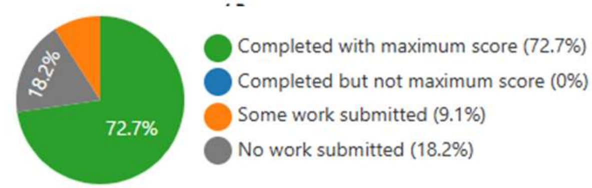
Today's topics:

- A few logistics
- Playing with magnets
- Some simple analogies (The full physics requires quantum physics!)
- Distinguishing different types of magnetism
- How do we measure them?

Please raise your hand with questions anytime. If I need to finish a thought, I'll just take a second before I call on you.

Don’t stress too much over Perusall score, it’s unlikely to bring you down a letter grade

Assignment	Submission deadline	Score	
Making the most of learning with Perusall	Wed Aug 27, 2025 5:00 pm EDT	2 / 3 ⌛	Download ▾
Tutorial reading 1 (only part 1 is required, part 2 is appendices)	Wed Aug 27, 2025 5:00 pm EDT		Download ▾
Syllabus Review and Short Tutorial Reading	Wed Sep 3, 2025 5:00 pm EDT		Download ▾
Short tutorial reading with optional appendices	Wed Sep 10, 2025 5:00 pm EDT		Download ▾
Tutorial reading on what you can learn from x-ray diffraction and review follow-up on anisotropy	Wed Sep 24, 2025 5:00 pm EDT		Download ▾
Average score (for assignments past their deadline)			



115 comments, **12** questions, **0** unanswered questions

46 minutes average active engagement time

- This is my 2nd time using Perusall.
- Grading was a little confusing.
- My goal is to get you to interact with the material, not stress over grading.
- If the grading is too harsh, I’ll bump it up, but not all the way from 0. Just make sure you’re interacting with the reading assignments.

Science is a Team Sport That Requires Practice

- You will have 1 or 2 partners.
- There are many benefits to working with others, even/especially if you know more than your partner(s). Teaching is the best way to learn!
- It’s also a good opportunity to build community and network. Recommended by older WVU students too!
- Social interaction is important in science.

Project Proposal

When you ask the government, industry or even your parents for money, they want to know for what you want it and often why. In science, you have to write a proposal. Answering these questions will not only tell me what you plan to do on your project, but also you will motivate why you think this approach could be valuable.

- What material will you measure? **What is scientifically interesting about this specific material?**
- **What experimental parameters will you vary?**
- **What do you expect to learn from your experiment?**
- **Why do you think learning that could be important?**
- Beyond magnetization measurements, are there additional measurements you think you'd like to do if time? If so, why do you think these measurements might be useful for your project?

Feedback Scaffolding

How do the pieces fit?

Project Proposal

What experimental variables will you vary?

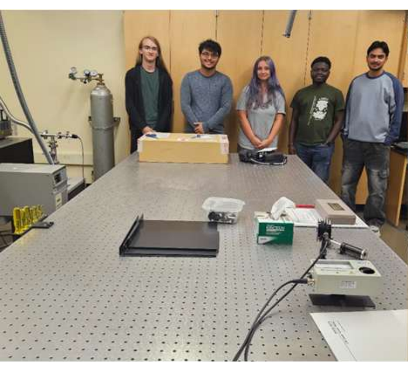
Why do you think this work could be important?

What do you think you will learn about?

What material will you measure? Why did you pick this material?

Early Lab Notebook

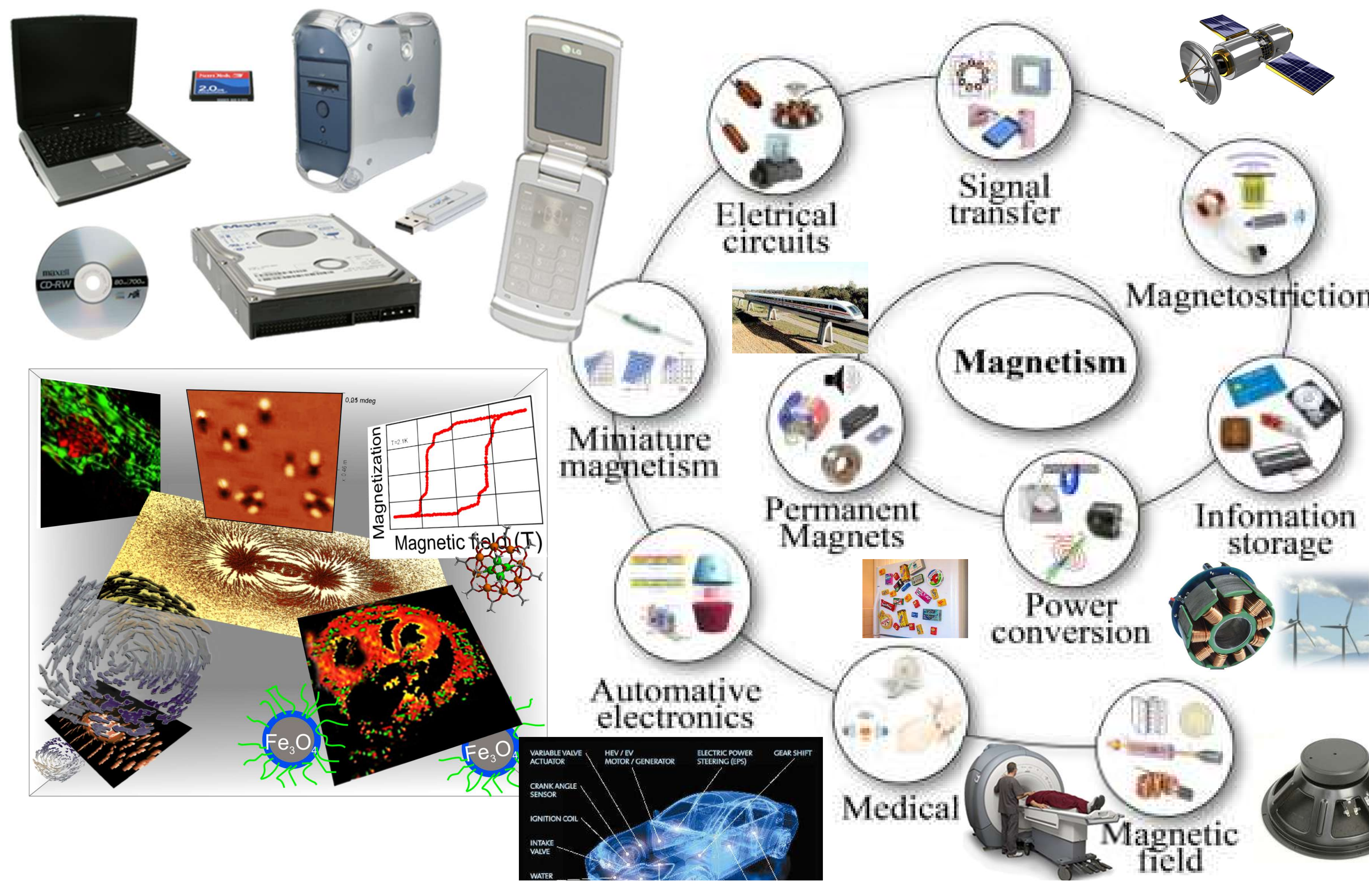
Category
Introduction/ motivation/ goals
Figures explaining the background
Description of the uniqueness of the material

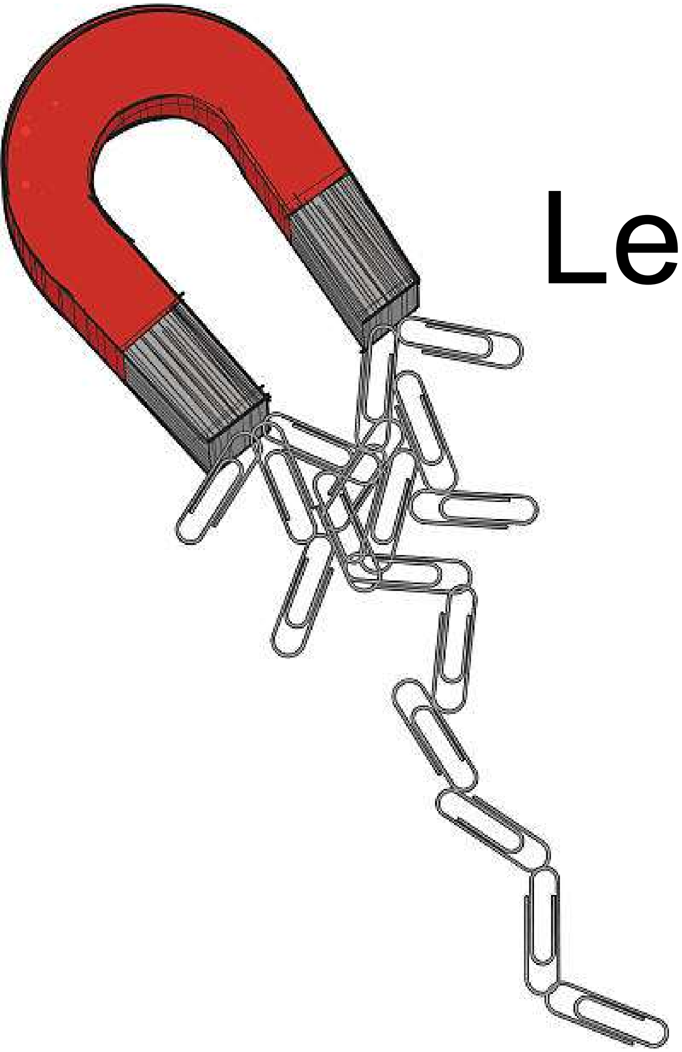


Why Start with Magnetism?

