIT OpenCourseWare.

$\mu_r = 1 + \chi_m$ is the *relative permeability* of the material

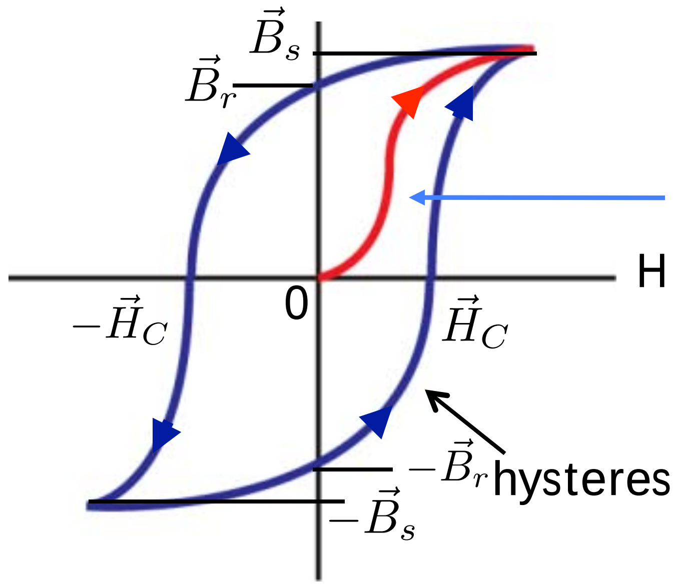
$\mu = \mu_o\mu_r$ is the *permeability* of the material

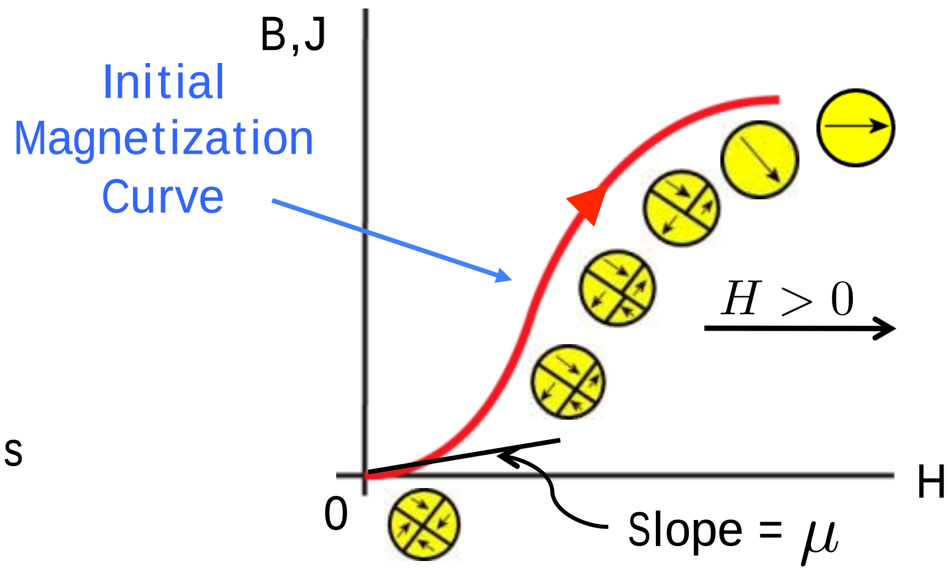
Magnetic Storage





Ferromagnetic Materials





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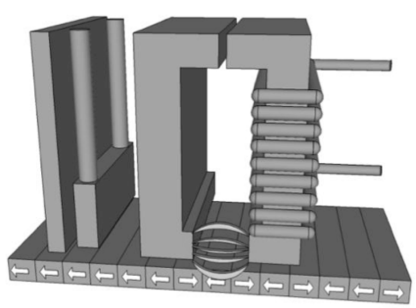
Hr : coercive magnetic field strength
Bs : remanence flux density
B : saturation flux density

