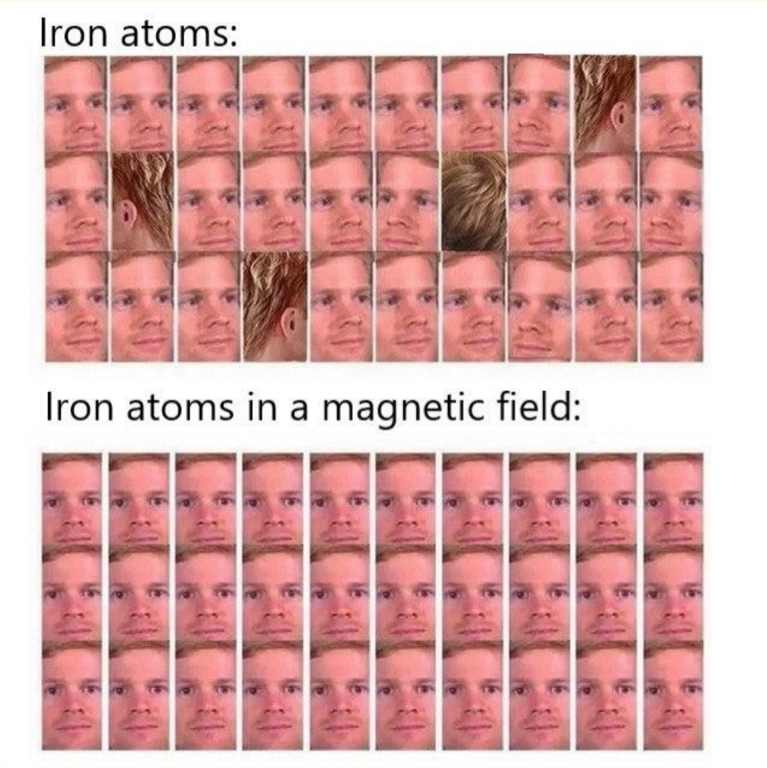
MAXWELL’S EQUATIONS & MAGNETISM OF MATTER

CHAPTER 32



- Electromagnetic Oscillations & Alternating Current
- **Maxwell’s Equations & Magnetism of Matter**
- Electromagnetic Waves
- Images
- Interference
- Diffraction

Videos links:

Magnetism: Crash Course Physics #32

Ampère's Law: Crash Course Physics #33

Maxwell's Equations: Crash Course Physics #37

Here's What Maxwell's Equations ACTUALLY Mean.

The 4 Maxwell Equations. Get the Deepest Intuition! (more mathematical point of view)

MAGNETS: How Do They Work?

How do magnets work?

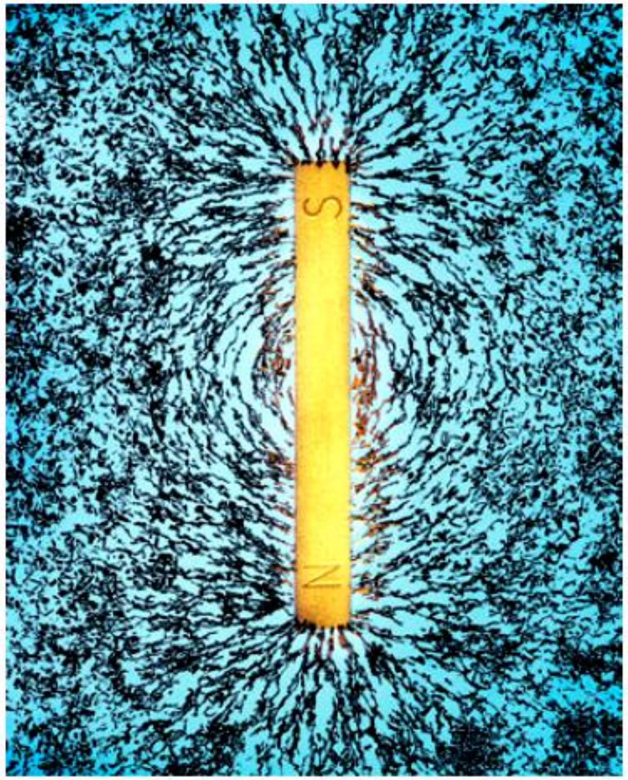
Paramagnetism and ferromagnetism in solids

What the HECK are Magnets? (Electrodynamics)

MAXWELL'S EQUATIONS & MAGNETISM OF MATTER

Textbook: Chapter 32

- GAUSS'S LAW FOR MAGNETIC FIELDS
- INDUCED MAGNETIC FIELDS
- DISPLACEMENT CURRENT
- MAXWELL'S EQUATIONS
- MAGNETS
- MAGNETISM AND ELECTRONS
- DIAMAGNETISM, PARAMAGNETISM & FERROMAGNETISM



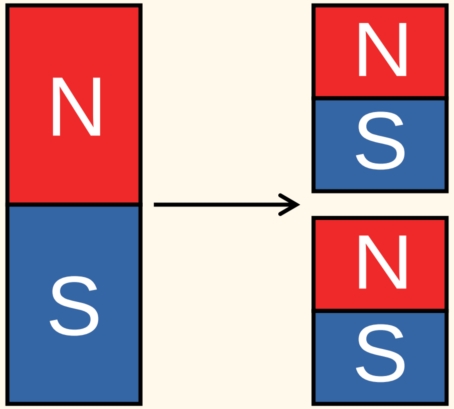
Richard Megna/Fundamental Photographs

A magnet has 2 poles: **N and S**
→ **Magnetic Dipole**

If we break a magnet in 2
→ 2 magnets with two poles
So far we know, magnetic monopoles **do not exist**

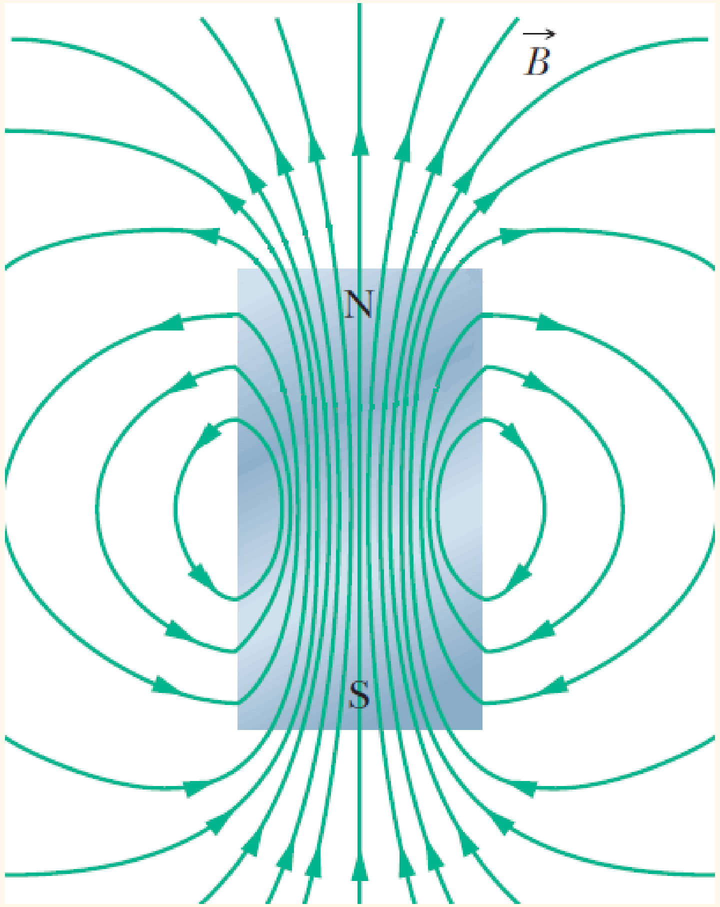
Stated by Gauss's Law for magnetic fields

$$\phi_B = \oiint \vec{B} \cdot d\vec{A} = 0$$



N is *source*
→ Field diverge

S is *sink*
→ Field converge



Note: we can also write Gauss's Law as : $\nabla \cdot \vec{B} = div\,\vec{B} = 0$

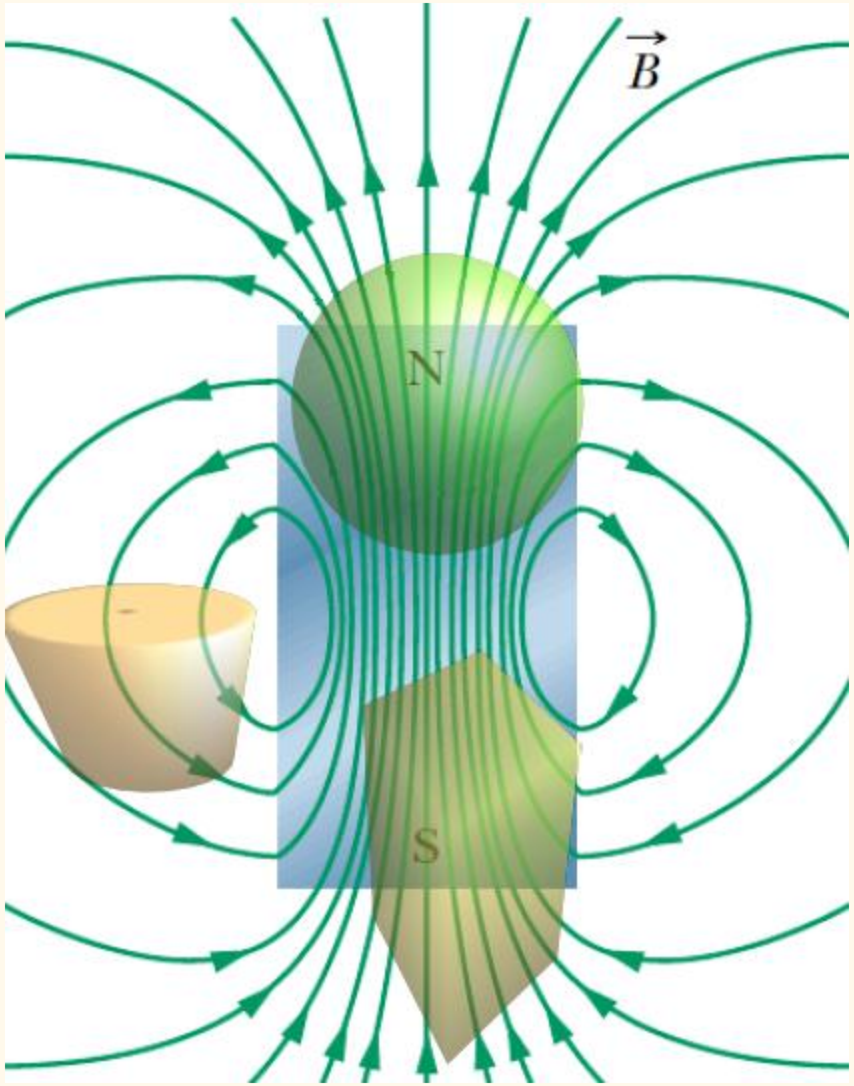
Note: Today’s lecture is about magnetism of matter but we will leave this aside for now to terminate the equations of Maxwell

Gauss's Law for magnetic fields

$$\phi_B = \oiint \vec{B} \cdot d\vec{A} = 0$$

The flux of the magnetic field through a closed surface is zero

There is always N and S poles associated to the boundaries of the surface where field lines enter / exit the surface



Example: flux of an uniform magnetic field through a cylinder $\vec{B} = B\vec{e_z}$

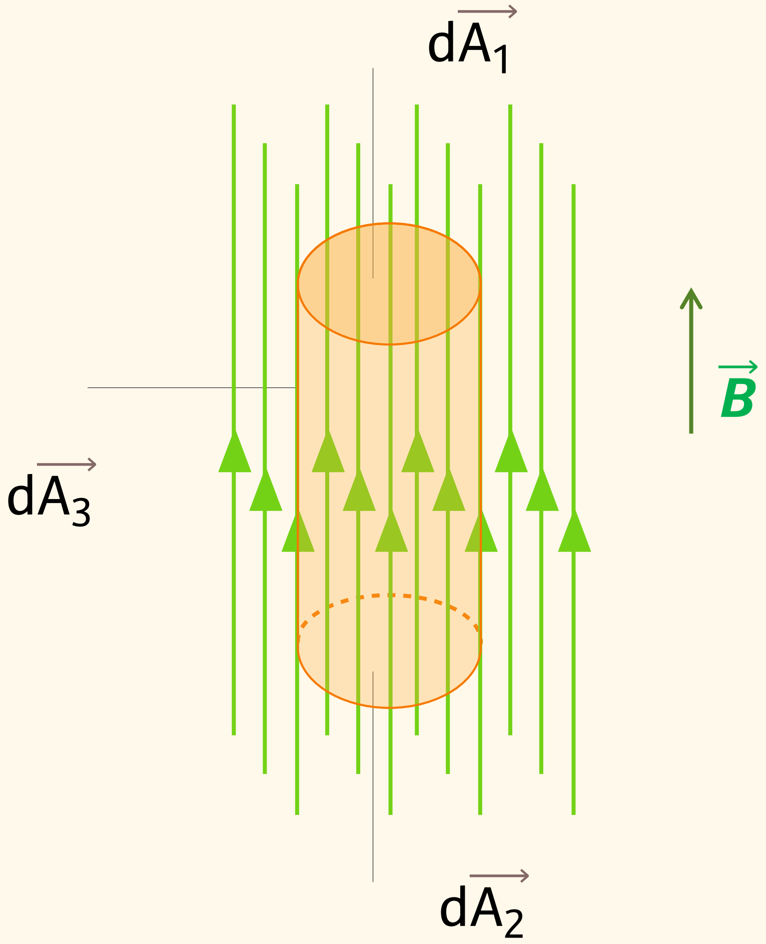
We must consider 3 surfaces:
A_1 (top), A_2 (bottom) and A_3 (shaft)

We have:

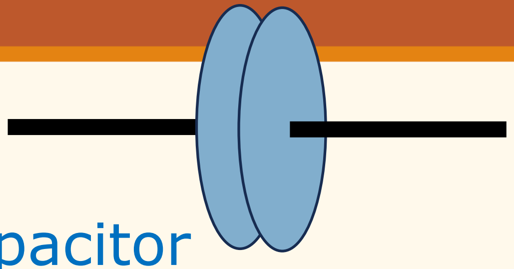
$$\iint_{top} \vec{B} \cdot d\vec{A_1} = B\, A_1$$

$$\iint_{bot} \vec{B} \cdot d\vec{A_2} = -B\, A_2$$

$$\iint_{shaft} \vec{B} \cdot d\vec{A_3} = 0$$



So ϕ_B through the cylinder equals $\boldsymbol{\phi_B = \oiint \vec{B} \cdot d\vec{A} = B\, A_1 - B\, A_2 + 0 = 0}$