- Yes—magnetism is hard. And that’s exactly why we’re starting with it.
- Physics isn’t about memorizing formulas—it’s about taking things that seem confusing and making sense of them. Magnetism is perfect for that: it’s everywhere, it’s invisible, and it’s complicated.
- If you can learn to make sense of magnetism, you’ll see that you can make sense of *anything* in physics. That’s the job of a physicist—turning mystery into understanding.

Magnetic materials: the backbone of technology





Let’s Play With Magnets!

What’s going on?!?

If you had to classify these materials into 2 or 3 groups, how would you do it?

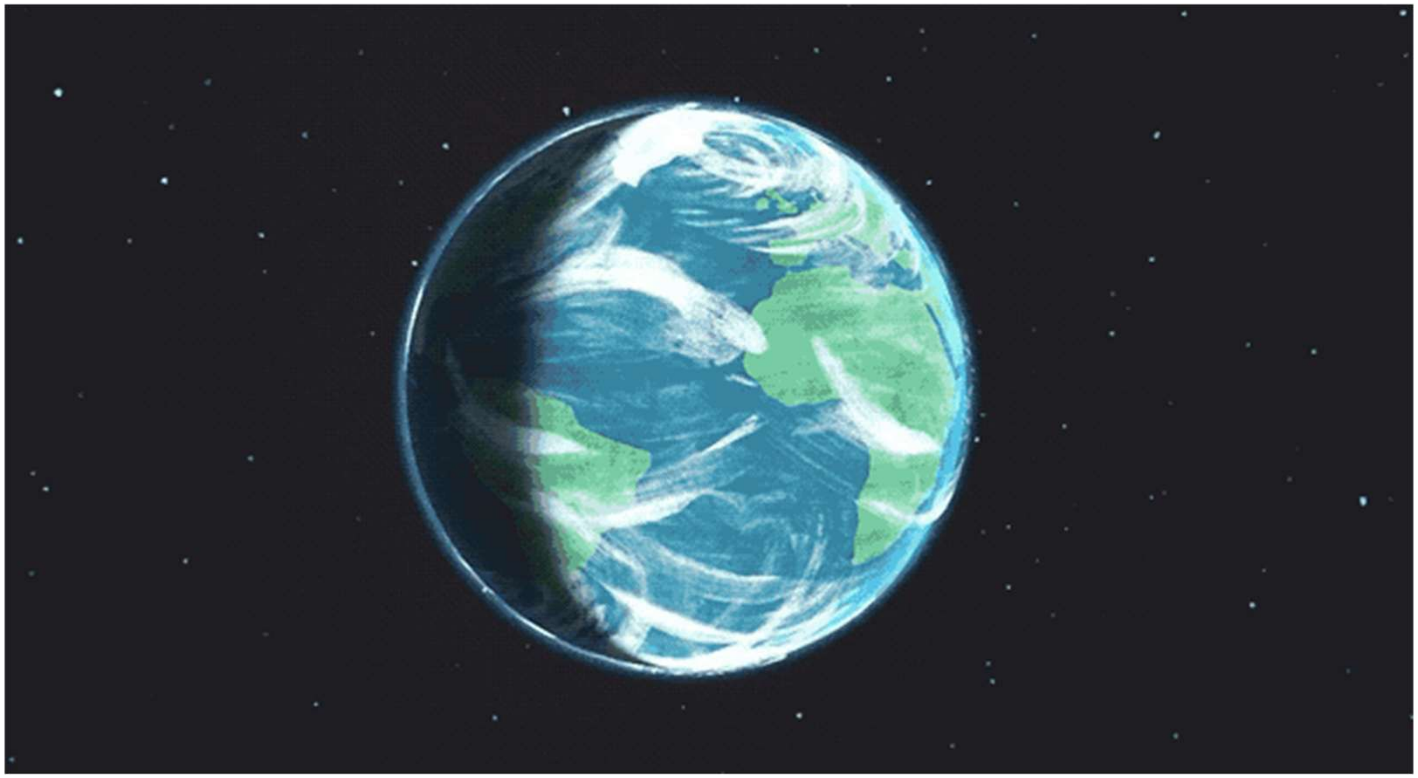
Why Do Only Some Materials Stick to Magnets?

Aren't all atoms made of the same stuff?

Where Does Magnetism Come From?

(The real answer is complicated; even experts struggle.)

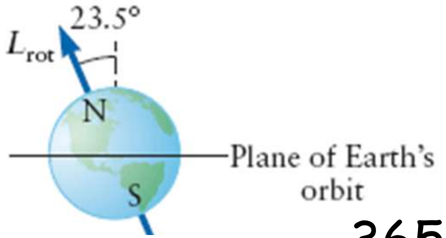
It is a quantum effect, but it has a classical analogy.

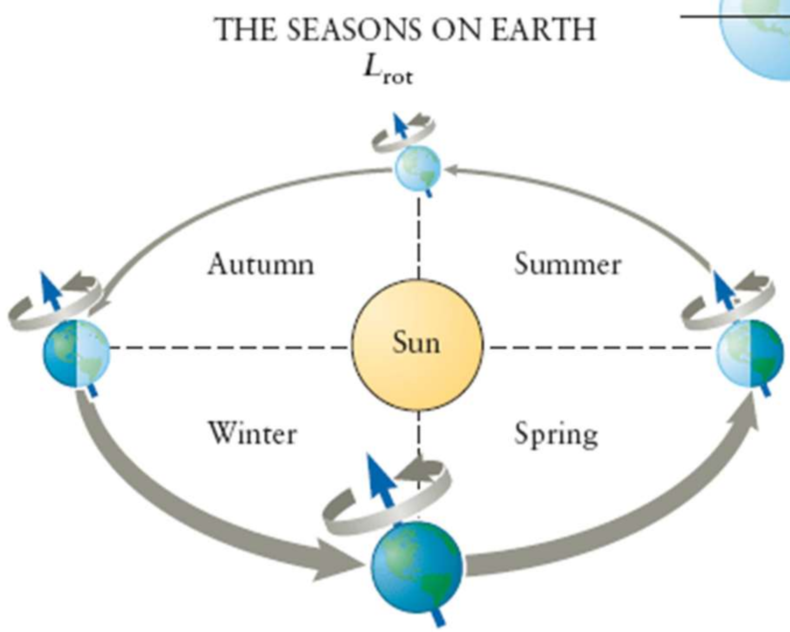


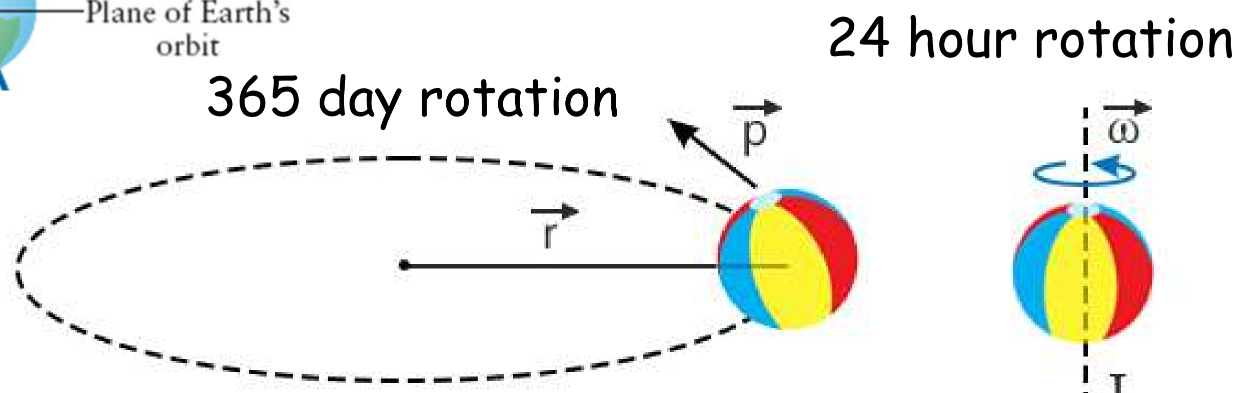
If I asked you about the rotational motion of the Earth, what kind of clarification might you ask?

