A Conceptual Introduction to the Physics of Magnetic Particles

Tim St Pierre

School of Physics

The University of Western Australia

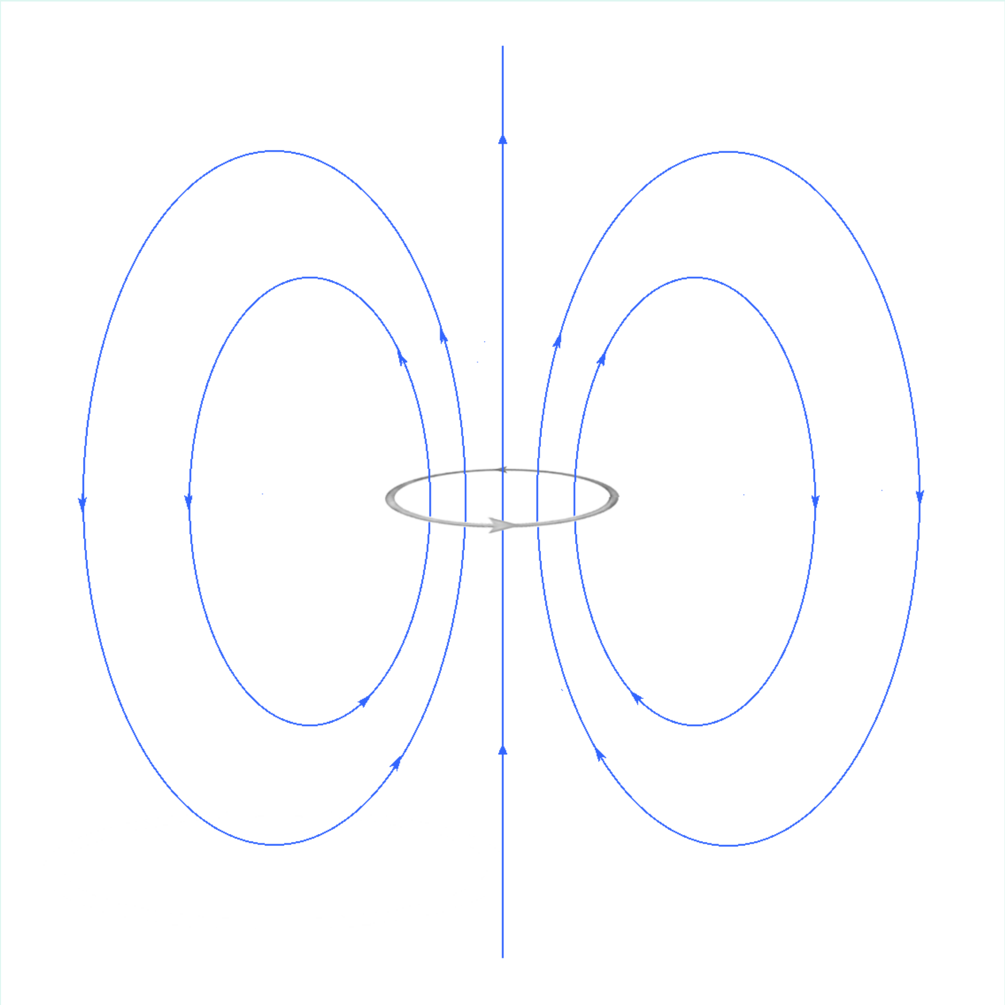
Outline of Lectures

- **Lecture 1**
  - Magnetic Moments and Magnetic Fields
  - Magnetic Materials - an Empirical Approach
- **Lecture 2**
  - Magnetic Materials - the Microscopic Picture
  - Small Particle Magnetism
- **Lecture 3**
  - Magnetic Particles in Fluids
  - Design of magnetic carriers

Lecture 1

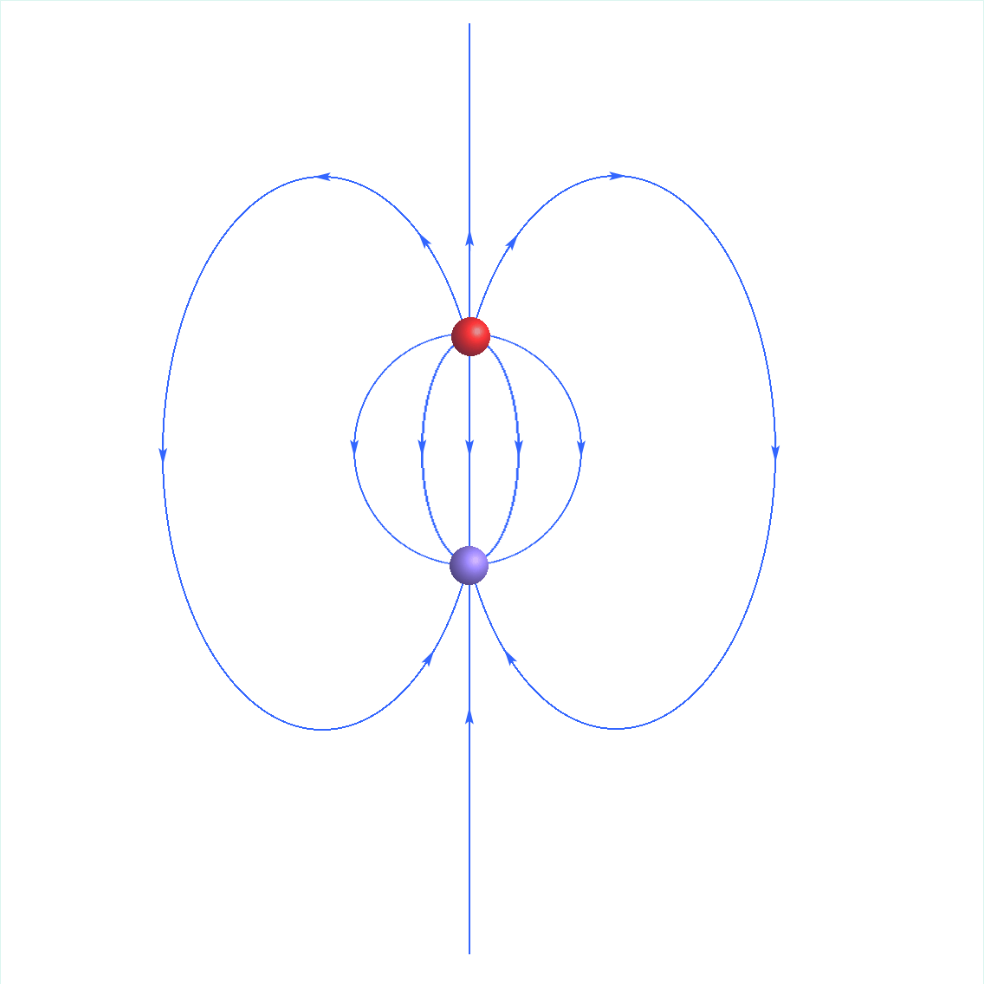
Magnetic Moments and Magnetic Fields

Magnetic fields are generated by movement of electric charges



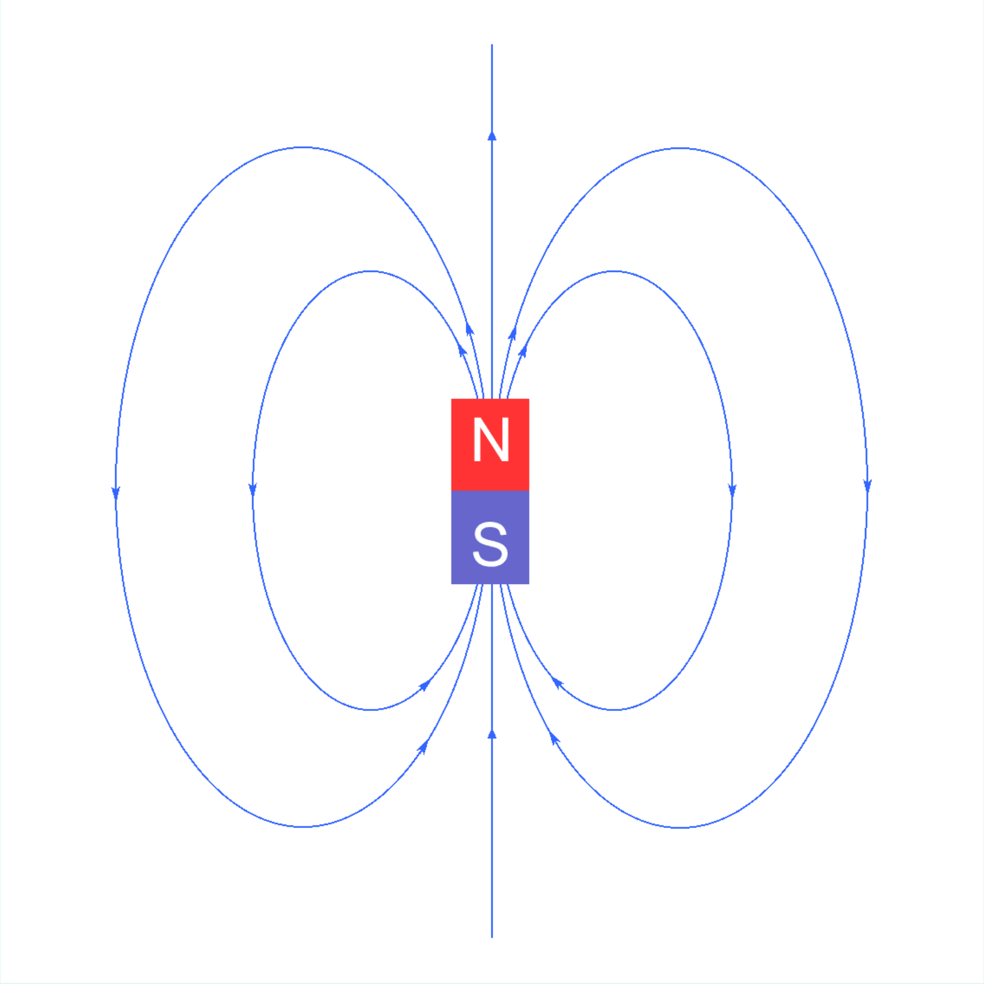
A loop of electric current generates a magnetic dipole field

A magnetic dipole



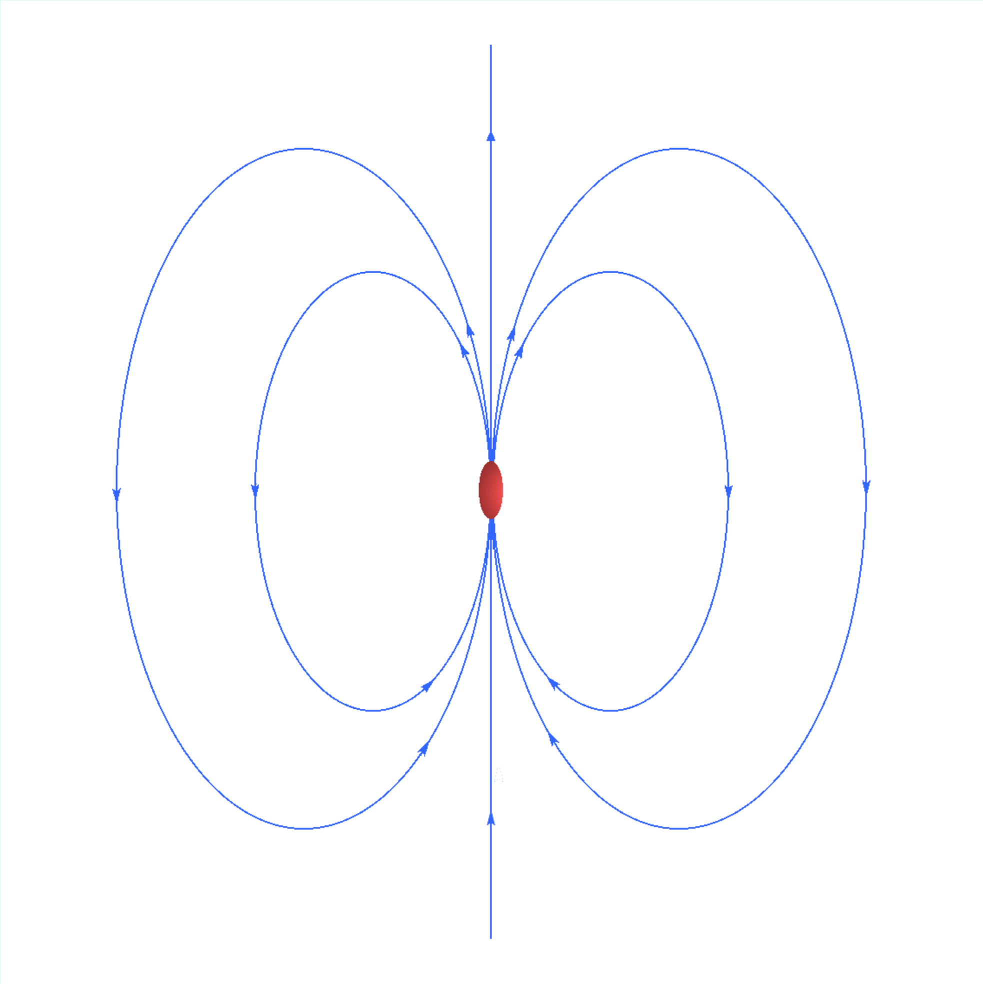
- Field lines run from the North pole to the South pole
- Field lines indicate the direction of force that would be experienced by a North magnetic monopole

A bar magnet



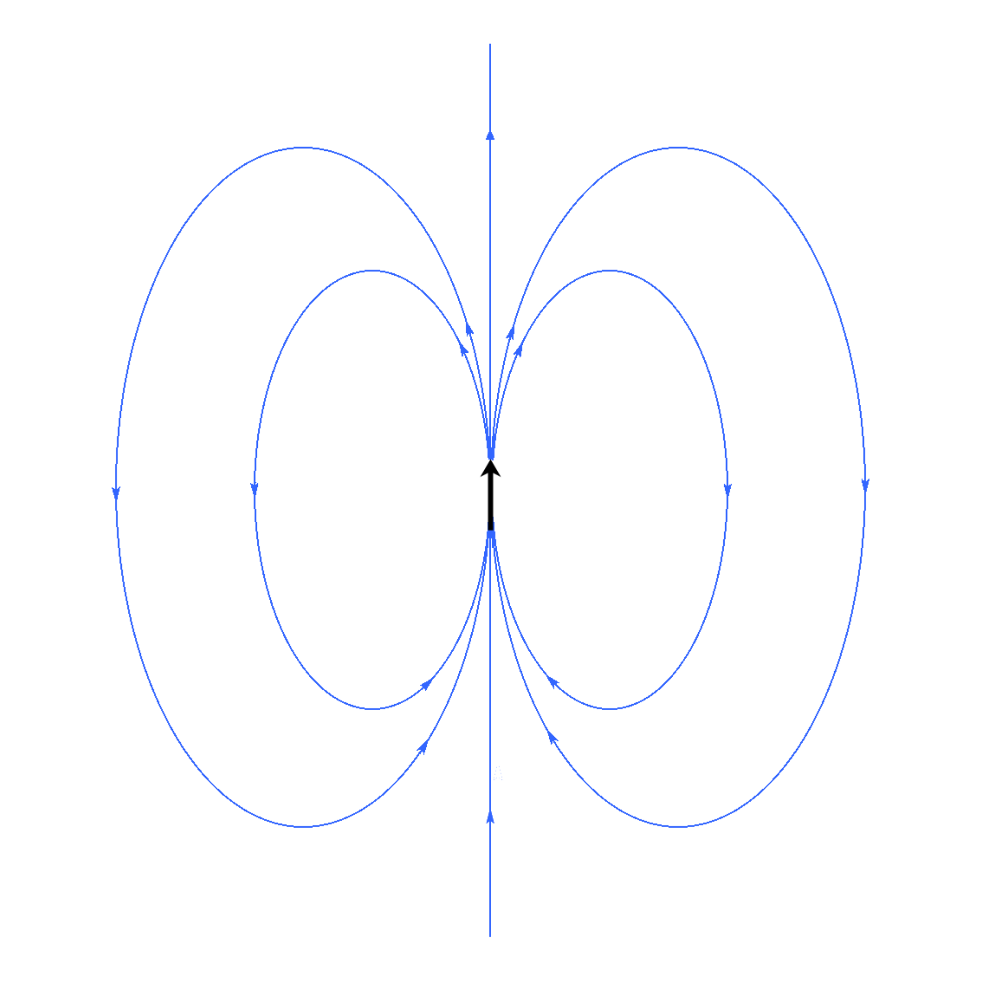
A simple bar magnet behaves like a magnetic dipole

Far field picture



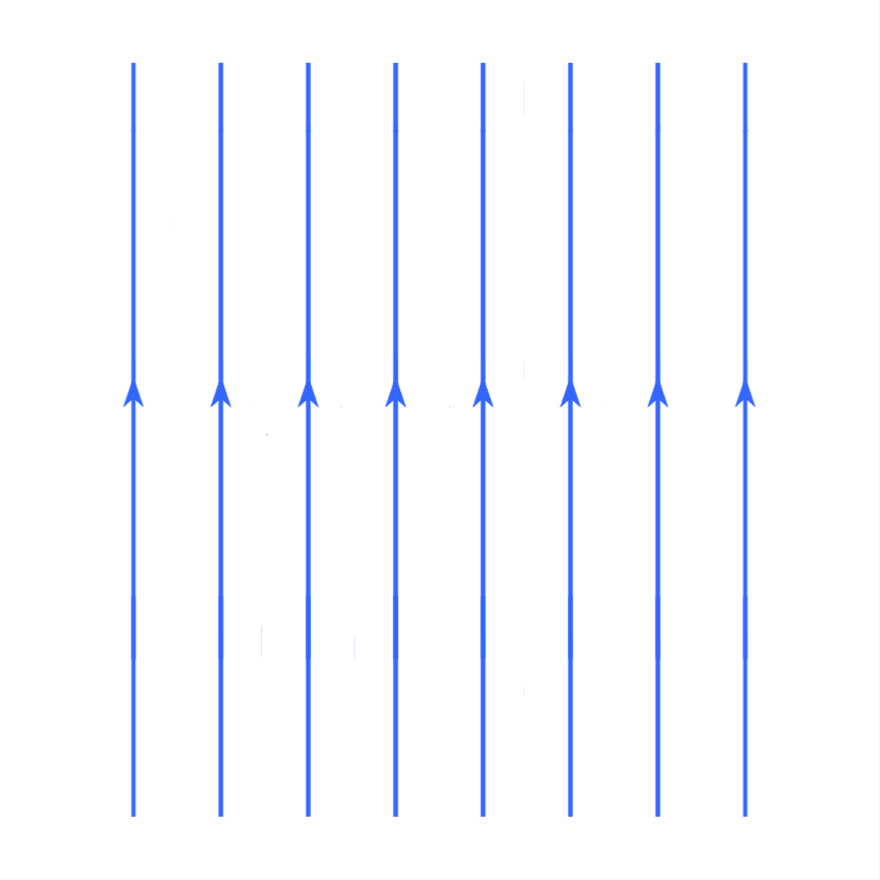
- Sometimes the dipoles are very small compared with their spatial field of influence
- An electron, for example

Schematic representation



- A magnetic dipole is often represented schematically as an arrow.
- The head of the arrow is the North pole.