A changing magnetic flux induces an emf

→ **Faraday's law of induction**

$$\oint \vec{E} \cdot d\vec{S} = -\frac{d\phi_B}{dt}$$

By symmetry, a changing electric flux induces a magnetic field

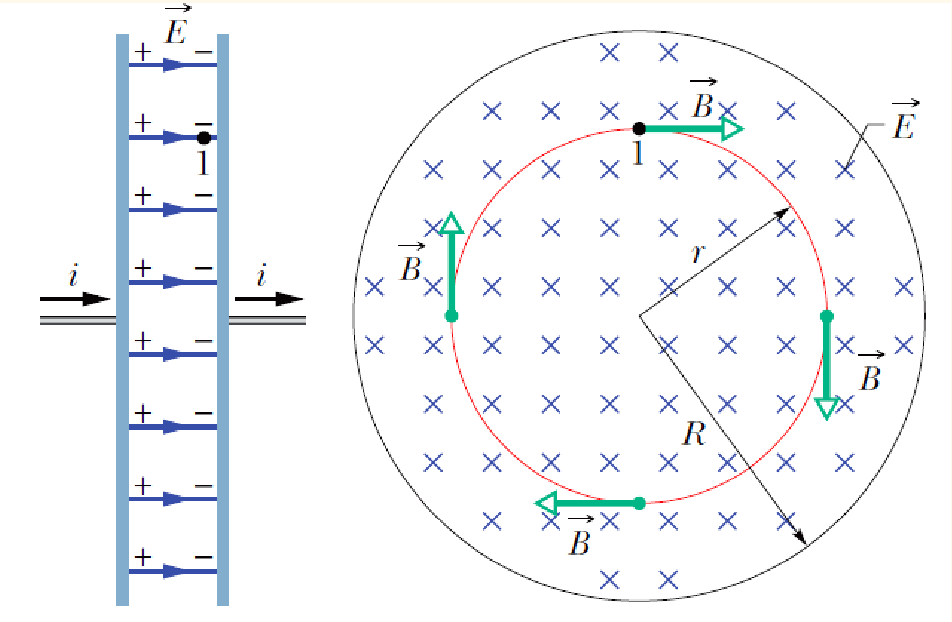
→ **Maxwell's law of induction**

$$\oint \vec{B} \cdot d\vec{S} = \mu_0 \epsilon_0 \frac{d\phi_E}{dt}$$

Example: Charging a capacitor

→ Time-varying E field between plates

→ Creation of a B field

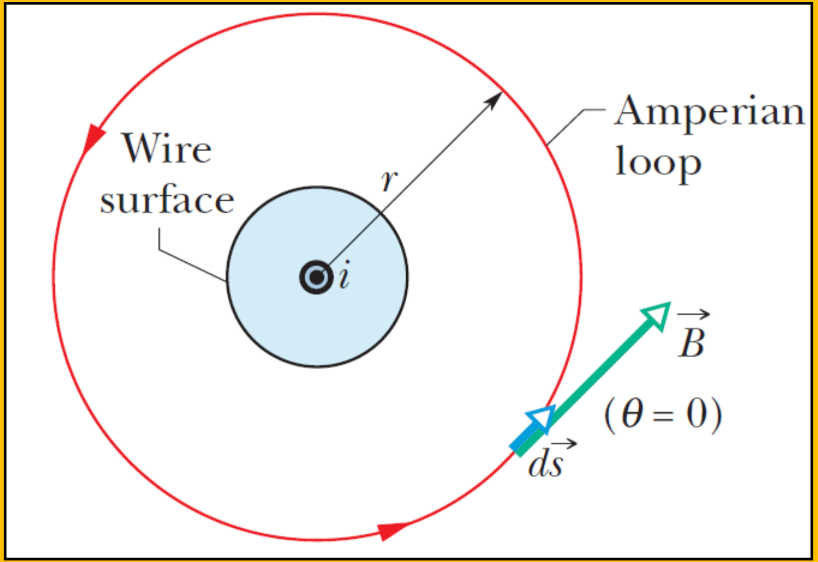


Side view Front view

μ_0: Vacuum permeability $1.26\ 10^{-6}$ H/m ε_0: Vacuum permittivity $8.85\ 10^{-12}$ F/m

Circulation of B in a closed loop
→ already seen in Ampere's law

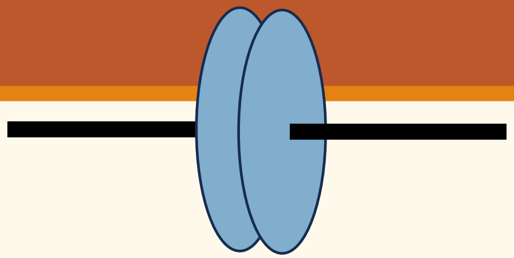
$$\oint \vec{B} \cdot d\vec{S} = \mu_0 i_{enc}$$



Combination of Maxwell's induction and Ampere law leads to the **Maxwell-Ampere law (M-A)**

$$\oint \vec{B} \cdot d\vec{S} = \mu_0 \epsilon_0 \frac{d\phi_E}{dt} + \mu_0 i_{enc}$$

For magnetic fields **not created** by a magnetic material



We define a **fictitious current** called **displacement current i_d**

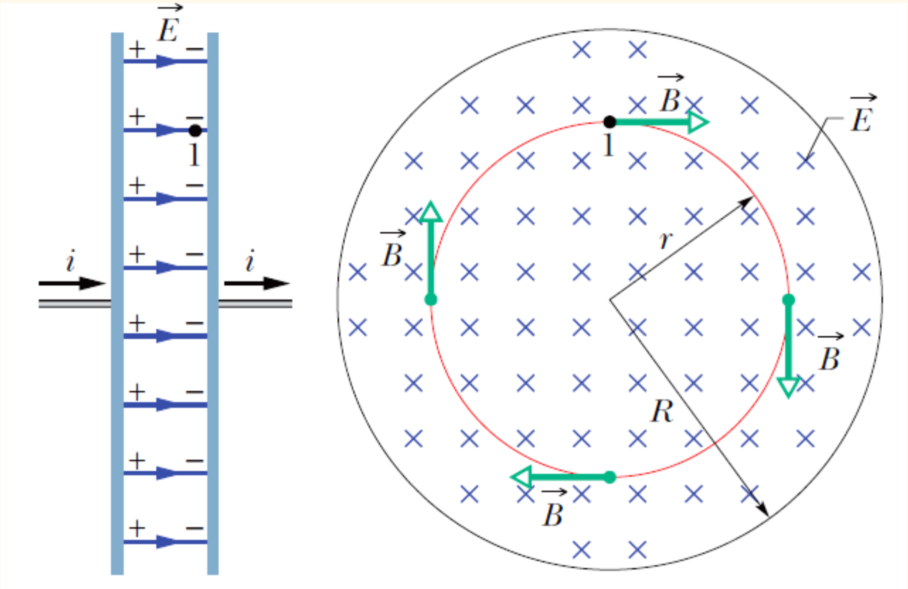
No charges are actually moving

$$i_d = \epsilon_0 \frac{d\phi_E}{dt}$$

That allows to simplify M-A law as:

$$\oint \vec{B}.d\vec{S} = \mu_0 i_{d_{enc}} + \mu_0 i_{enc}$$

If we go back to the example of the charging capacitor, charge accumulate on the plates but do not move inside
→ We must consider i_d here

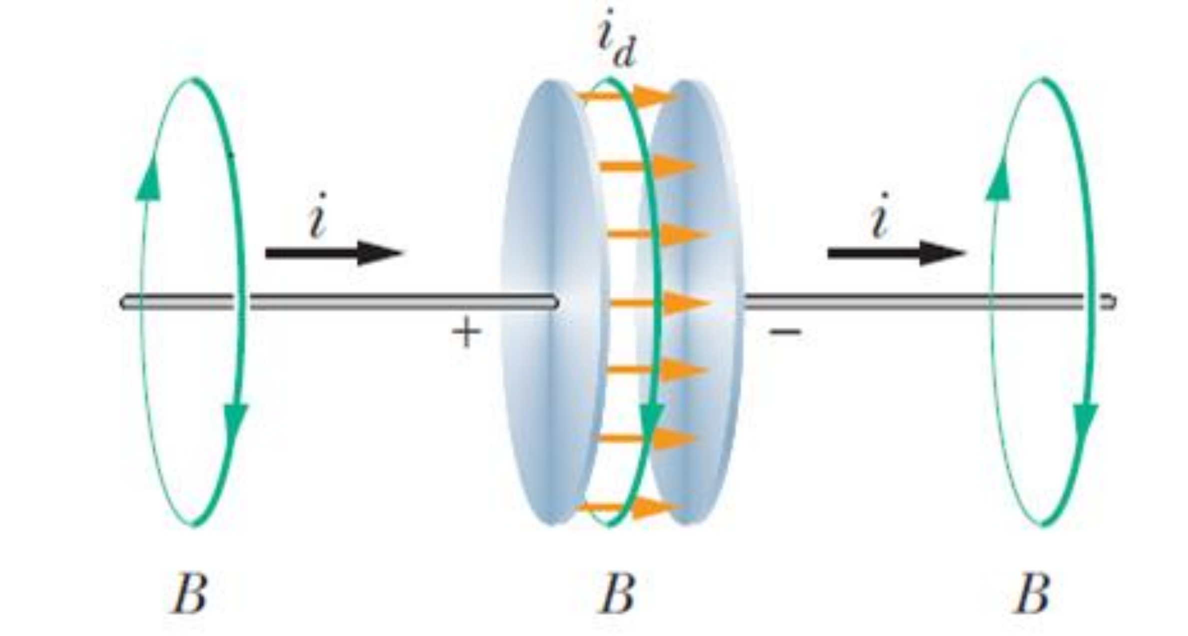


Side view Front view

Charge stored on a plate of surface A:

$$q = \epsilon_0 A E$$

We suppose E uniform an neglect fringes effects



Current (non-fictitious):

$$i = \frac{dq}{dt} = \epsilon_0 A \frac{dE}{dt}$$

Current (fictitious):

$$i_d = \epsilon_0 \frac{d\phi_E}{dt} = \epsilon_0 \frac{d}{dt}\left(\iint \vec{E} \cdot d\vec{A}\right) = \epsilon_0 \frac{d}{dt}(EA) = \epsilon_0 A \frac{dE}{dt}$$

i and i_d have the same value

What is the magnetic field ?

Ampere law:

$$\oint \vec{B}\,.\,d\vec{S} = \mu_0 i_{enc}$$

Amperian loop inside the capacitor

$$2\pi r B = \mu_0 i_d \frac{\pi r^2}{\pi R^2}$$

Surface ratio

$$B = \frac{\mu_0\, i_d}{2R^2} r$$

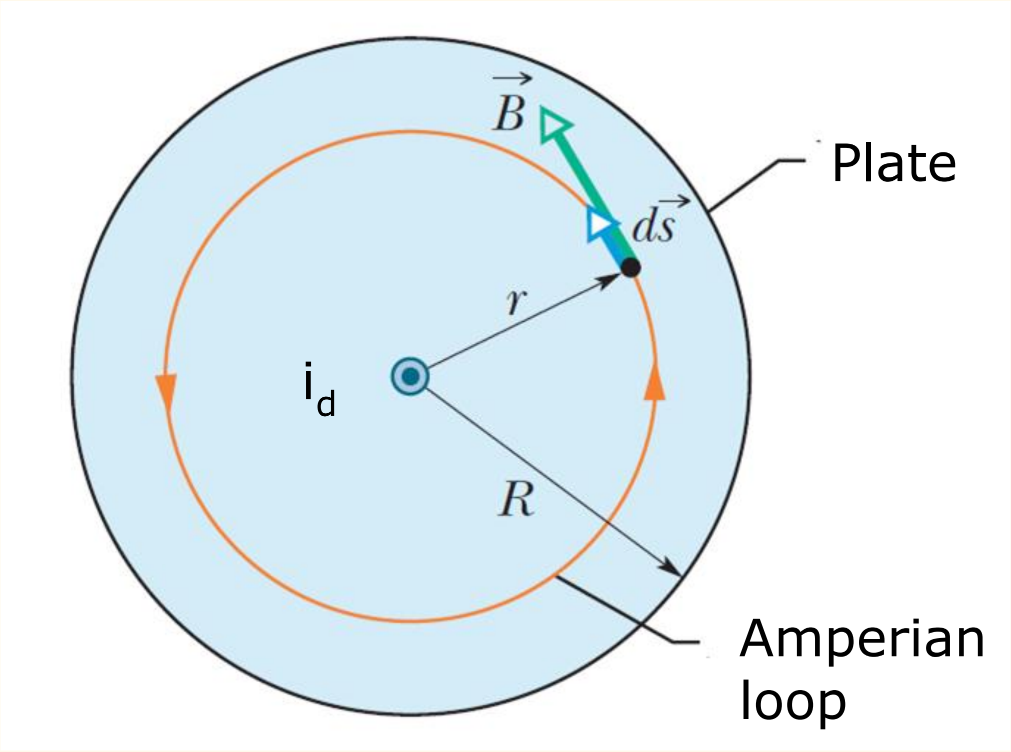
Inside

Amperian loop outside the capacitor

$$2\pi r B = \mu_0 i_d$$

$$B = \frac{\mu_0 i_d}{2\pi r}$$

Outside



MAXWELL'S EQUATIONS

Through this class, we studied the four equations of Maxwell:
Assuming no dielectric or magnetic materials

Gauss's law for electricity or Maxwell-Gauss law (M-G)	$\oiint \vec{E}\,.\,d\vec{A} = \frac{q_{enc}}{\epsilon_0}$
Gauss's law for magnetism or Maxwell-Thomson law or Maxwell-flux law (M-ϕ)	$\oiint \vec{B}\,.\,d\vec{A} = 0$
Maxwell-Faraday law (M-F)	$\oint \vec{E}\,.\,d\vec{S} = -\frac{d\phi_B}{dt}$
Maxwell-Ampere law (M-A)	$\oint \vec{B}\,.\,d\vec{S} = \mu_0\epsilon_0\frac{d\phi_E}{dt} + \mu_0 i_{enc}$

MAXWELL'S EQUATIONS

Through this class, we studied the four equations of Maxwell:
Assuming no dielectric or magnetic materials

(M-G)	Relates the electric flux to the enclosed electric charge	$\oiint \vec{E} \, . \, d\vec{A} = \frac{q_{enc}}{\epsilon_0}$
(M-ϕ)	There is no magnetic monopole	$\oiint \vec{B} \, . \, d\vec{A} = 0$
(M-F)	Relates the induced electric field to the varying magnetic field	$\oint \vec{E} \, . \, d\vec{S} = -\frac{d\phi_B}{dt}$
(M-A)	Relates the induced magnetic field to the current and the varying electric field	$\oint \vec{B} \, . \, d\vec{S} = \mu_0 \epsilon_0 \frac{d\phi_E}{dt} + \mu_0 i_{enc}$

Through this class, we studied the four equations of Maxwell:
Assuming **no dielectric or magnetic materials**

(M-G) $$\oiint \vec{E} . d\vec{A} = \frac{q_{enc}}{\epsilon_0}$$

(M-ϕ) $$\oiint \vec{B} . d\vec{A} = 0$$

(M-F) $$\oint \vec{E} . d\vec{S} = -\frac{d\phi_B}{dt}$$

(M-A) $$\oint \vec{B} . d\vec{S} = \mu_0 \epsilon_0 \frac{d\phi_E}{dt} + \mu_0 i_{enc}$$