(More physics-y: How to define angular momentum of Earth)

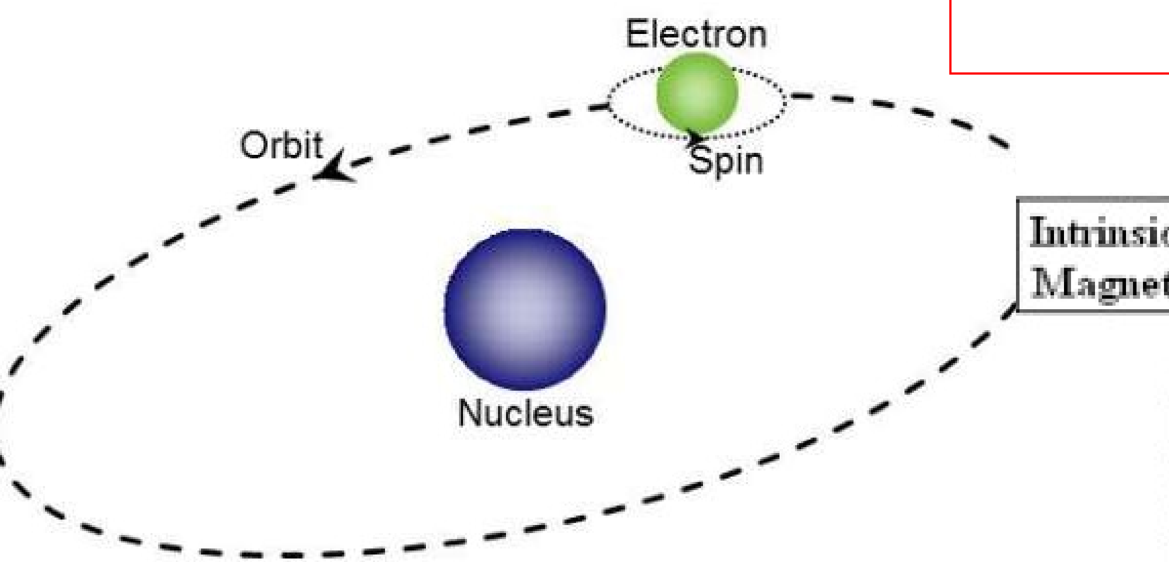
Classical: Earth model



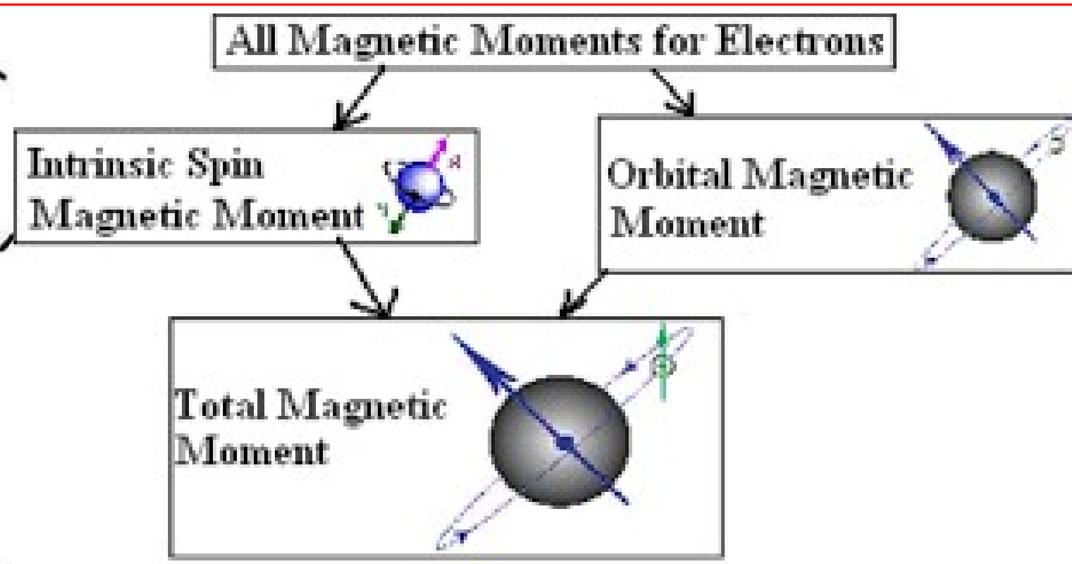




Magnetic moments are produced by the angular momentum of the electrons in atoms

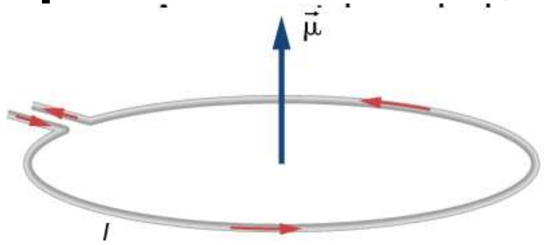


The orbit of a spinning electron about the nucleus of an atom.

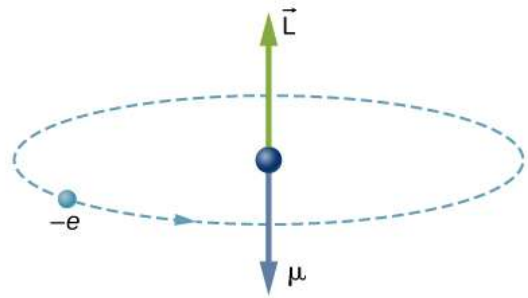


What is the magnetic moment μ?

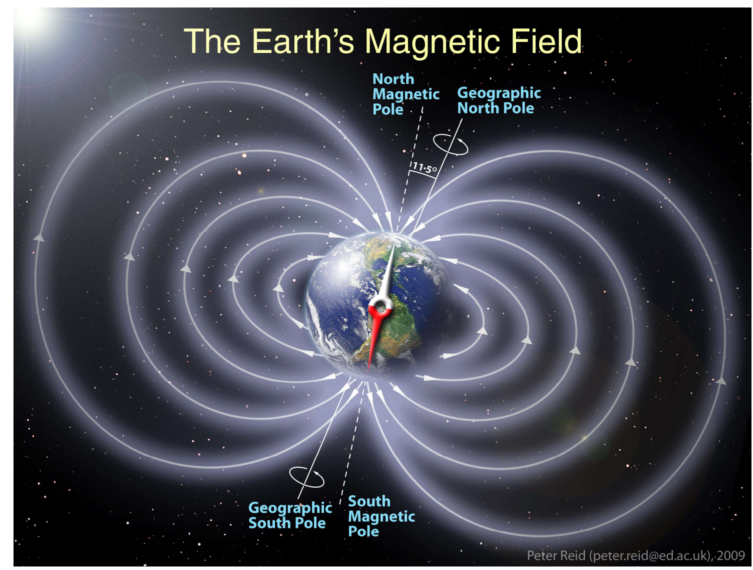
The magnetic moment is the magnetic **strength and orientation** of a magnet or other object that produces a magnetic field, expressed as a **vector**.