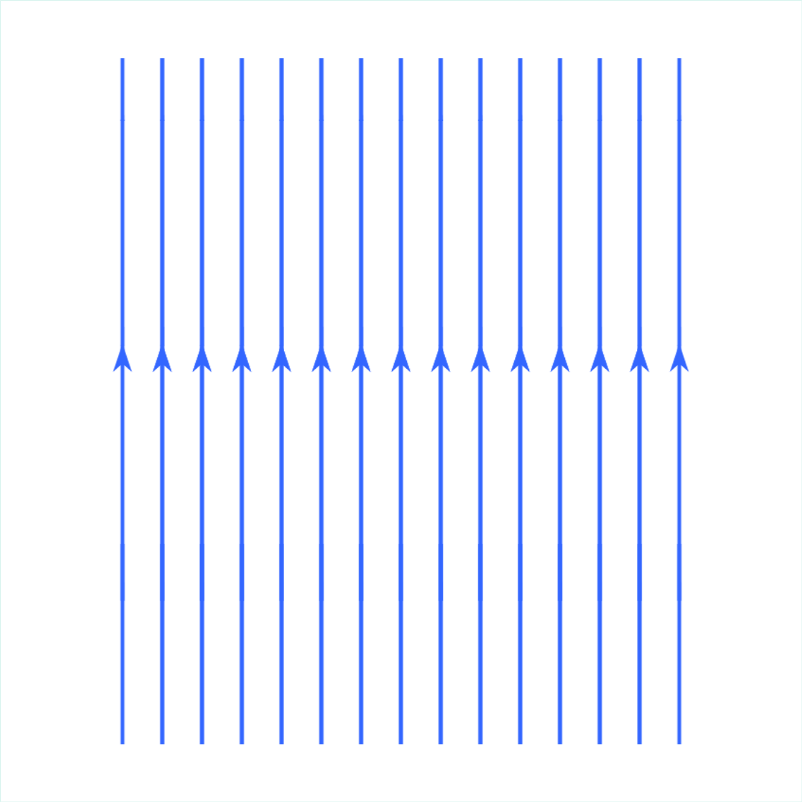
Flux density, *B*



- **Density of flux (or field) lines determines forces on magnetic poles**
- **Direction of flux indicates direction of force on a North pole**

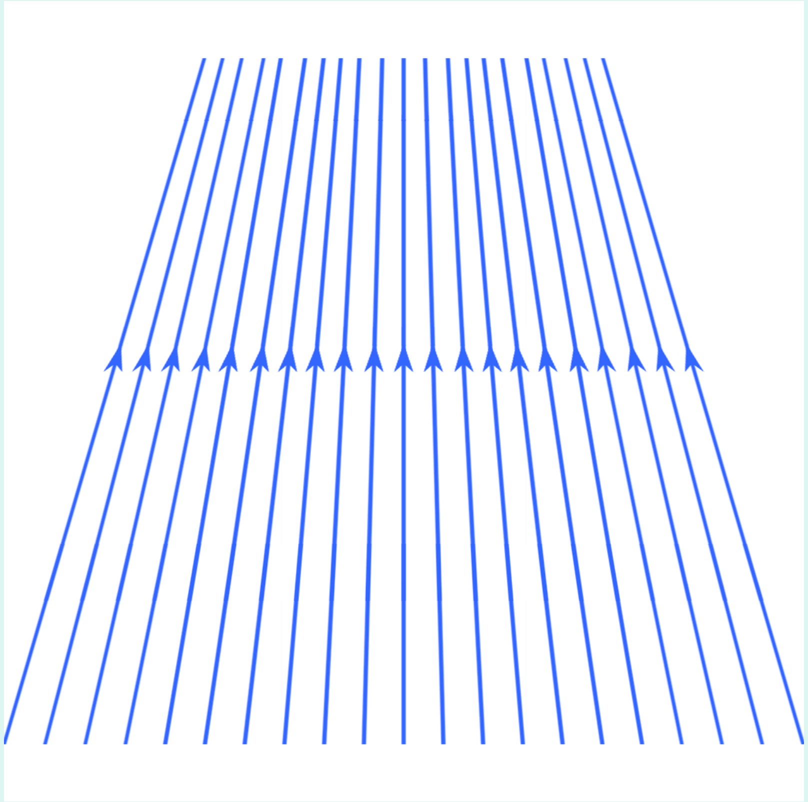
$$B = \phi / A$$

Flux density, *B*



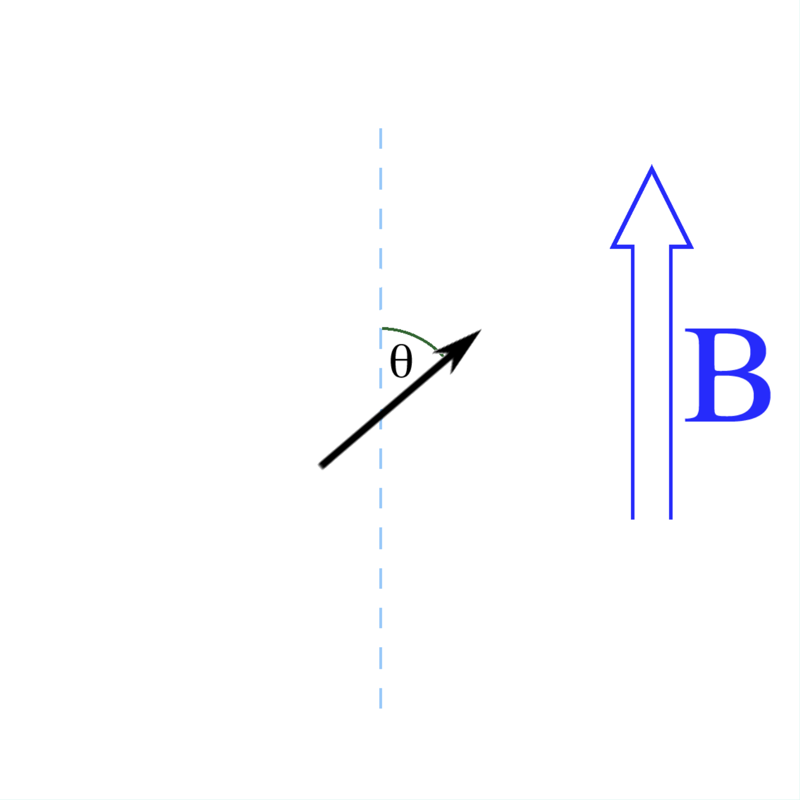
- **Higher flux density exerts more force on magnetic poles**

Magnetic field gradients



- **Magnetic field gradients exist when flux lines converge of diverge**

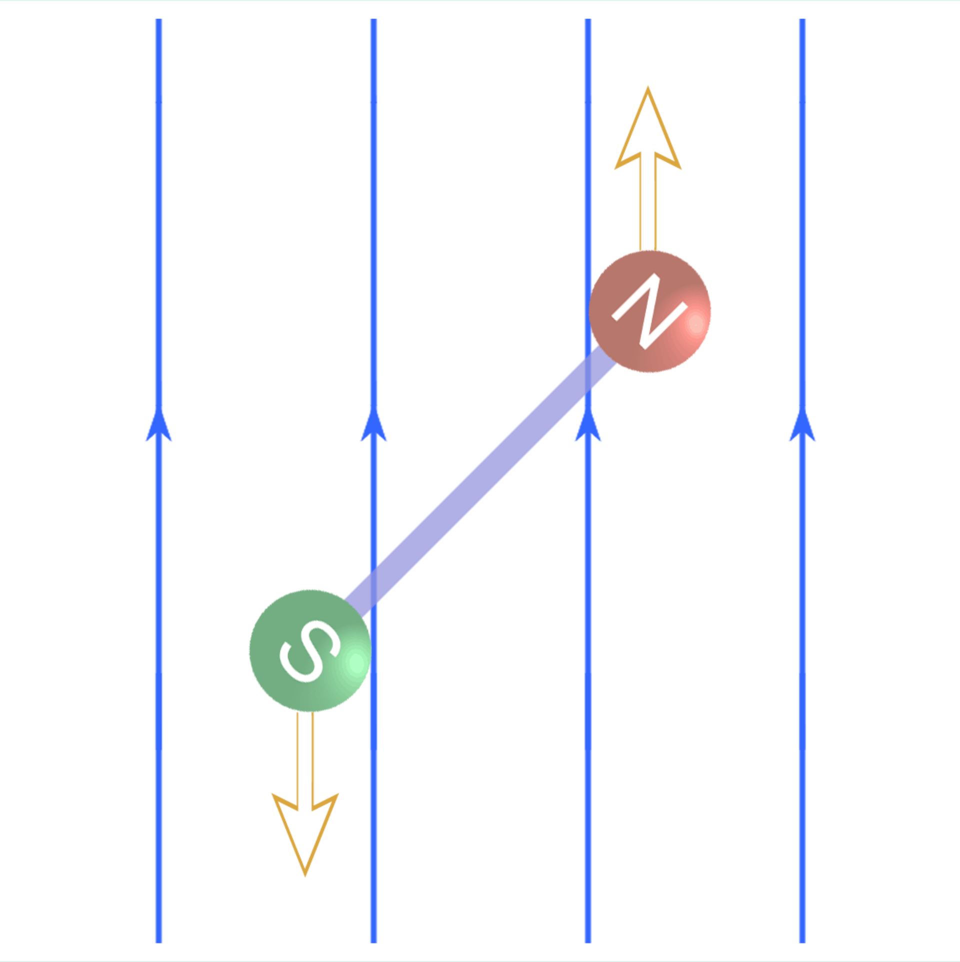
Magnetic Moment



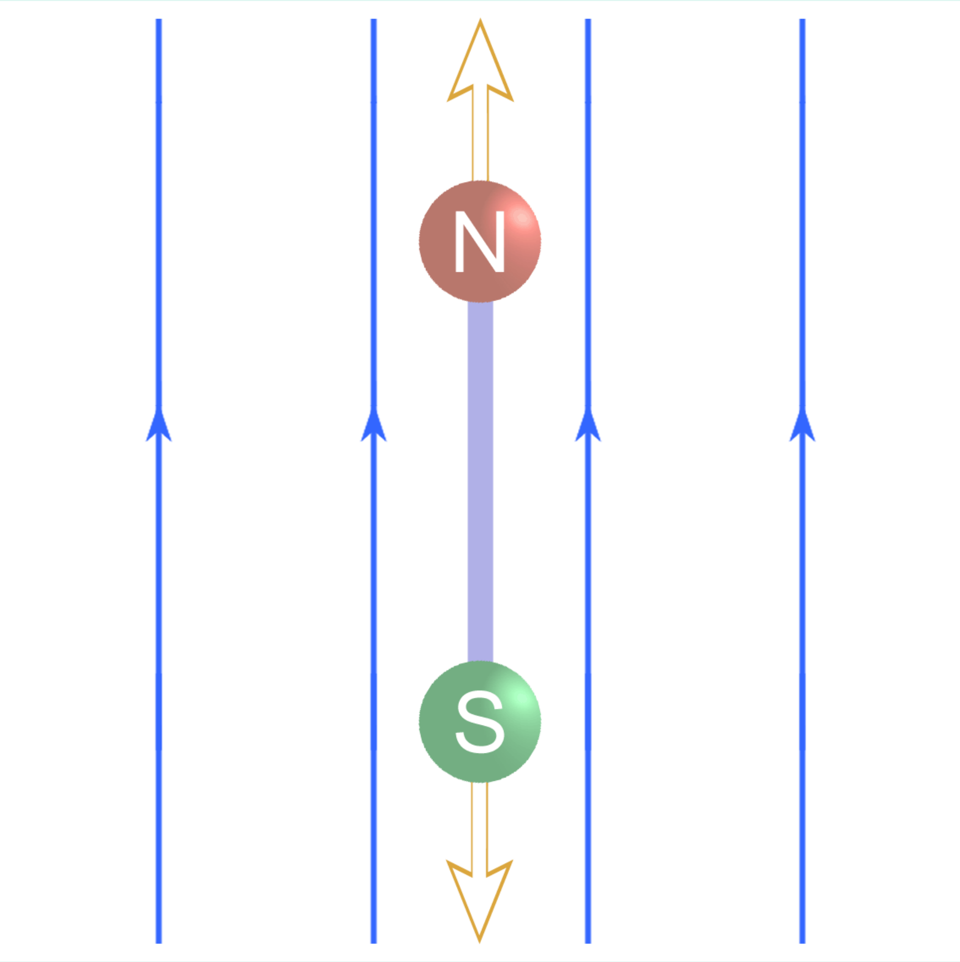
- **A magnetic dipole in a field *B* experiences a torque, τ**
- **Magnitude of τ depends on B and magnetic dipole moment, *m*.**

$$\tau = mB\sin(\theta)$$

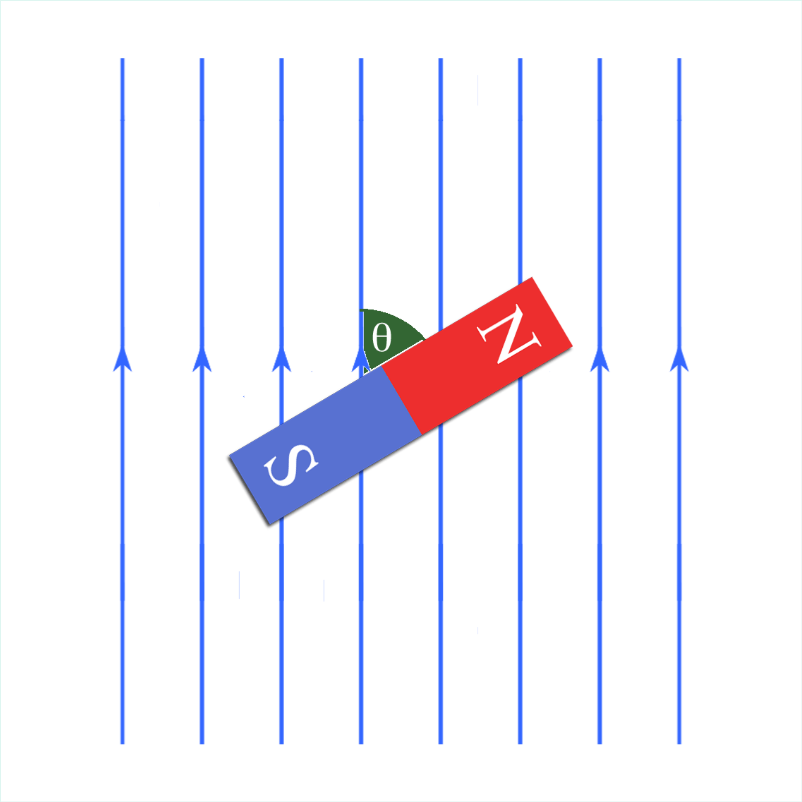
Magnetic dipole in a field



Magnetic dipole in a field



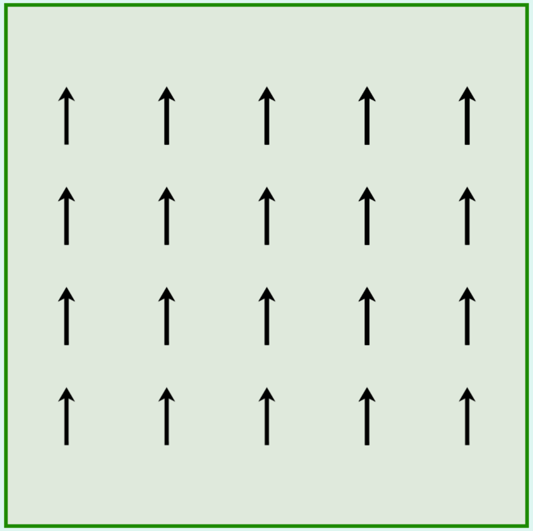
Compass needles



- A magnetic compass needle has a magnetic moment
- Needle is oriented in the Earth's magnetic field.
- Note that both magnetic moment and field are vectors

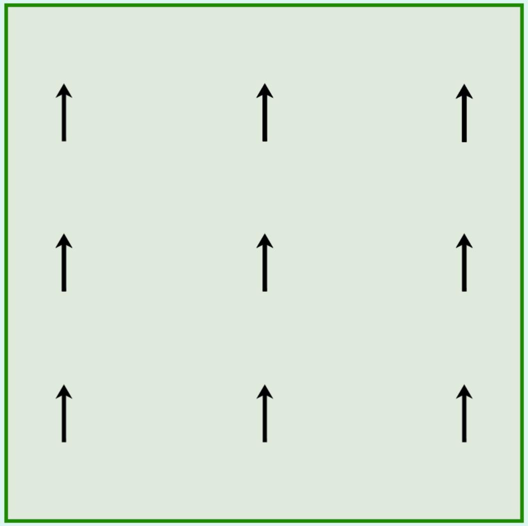
Magnetic Materials -
an Empirical Approach

Magnetization, *M*



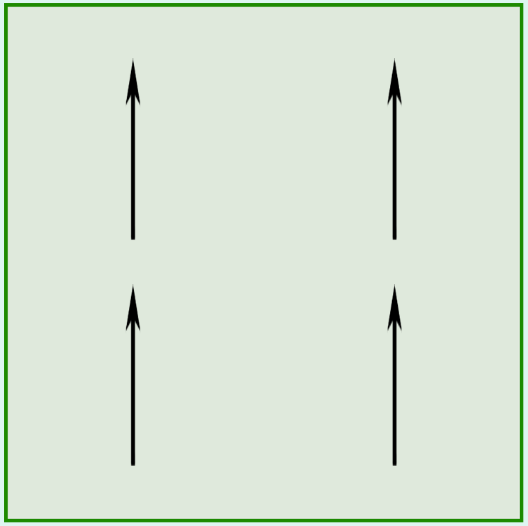
- **Material with a net magnetic moment is magnetized**
- **Magnetization is the magnetic moment per unit volume within the material**

Magnetization depends on………



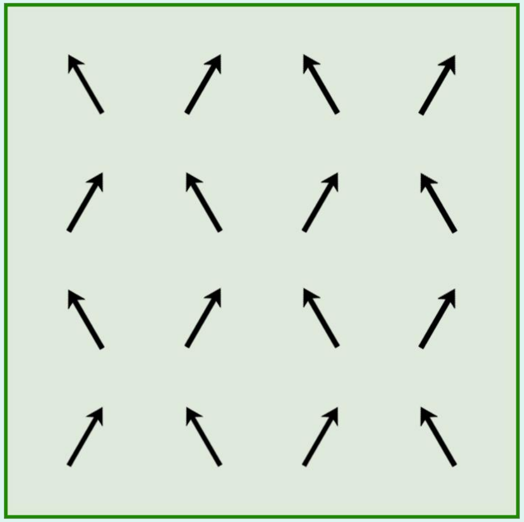
- **Number density of magnetic dipole moments within material**

Magnetization depends on………



- **Magnitude of the magnetic dipole moments within the material**

Magnetization depends on……..

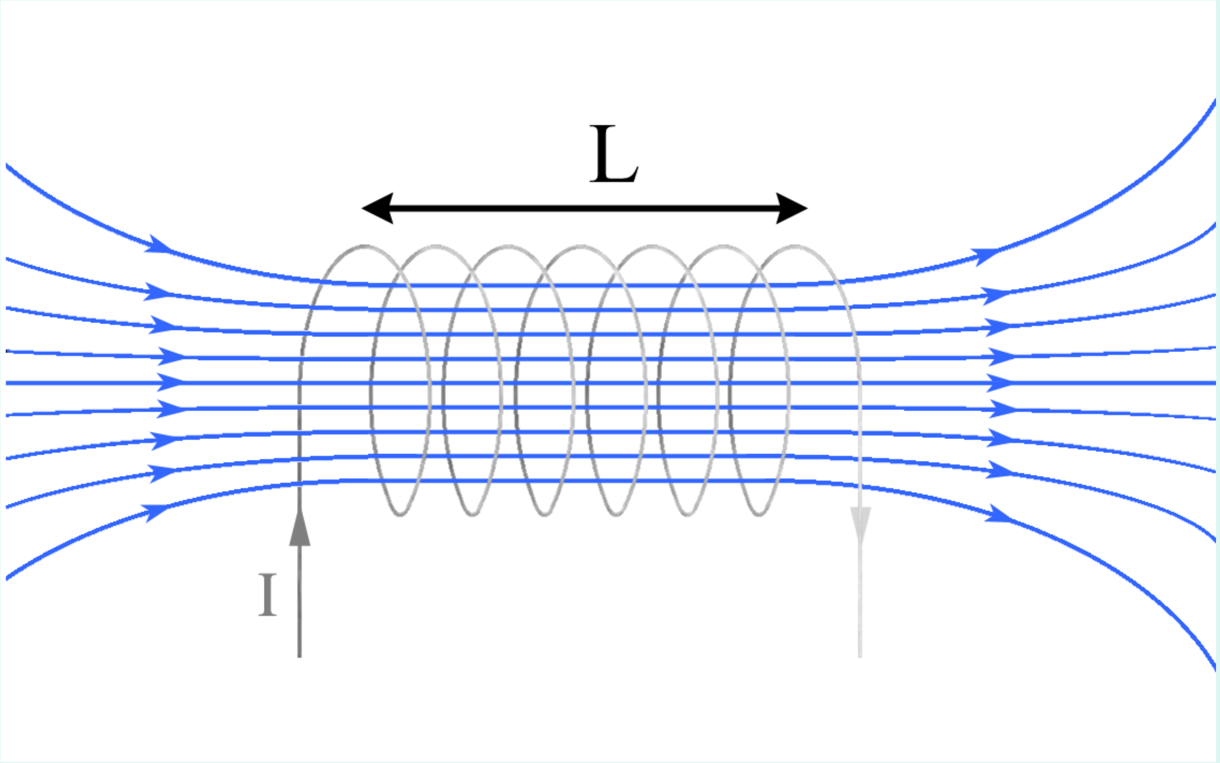


- **The arrangement of the magnetic dipoles within the material**

Magnetization in materials arises from…….

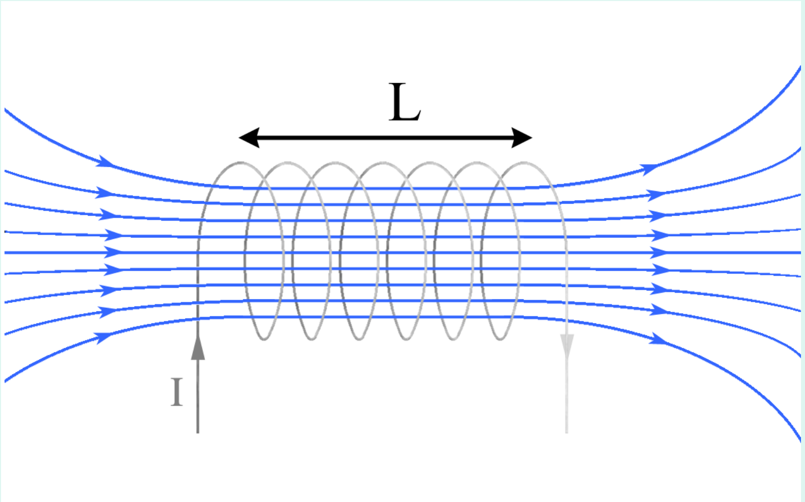
- **unpaired electron spins mainly**
- **the orbital motion of electrons within the material to a lesser extent**

Generating a uniform magnetic field in the laboratory



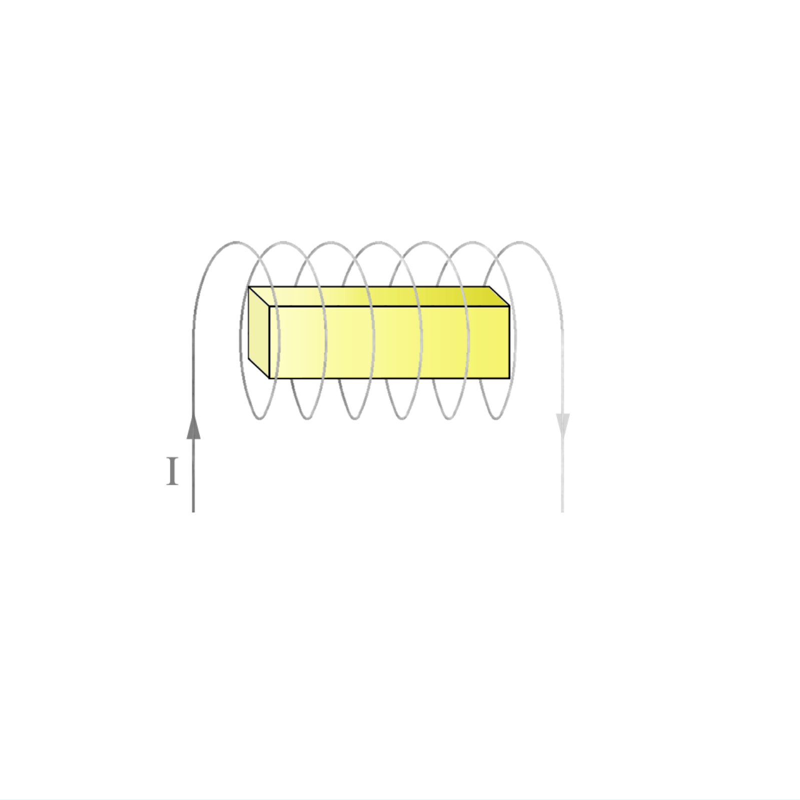
- **An electric current run through a conducting coil (solenoid) generates a uniform flux density within the coil**

Flux density in vacuum (or air) within coil……..