Note: Here these equations are in the **integral form**
→ other forms exist

Through this class, we studied the four equations of Maxwell:
Assuming **no dielectric or magnetic materials**

(M-G) $\nabla . \vec{E} = \frac{\rho}{\epsilon_0}$

(M-ϕ) $\nabla . \vec{B} = 0$

(M-F) $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

(M-A) $\nabla \times \vec{B} = \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} + \mu_0 j_{enc}$

Note: Here these equations are in the **integral form**
→ other forms exist

MAXWELL'S EQUATIONS

Through this class, we studied the four equations of Maxwell:
Assuming **no dielectric or magnetic materials**

(M-G) $$div\,\vec{E} = \frac{\rho}{\epsilon_0}$$

(M-ϕ) $$div\,\vec{B} = 0$$

(M-F) $$rot\,\vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

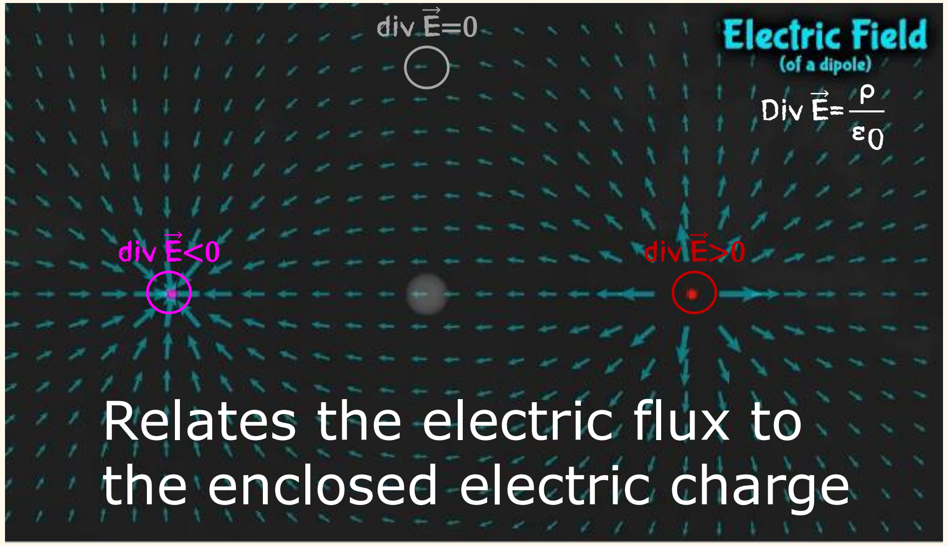
(M-A) $$rot\,\vec{B} = \mu_0 \epsilon_0 \frac{\partial \vec{E}}{dt} + \mu_0 j_{enc}$$

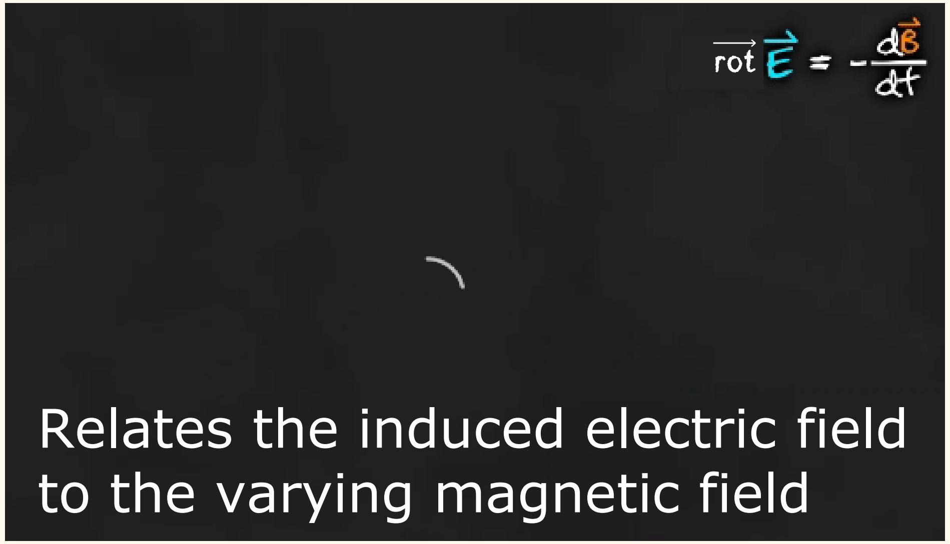
Note: Here these equations are in the **integral form**
→ other forms exist

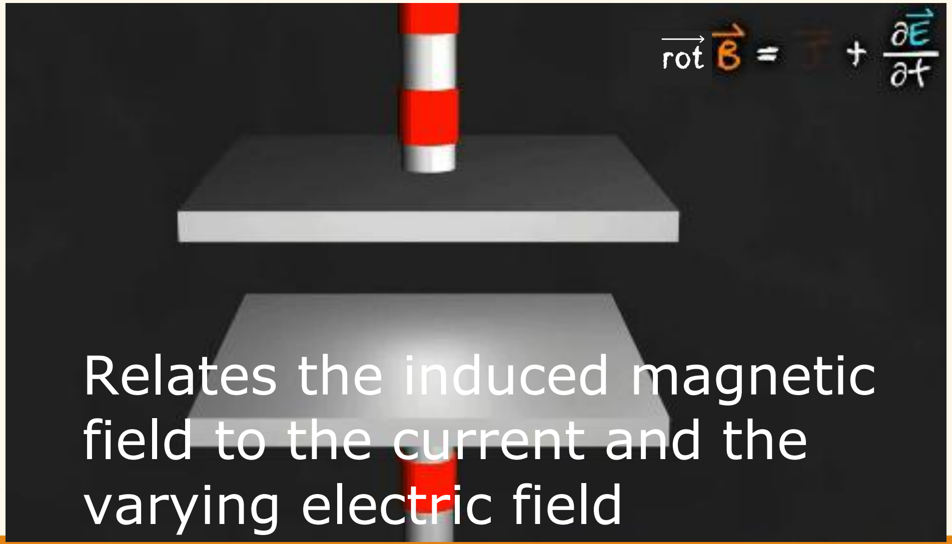
MAXWELL'S EQUATIONS

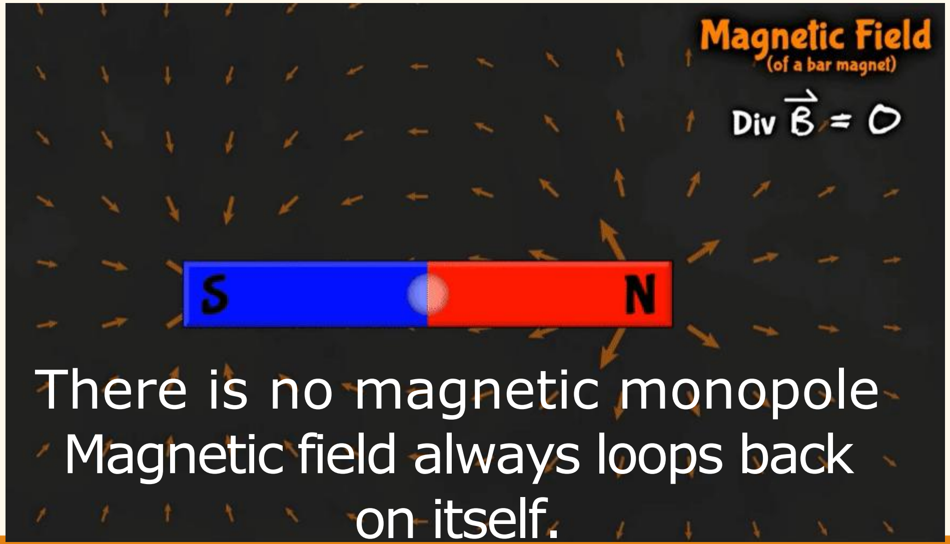
	Differential forms (local)	Integral forms
Maxwell-Gauss An electric field is generated by electric charges.	$\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon_0}$	$\oiint_S \vec{E}\,.\,\vec{dS} = \frac{q_{enc}}{\varepsilon_0}$
Maxwell-Thomson There is no such thing as a 'magnetic charge', and the magnetic field $\vec{B}$ always loops back on itself.	$\vec{\nabla}.\vec{B} = 0$	$\oiint_S \vec{B}\,.\,\vec{dS} = 0$
Maxwell-Faraday The variation of a magnetic field can create (induce) an electric field..	$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\oint_C \vec{E}\,.\,\vec{dl} = -\frac{\partial \Phi_B}{\partial t}$
Maxwell-Ampère Magnetic fields can be generated by electric currents and by the variation of an electric field	$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$	$\oint_C \vec{B}\,.\,\vec{dS} = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_E}{\partial t}$

MAXWELL’S EQUATIONS







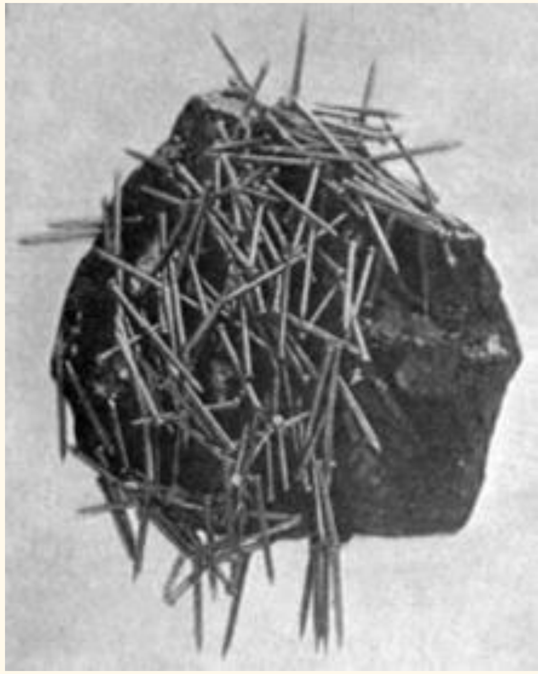


Note: Now we go back to the magnetism of matter

First now magnets: lodestones
→ stones naturally magnetized that attract some metals

Earth can be considered as a magnet
→ magnetic moment $\vec{\boldsymbol{\mu}}$
Orientation may vary and is even reversed over long periods

→ Phenomena poorly understood



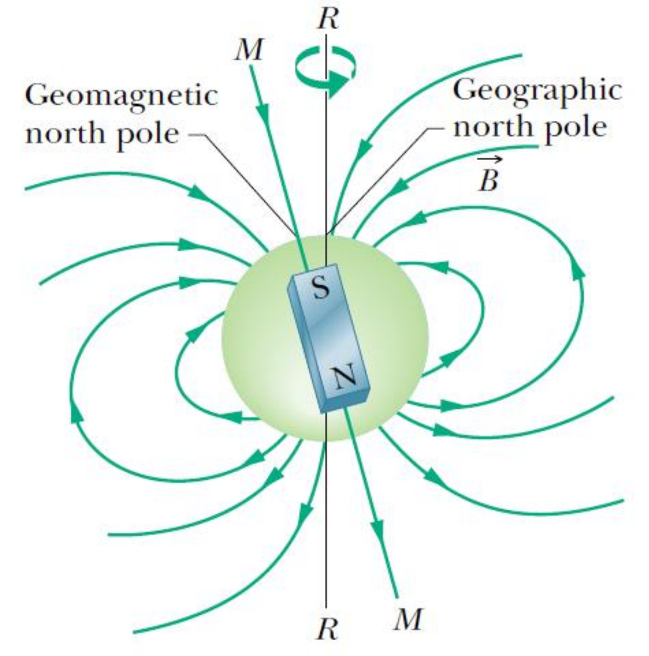


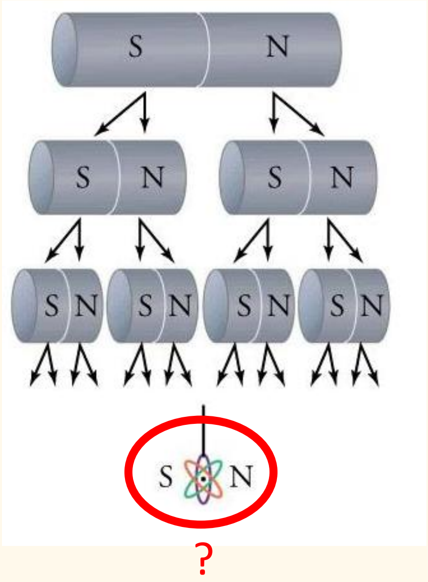
Image: wikipedia.org

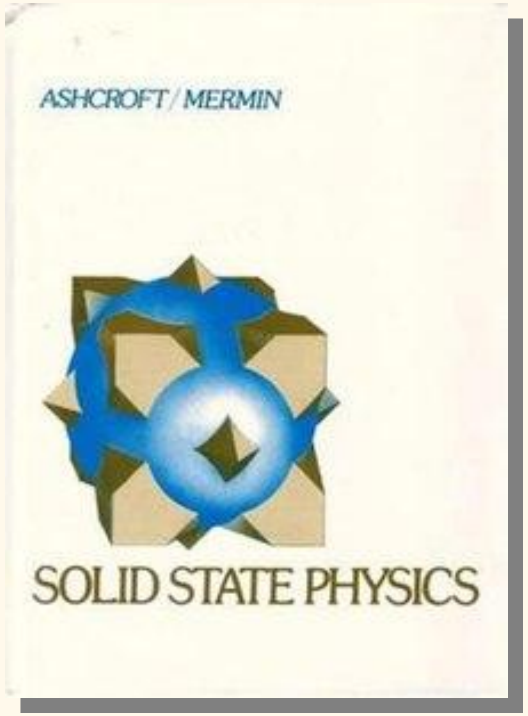
What do we know about the magnetism of matter ?