Current-carrying loop



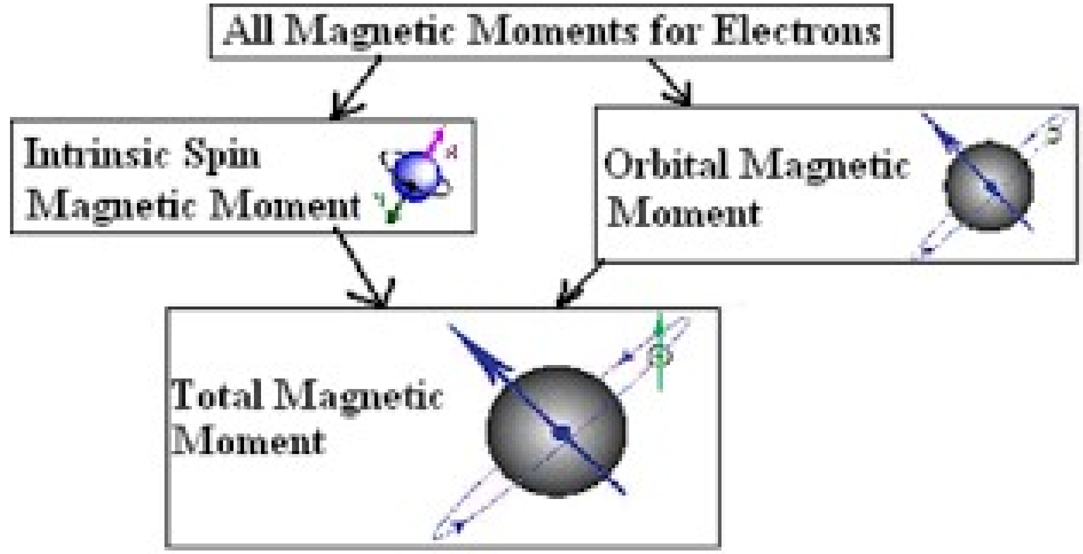
Hydrogen atom

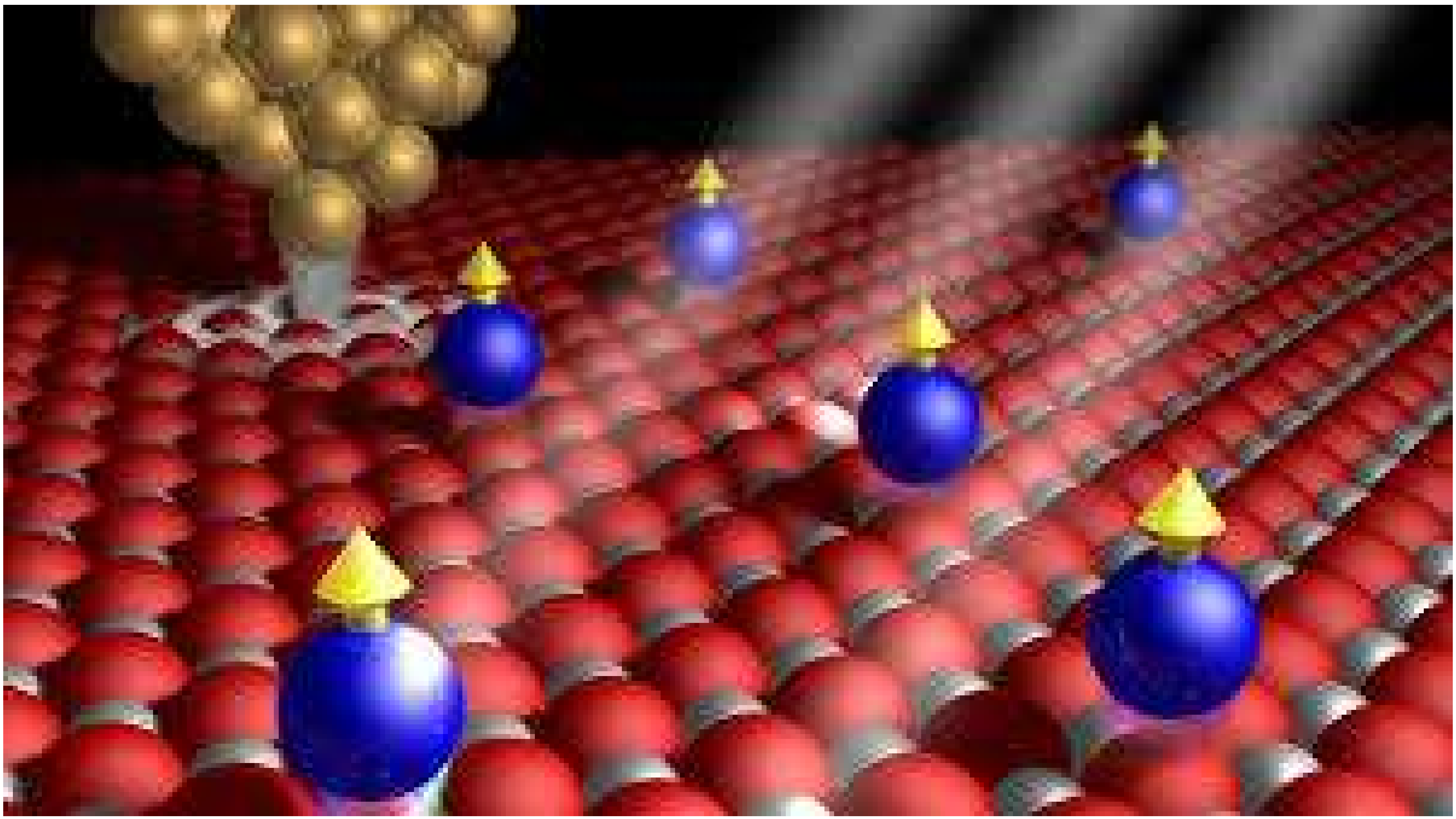


Examples of objects with magnetic moments:

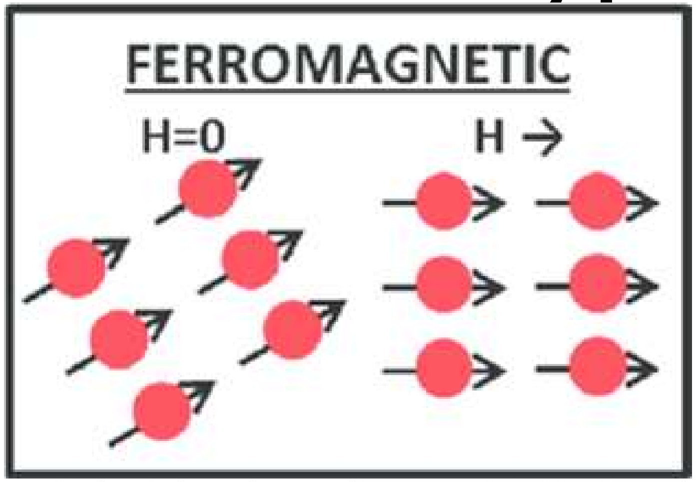
- loops of electric current,
- permanent magnets,
- elementary particles (such as electrons),
- various molecules and materials
- many astronomical objects (many planets, some moons, stars, etc).

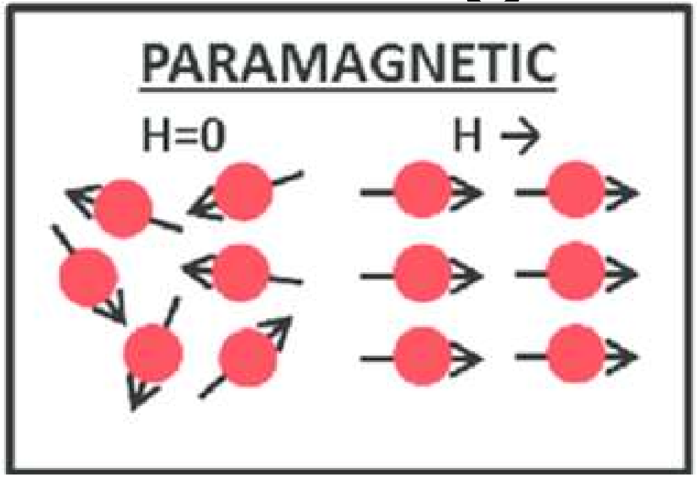
Each atom can have a magnetic moment. They may or may not align.