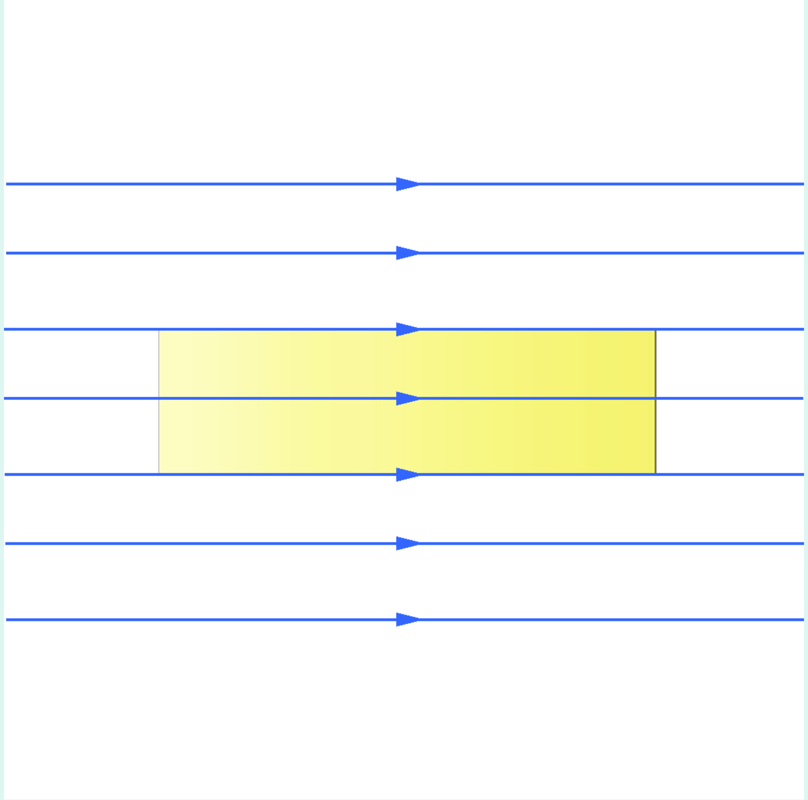
- **Increases in proportion to the electric current**
- **Increases in proportion to the number of turns per unit length in the coil**

Inserting a specimen into the coil



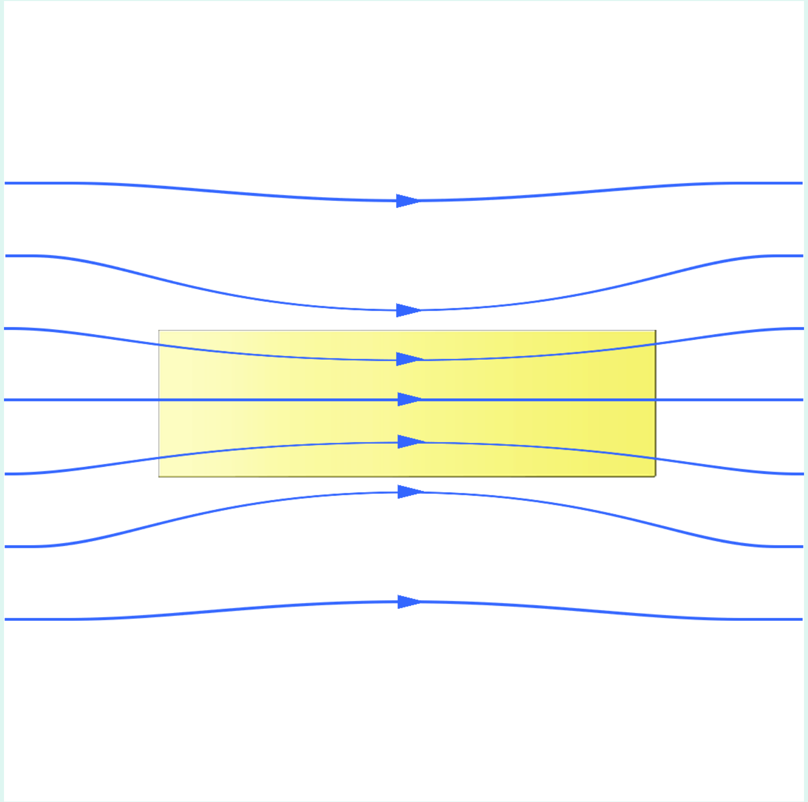
- **Generally, the orbital and spin magnetic moments within atoms respond to an applied magnetic field**
- **Flux lines are perturbed by specimen**

Specimen in magnetic field



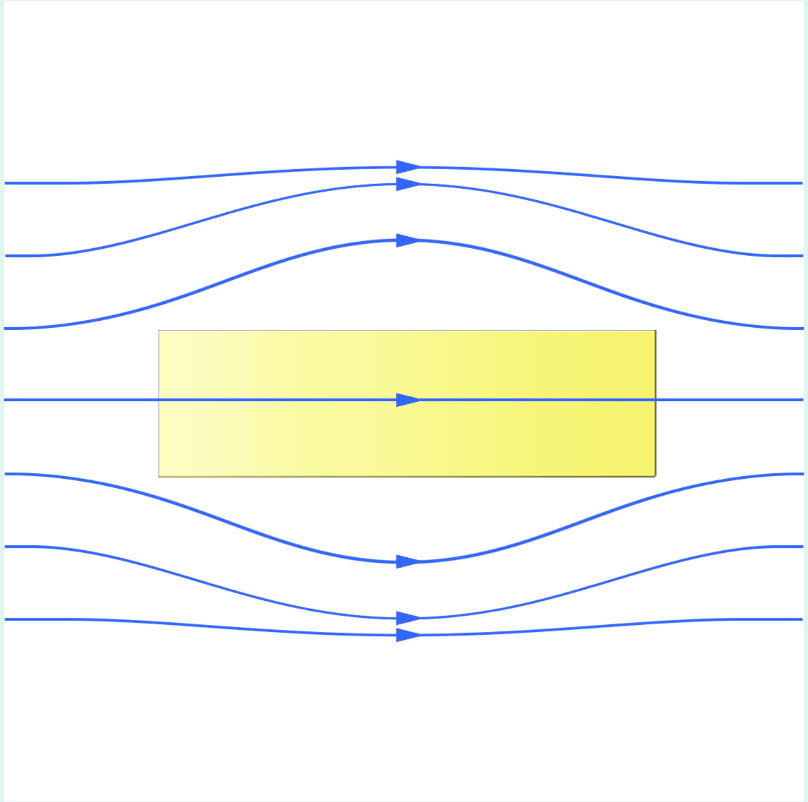
- **If specimen has no magnetic response, flux lines are not perturbed**

“Magnetic” materials



- “magnetic” materials tend to concentrate flux lines
- Examples: materials containing high concentrations of magnetic atoms such as iron, cobalt

Diamagnetic materials

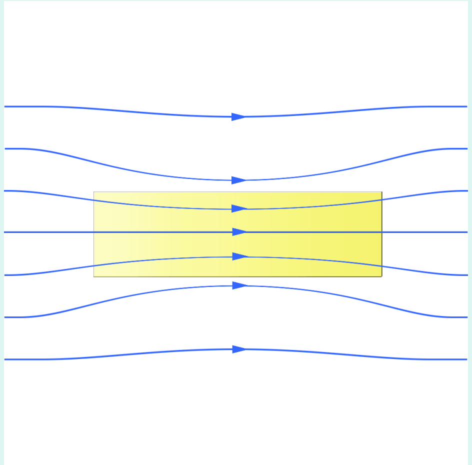


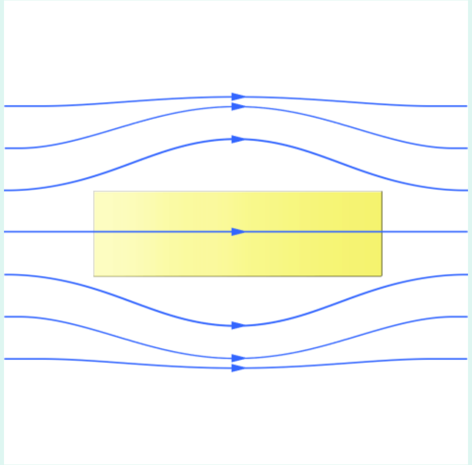
- **Diamagnetic materials tend to repel flux lines weakly**
- **Examples: water, protein, fat**

Flux density *B* within material determined by both……

- **Geometry and current in solenoid**
- **Magnetic properties of the material**
- **Geometry of material**

$$\boldsymbol{B} = \mu_0 (\boldsymbol{H} + \boldsymbol{M})$$



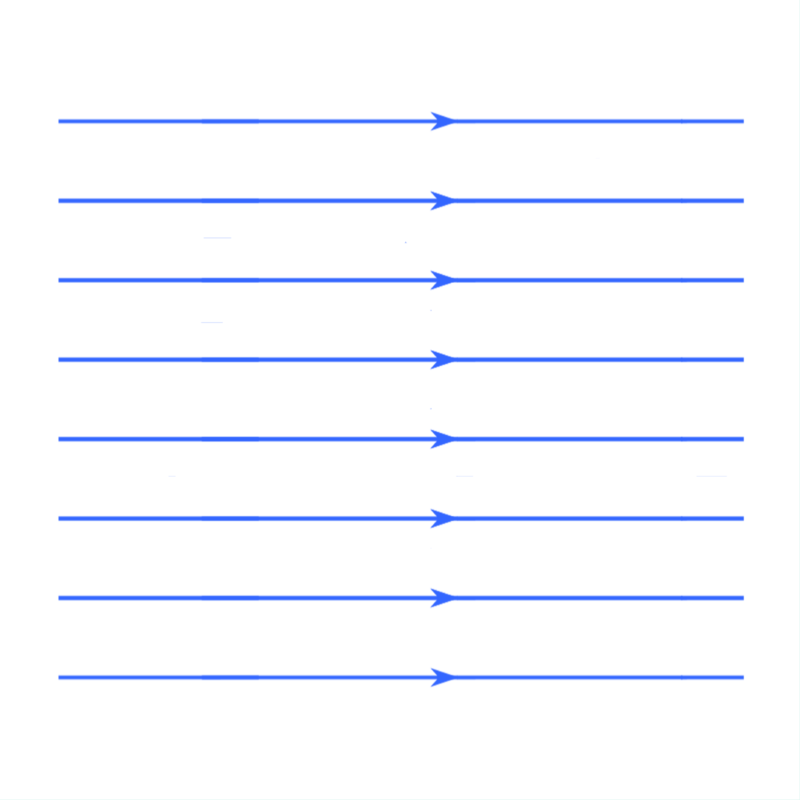


The $\boldsymbol{H}$ Field

- **H is called the magnetic field strength**

- **μ_0 is a constant called the permeability of free space**

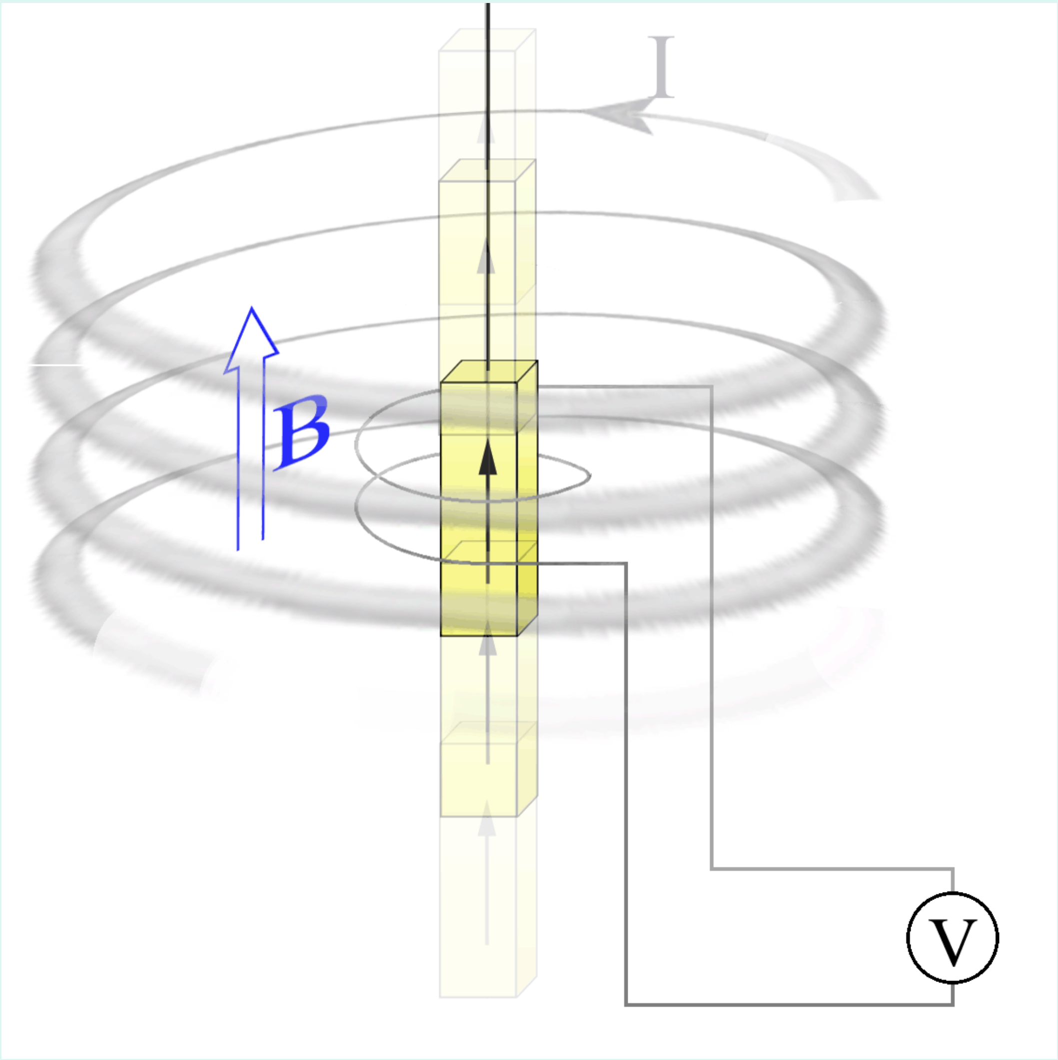
In the absence of material in the solenoid……



- **There is no magnetization M**
- **So…..**

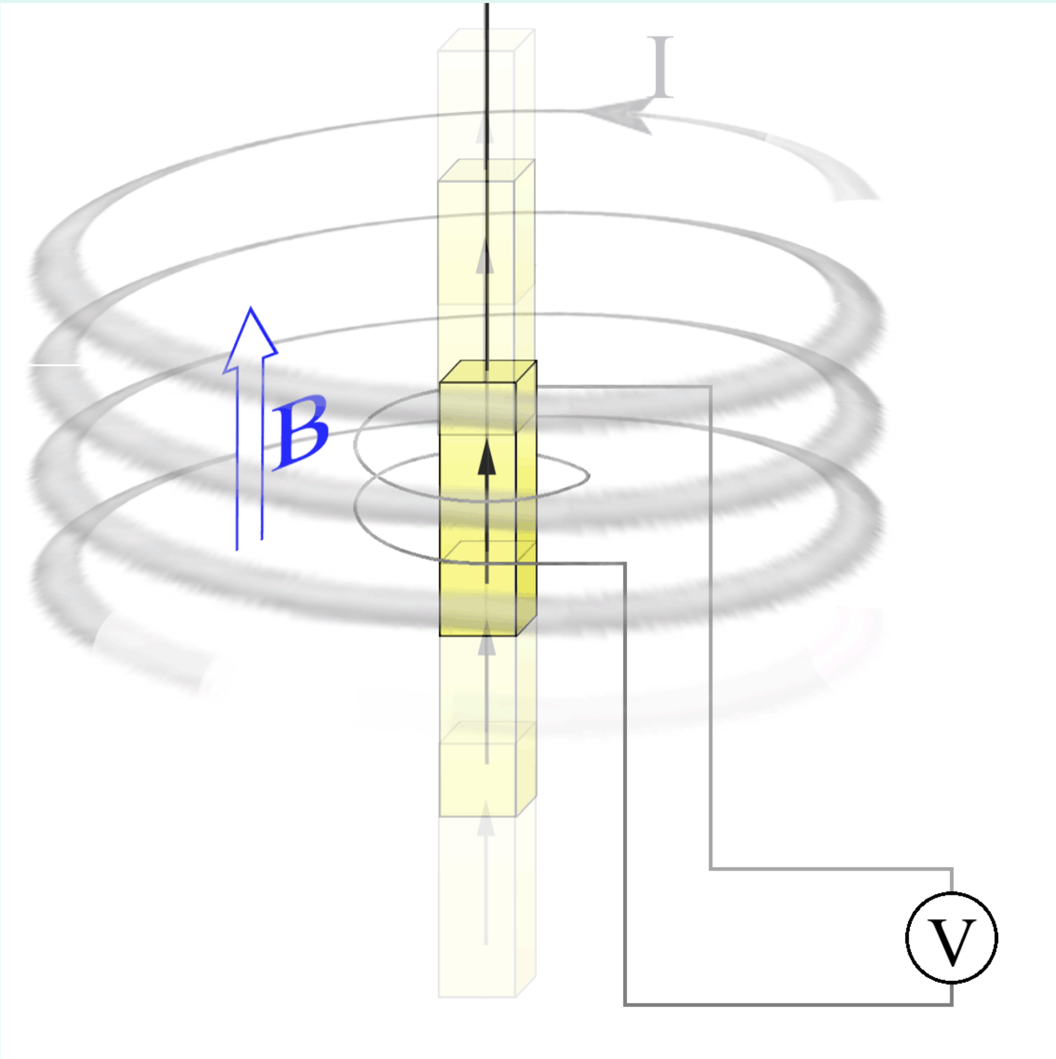
$$\boldsymbol{B} = \mu_0 \boldsymbol{H}$$

Measuring magnetic moment of specimen



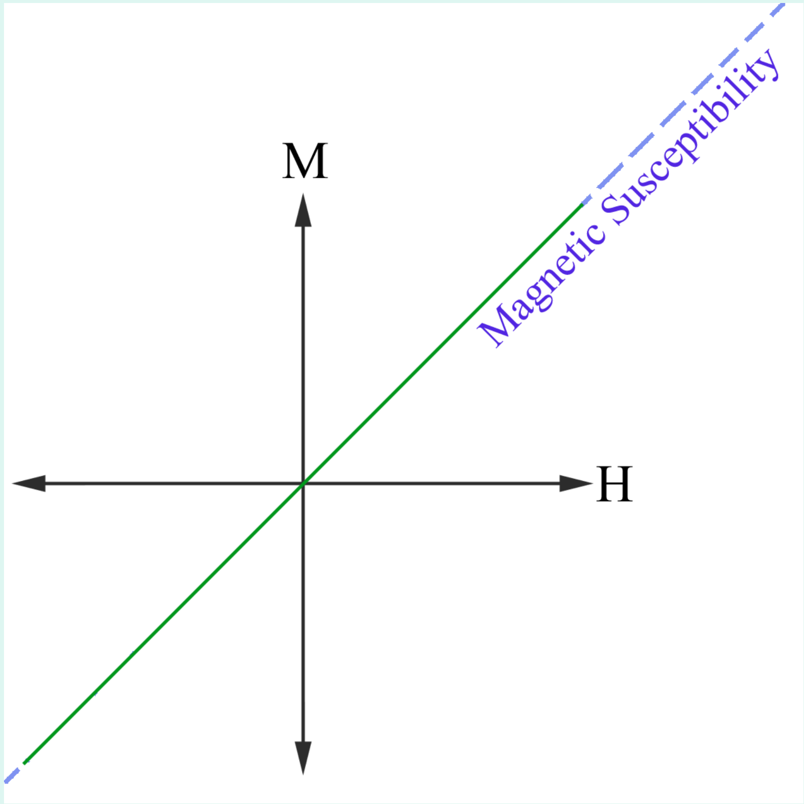
- **Pass specimen thru small "sensing" coil**
- **Measure voltage generated across coil**
- **Voltage proportional to moment on specimen**