Understanding of magnetism of matter requires concepts of modern Physics
→ **Quantum Physics**
→ **Statistical Physics**

These concepts are presented in this class but you will study the proper formalism in advanced courses

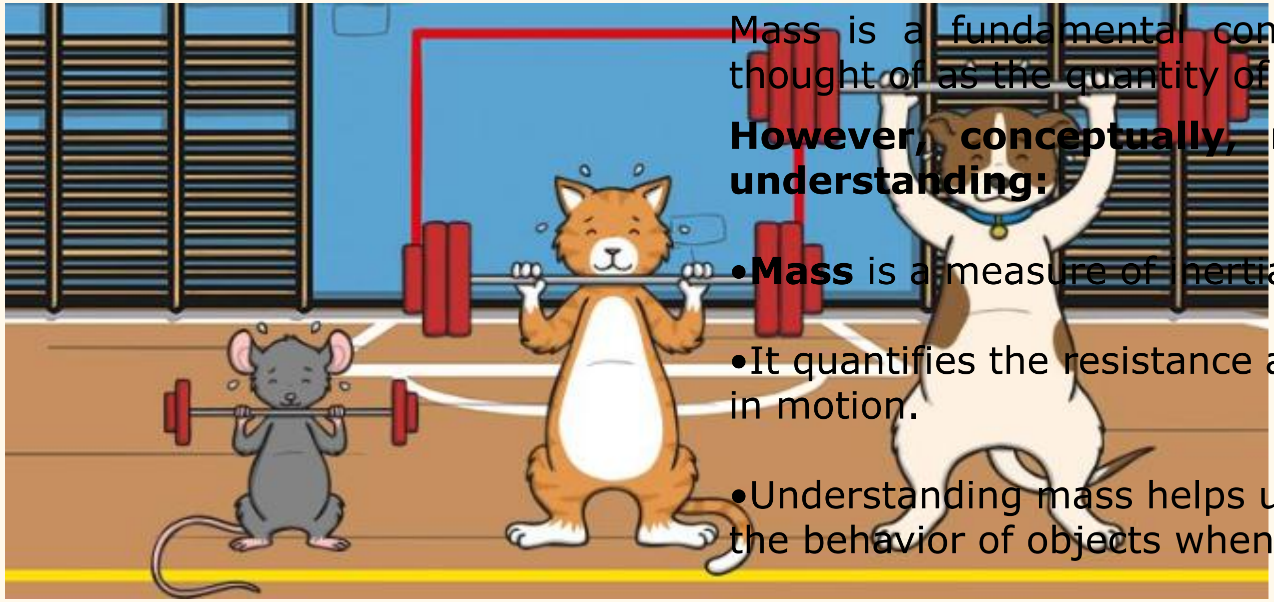
Recommended reading in the upcoming years:





Solid State Physics, Saunders College Publishing, *N. W. Aschroft & N. D. Mermin*

What is mass ?

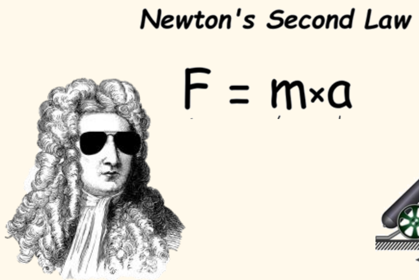


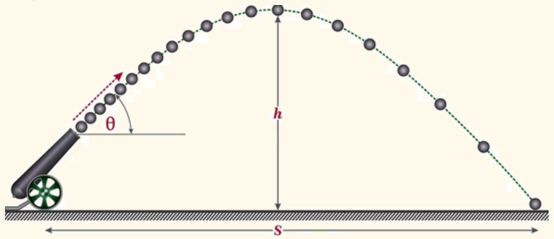
Mass is a fundamental concept in physics, often thought of as the quantity of matter in an object.

However, conceptually, mass has a deeper understanding:

- **Mass** is a measure of inertia.
- It quantifies the resistance an object has to changes in motion.
- Understanding mass helps us describe and predict the behavior of objects when forces are applied.

Concept of mass leads to classical physics

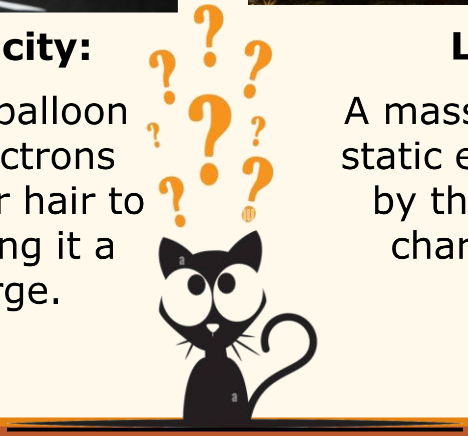




What is charge ?

Static electricity:

When you rub a balloon on your hair, electrons transfer from your hair to the balloon, giving it a negative charge.



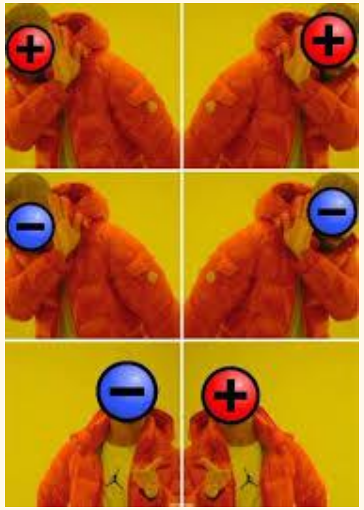
Lightning:

A massive discharge of static electricity caused by the separation of charges in clouds.

Conceptually, charge is the property that causes objects to attract or repel each other.

It’s (like mass) a fundamental property of matter

- Charge is a fundamental property that quantifies an object's ability to experience and exert electrostatic forces.
- It explains the attraction and repulsion between particles.
- Understanding charge is crucial for explaining and predicting electrical and magnetic phenomena

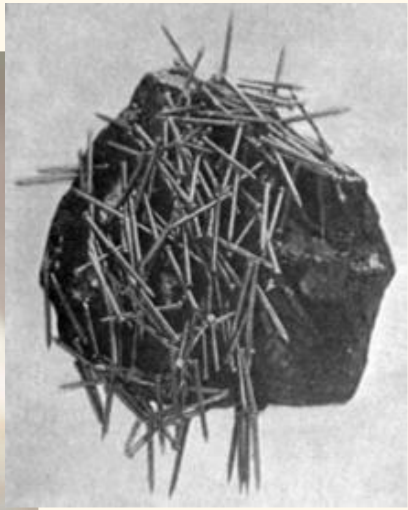


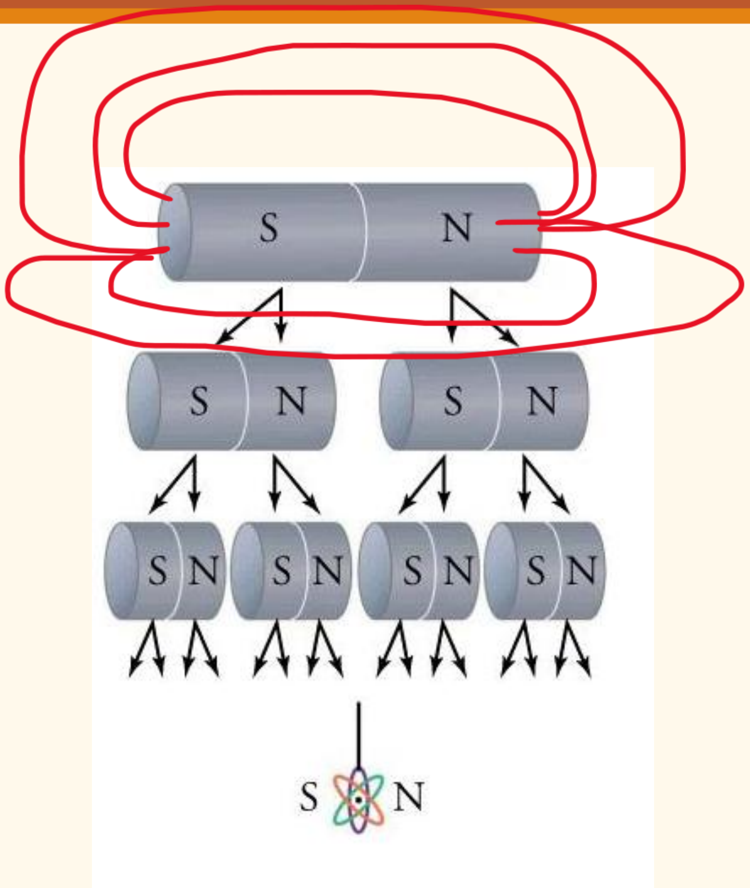
Concept of charge leads to electromagntism and Maxwell’s equations

$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

What is spin ?

Some materials exhibit magnetic propertis
Without any charge current !

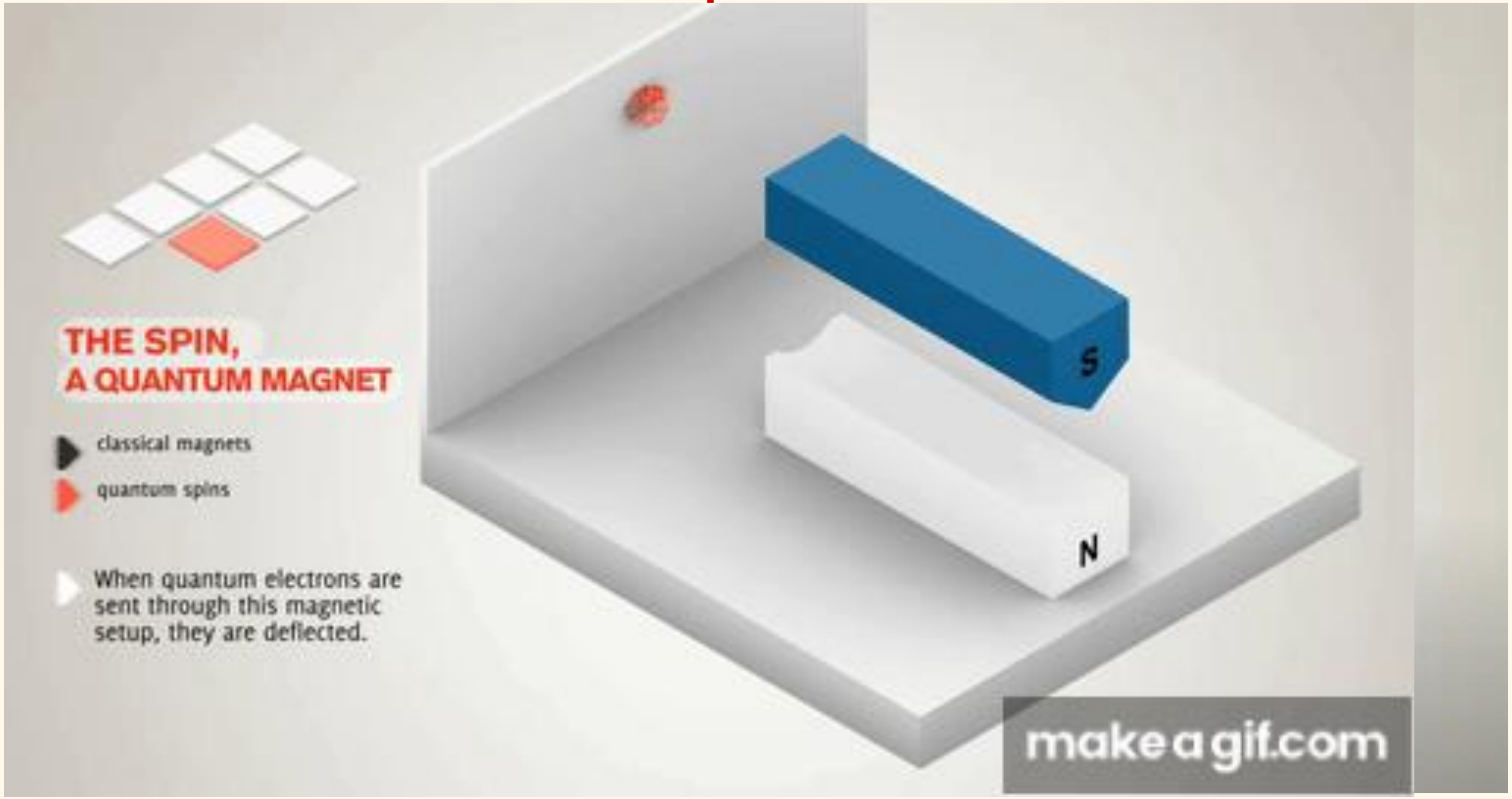




Maybe atoms carry **mass**,
charge
and also a **small elementary magnet** ?

What is spin ?

wHAT?!

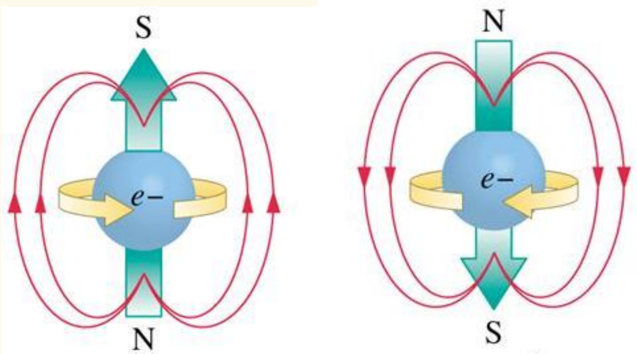


THE SPIN,
A QUANTUM MAGNET
classical magnets
quantum spins
When quantum electrons are sent through this magnetic setup, they are deflected.
S
N
makeagif.com

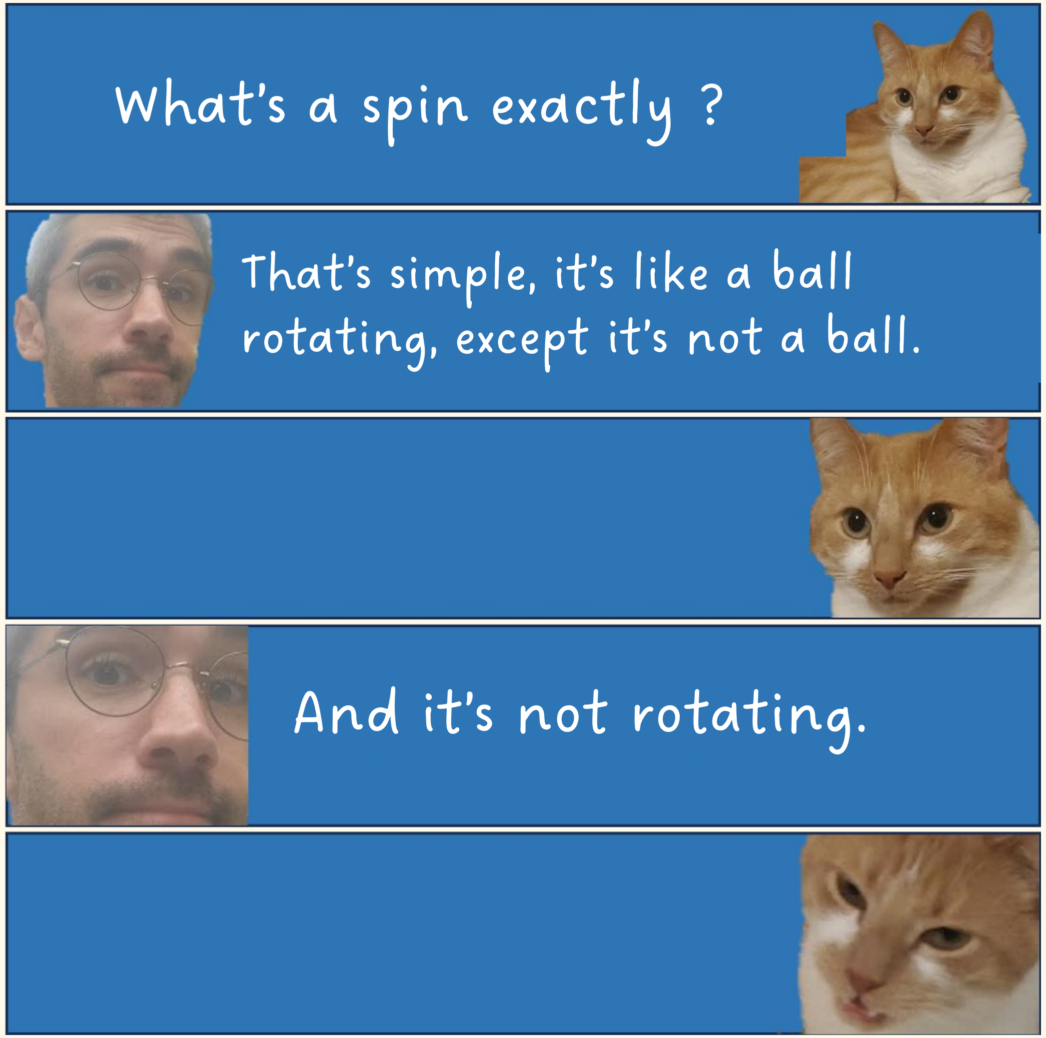
What is spin ?