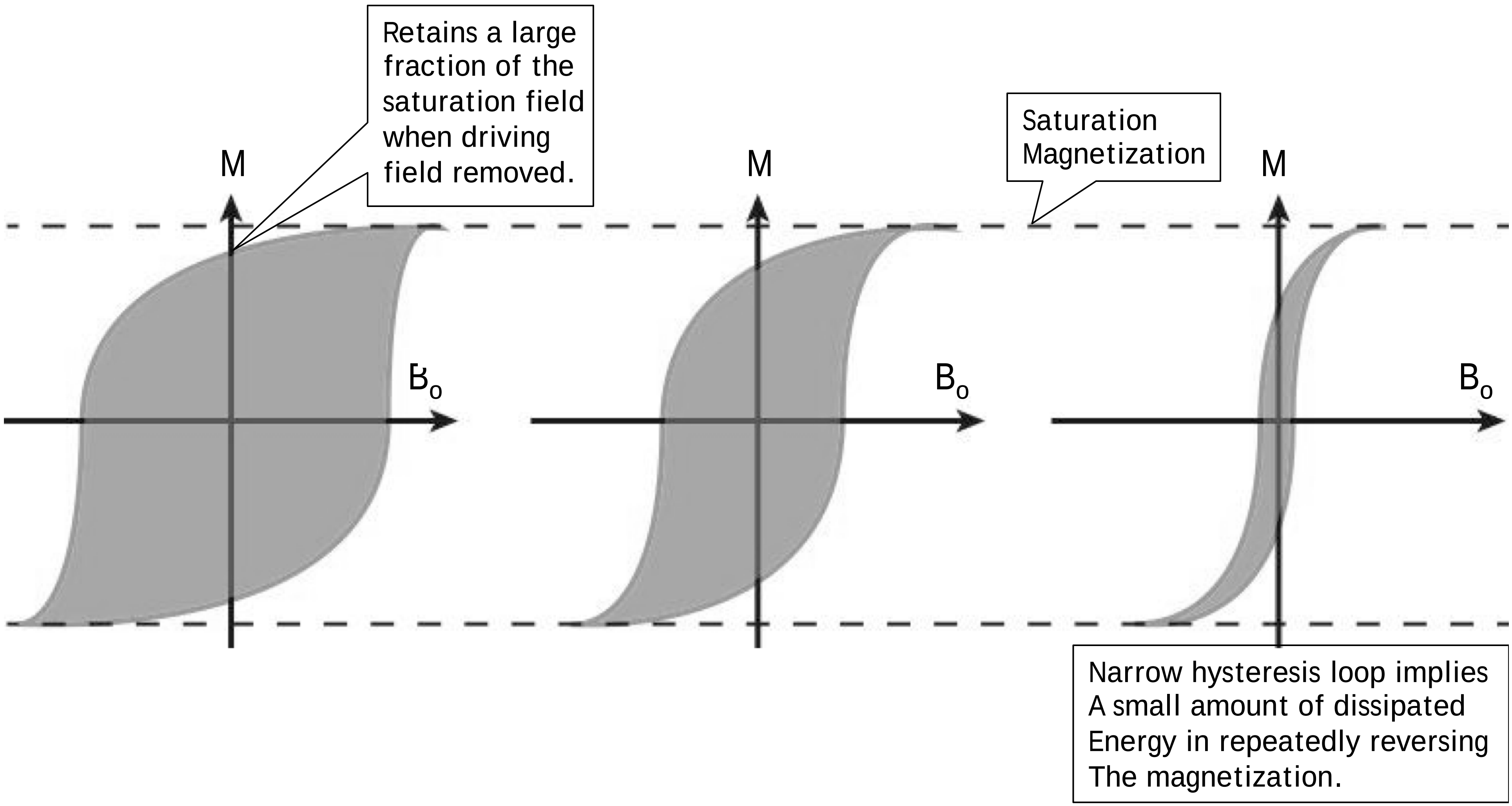
Behavior of an initially unmagnetized material.
Domain configuration during several stages of magnetization.