Measuring magnetic moment of specimen



- **Use large coil to apply magnetic field to specimen**
- **Use a cryostat or furnace to vary temperature of specimen**

Response of material to applied magnetic field strength *H*



- **Generally, *M* changes in magnitude as *H* is varied.**
- **Magnitude of response is called the "magnetic susceptibility" of the material**

Response of material to applied magnetic field strength $\boldsymbol{H}$

- **Diamagnetic materials have a very weak negative response**
- **i.e. they have a small negative magnetic susceptibility**

Magnetic susceptibility, χ

- **Magnetic susceptibility is sometimes written as**

$$\chi = M/H$$

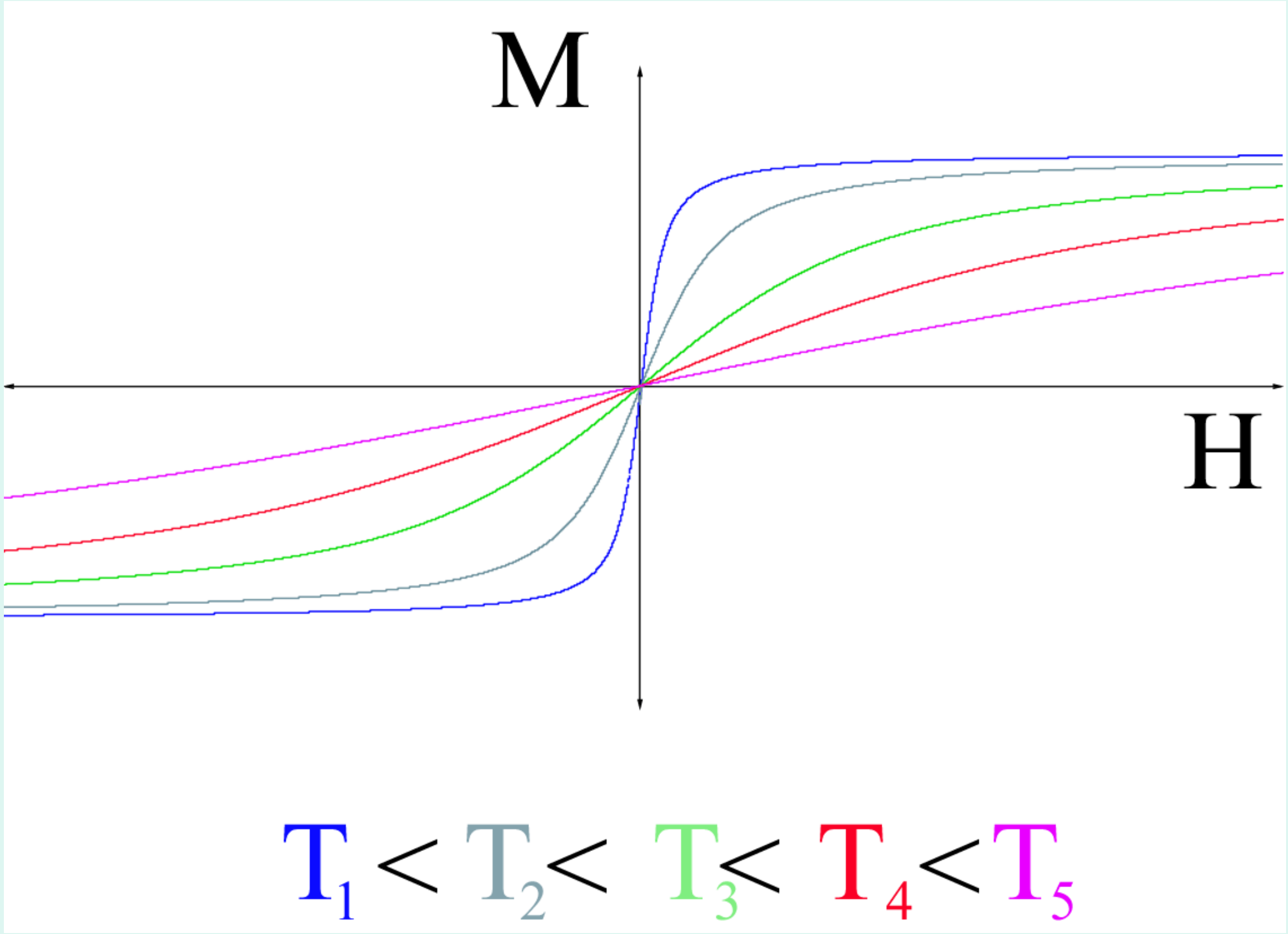
- **And sometimes as the slope of *M* vs *H***

$$\chi = dM/dH$$

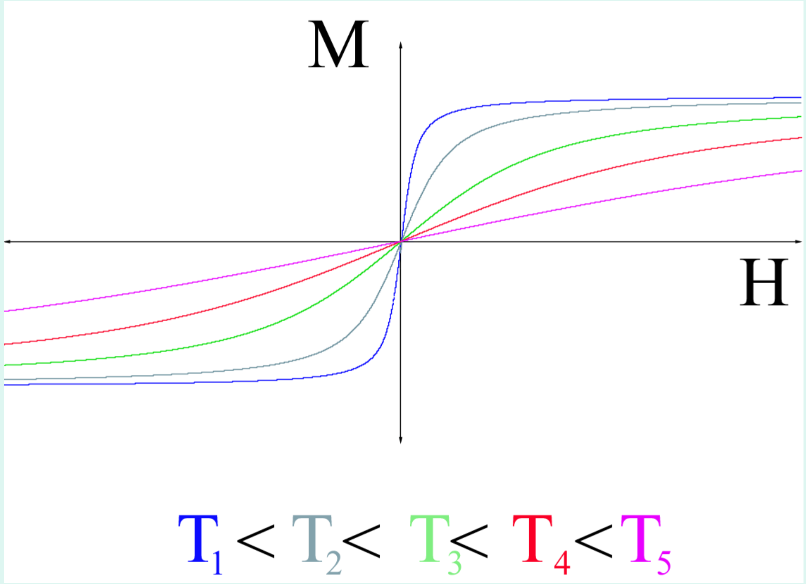
How does $\boldsymbol{M}$ respond to $\boldsymbol{H}$?

- **There is a variety of ways that $\boldsymbol{M}$ responds to $\boldsymbol{H}$**
- **Response depends on type of material**
- **Response depends on temperature**
- **Response can sometimes depend on the previous history of magnetic field strengths and directions applied to the material**

Non-linear responses

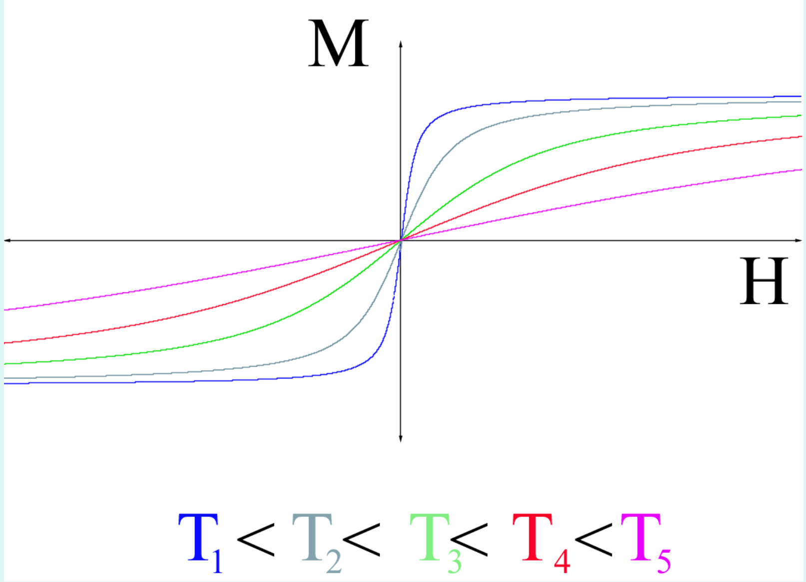


Non-linear responses



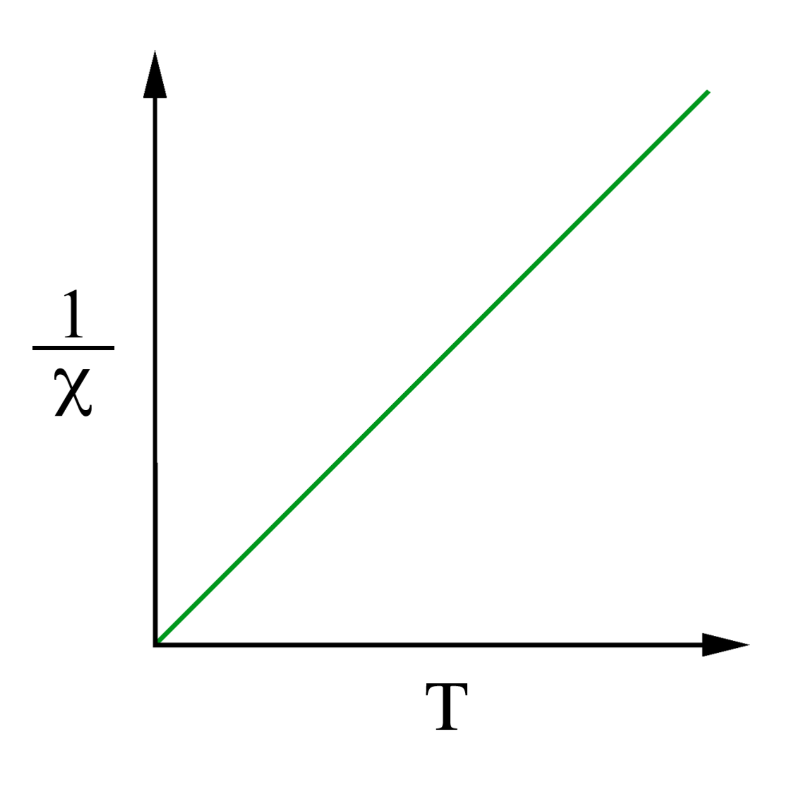
- **Generally, the response of *M* to *H* is non-linear**
- **Only at small values of *H* or high temperatures is response sometimes linear**

Non-linear responses



- ***M* tends to saturate at high fields and low temperatures**

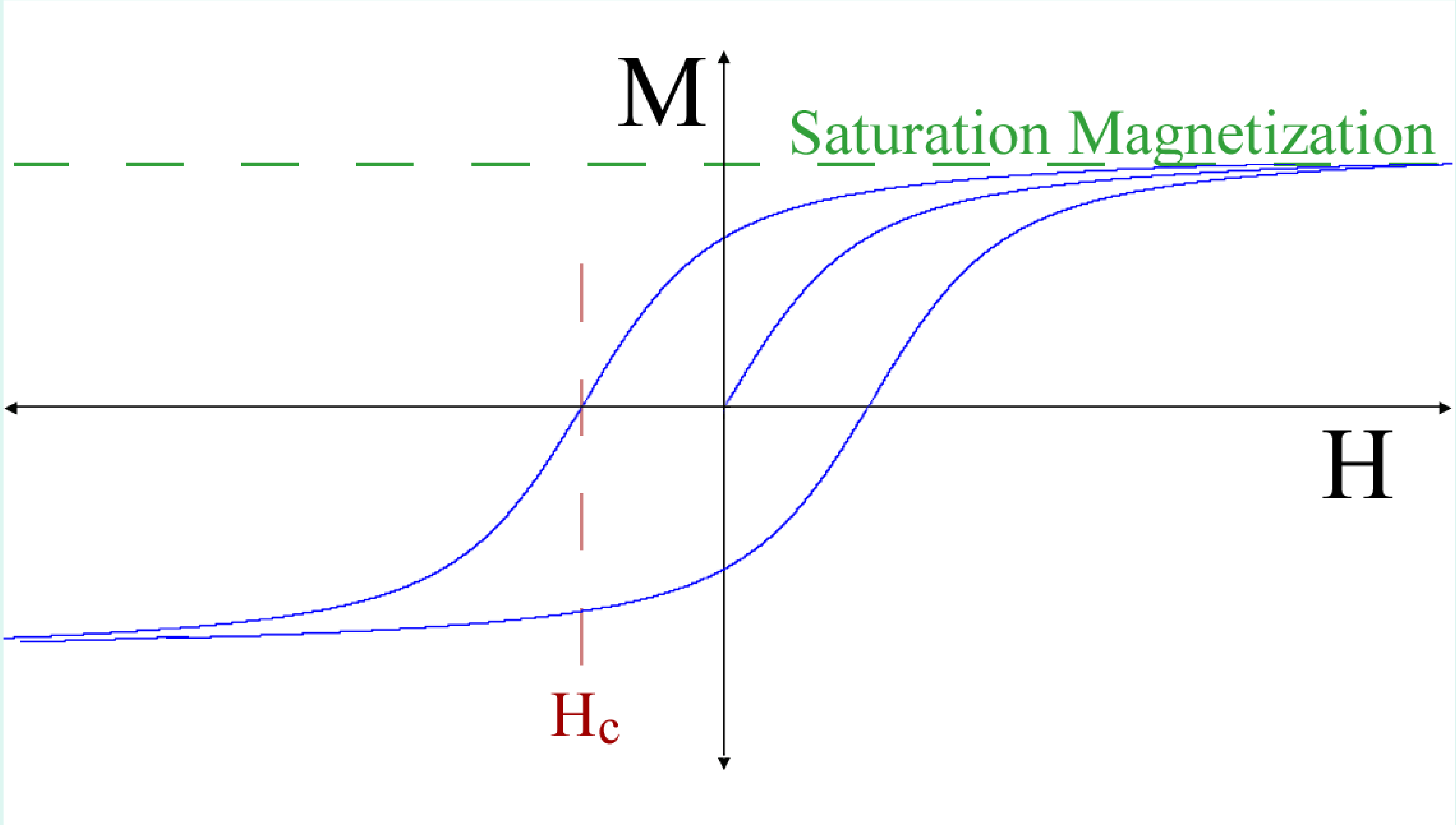
Low field magnetic susceptibility



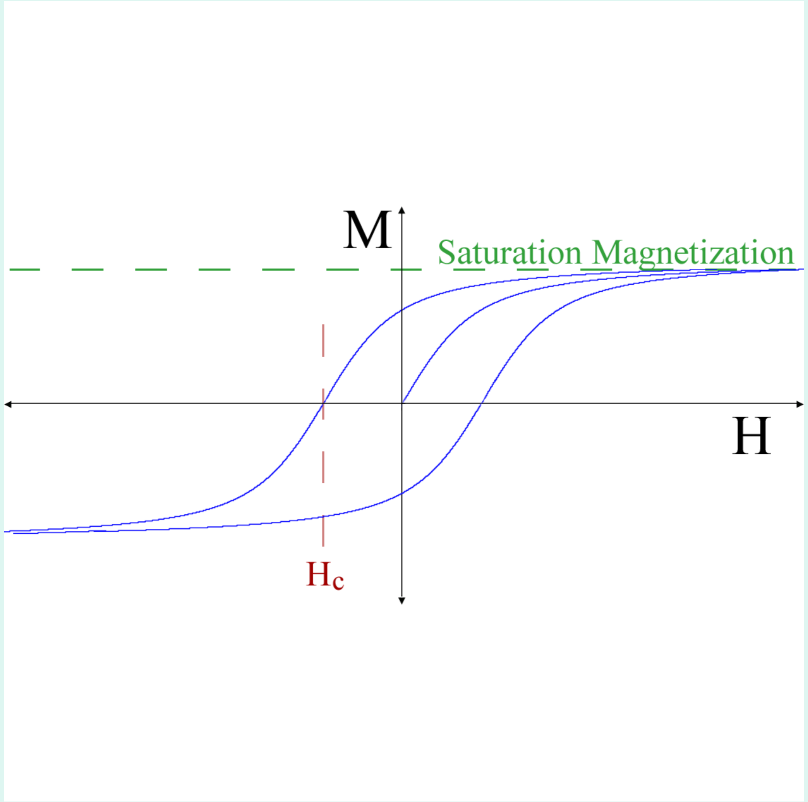
- **For some materials, low field magnetic susceptibility is inversely proportional to temperature**

- **Curie's Law**

Magnetic hysteresis

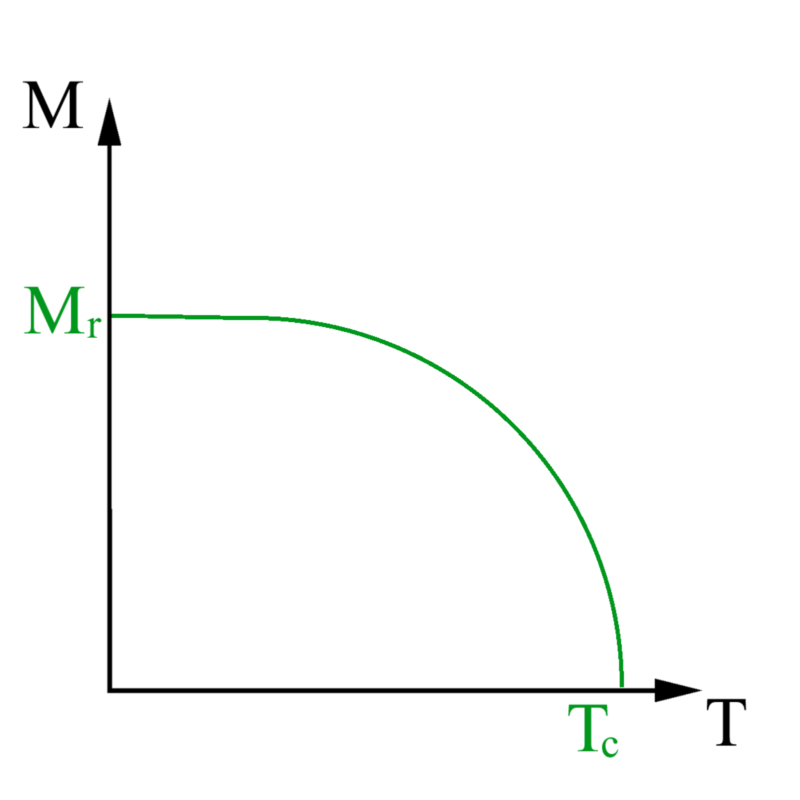


Magnetic hysteresis



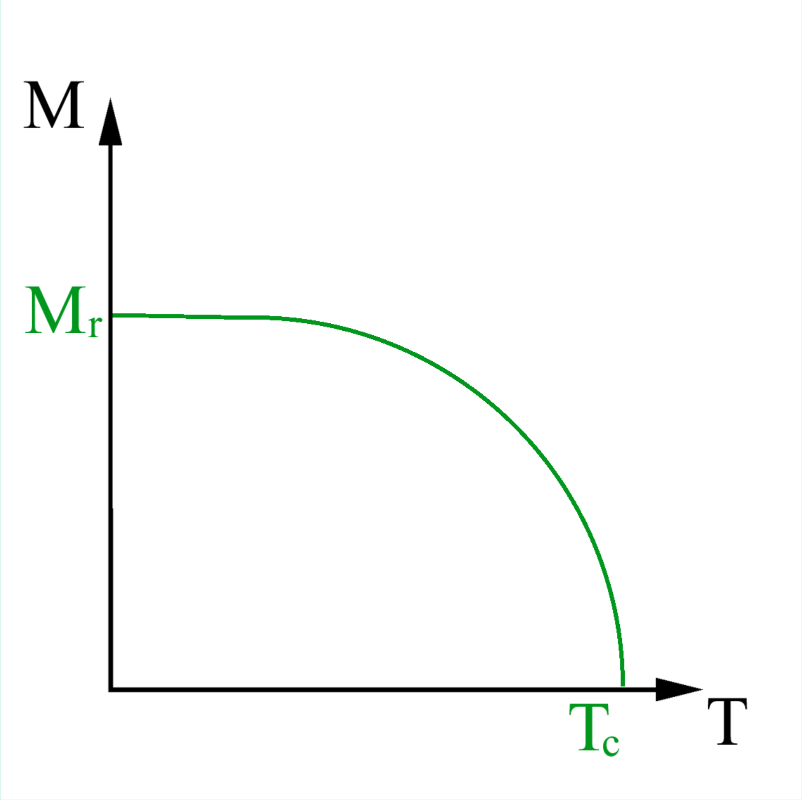
- ***M*** **depends on previous state of magnetization**
- **Remnant magnetization** M_r **remains when applied field is removed**
- **Need to apply a field (coercive field) in opposite direction to reduce** ***M*** **to zero.**

Effect of temperature on remnant magnetization



- **Heating a magnetized material generally decreases its magnetization.**
- **Remnant magnetization is reduced to zero above Curie temperature T_c**