Just like mass or charge, **each particle has a spin**.

It can be seen as an "**intrinsic magnet**" or an **angular momentum** due to the way the particle "spins on itself."



But....



Spin of electrons

e^- have an **intrinsic** spin angular momentum $\vec{S}$ → **cannot be measured**

One component along a **quantification axis (S_z)** **can be measured**
For **e^-** S_z can have **2 values** for ***spin up*** ↑ and ***spin down*** ↓

$$S_z = m_s \frac{h}{2\pi}$$

m_s: Spin magnetic quantum number = ± 1 / 2
h: Planck constant = 6.63 10^{-34} J.s

$\vec{S}$ has no equivalent in *classical physics*
→ e^- **are not** small spinning charged spheres

Spin magnetic dipole moment of electrons

To $\vec{S}$ is related a magnetic dipole moment $\overrightarrow{\mu_S}$ → **cannot be measured**

$$\overrightarrow{\boldsymbol{\mu_s}} = -\boldsymbol{e}\frac{\vec{\boldsymbol{S}}}{\boldsymbol{m_e}}$$

e: Elementary charge = 1.60 10^{-19} C
m_e : Electron mass = 9.11 10^{-31} kg

One component along a **quantification axis (μ_{s_z}) can be measured**

$$\mu_{s_z} = -e\frac{S_z}{m_e} = \mp\frac{1}{2}\frac{e}{m_e}\frac{h}{2\pi}$$

$$\mu_{s_z} = \mp\,\mu_B$$

$$\mu_B = \frac{eh}{4\pi m_e}$$

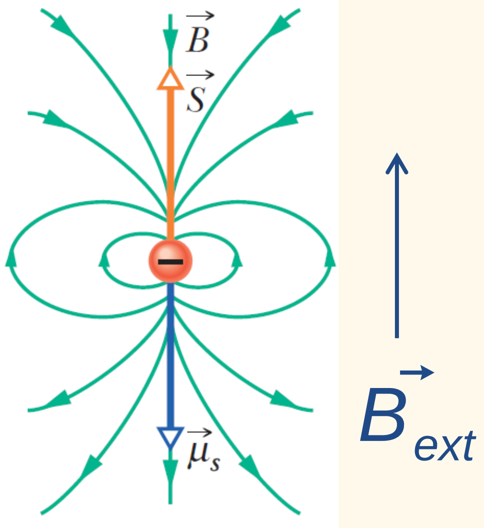
Bohr Magneton
= 9.27 10^{-34} J / T

The spin magnetic dipole moment and the spin are **antiparallel**

$$\vec{\mu_s} = -\frac{e}{m_e}\vec{S}$$

The magnetic dipole creates a magnetic field

Let's consider this e⁻ in an **external magnetic field** oriented along the quantification axis



Energy contribution:

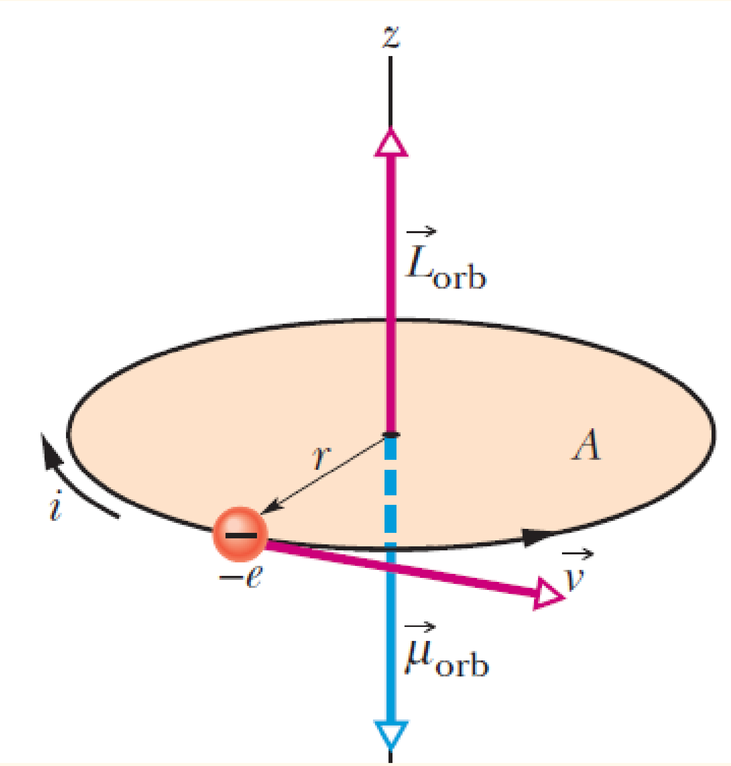
$$U = -\vec{\mu_S} . \vec{B_{ext}}$$
$$= -\mu_{S_z} B_{ext}$$
$$= \pm\mu_B B_{ext}$$

U is positive or negative for spin ↑ or ↓

Next : electrons in atoms

Magnetism of electrons in atoms

In a **oversimplified picture**, e^- in atoms orbit around the nucleus



→ **orbital angular momentum $\overrightarrow{L_{orb}}$**

Cannot be measured

One component along a quantification axis **($L_{orb\ z}$) can be measured**

$$L_{orb\ z} = m_l \frac{h}{2\pi}$$

m_l: Orbital magnetic quantum number

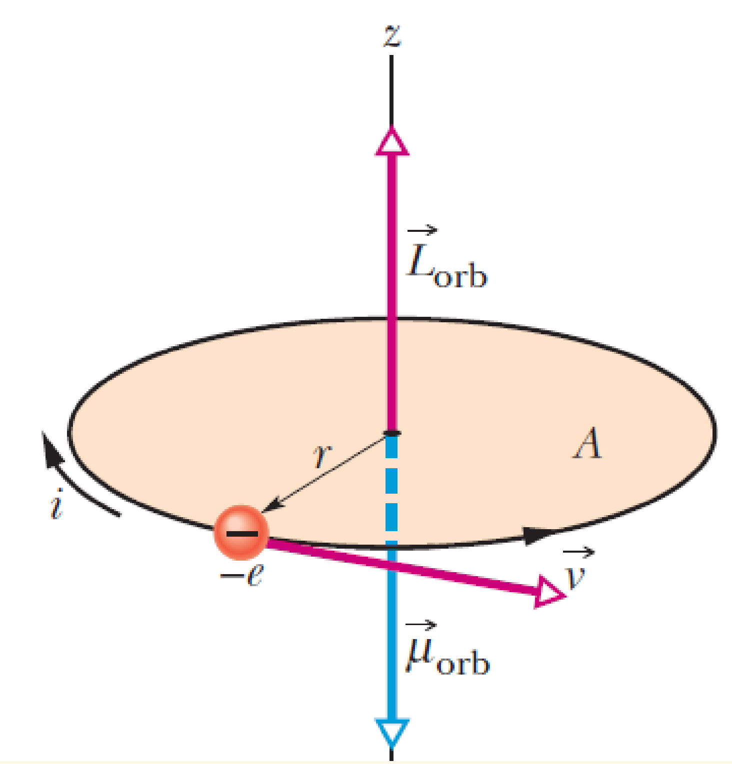
$m_l = 0, \pm 1, \pm 2, \ldots, \pm$ limit

Magnetism of electrons in atoms

To $\overrightarrow{L_{orb}}$ is related (another) magnetic dipole moment

$\overrightarrow{L_{orb}}$ → **cannot be measured**

$$\overrightarrow{\mu_{orb}} = -\frac{e}{2m_e}\overrightarrow{L_{orb}}$$



One component along a quantification axis **($\mu_{orb\,z}$) can be measured**

$$\mu_{orb\,z} = -m_l \mu_B$$

Energy contribution for an orbiting e^- in an external B along z:

$$U = -\overrightarrow{\mu_{orb}} \cdot \overrightarrow{B_{ext}} = -\mu_{orb\,z} B_{ext} = m_l \mu_B B_{ext}$$

Magnetism of electrons in materials

Electrons have a **Spin magnetic dipole moment** and an **Orbital magnetic dipole moment** that combine vectorially

$$\overrightarrow{\mu_s} = -\frac{e}{m_e}\vec{S}$$

$$\overrightarrow{\mu_{orb}} = -\frac{e}{2m_e}\overrightarrow{L_{orb}}$$

→ The **vectorial combination** of all the resultant magnetic dipole moments of **all the e⁻ in an atom**, and **all the atoms** in the material **may create a magnetic field**

→ **The material is therefore magnetic**

Next : Different class of magnetic materials

Three main phenomena for the magnetism of materials:

- Diamagnetism:

All materials under – not too strong – $\overrightarrow{B_{ext}}$ creates a net $\vec{\mu}$ in atoms

Disappear when $\overrightarrow{B_{ext}}$ turned off

- Paramagnetism

Atoms have a net $\vec{\mu}$ but the sum is null $-\overrightarrow{B_{ext}}$ creates a global net $\vec{\mu}$

Disappear when $\overrightarrow{B_{ext}}$ turned off

- Ferromagnetism

Atoms have a net $\vec{\mu}$ that combines over domains $-\overrightarrow{B_{ext}}$ align domains

Persist when $\overrightarrow{B_{ext}}$ turned off

The purpose of this chapter is to understand what it means and why.

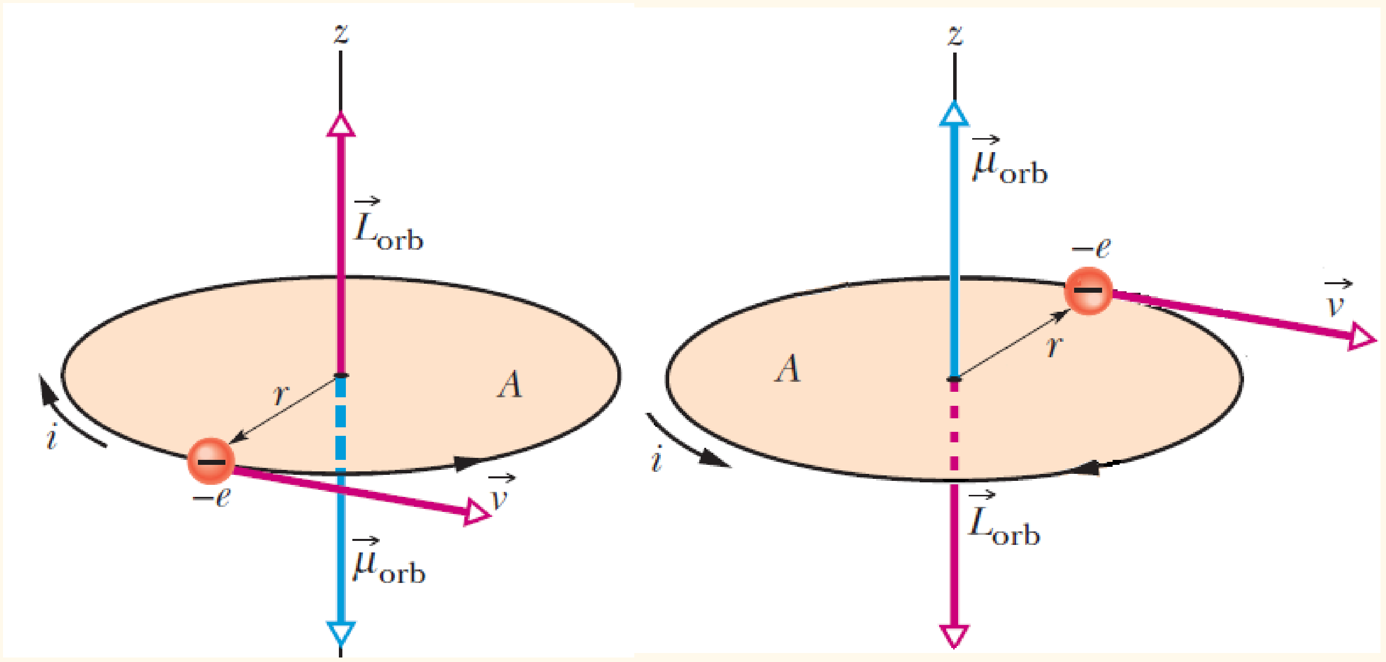
Diamagnetism

Simplified model

Atoms of the material have **no net $\vec{\mu}$**

We consider only $\overrightarrow{\mu_{orb}}$ of the e$^-$

The null sum of $\overrightarrow{\mu_{orb}}$ results of an equal number of e$^-$ orbiting clockwise and counter-clockwise



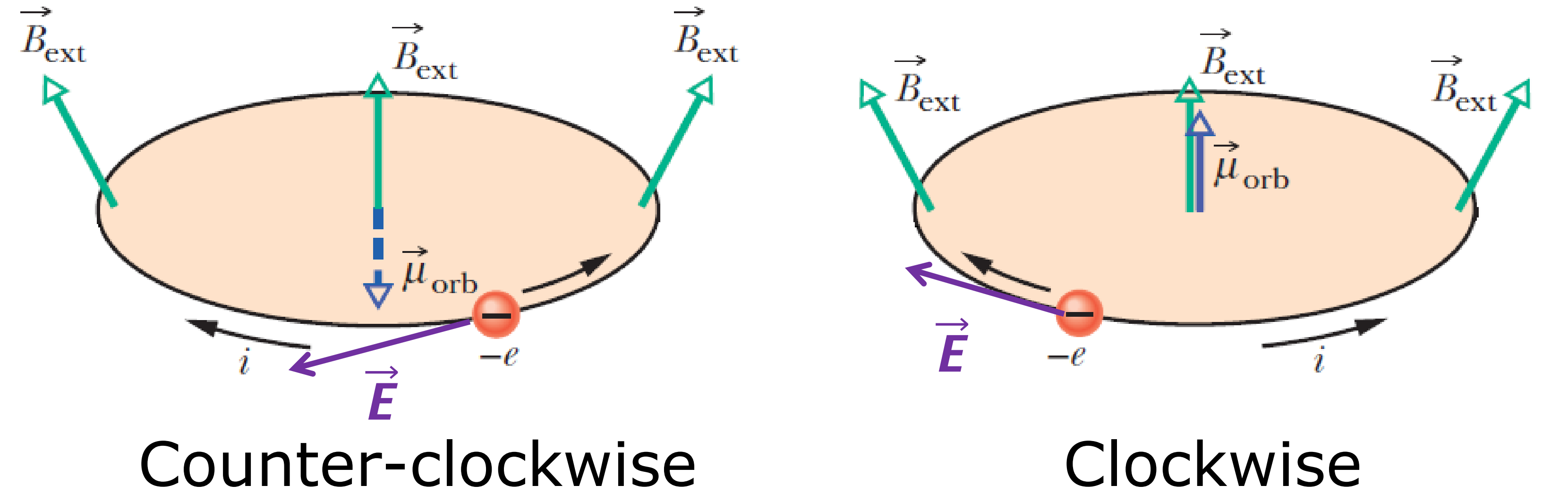
Counter-clockwise Clockwise

Diamagnetism

Sample in a **spatially non-uniform** $\overrightarrow{B_{ext}}$

Amplitude **increases**
0 → $\mathbf{B_{max}}$

(M-F) $\oint \vec{E} \cdot d\vec{S} = -\frac{d\phi_B}{dt}$



A counter-clockwise electric field circulate on the loop

$\vec{E}$ accelerate counter-clockwise e^- → |i| increases
$\vec{E}$ decelerate clockwise e^- → |i| decreases