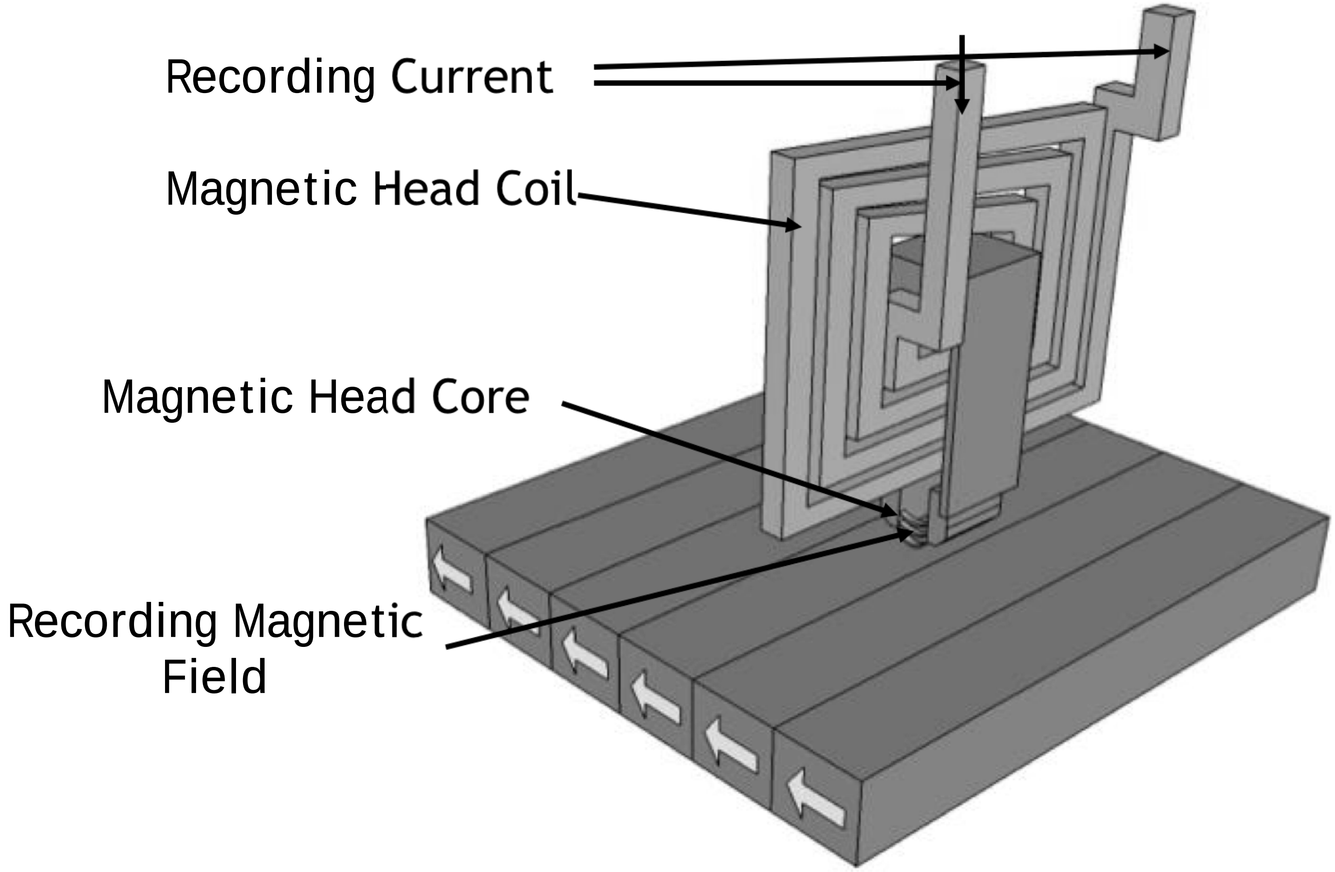
$$H \sim i$$

Choosing Magnetic Storage

Which material is most attractive for the storage media ?