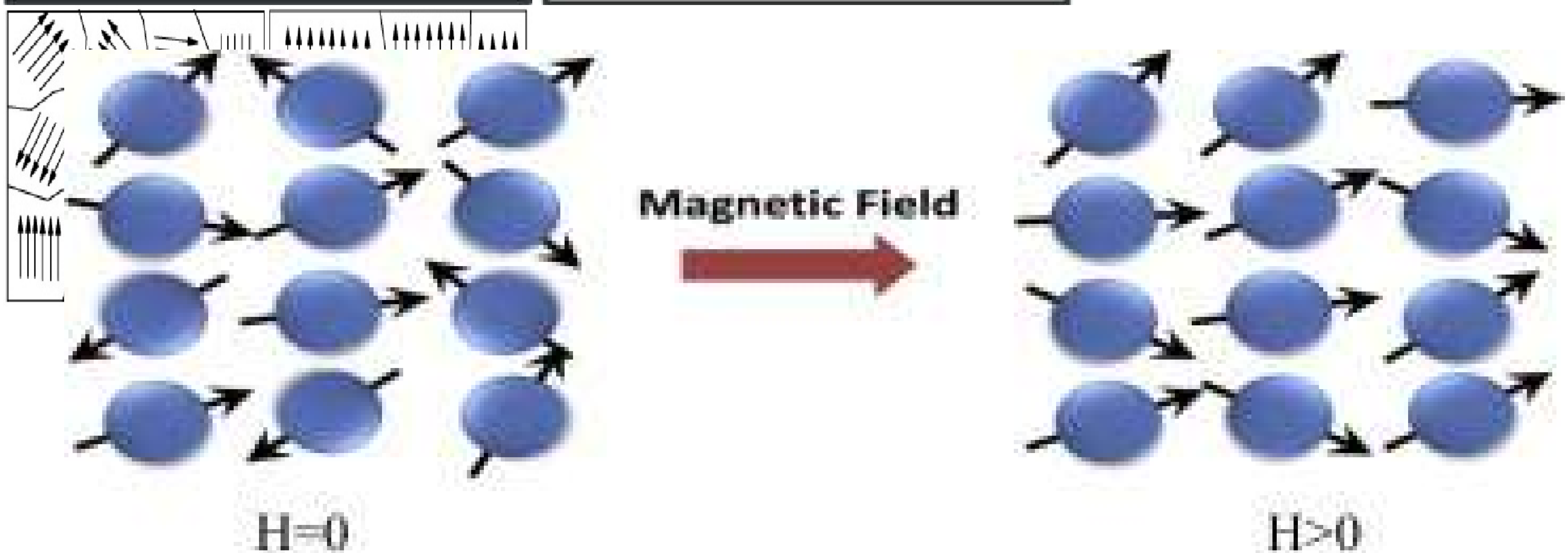


How they align distinguishes the types of magnetism

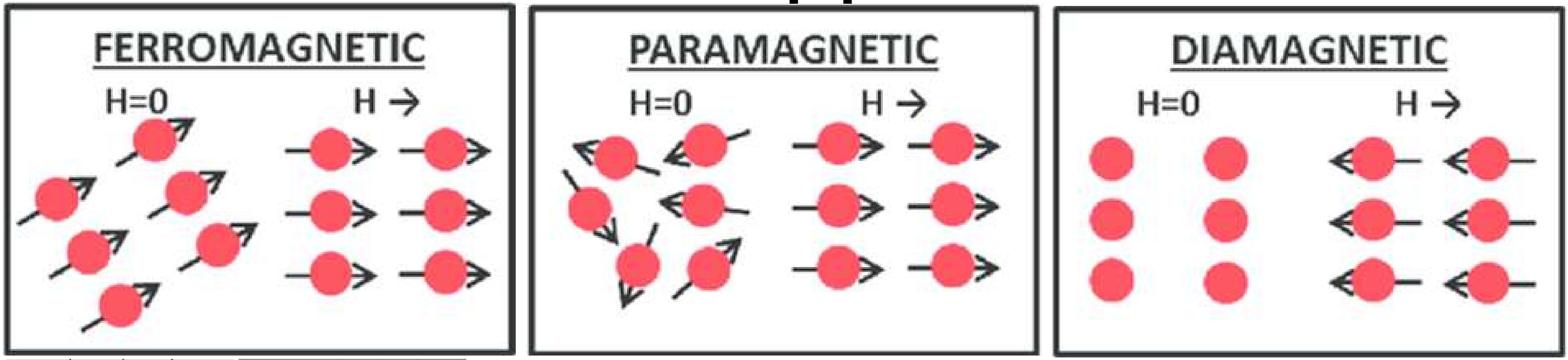


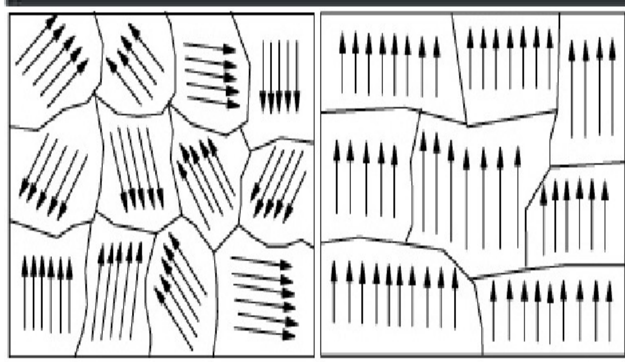


Magnetism isn't just about what's happening inside one atom. It's also about how nearby atoms interact with one another.



Different Magnets Have Different Applications





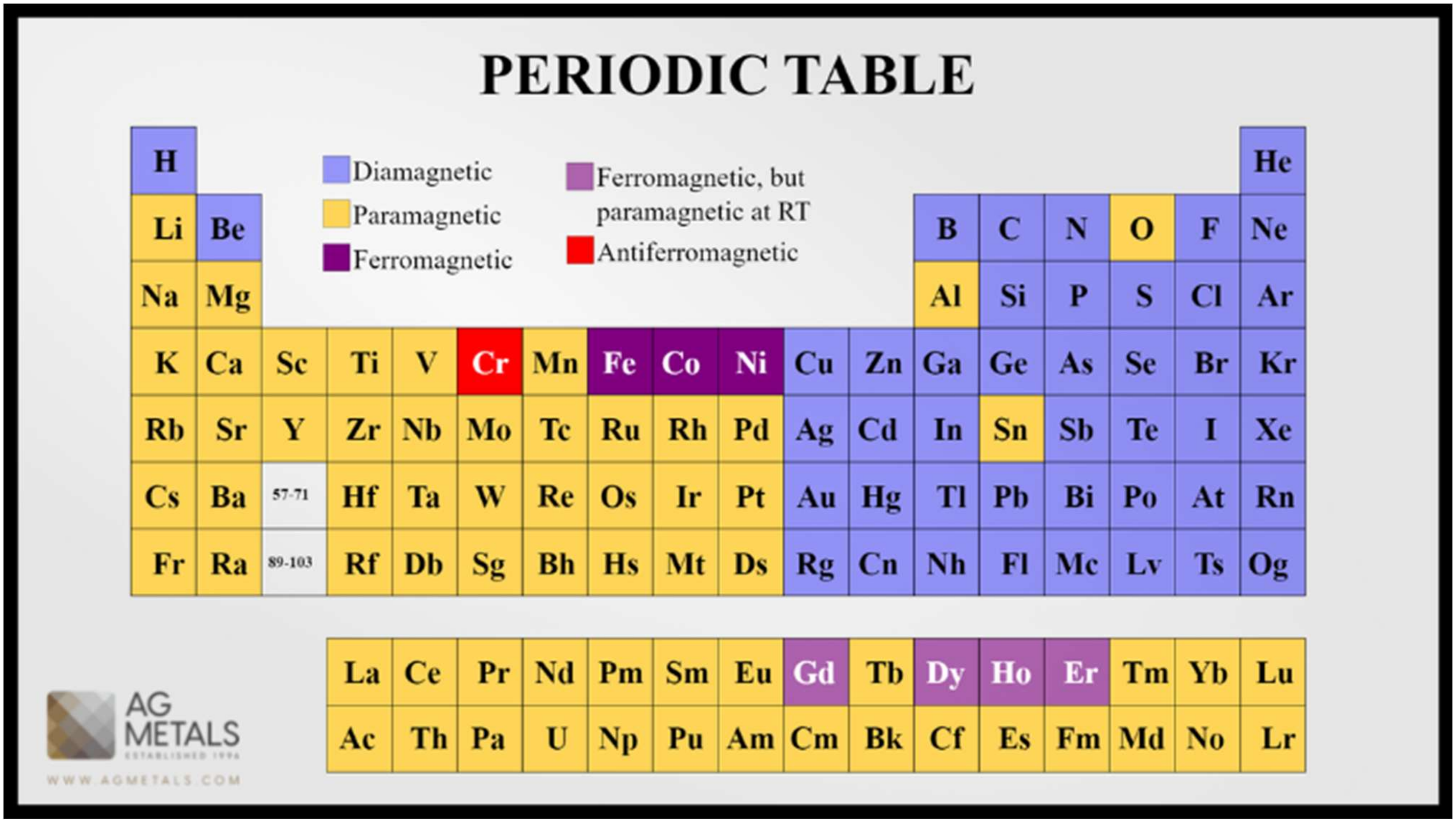
Paramagnets have magnetic atoms, but align randomly unless there is a field. Ferromagnets have magnetic atoms that cooperate with their neighbors.

Diamagnets don't have magnetic atoms.