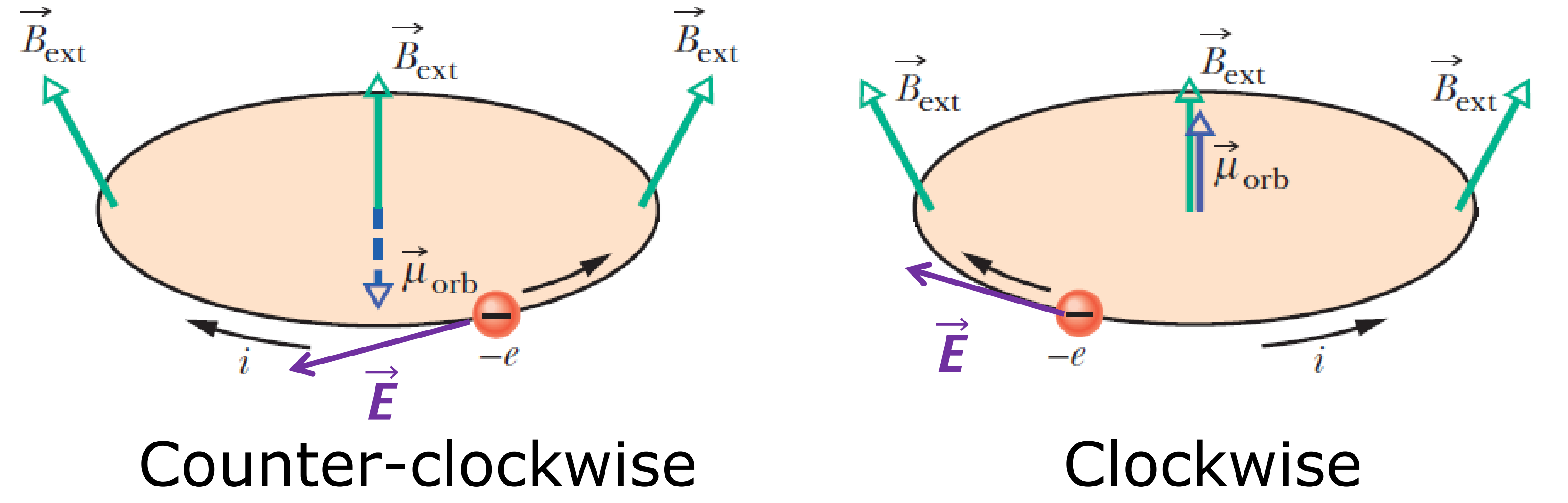
Diamagnetism

Sample in a **spatially non-uniform** $\vec{B}_{ext}$

Amplitude **increases**
0 → B_{max}

In this loop model:

$\mu_{orb} = i A$



$\vec{E}$ accelerate counter-clockwise e⁻ → |i| increases

$\vec{E}$ decelerate clockwise e⁻ → |i| decreases

→ counter-clockwise e⁻ have an increased μ_{orb}
→ clockwise e⁻ have a decreased μ_{orb}

Net downward μ generated ⟶ creates a field opposed to B_{ext}

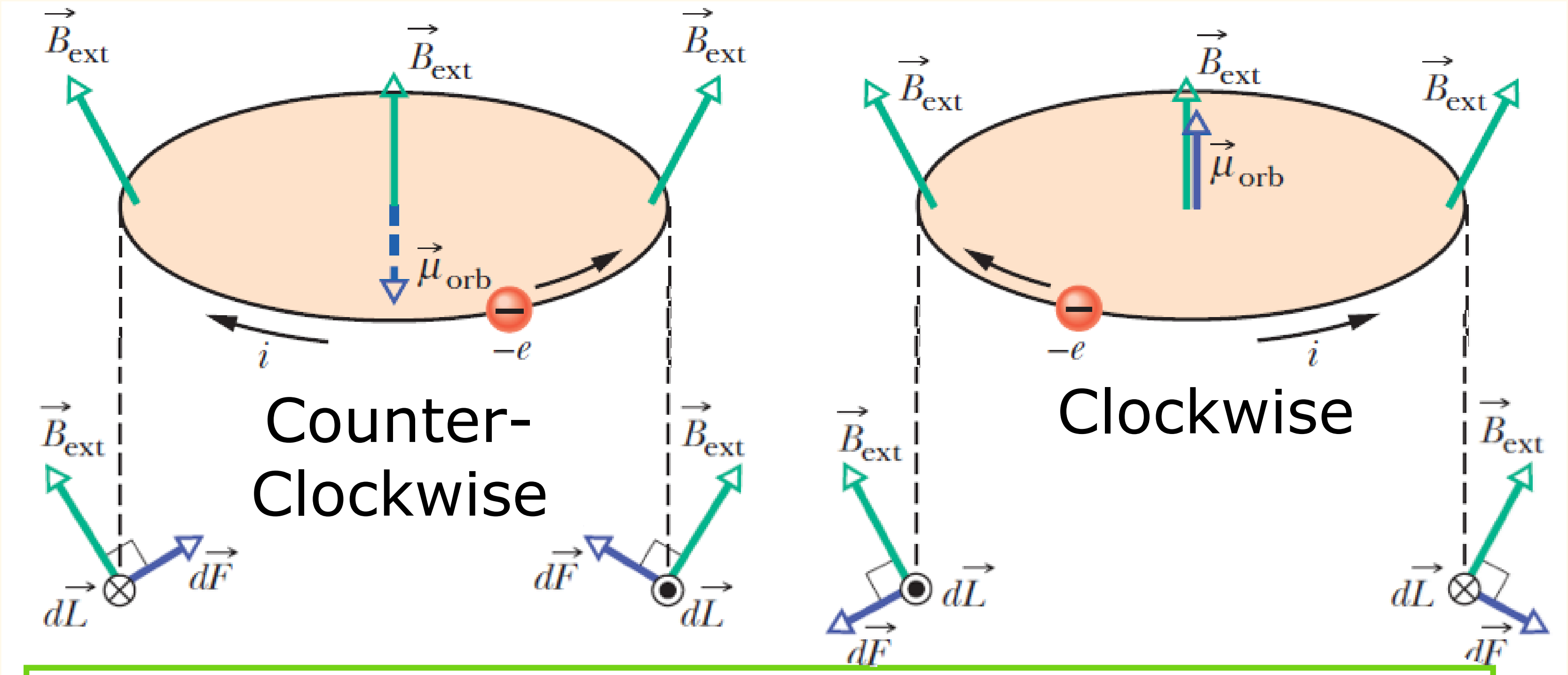
Diamagnetism

Sample in a **spatially non-uniform** $\vec{B}_{ext}$

Amplitude **increases** **0** → $\mathbf{B_{max}}$

A **magnetic force** is applied on the e^-

$$d\vec{F} = i\vec{dL} \times \vec{B}_{ext}$$



$\vec{E}$ accelerate counter-clockwise e^- → |i| increases

$\vec{E}$ decelerate clockwise e^- → |i| decreases

Integrated over the loop:

$F_{\uparrow}$ upward for counter-clockwise e^- ⟶ $\mathbf{F_{\uparrow} > F_{\downarrow}}$

$F_{\downarrow}$ downward for clockwise e^-

Diamagnetism

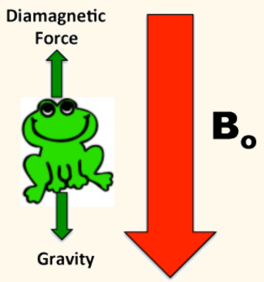
Sample in a **spatially non-uniform** $\overrightarrow{B_{ext}}$

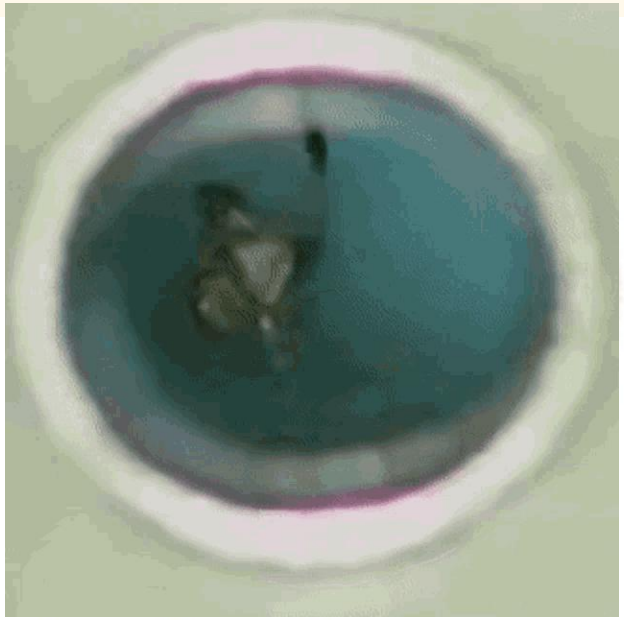
Net downward μ generated
→ creates a field opposed to B_{ext}

Force applied on electrons $F_{\uparrow} > F_{\downarrow}$
→ towards lesser field regions

Amplitude **increases**
0 → B_{max}

If $\overrightarrow{B_{ext}}$ strong enough, the resulting force on all the sample can compensate weight



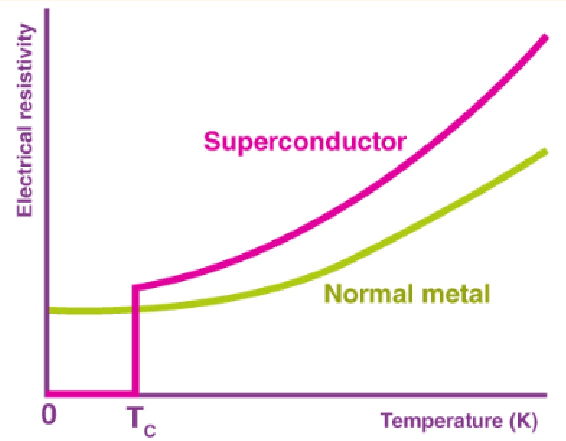


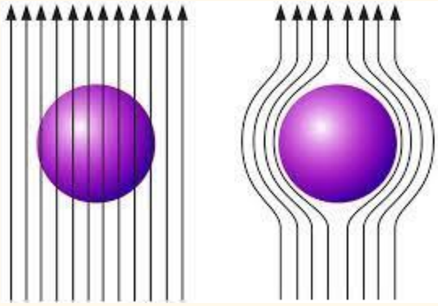
Courtesy A.K. Geim, University of Manchester, UK

But the effects of diamagnetism are small compared to para- and ferromagnetism

Diamagnetism

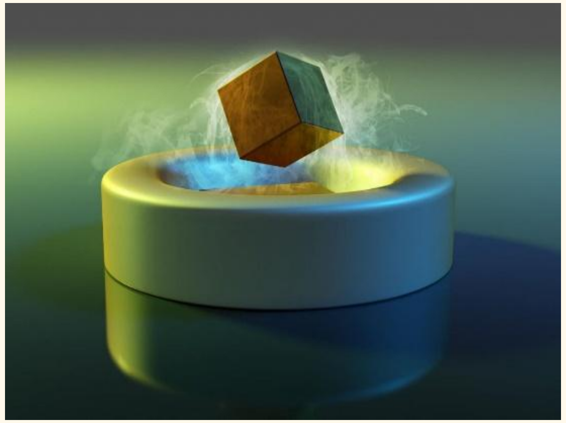
The special case of **superconductors**

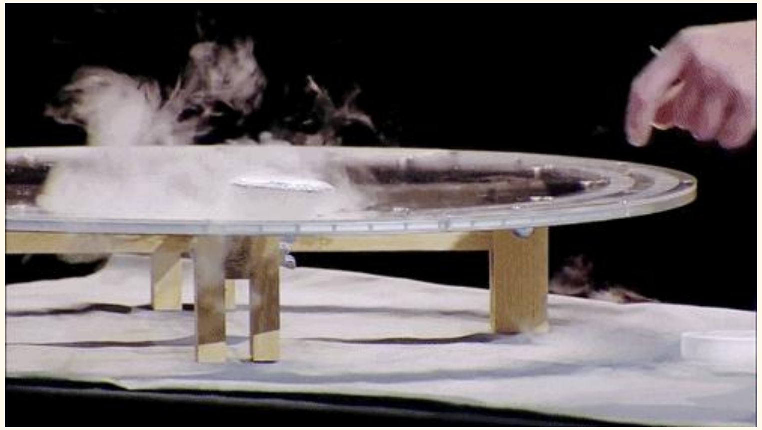




Superconductor are material with zero resistivity (below a specific temperature).
They can conduct electricity without any loss !