Effect of temperature on remnant magnetization



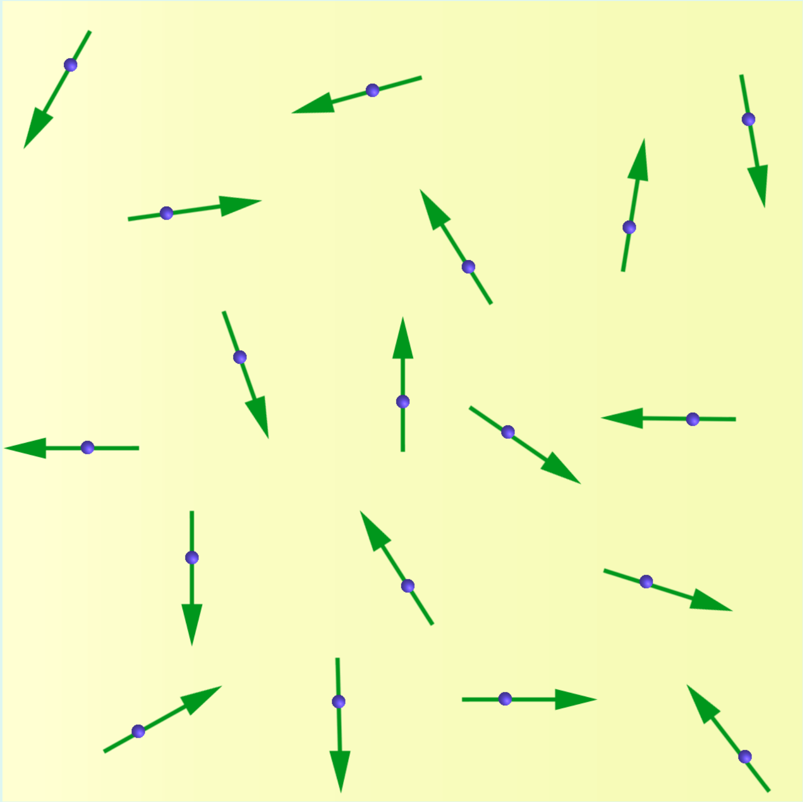
- **Heating a sample above its Curie temperature is a way of demagnetizing it**
- **Thermal demagnetization**

Lecture 2

The Microscopic Picture of Magnetic Materials

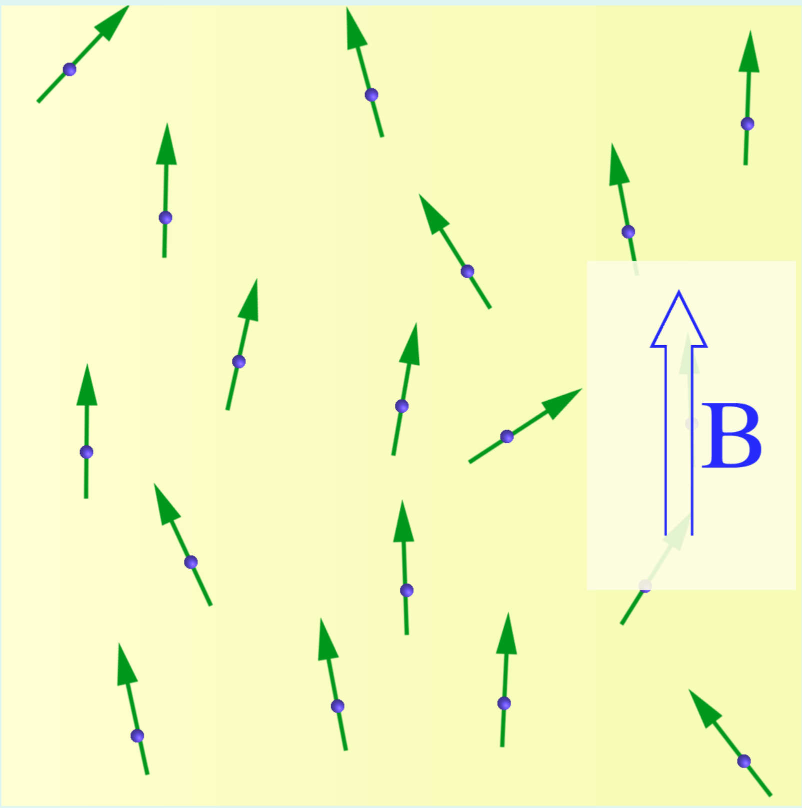
- **We will now revisit the experimentally observed magnetic behaviours and try to understand them from a microscopic point of view**

Paramagnetic gas



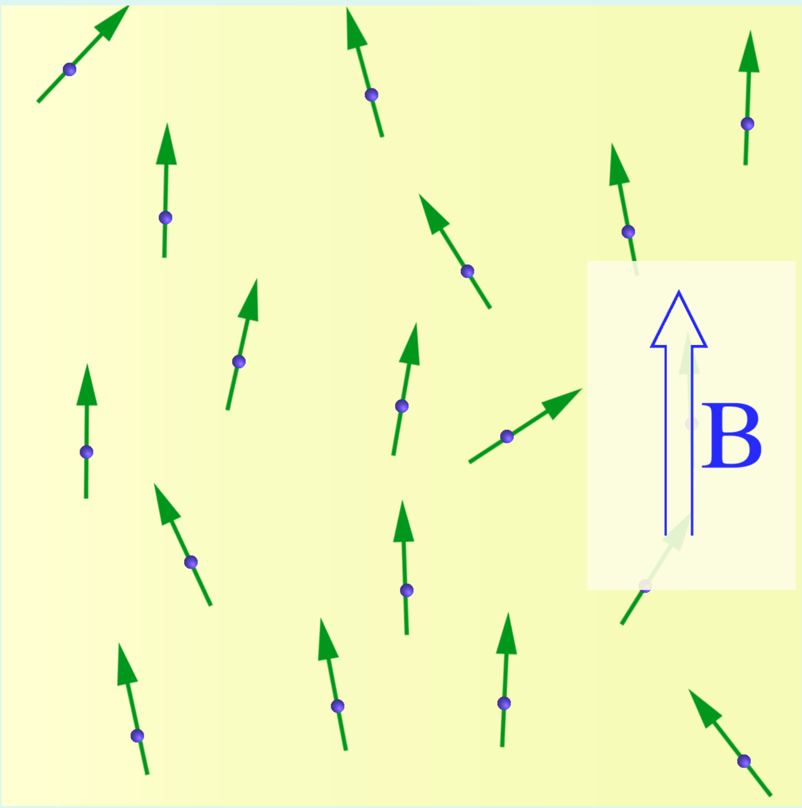
- **Imagine a classical gas of molecules each with a magnetic dipole moment**
- **In zero field the gas would have zero magnetization**

Paramagnetic gas



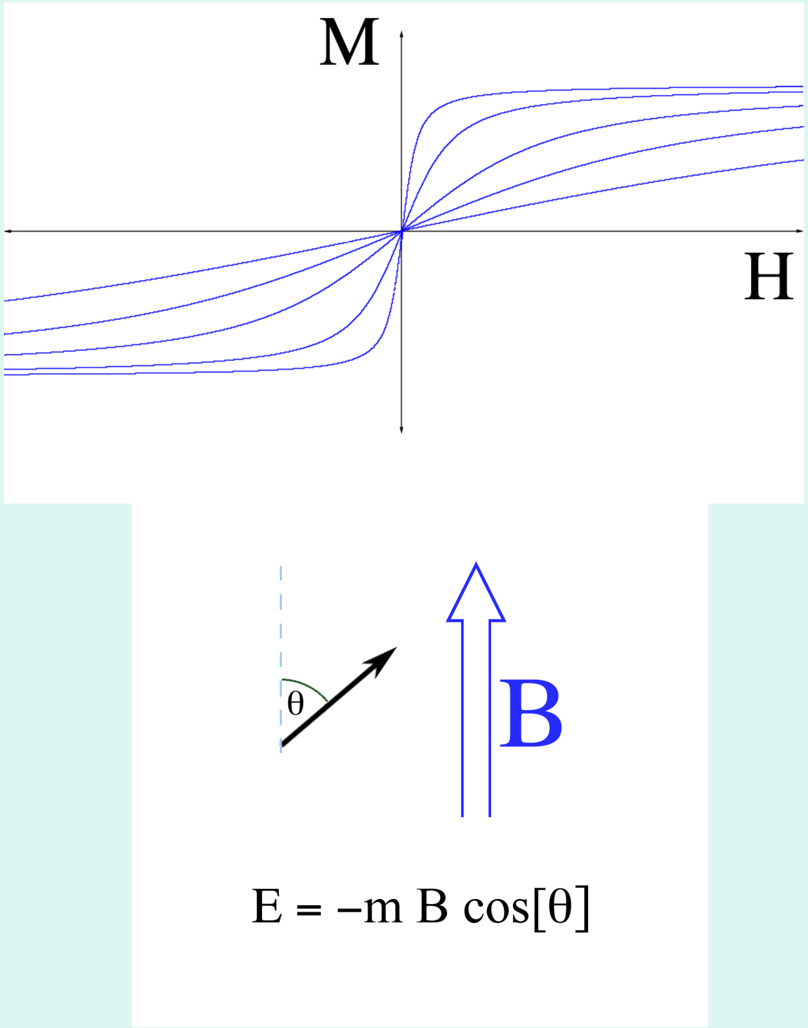
- **Applying a magnetic field would tend to orient the dipole moments**
- **Gas attains a magnetization**

Paramagnetic gas



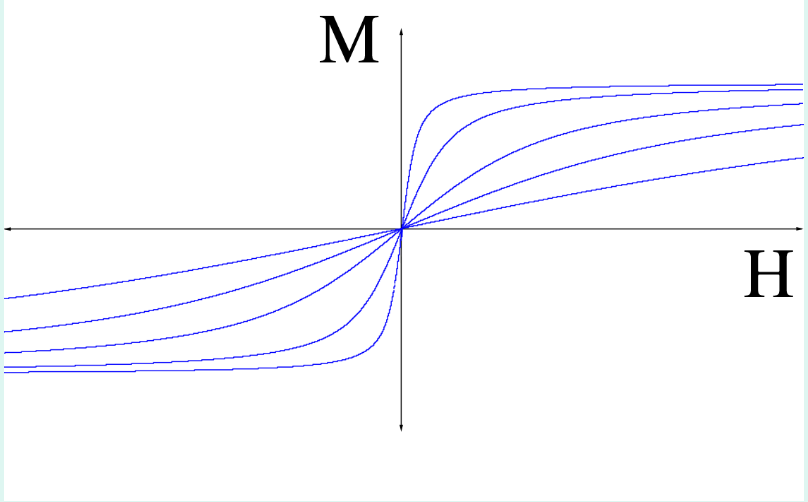
- **Very high fields would saturate magnetization**
- **Heating the gas would tend to disorder the moments and hence decrease magnetization**

Paramagnetic gas

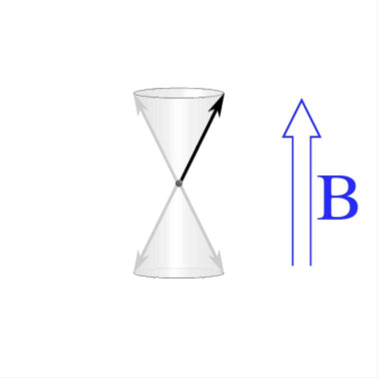


- **Theoretical model**
- **Non-interacting moments**
- **Boltzmann statistics**
- **Dipole interaction with *B***
- **Yields good model for many materials**
- **Examples: ferrous sulfate crystals, ionic solutions of magnetic atoms**

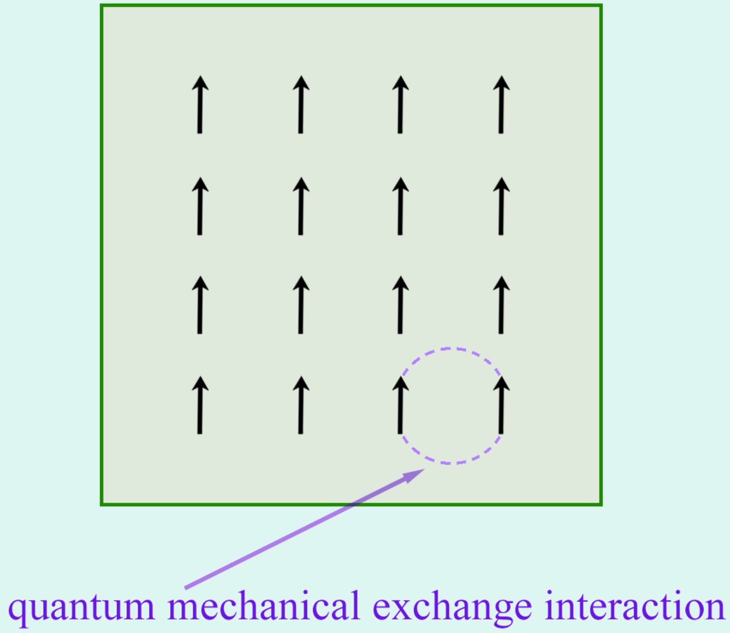
Paramagnetic gas



- **Classical model yields Langevin function**
- **Quantum model yields Brillouin function**

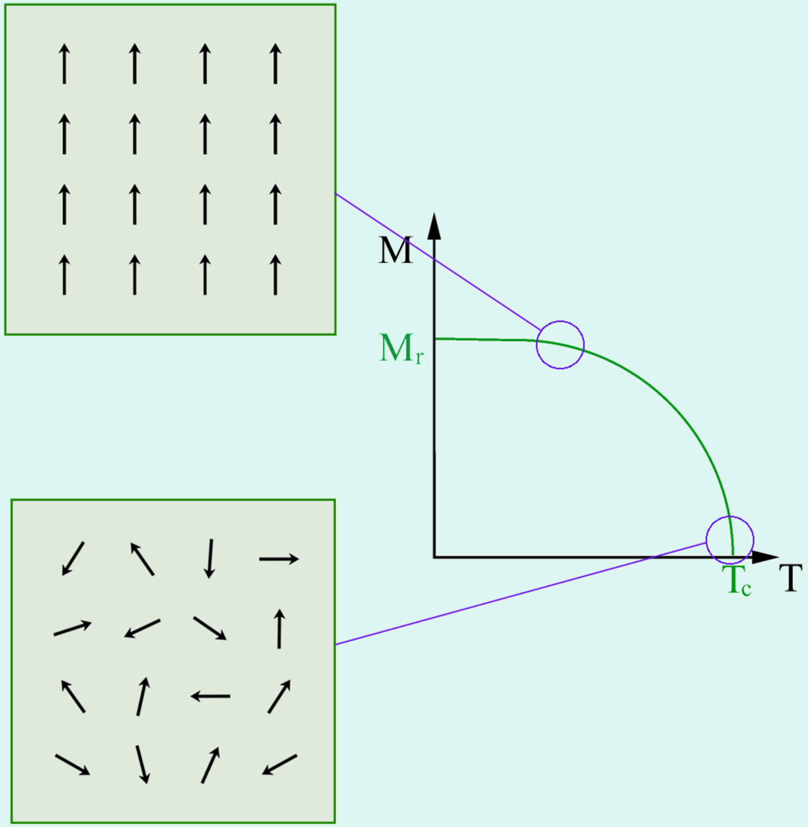


Ferromagnetism



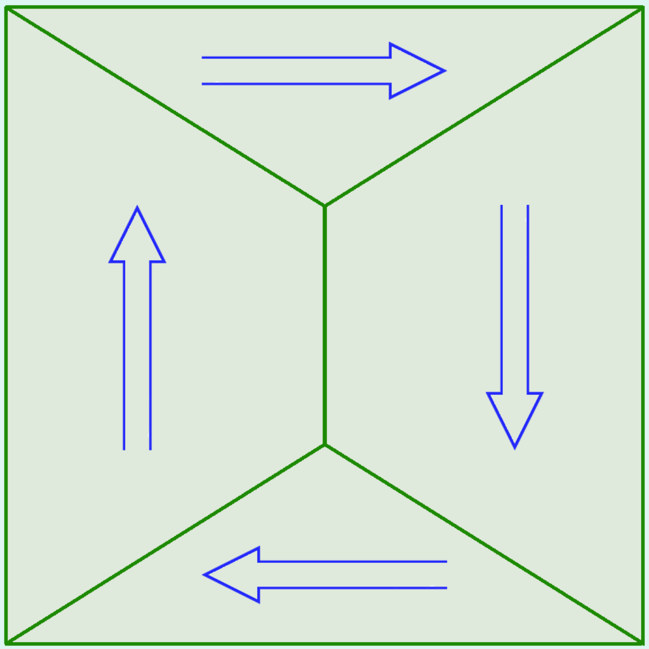
- **Materials that retain a magnetization in zero field**
- **Quantum mechanical exchange interactions favour parallel alignment of moments**
- **Examples: iron, cobalt**

Ferromagnetism



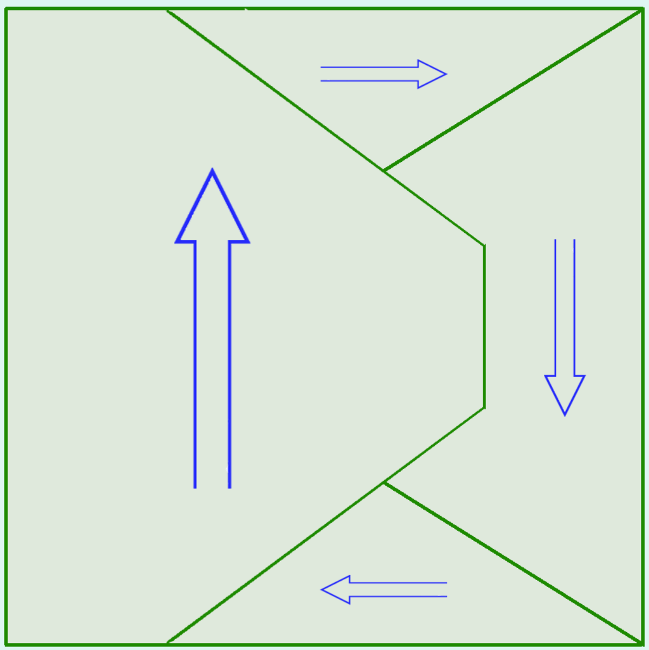
- Thermal energy can be used to overcome exchange interactions
- Curie temp is a measure of exchange interaction strength
- Note: exchange interactions much stronger than dipole-dipole interactions

Magnetic domains



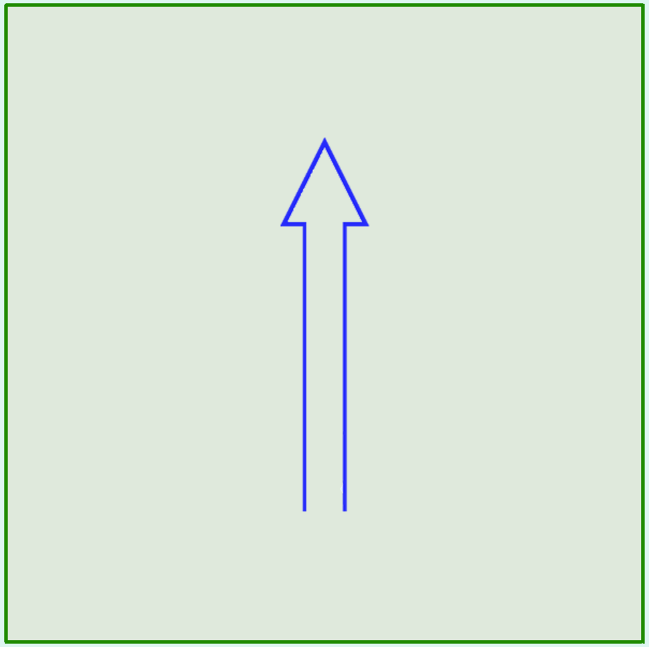
- **Ferromagnetic materials tend to form magnetic domains**
- **Each domain is magnetized in a different direction**
- **Domain structure minimizes energy due to stray fields**

Magnetic domains



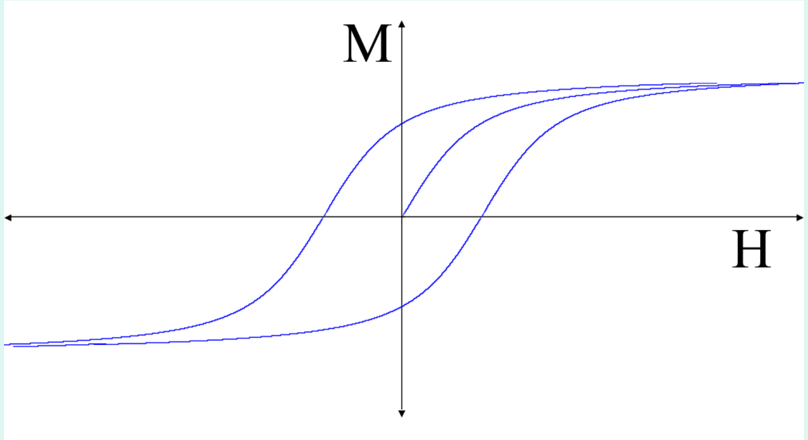
- **Applying a field changes domain structure**
- **Domains with magnetization in direction of field grow**
- **Other domains shrink**

Magnetic domains



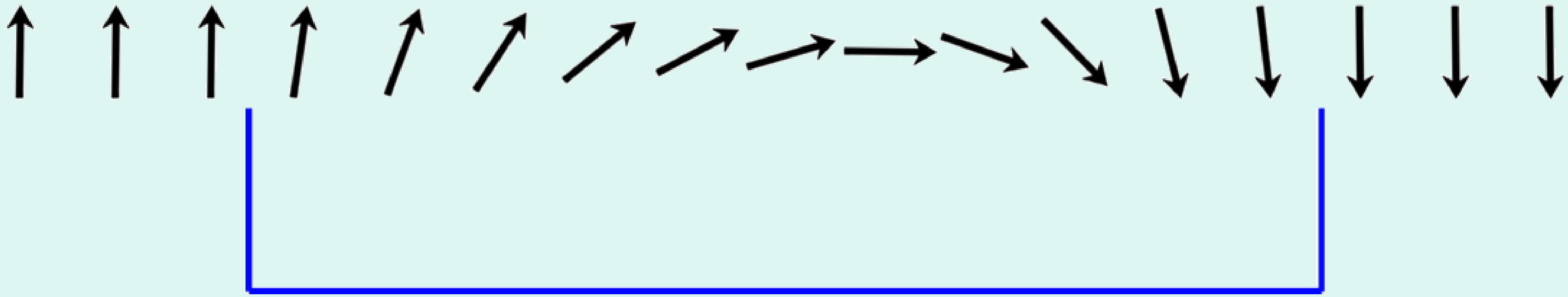
- **Applying very strong fields can saturate magnetization by creating single domain**