Elemental Materials

To get a permanent magnet, two unlikely things must happen at the same time:

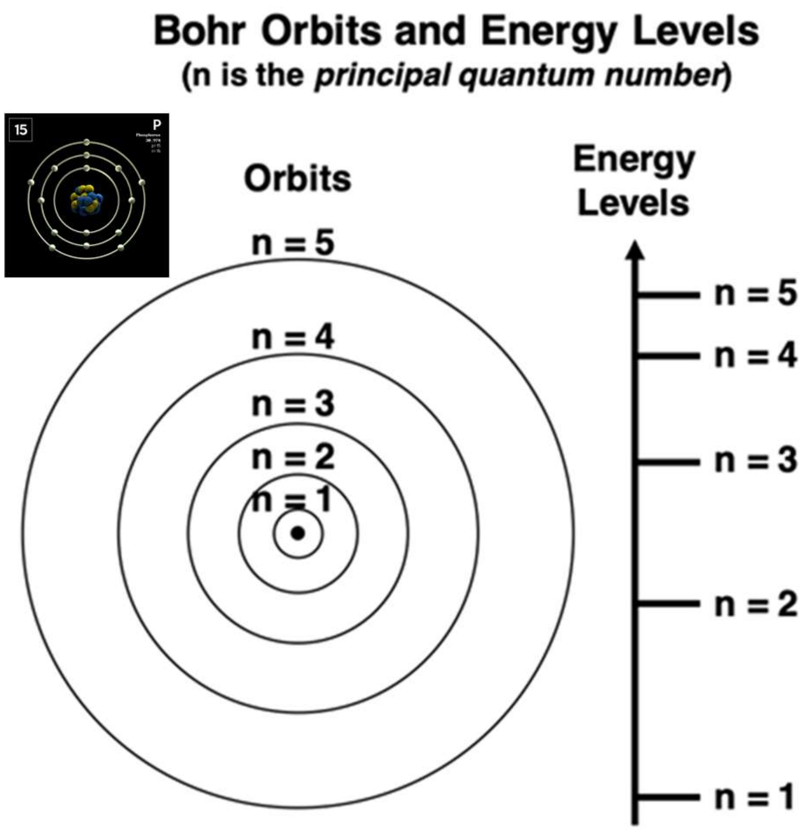
1. The atoms must have their own tiny magnetic moments.
2. Those moments must spontaneously line up together.



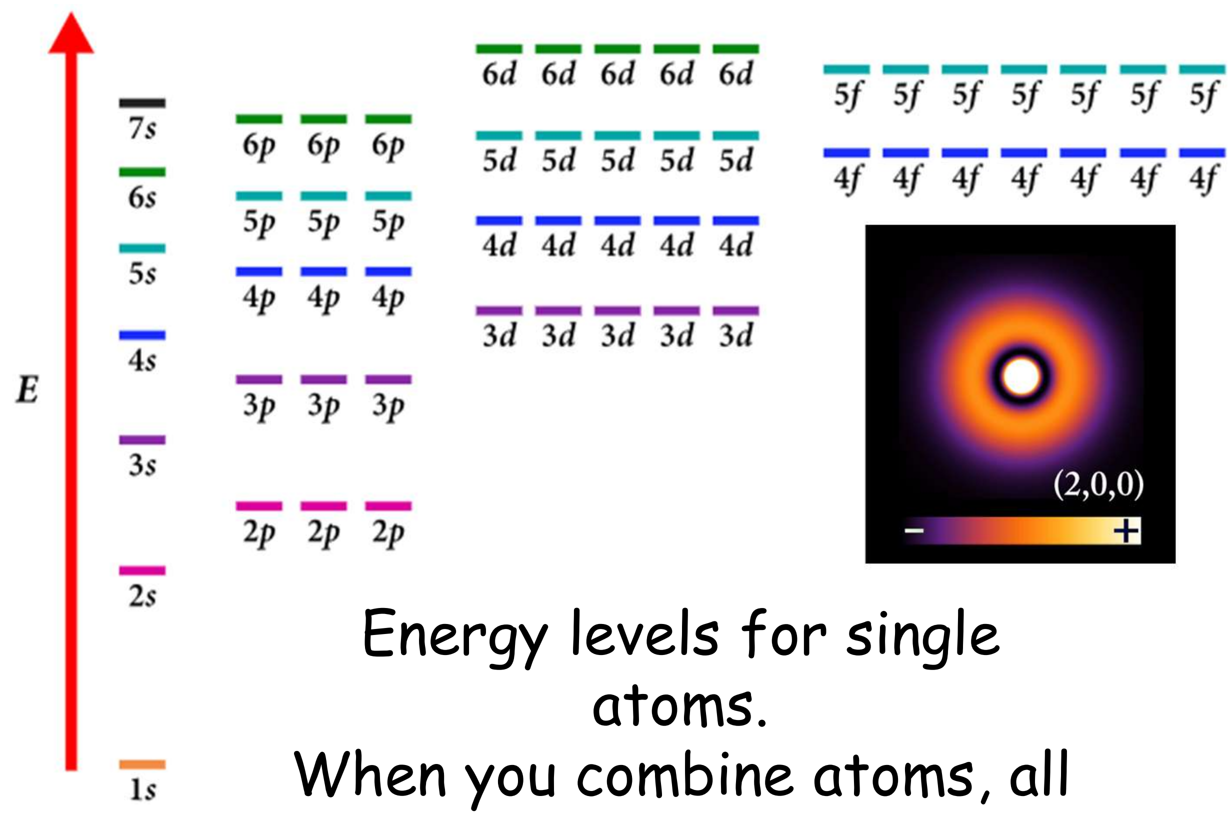
Energy levels

Good news: we don’t need to understand the details to study the effects!

You will learn more in modern physics!