But superconductor are considered has **perfect diamagnetic material.**
They repel completely any magnetic field





Paramagnetism

All atoms have net $\overrightarrow{\mu_{atom}}$ **randomly oriented** in absence of $\overrightarrow{B_{ext}}$

Sample has **no net** $\vec{\mu}$

When $\overrightarrow{B_{ext}}$ is applied, $\overrightarrow{\mu_{atom}}$ are oriented parallel to $\overrightarrow{B_{ext}}$

Sample has **net** $\vec{\mu}$ that generates a magnetic field

Parallel to $\overrightarrow{B_{ext}}$

$U = -\vec{\mu} \cdot \overrightarrow{B_{ext}}$

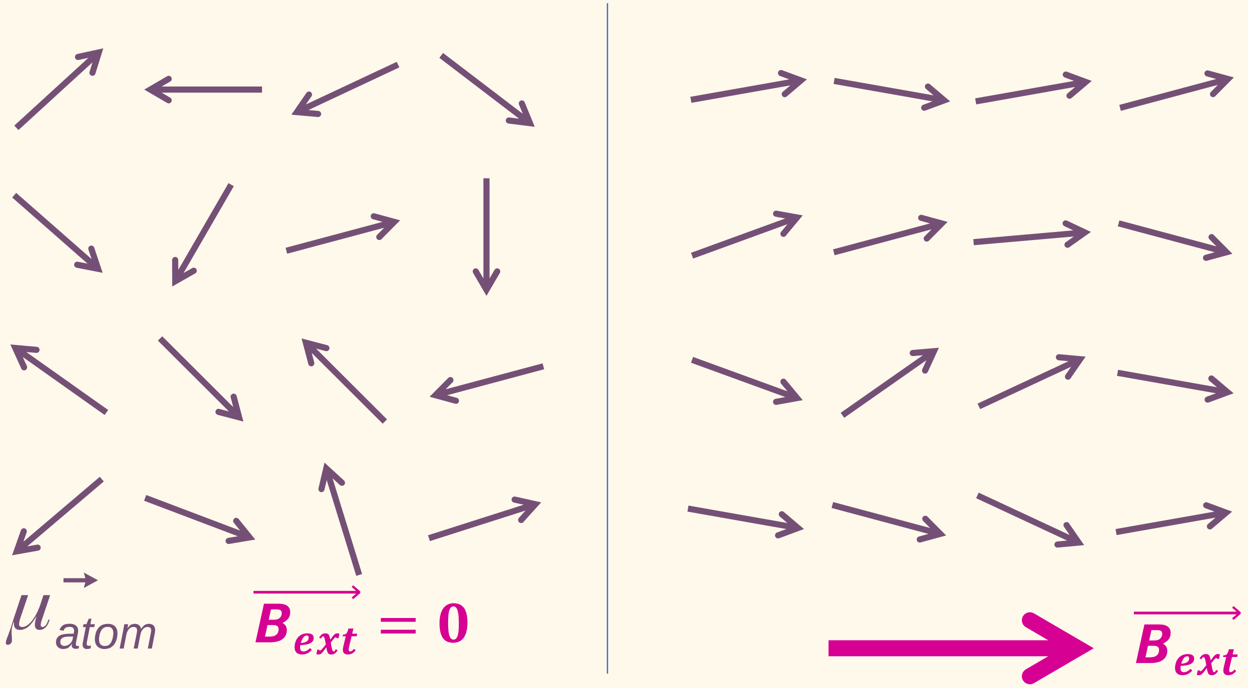
Lower energy when parallel

If $\overrightarrow{B_{ext}}$ is non-uniform, the sample moves towards higher field regions

Paramagnetism

All atoms have net $\overrightarrow{\mu_{atom}}$ **randomly oriented** in absence of $\overrightarrow{B_{ext}}$

When $\overrightarrow{B_{ext}}$ is applied, $\overrightarrow{\mu_{atom}}$ are oriented *"parallel"* to $\overrightarrow{B_{ext}}$



For N atoms, the total $\vec{\mu}$ should be $N.\overrightarrow{\mu_{atom}}$

But thermal agitation prevents complete alignment with $\overrightarrow{B_{ext}}$

Paramagnetism

Thermal agitation

Energy: $\frac{3}{2}k_B T$

k_B: Boltzmann Constant = 1.38 10^{-23} J/K
T: Temperature (K)

To compare with the difference in energy between parallel and antiparallel alignment of atomic $\vec{\mu}$ with $\overrightarrow{B_{ext}}$

$$U = -\overrightarrow{\mu_{atom}}.\overrightarrow{B_{ext}}$$

$$\Delta U = 2\mu_{atom}B_{ext}$$

For ordinary magnetic field and temperature $\mathbf{k_B T >> \Delta U}$

$\rightarrow$ the net sample magnetic dipole moment is not N $\overrightarrow{\mu_{atom}}$

Paramagnetism

We define the **Magnetization** M of a material as:

$$\vec{M} = \frac{measured\ \vec{\mu}}{Volume} \quad \text{so} \quad \overrightarrow{M_{max}} = \frac{N\ \overrightarrow{\mu_{atom}}}{Volume}$$

Saturation of magnetization

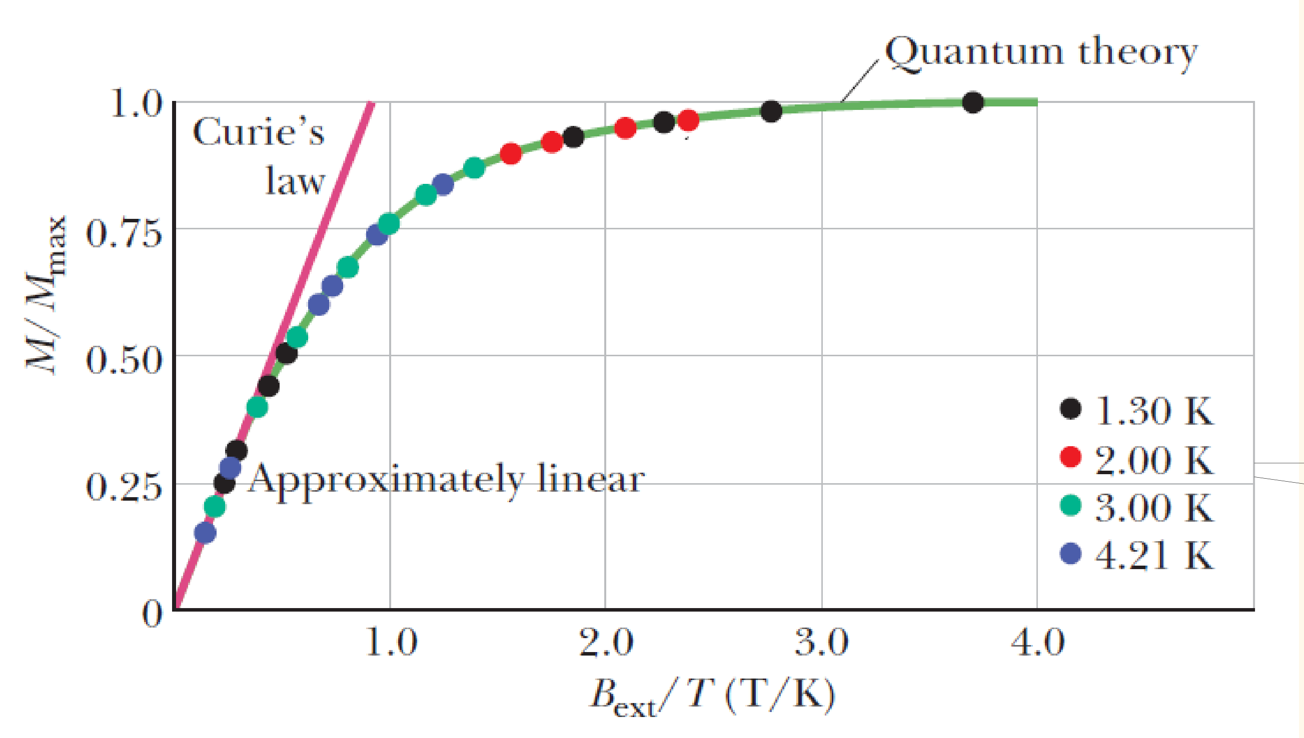
The amplitude of the magnetization follows Curie's law for moderate B_{ext} / T ratios

$$\boldsymbol{M} = \boldsymbol{C}\frac{\boldsymbol{B_{ext}}}{\boldsymbol{T}}$$

C: Curie Constant (for a given particle)

M / M_{max} follows Curie's law for moderate B_{ext} / T ratios

Paramagnetism



A *magnetization curve* for paramagnetic salt potassium chromium sulfate.
Based on measurements by W. E. Henry.

Challenging to go down to a few K

M / M_{max} follows Curie's law for moderate B_{ext} / T ratios

Paramagnetism

Net μ generated → creates a field parallel to B_{ext}

Force applied → towards higher field regions

But thermal agitation prevents complete alignment of $\overrightarrow{\mu_{atom}}$ with $\overrightarrow{B_{ext}}$

$$\boldsymbol{M} = \boldsymbol{C}\frac{\boldsymbol{B_{ext}}}{\boldsymbol{T}}$$

External magnetic field turned off

→ random orientation of $\overrightarrow{\mu_{atom}}$ due to thermal agitation

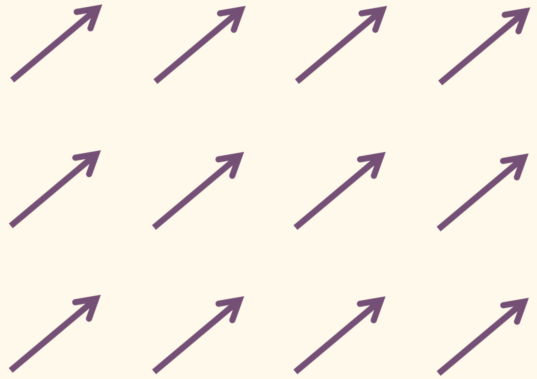
Ferromagnetism

Note: To simplify the picture, for now Sample = 1 magnetic domain

Atoms of the material have a $\overrightarrow{\mu_{atom}}$

In absence of $\overrightarrow{B_{ext}}$, $\overrightarrow{\mu_{atom}}$ **are parallel** due to Exchange Coupling

→ Sample has a **net**



For **T > T_c (Curie Temperature)**
Thermal agitation overcomes Exchange Coupling and material becomes paramagnetic

Image: wikipedia.org

Typical ferromagnetic (FM) materials i.e. *"magnet"*:

Co, Ni, Fe and their alloys

Ferromagnetism

Example of characterization of a FM: Rowland ring

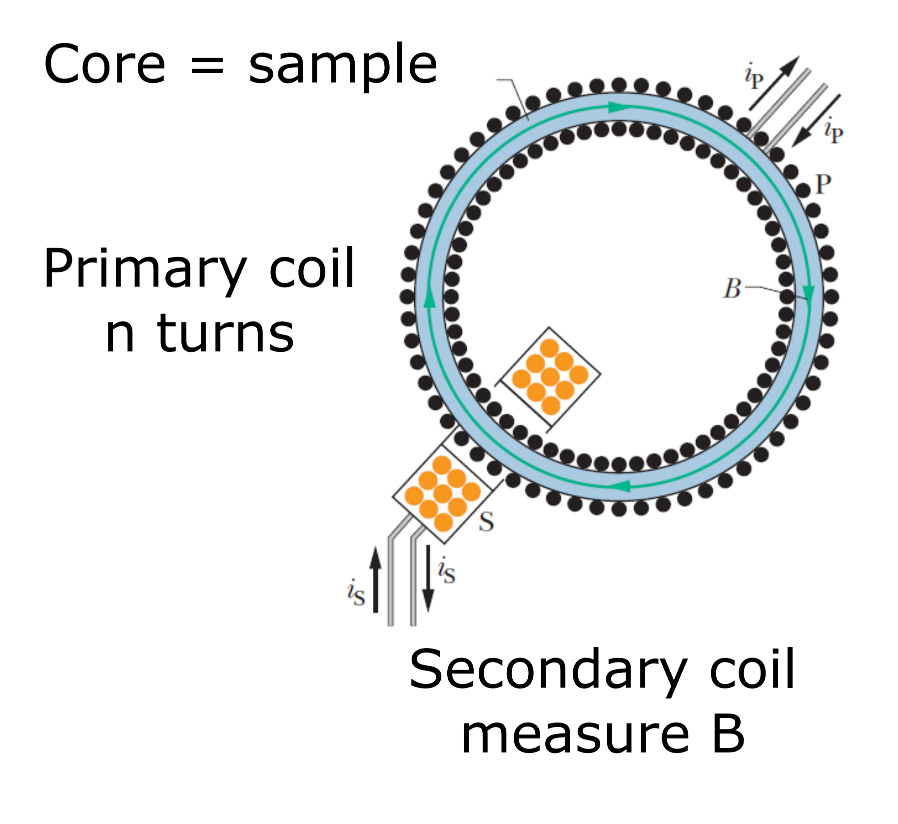
Without sample: $B_0 = \mu_0 ni$

With sample: $B = B_0 + B_M$

B_M field created by the sample proportional to magnetization

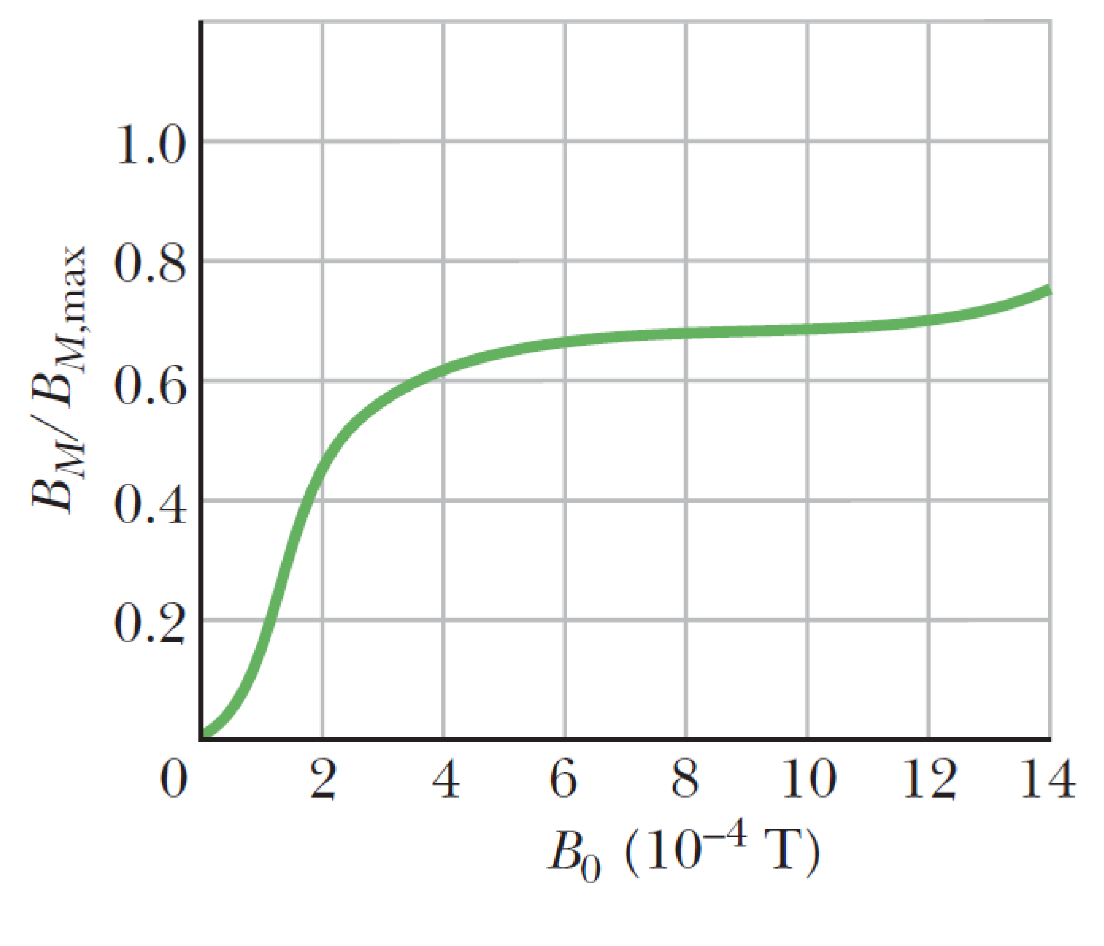
B_M max = field at saturation

Note: we assume T << T_C (for Fe T_C = 1043 K)



Ferromagnetism

Result:



- Without B_0 no B_M
- B_M increases with B_0
- We do not reach B_M max

Why is the FM sample not naturally saturated ?