Magnetic domains



- **Removing the field does not necessarily return domain structure to original state**
- **Hence results in magnetic hysteresis**

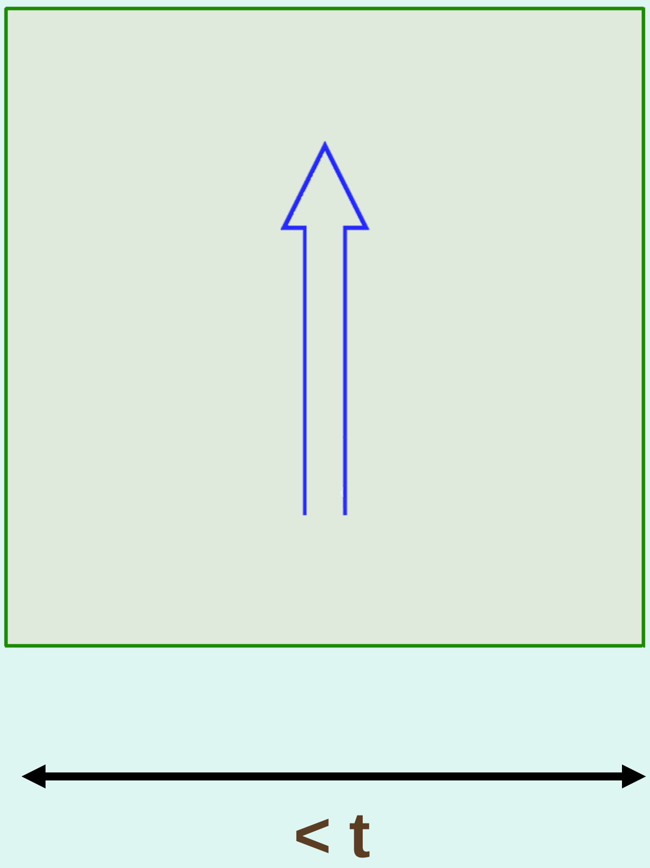
Magnetic domain walls



Wall Thickness "t"

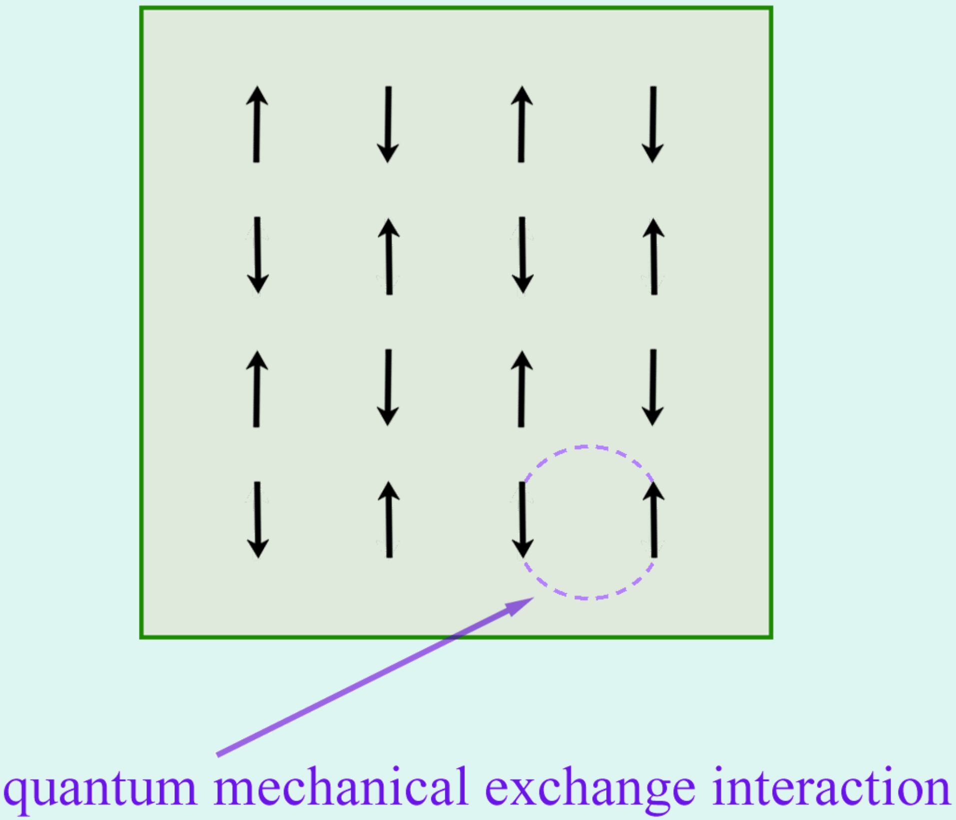
Wall thickness, t, is typically about 100 nm

Single domain particles



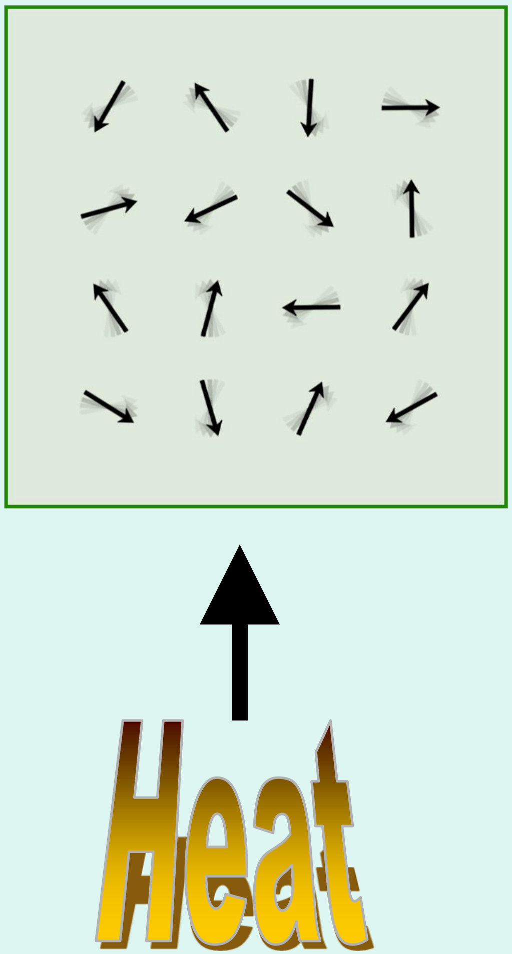
- **Particles smaller than “t” have no domains**

Antiferromagnetism



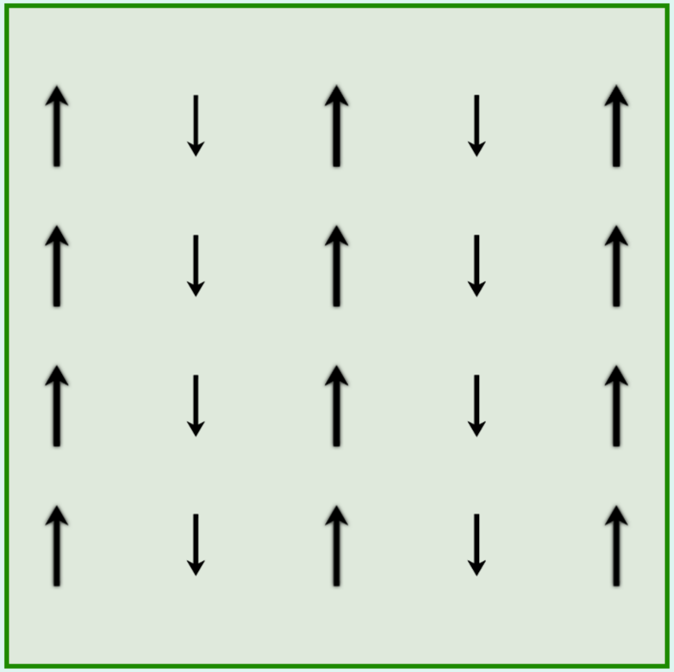
- **In some materials, exchange interactions favour antiparallel alignment of atomic magnetic moments**
- **Materials are magnetically ordered but have zero remnant magnetization and very low χ**
- **Many metal oxides are antiferromagnetic**

Antiferromagnetism



- **Thermal energy can be used to overcome exchange interactions**
- **Magnetic order is broken down at the Néel temperature (c.f. Curie temp)**

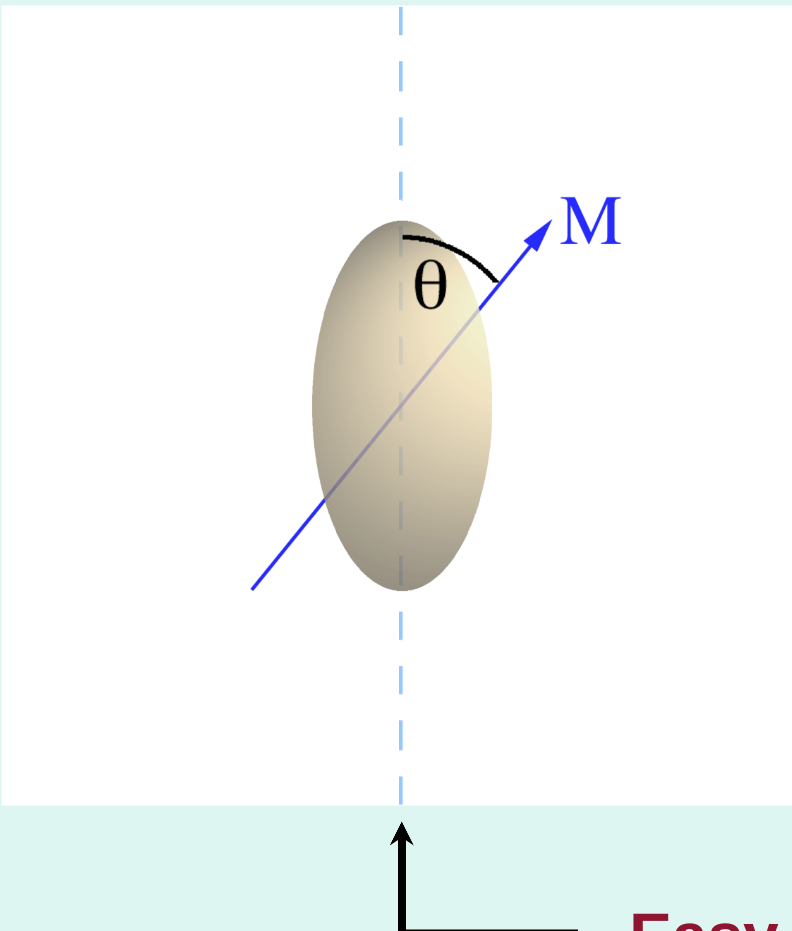
Ferrimagnetism



- **Antiferromagnetic exchange interactions**
- **Different sized moments on each sublattice**
- **Results in net magnetization**
- **Example: magnetite, maghemite**

Small Particle Magnetism

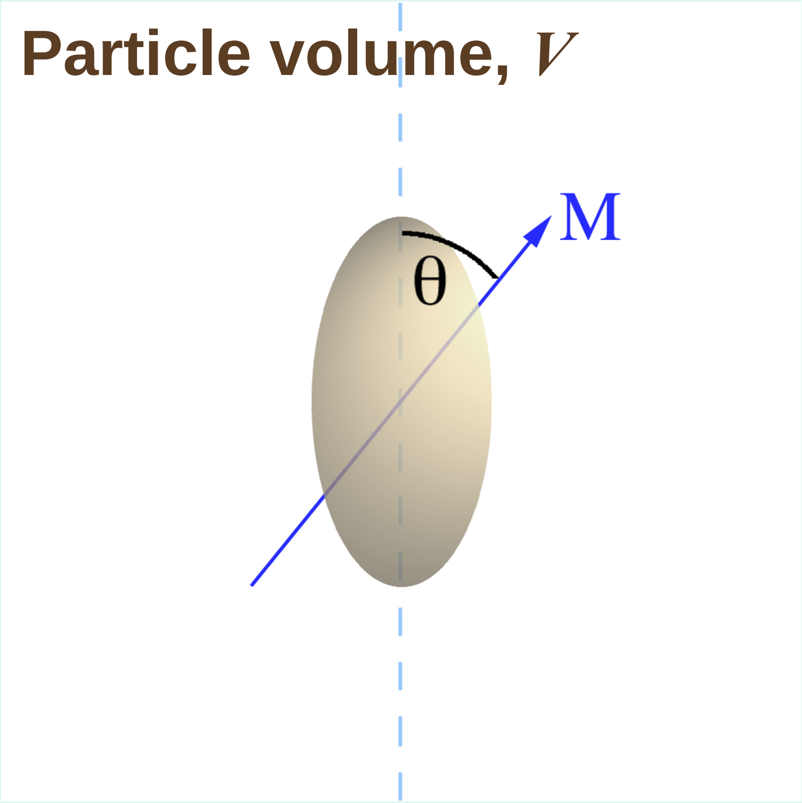
Stoner-Wohlfarth Particle



Easy axis of magnetization

- **Magnetic anisotropy energy favours magnetization along certain axes relative to the crystal lattice**

Stoner-Wohlfarth Particle

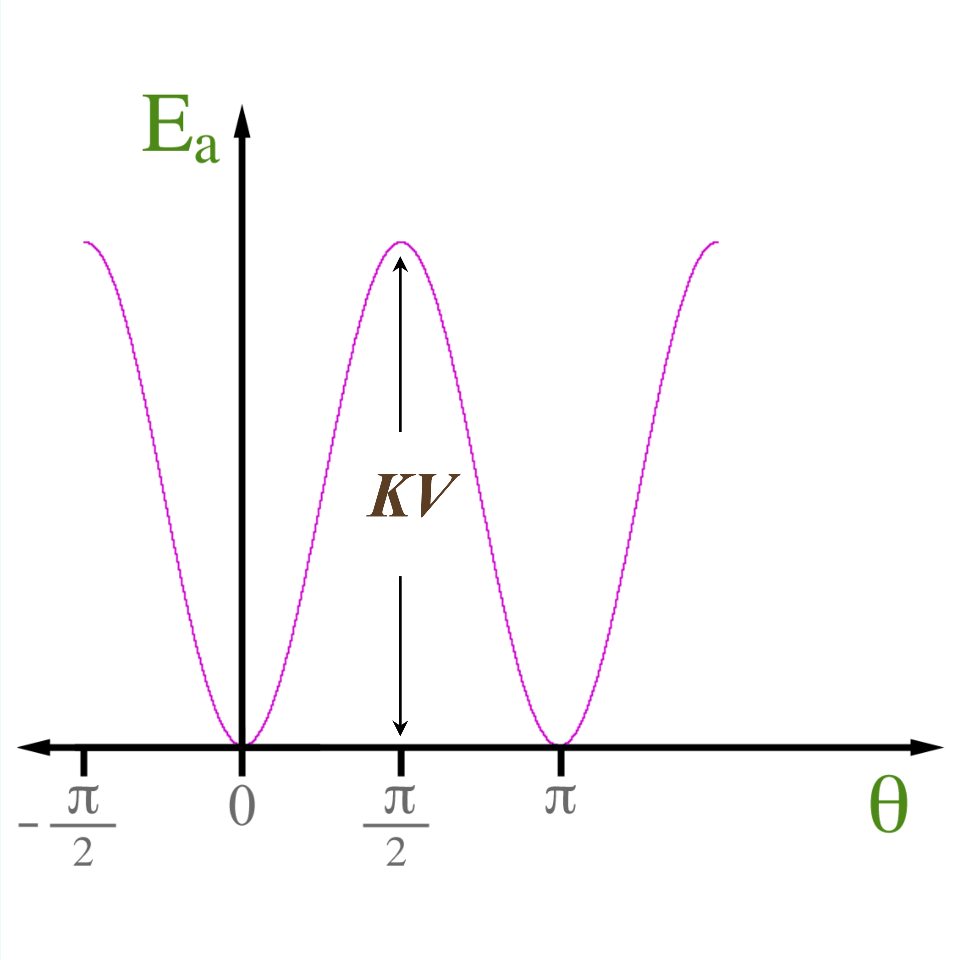


- **Uniaxial single domain particle**
- **Magnetocrystalline magnetic anisotropy energy given by**

$$E_a = KV\sin^2(\theta)$$

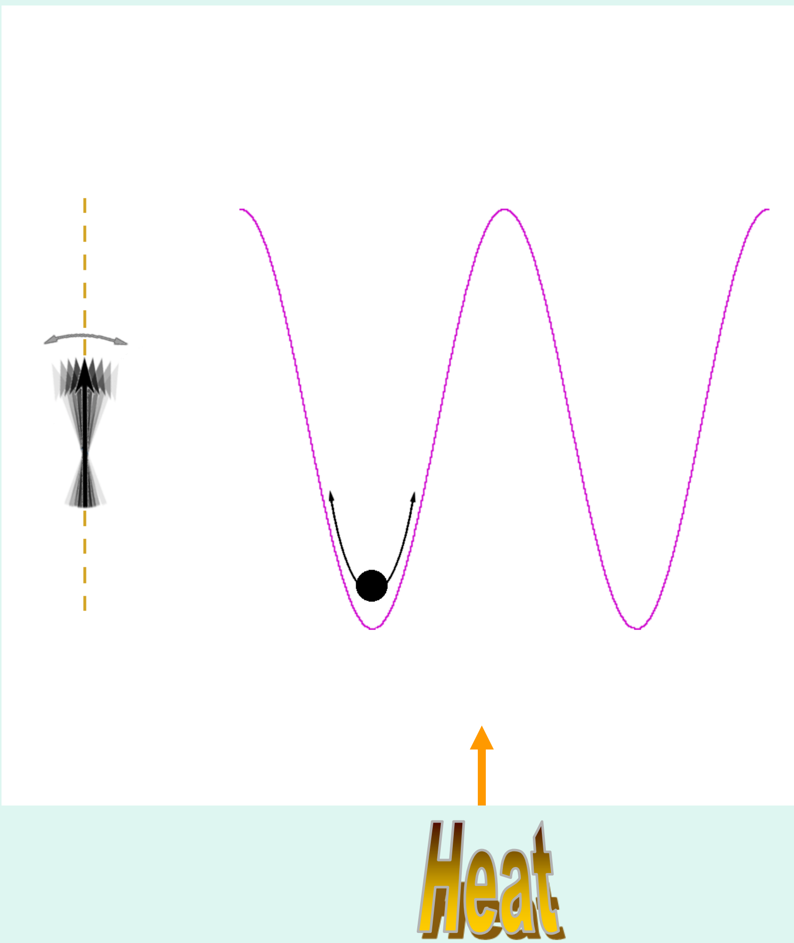
- ***K* is a constant for the material**

Stoner-Wohlfarth Particle



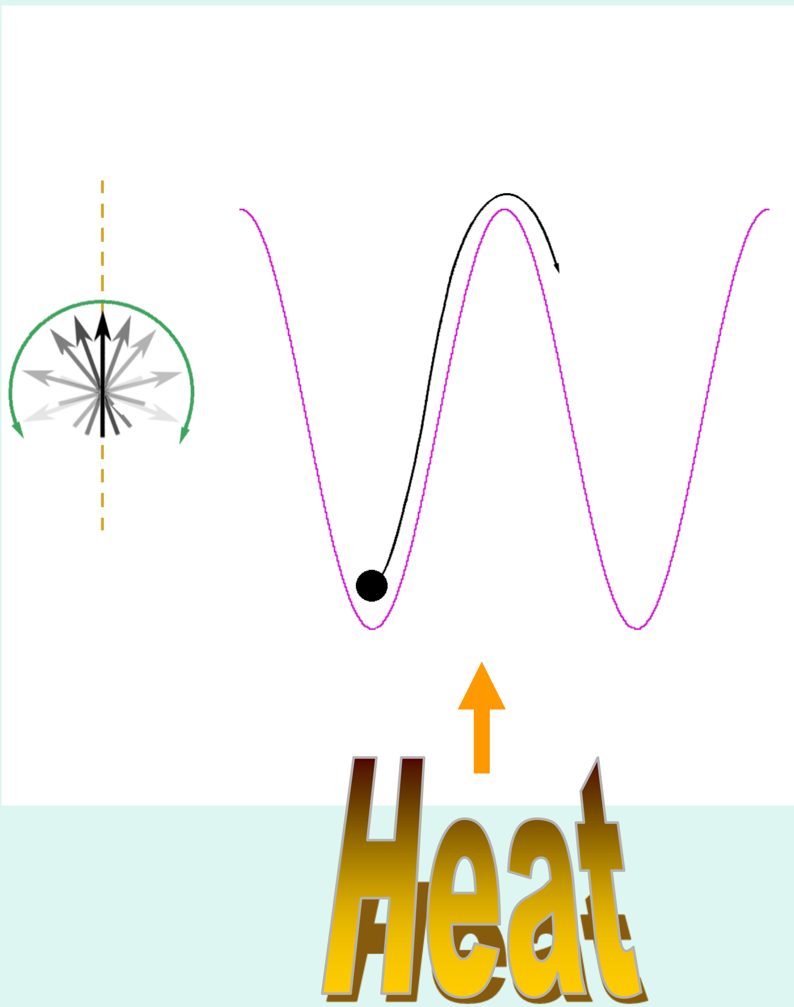
$$E_a = KV\sin^2(\theta)$$

Thermal activation



- **At low temperature magnetic moment of particle trapped in one of the wells**
- **Particle magnetic moment is “blocked”**