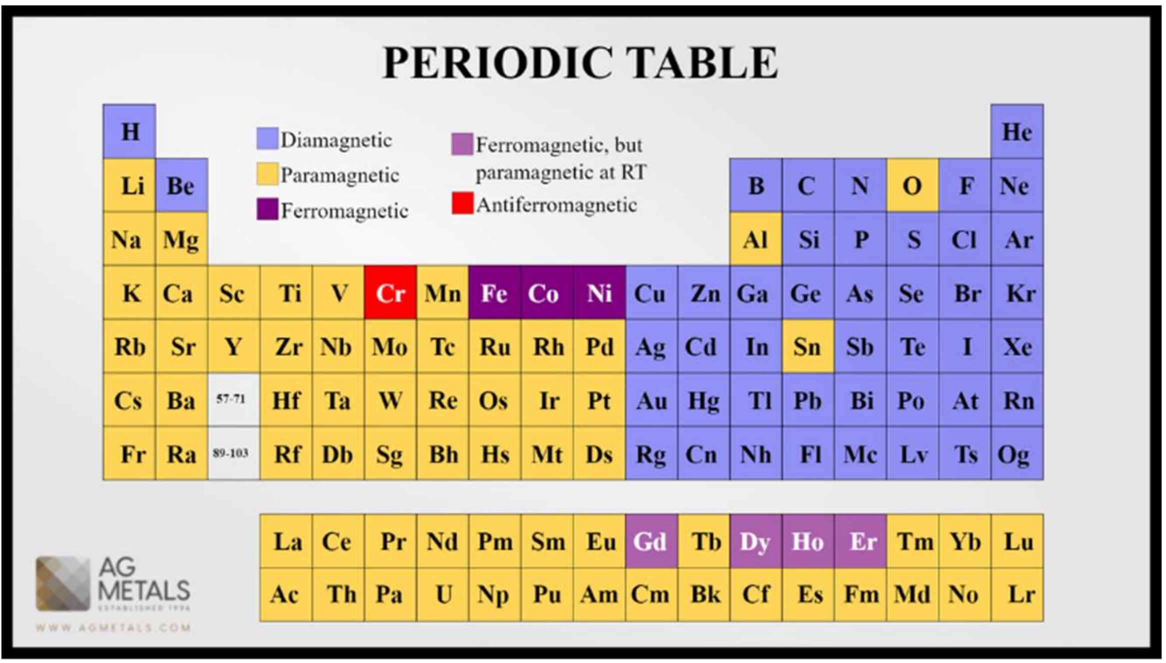
Simplification

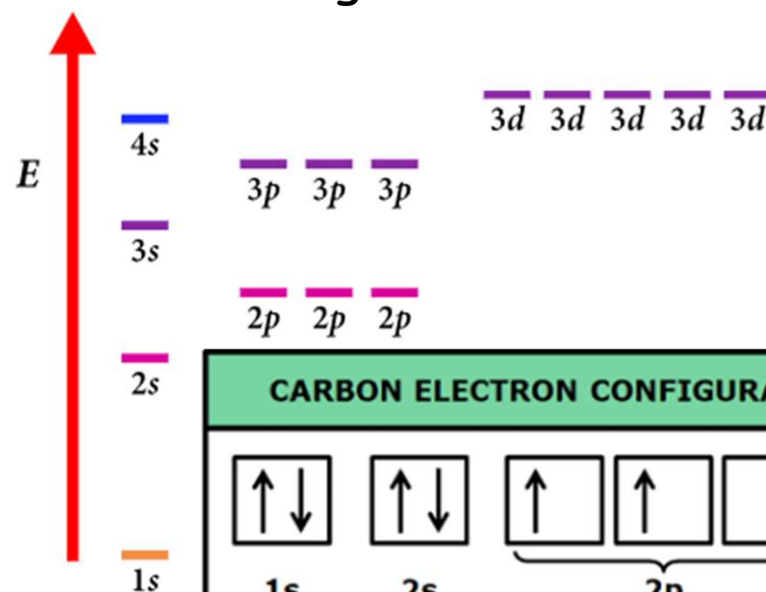


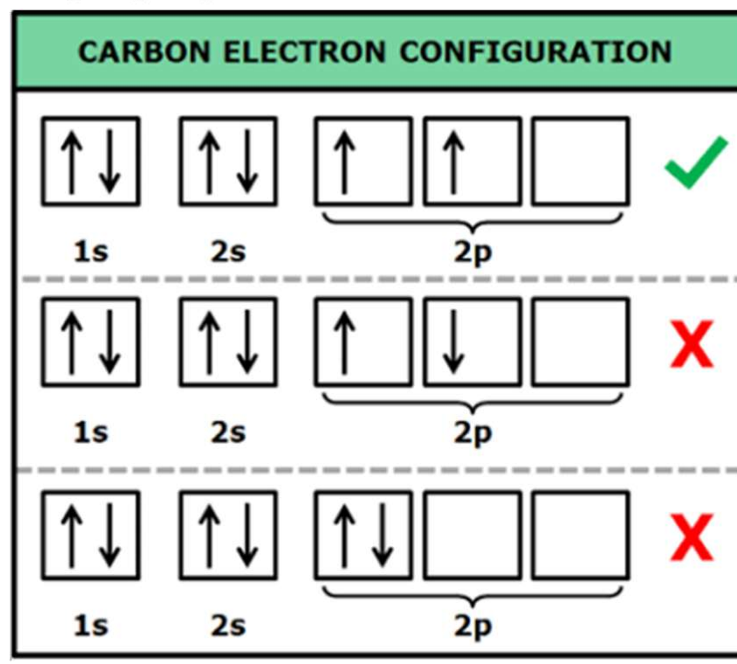
Energy levels for single atoms.
When you combine atoms, all sorts of things can change!

But some of these are right next to each other! (Even/odd)

On right is the atomic energy levels. However, when atoms are brought together into a crystal, electrons in neighboring atoms begin to interact. In some materials, such as iron, the lowest-energy arrangement is for many electron spins to align in the same direction. This creates a net magnetic moment.

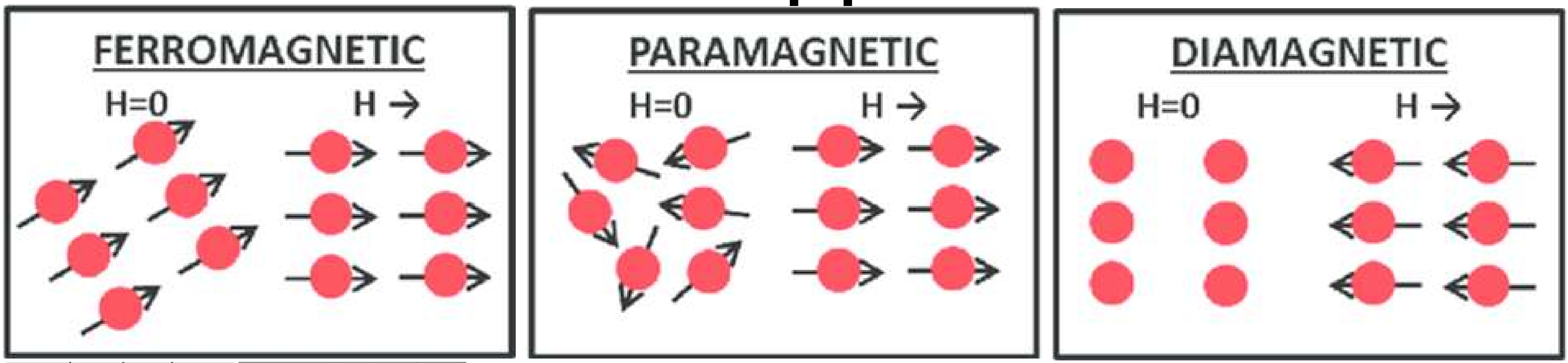


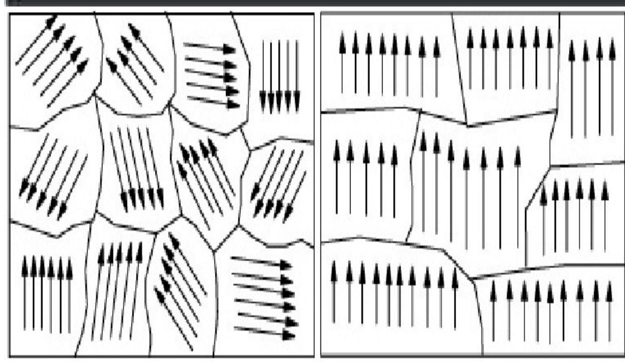




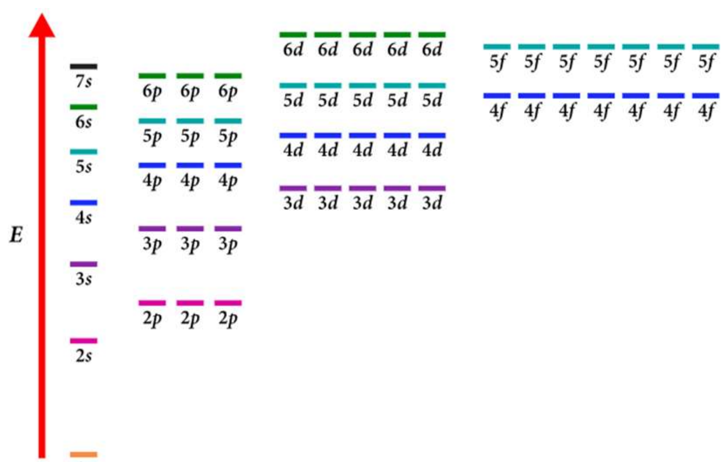
This would seem to suggest that carbon is magnetic. Anyone have any guess why it isn't?

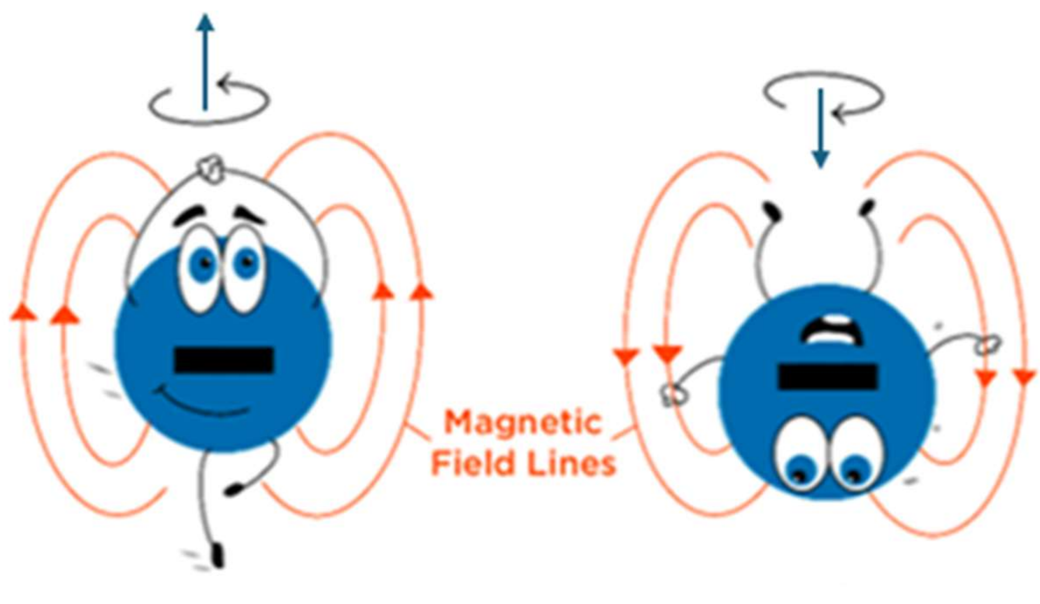
Different Magnets Have Different Applications





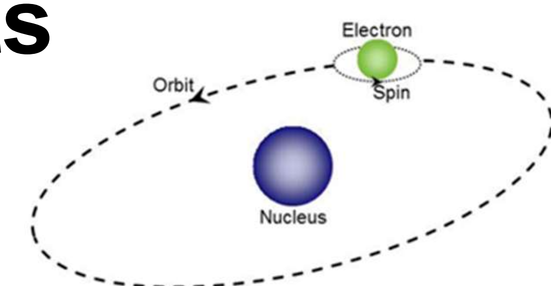
In most diamagnetic materials, there are no unpaired spins.