Why does it has no $\vec{\mu}$ at the beginning of the experiment ?

Ferromagnetism

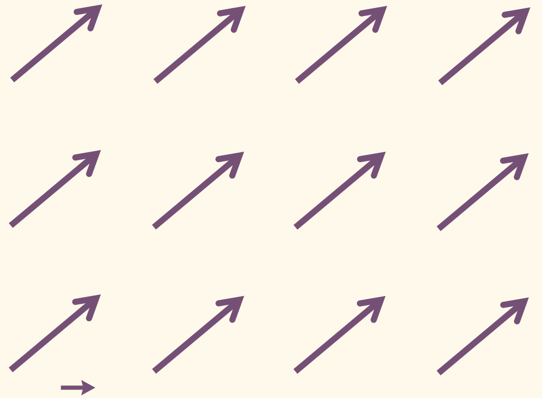
Oversimplification → wrong predictions

~~Note: To simplify the picture, for now Sample = 1 magnetic domain~~

Atoms of the material have a $\overrightarrow{\mu_{atom}}$

In absence of $\overrightarrow{B_{ext}}$, $\vec{\mu}$ **are parallel** due to Exchange Coupling

→ Sample has a **net**



For **T > T_c (Curie Temperature)**
Thermal agitation overcomes Exchange Coupling and material becomes paramagnetic

Image: wikipedia.org

Typical ferromagnetic (FM) materials i.e. *"magnet"*:

Co, Ni, Fe and their alloys

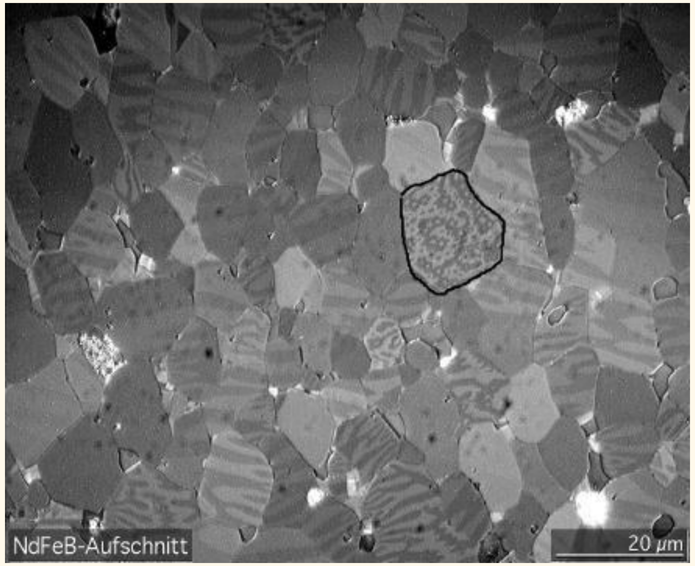
Ferromagnetism

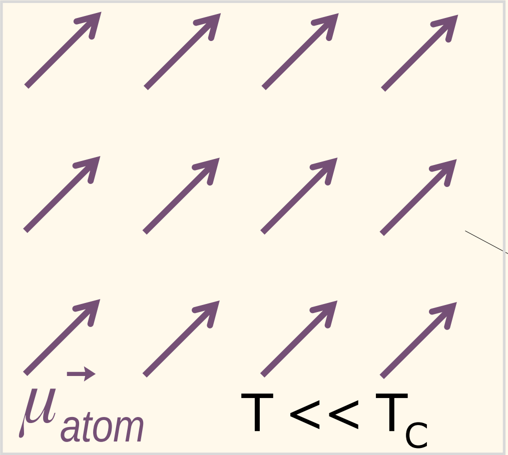
Atoms of the material have a $\overrightarrow{\mu_{atom}}$

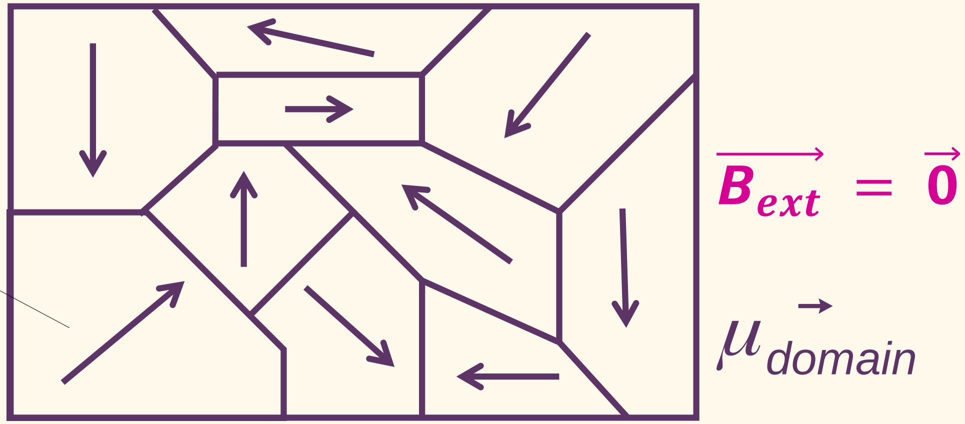
In absence of $\overrightarrow{B_{ext}}$, $\overrightarrow{\mu_{atom}}$ **are parallel** due to Exchange Coupling over **small domains**

→ Domains have a **net** $\overrightarrow{\mu_{domain}}$

→ Sample has a **no net** $\vec{\mu}$ (or very small)







Note: There is domains even in single crystals.

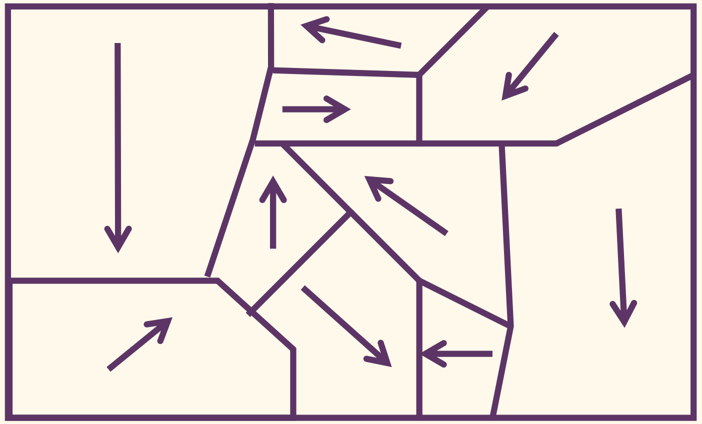
In polycrystalline structures magnetic domains and microcrystals do not have the same boundaries

Ferromagnetism

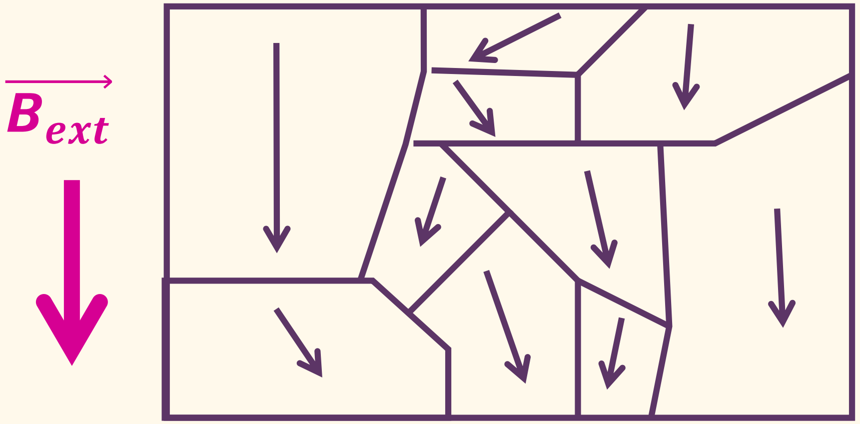
Growth of domains parallel to $\overrightarrow{B_{ext}}$ + **alignment** of the other domains

→ Sample have a **net** $\vec{\mu}$

$\overrightarrow{B_{ext}} = 0$



$\overrightarrow{B_{ext}}$



Ferromagnetism

The net $\vec{\mu}$ of the sample generates a field that is parallel to $\overrightarrow{B_{ext}}$

If $\overrightarrow{B_{ext}}$ is non-uniform
→ force toward higher field regions

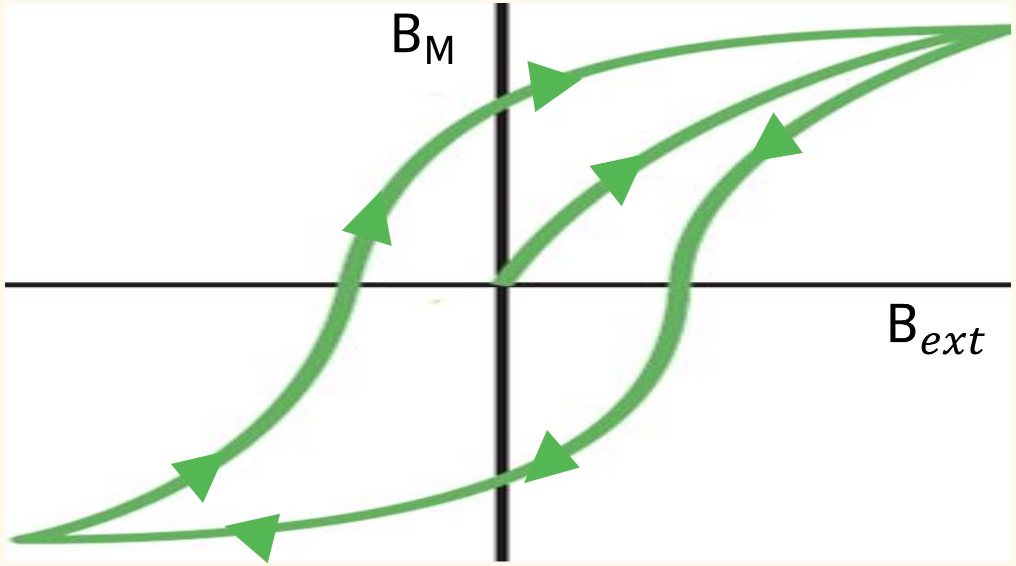
What happens if we turn off or reverse its direction ?

Magnetization persists
→ **Memory** of previous events

Hysteresis loop

Growth of domains parallel to $\overrightarrow{B_{ext}}$ + **alignment** of the other domains

→ Sample have a **net** $\vec{\mu}$



Ferromagnetism

Net μ generated
→ creates a
field parallel to B_{ext}

Force applied
→ towards higher
field regions

Magnetization persists
→ Memory of previous events

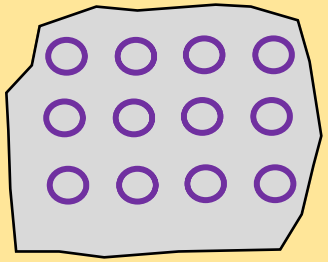
Hysteresis loop

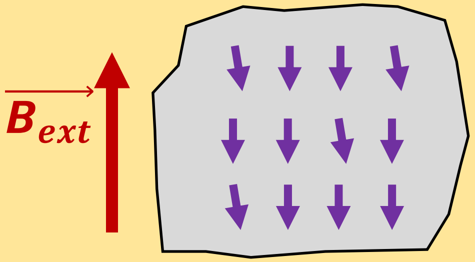
For **$T > T_C$ (Curie Temperature)**
Thermal agitation overcomes Exchange Coupling and material becomes paramagnetic

Magnetic materials

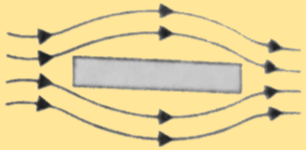
	No magnetic field	In presence of magnetic field	Properties

Diamagnetism



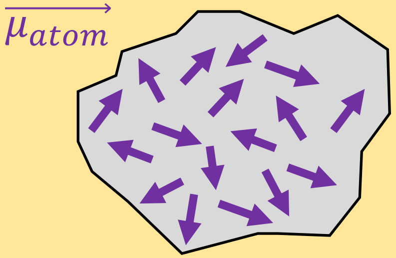


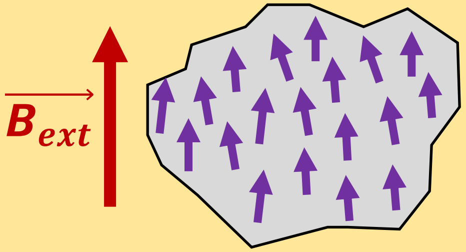
- → **Slightly repelled by strong magnets**
- → **The lines of magnetic forces tend to avoid the substance**



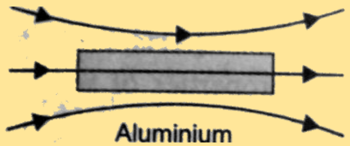
Ex: Antimony, Bismuth, Copper, gold, silver, Quartz, Mercury, Alcohol, Water, Air, Argon, etc

Paramagnetism



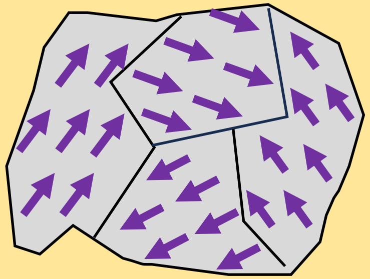


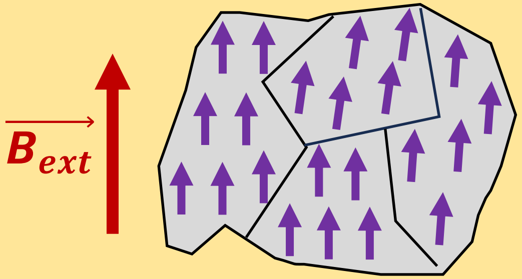
- → **Slightly attracted by strong magnets**
- → **The lines of forces prefer to pass through the substance rather than air**



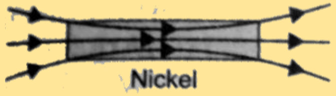
Ex: Aluminium, Chromium, Alkalo and Alkaline earth metals, platinum, Oxygen, etc.

Ferromagnetism





- → **Strongly attracted to magnets**
- → **The lines of forces tend to crowd into the specimen**
- → **Magnetization persist after turning off the external field**



Ex: Iron, Cobalt, Nickel, Gabolinium, Dysprosium, etc.

KEY POINTS

Gauss law for magnetic fields → no magnetic monopoles $\phi_B = \oiint \vec{B} . d\vec{A} = 0$

Maxwell – Ampere equation $\oint \vec{B} . d\vec{S} = \mu_0 \epsilon_0 \frac{d\phi_E}{dt} + \mu_0 i_{enc}$

Displacement current characterize induced magnetic field in capacitors

Electrons have Spin $\vec{S}$ and Magnetic Orbital moment $\overrightarrow{L_{orb}}$ and respective $\overrightarrow{\mu_S}$ and $\overrightarrow{\mu_{orb}}$

Magnetic phenomena in materials are related to their electronic properties

Differences between Dia- , Para- and Ferromagnetism in materials

READING ASSIGNMENT

Chapter 33 of the textbook