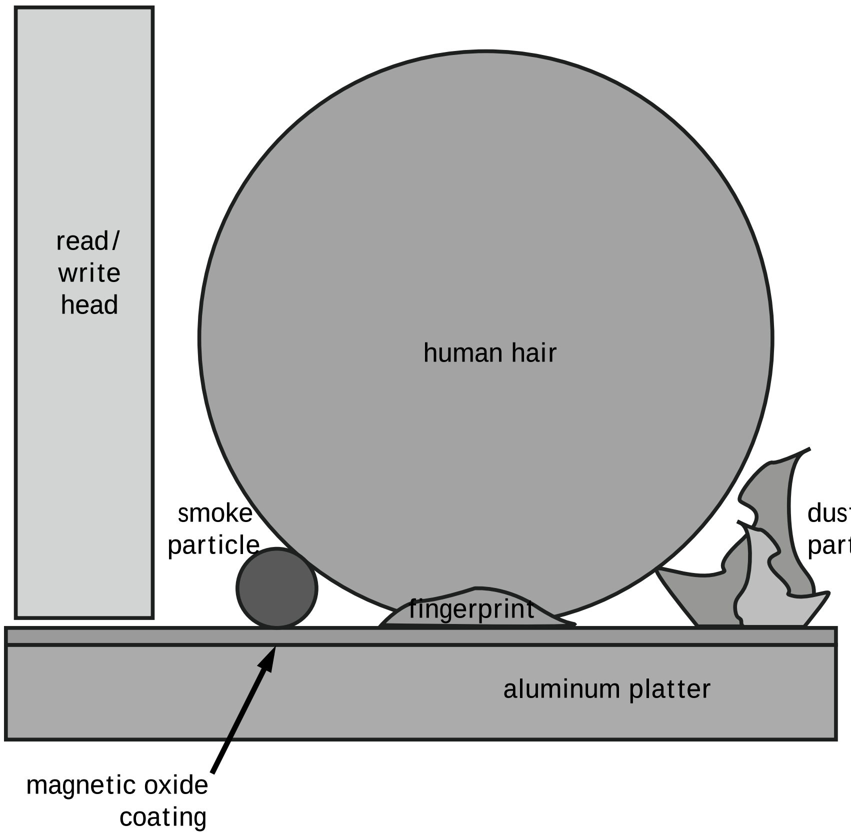


Thin Film Write Head



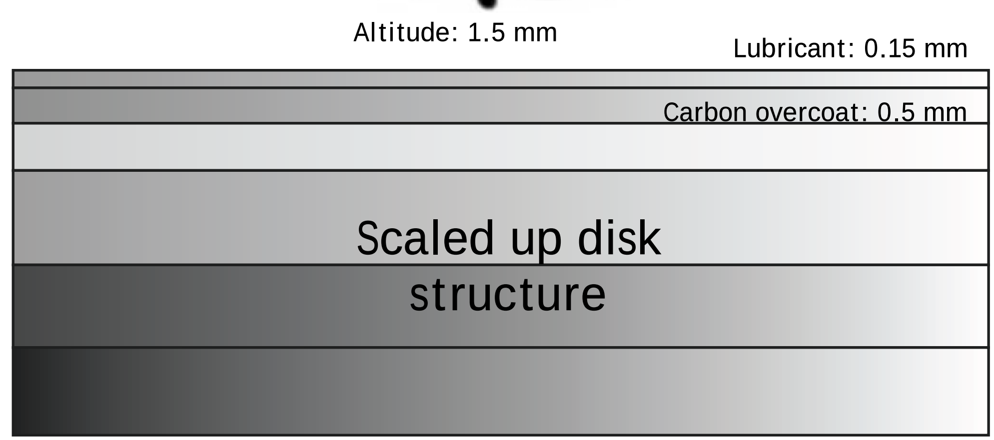
Close-up of a hard disk head resting on a disk platter. A reflection of the head and its suspension is visible on the mirror-like disk.

Practical Issues with Scaling

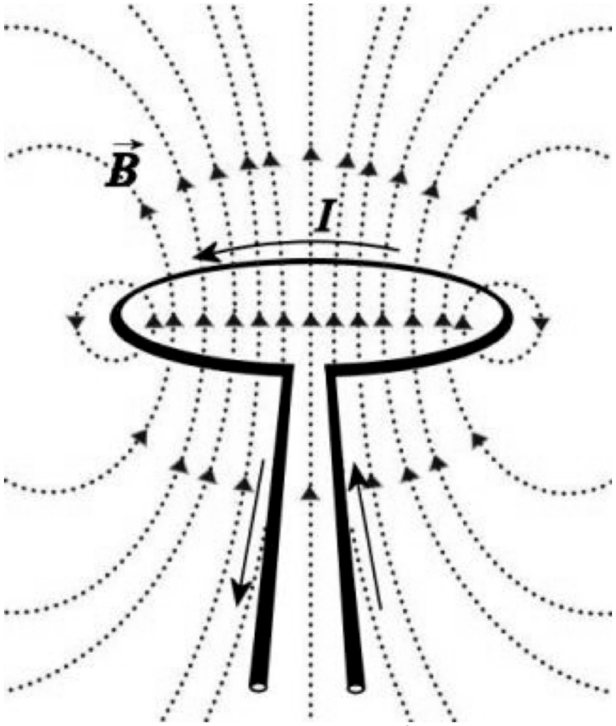


As the magnetic domain size shrinks, the read/write head must move closer to the hard drive surface...

Image in the Public Domain



Summary



Magnetic Moment

$$\overrightarrow{m} = i\,\overrightarrow{a}$$

$$\vec{M} = N\vec{m}$$

$$\vec{M} = \chi_m \vec{H}$$

$$\vec{B} = \mu_o\left(\vec{H} + \vec{M}\right)$$

$$= \mu_o\left(\vec{H} + \chi_m \vec{H}\right)$$

$$= \mu_o \mu_r \vec{H}$$