Thermal activation

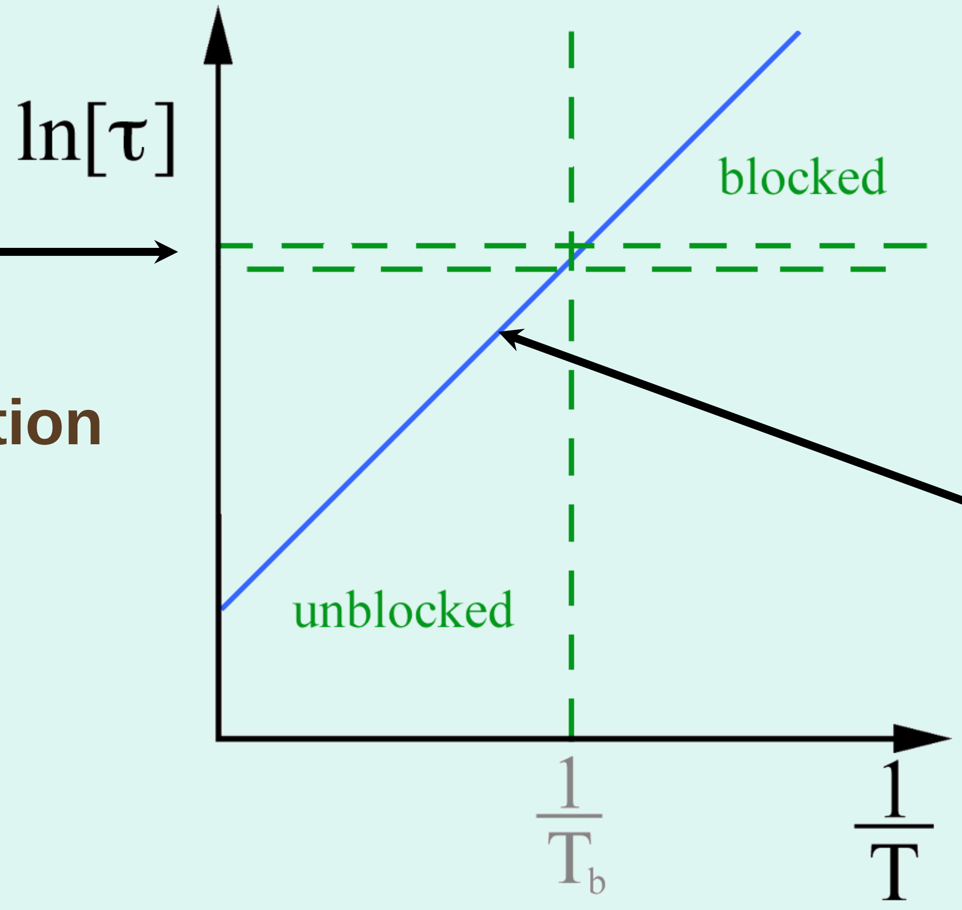


- **At higher temps, thermal energy can buffet magnetic moment between the wells**
- **Results in rapid fluctuation of moment**
- **Particle moment becomes "unblocked"**

Magnetic blocking temperature

- **The magnetic blocking temp, T_b, is the temp below which moment is blocked**
- **Blocking temperature depends on particle size and timescale of observation**
- **Larger particles have higher blocking temperatures**
- **The longer the observation time, the more likely it is that the moment will be observed to flip**

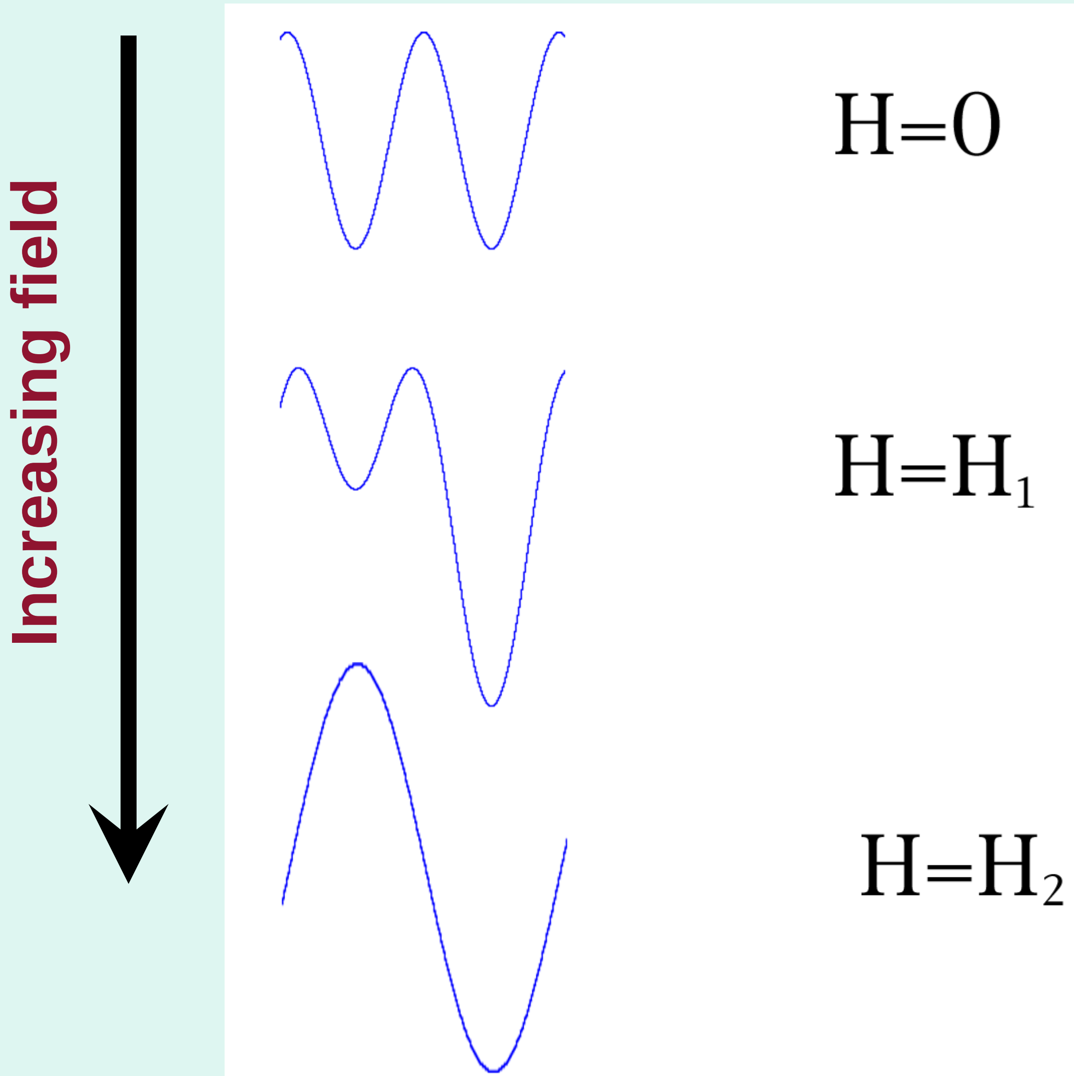
Fluctuation timescales, τ



Observation window

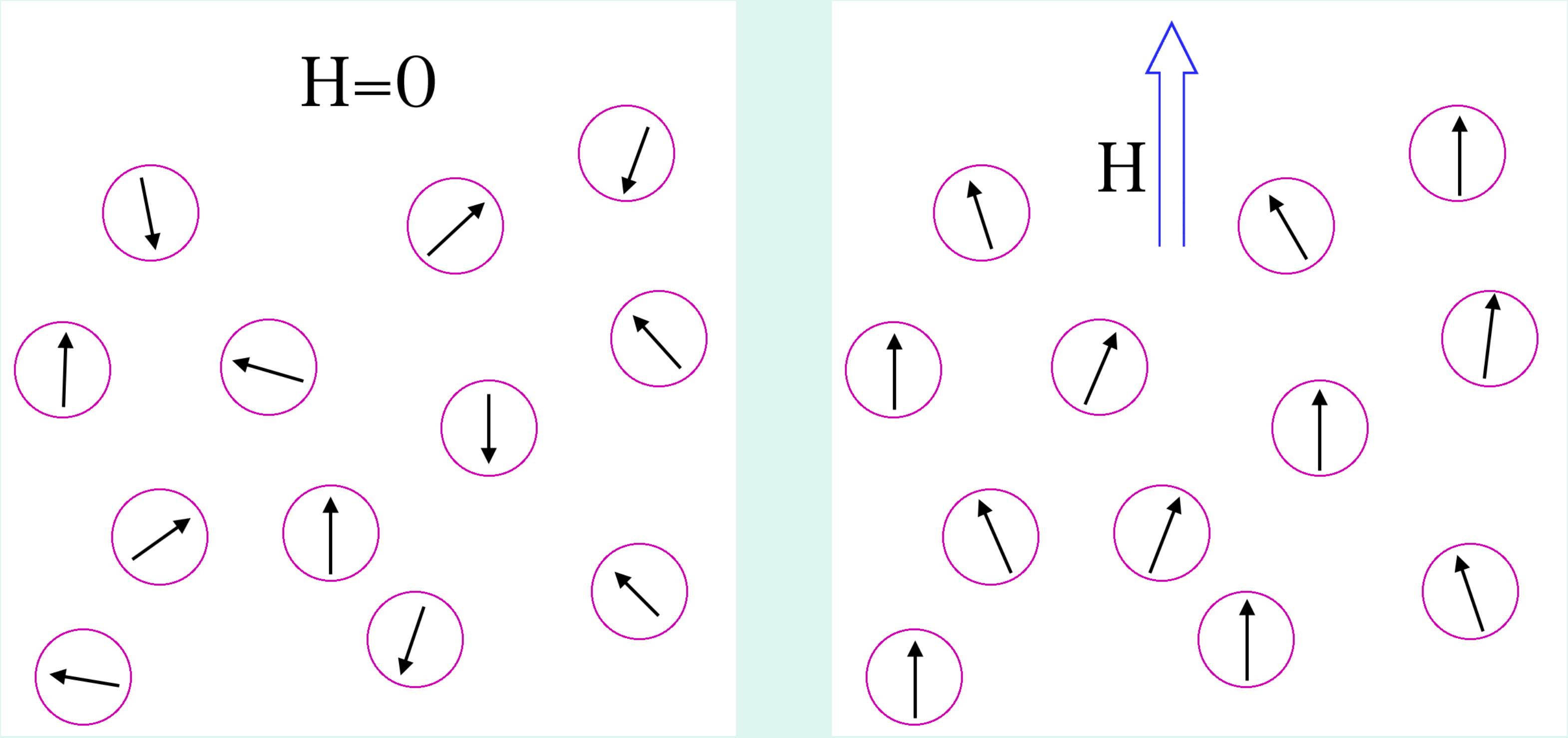
Slope ∝ Vol

Effect of applied field on single domain particles



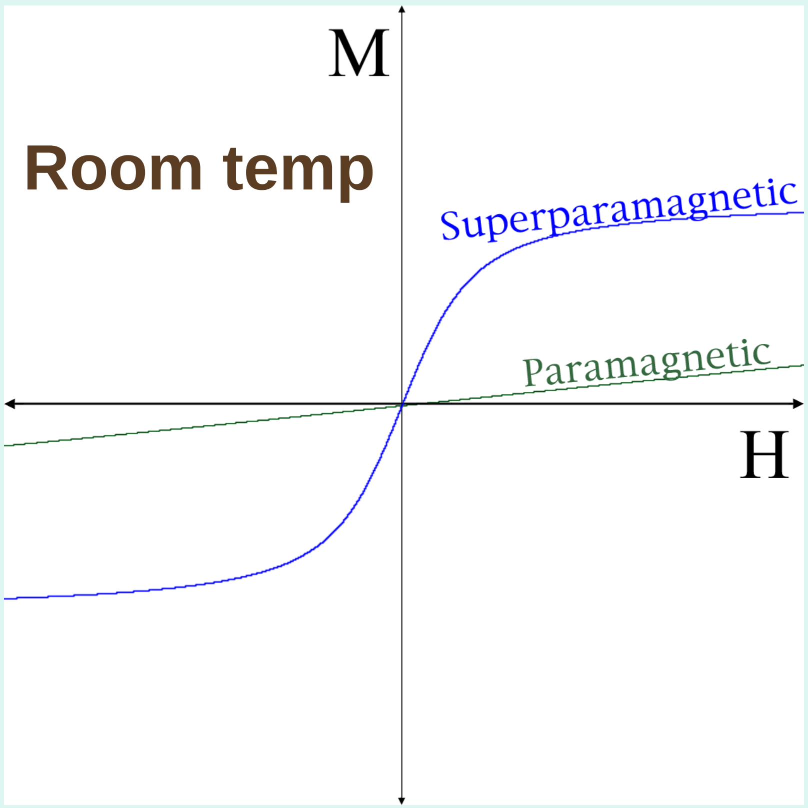
- **Applying field along easy axis favours moment aligned with field**
- **Above T_b this results in moment spending more time in lower well**
- **Particle exhibits time averaged magnetization in direction of field**

Superparamagnetism



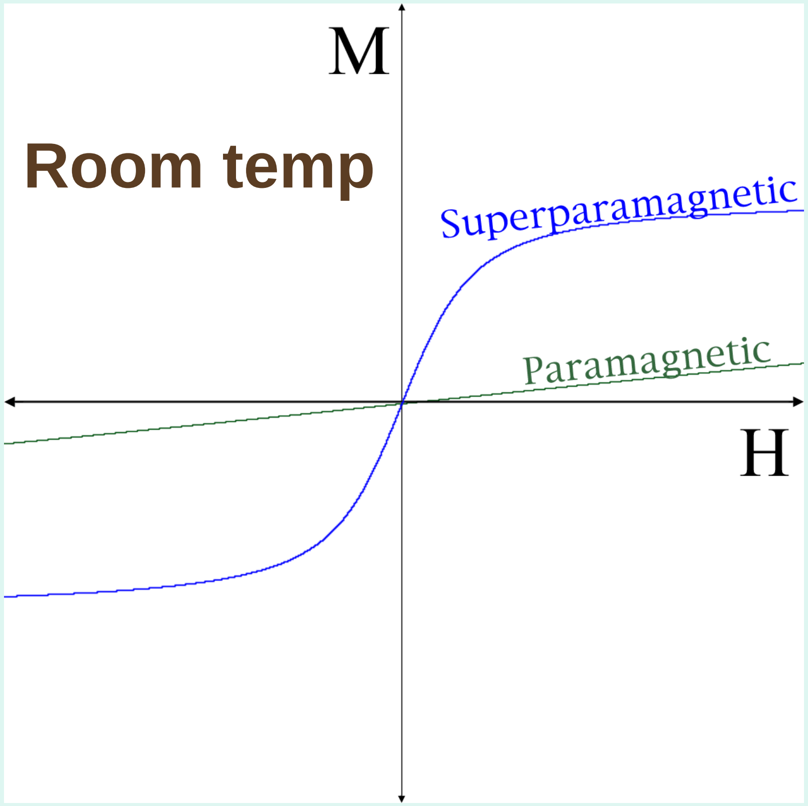
- **Unblocked particles that respond to a field are known as superparamagnetic**

Superparamagnetism



- **Response of superparamagnets to applied field described by Langevin model**
- **Qualitatively similar to paramagnets**
- **At room temperature superparamagnetic materials have a much greater magnetic susceptibility per atom than paramagnetic materials**

Superparamagnetism



Superparamagnets are often ideal for applications where…

- a high magnetic susceptibility is required
- zero magnetic remanence is required

Lecture 3

Magnetic particles in fluids

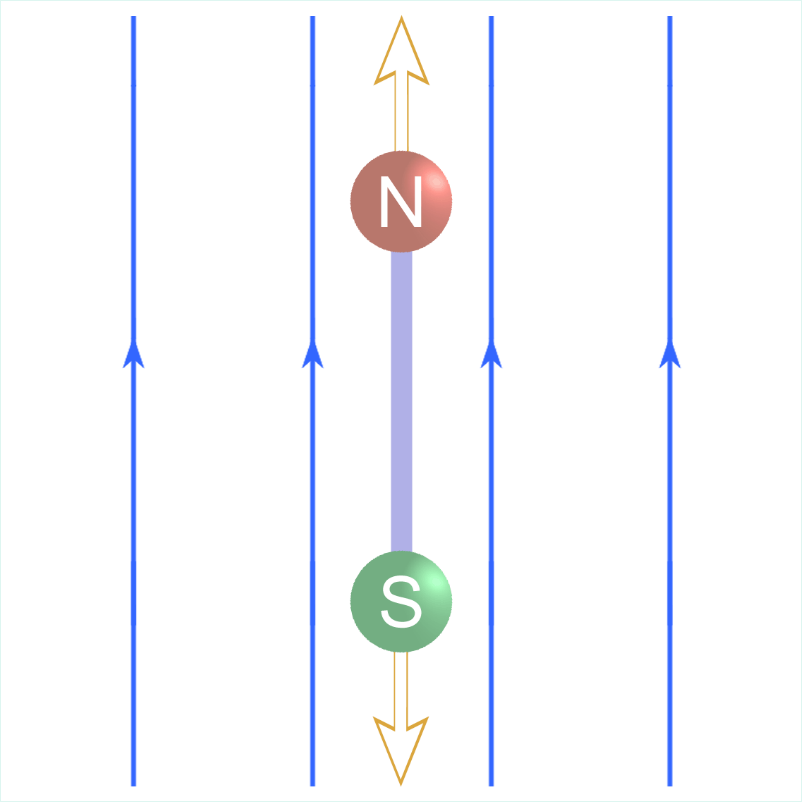
Magnetic particles in fluids

- **Most clinical and biotechnological applications of magnetic carriers involve suspensions of particles in fluids**
- **Here we review some of the basic principles governing the behaviour of magnetic particles in fluids**

Magnetic particles in fluids

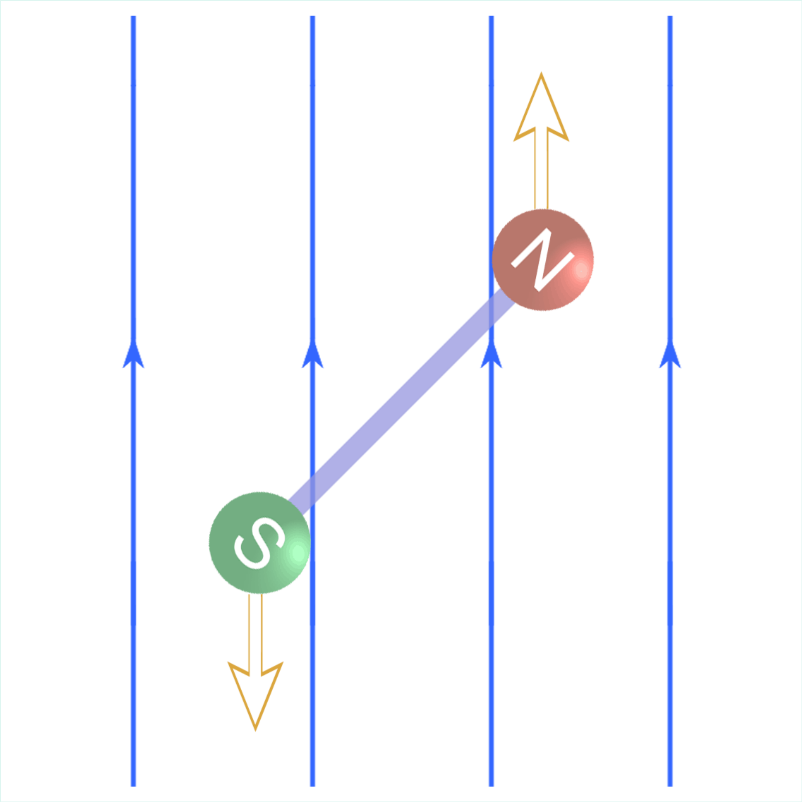
- **Several forces involved**
  - Force of applied magnetic fields on particles
  - Viscous drag forces
  - Interparticle magnetic forces
  - Interparticle electrostatic forces
  - Interparticle entropic “forces”

Single magnetic particle in fluid



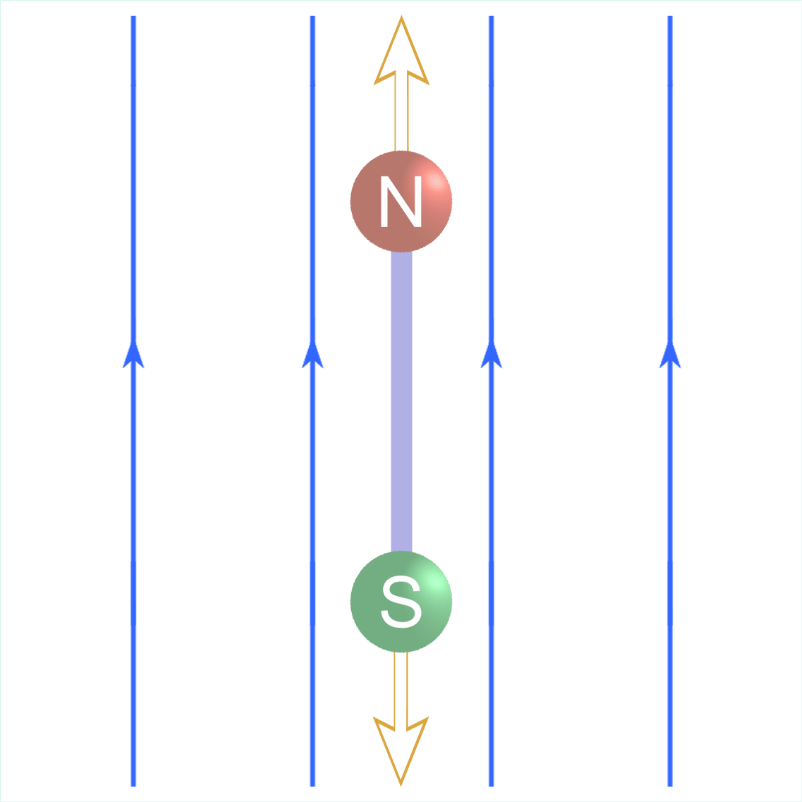
- **A uniform magnetic field tends to orient a magnetic dipole**
- **Uniform field does NOT exert translational force on dipole**
- **Forces on North and South pole balance**

Single magnetic particle in fluid



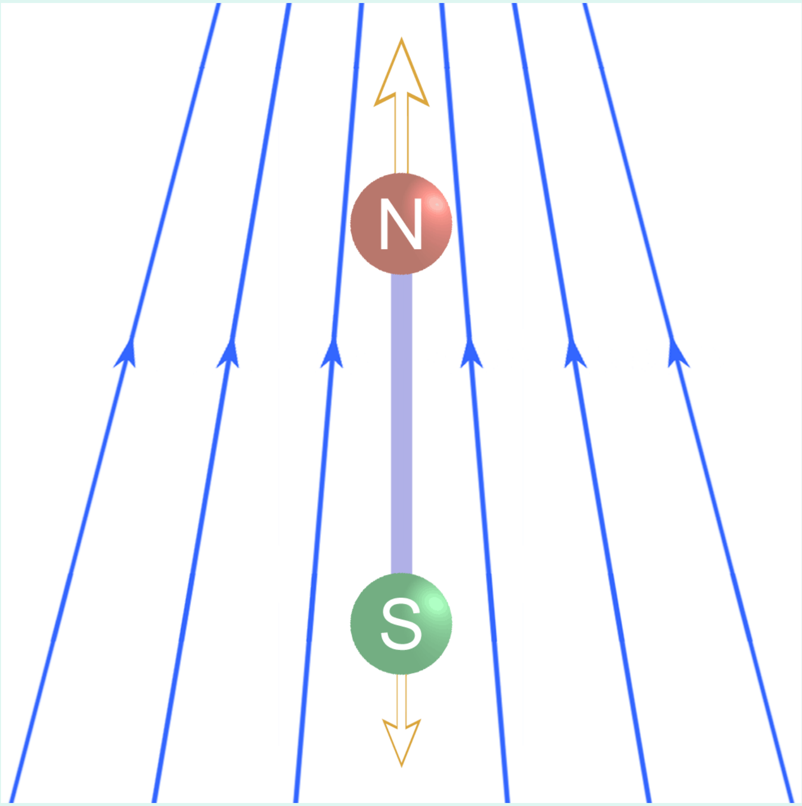
- **A uniform magnetic field tends to orient a magnetic dipole**
- **Uniform field does NOT exert translational force on dipole**
- **Forces on North and South pole balance**

Single magnetic particle in fluid



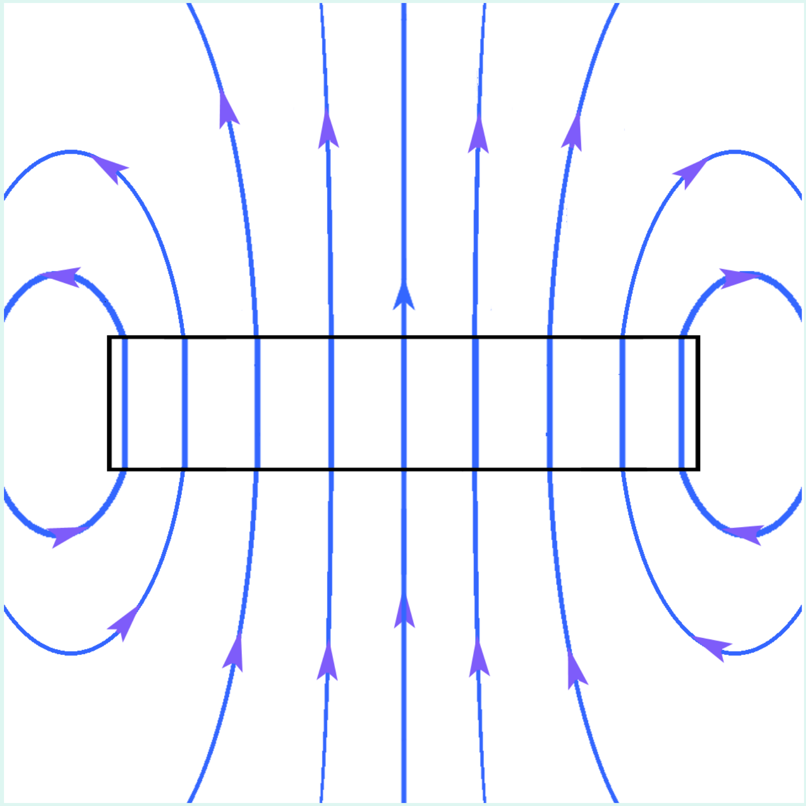
- **A uniform magnetic field tends to orient a magnetic dipole**
- **Uniform field does NOT exert translational force on dipole**
- **Forces on North and South pole balance**

Single magnetic particle in fluid



- **A field gradient is required to exert a translational force on dipole**
- **Figure shows a stronger force on the North pole than the South pole**
- **Net force causes translation**

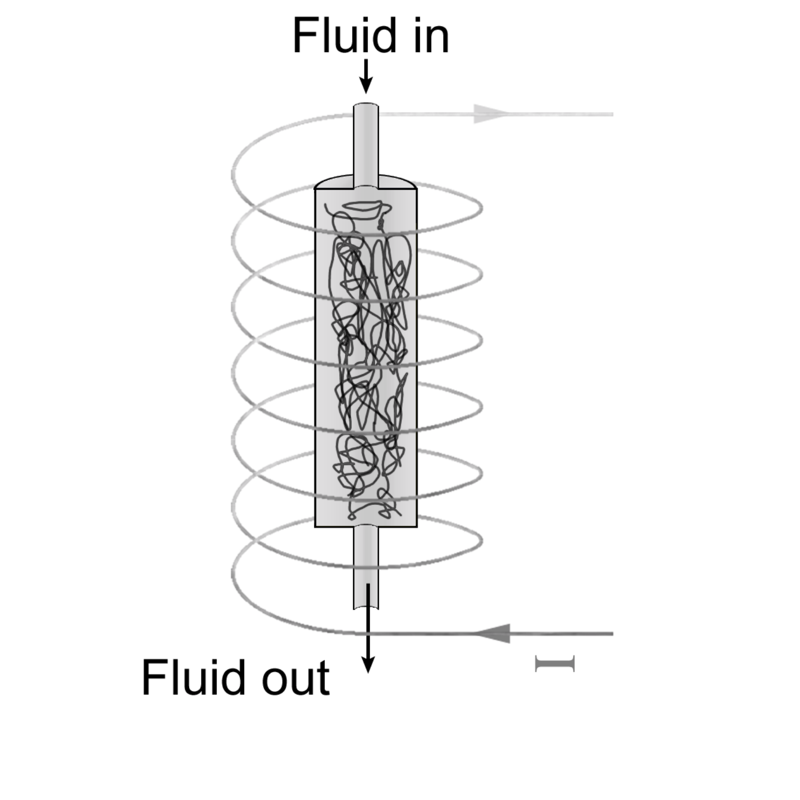
Magnetic Field Gradients



Disk-shaped magnet

- A simple bar magnet generates magnetic field gradients
- Gradients tend to be larger at sharp corners of magnet
- Fine or sharply pointed magnetized objects generate high field gradients

High field gradients used in magnetic separators



- **Fine wire with high mag susceptibility and low remanence used in a column**
- **Magnetic particle bearing fluid passed thru column with applied field**
- **Particles attracted to wire**
- **Particles can be released by removing applied field to demagnetize wire**

Reynolds Numbers

- **The Reynolds number of an object in a fluid is the ratio of inertial to viscous forces experienced by the object**
- **Micron and sub-micron particles in water have very low Reynolds numbers**
- **Velocity $\propto$ externally applied force**
- **i.e. objects reach their terminal speed almost instantaneously**

Field gradients applied to small magnetic particles in fluids

- **Speed of particle $\propto$ field gradient force**
- **Field gradient force $\propto$ moment on particle**
- **Moment on particle $\propto$ volume of particle**
- **$\therefore$ Speed $\propto$ volume of particle**
- **LARGER PARTICLES MOVE FASTER IN FIELD GRADIENT**

Field gradients applied to small magnetic particles in fluids

- **Magnetic separation techniques preferentially remove aggregates of particles**
- **Magnetic microspheres will move faster than nanospheres**

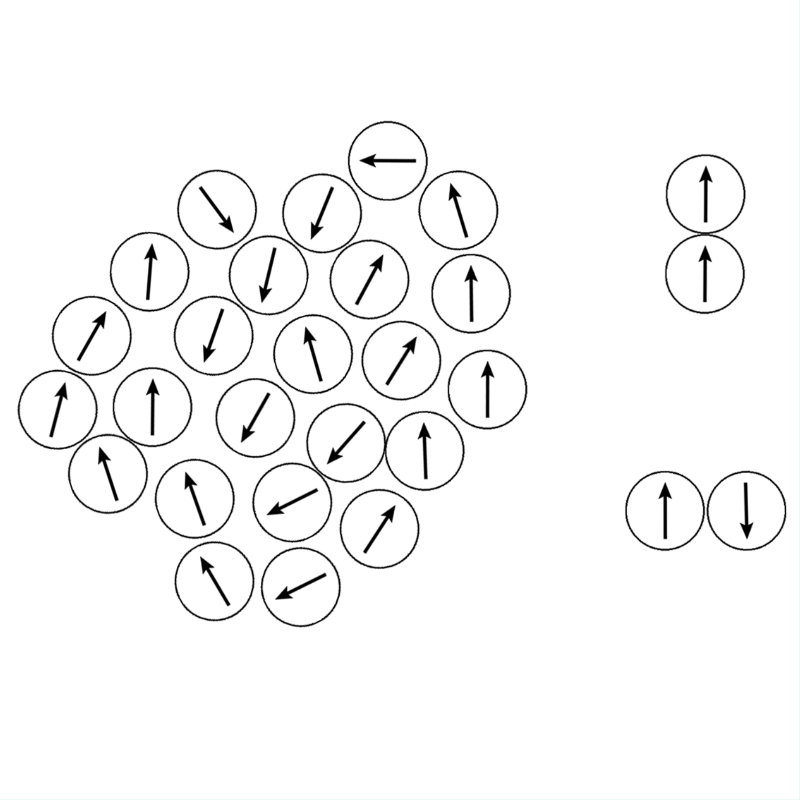
Interparticle interactions: Aggregation

- **More likely to occur as magnetic moments on particles increase (due to interparticle magnetic dipole interactions)**
- **Very large aggregates→precipitation (i.e. gravitational forces significant)**

Reversible and irreversible aggregation

- **Reversible**
  - Particles aggregate under applied field. Removing field lowers moments on particles sufficiently that repulsive forces dominate
- **Irreversible**
  - Applying field causes aggregation. Proximity of particles to each other results in mutual induction of dipole moments even in zero applied field. Attractive magnetic interactions within aggregate dominate

Demagnetizing interactions in clusters

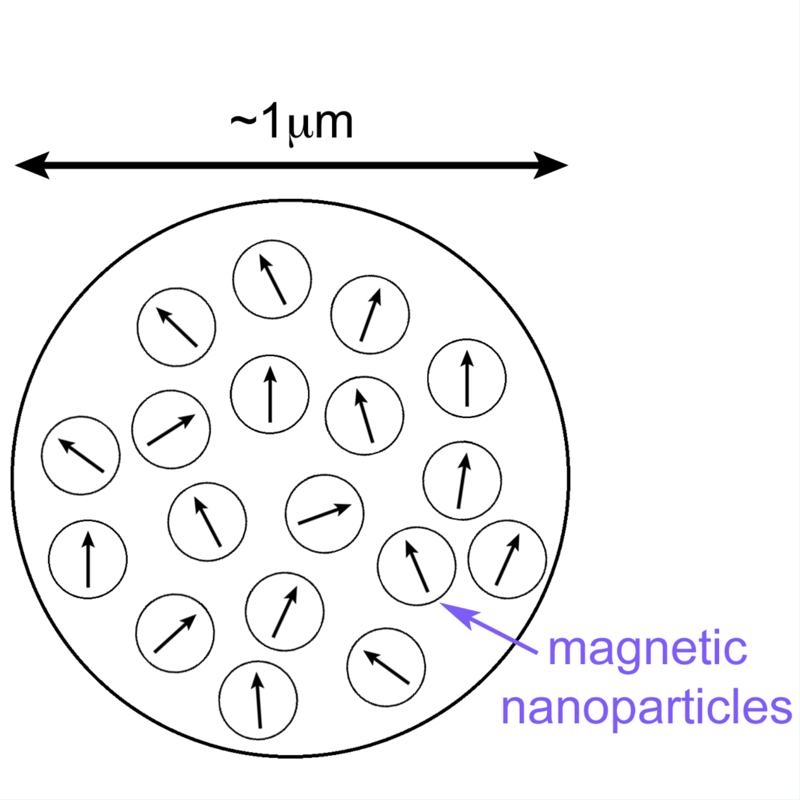


- **Particles in close proximity with each other**
- **Moments tend to arrange themselves such as to minimize magnetization of aggregate**
- **Clusters of particles may show reduced susceptibility in low fields**

Design of magnetic carriers

- **High χ generally desirable**
- **Low M_r desirable so that magnetic moments can be “switched off”**
- **High interparticle repulsion to reduce aggregation**
  - Electrostatic repulsion forces
  - Entropic repulsion forces
  - These forces are needed to overcome interparticle attractive magnetic forces. Determined by chemistry of particle coatings.

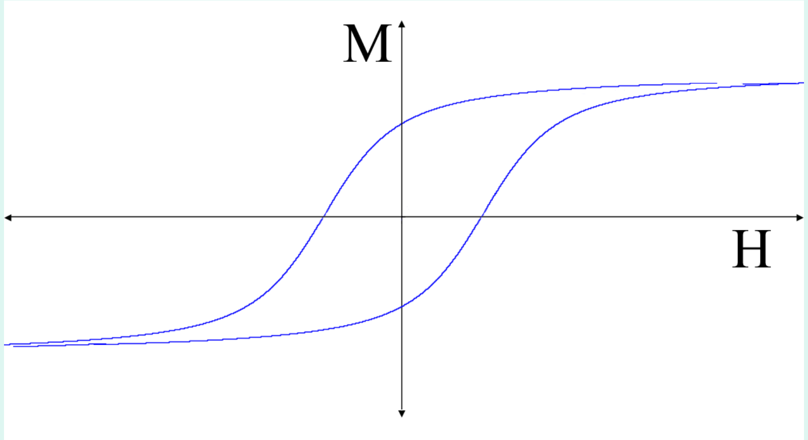
Design of magnetic microspheres



- **Make microsphere from aggregate of superparamagnetic nanoparticles**
- **SP particles give high χ and zero M_r**
- **Aggregate micron size yields faster movement in fluid**

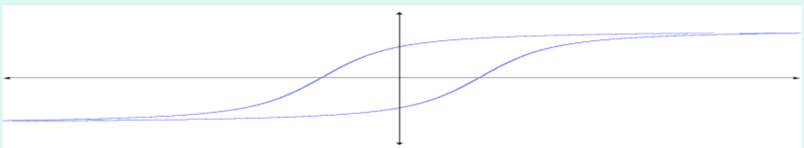
Particles for Special Applications

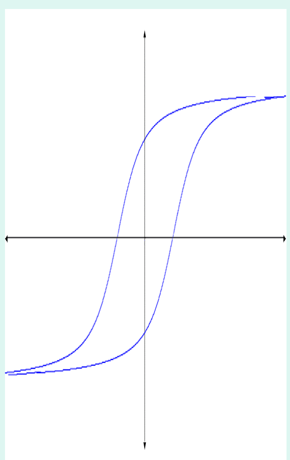
Particles for hyperthermia therapy



- **Magnetic hyperthermia therapy involves application of ac field to heat particles**
- **Heat generated per field cycle $\propto$ area within hysteresis loop**

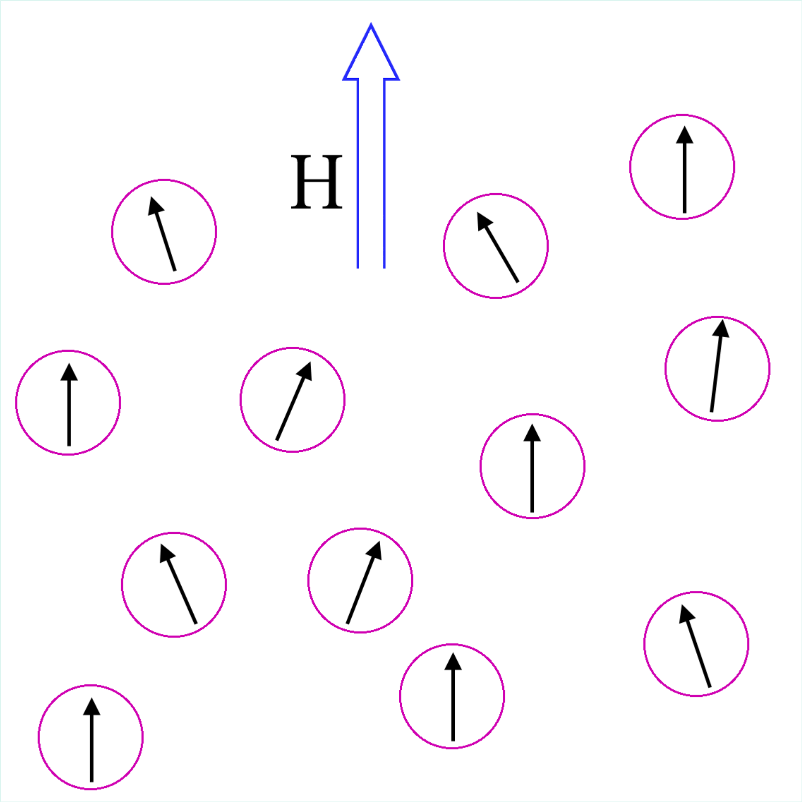
Particles for hyperthermia therapy





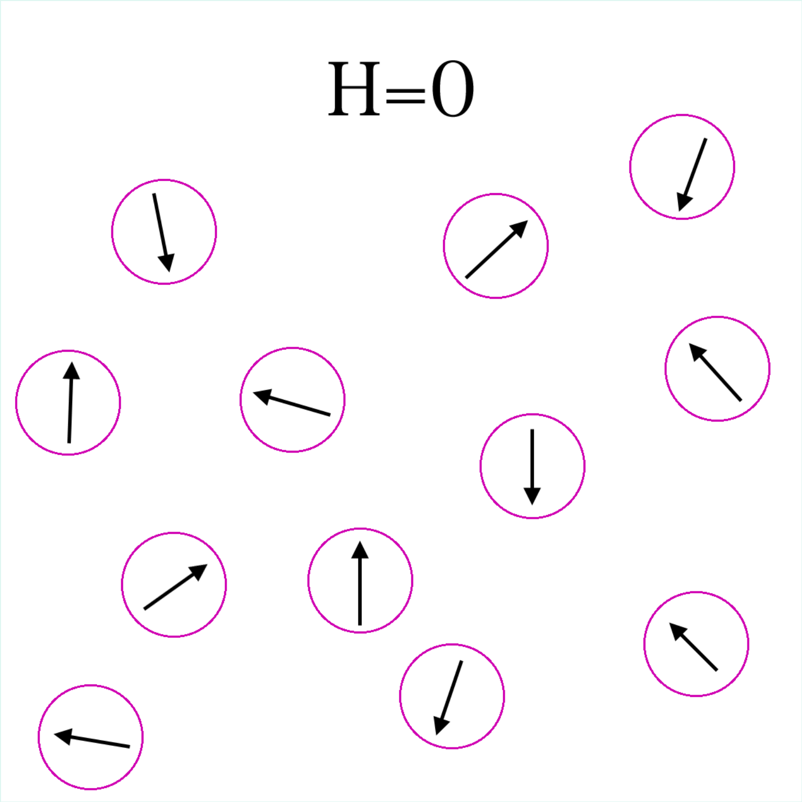
- **Therapeutic ac field amplitudes are limited (to avoid nerve stimulation)**
- **Particles with low coercivity but high M_s are preferred**

Particles for Brownian rotation studies



- **Magnetically blocked particles required**
- **Must stay in suspension**
- **Observe time dependent magnetic behaviour of fluid due to physical Brownian rotation of blocked dipoles**

Particles for Brownian rotation studies



- **Magnetically blocked particles required**
- **Must stay in suspension**
- **Observe time dependent magnetic behaviour of fluid due to physical Brownian rotation of blocked dipoles**

Acknowledgements

- **Thanks to Adam Fleming (School of Physics, UWA) for help with creating graphics**

Scientific and Clinical Applications of Magnetic Carriers

- **Magnetic separation applications**
- **Magnetically targeted drug delivery**
- **Magnetic labelling**
- **Magnetic hyperthermia therapy**