Why Diamagnets Point Opposite to the Field

- Magnets like iron get *pulled* into a magnetic field. Diamagnets, like bismuth or copper, do the opposite: they **develop a weak magnetization that points opposite to the applied field.**



- **Electrons are moving charges.** A moving charge is like a tiny current loop, and current loops make magnetic fields.
- **A magnetic field nudges these electron clouds.** Nature doesn't like sudden changes in magnetic flux, so they oppose

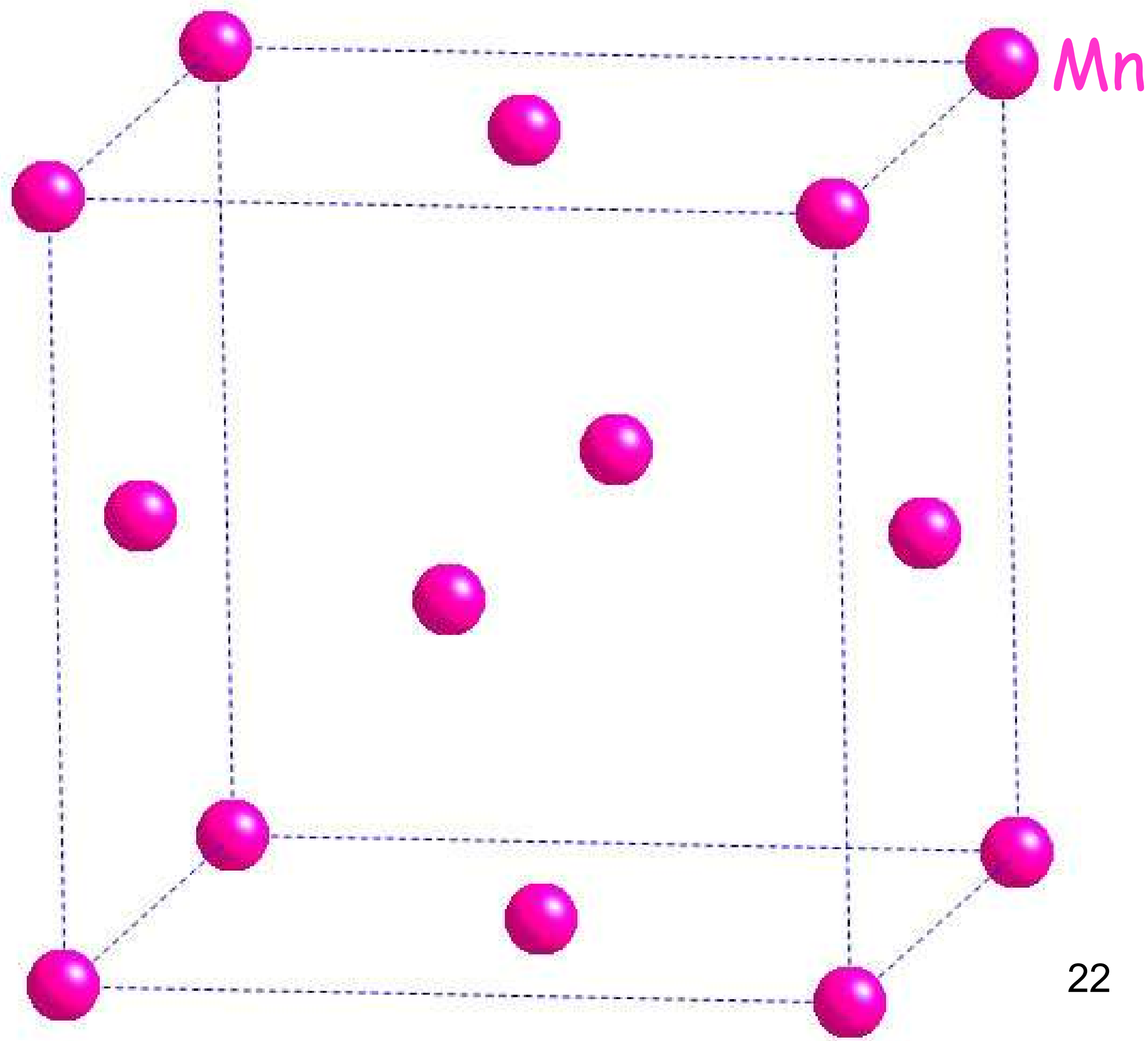
Example spin alignment

<u>Example:</u>

Magnetism of MnO

Corners and all of the face centers known as the face-center cubic crystal structure

Manganese oxide



Example spin alignment

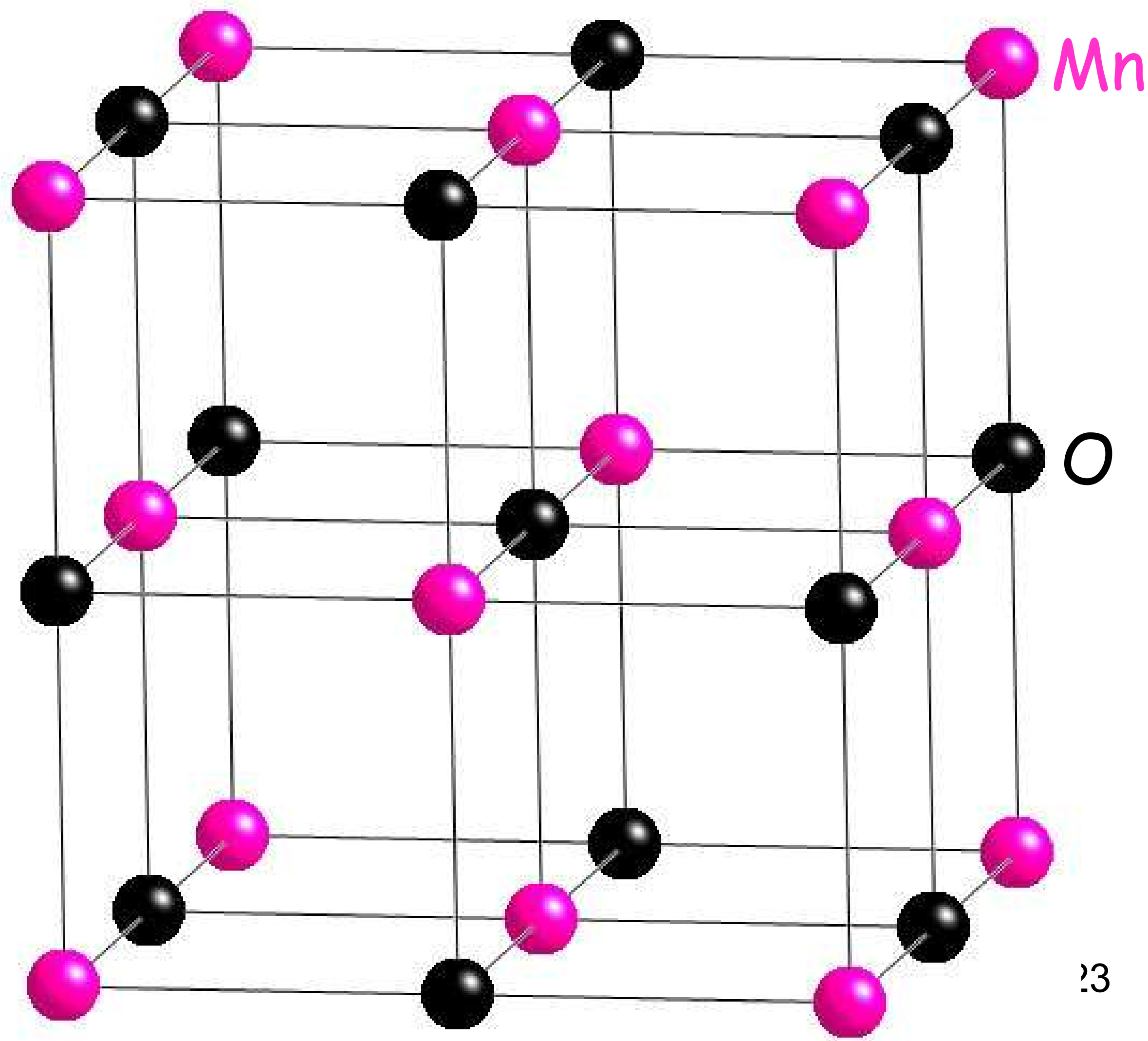
<u>Example:</u>

Magnetism of MnO

Corners and all of the face centers known as the face-center cubic crystal structure

O^{2-} ions
in the centers of all edges and in the body center

Still an FCC crystal structure



Example spin alignment

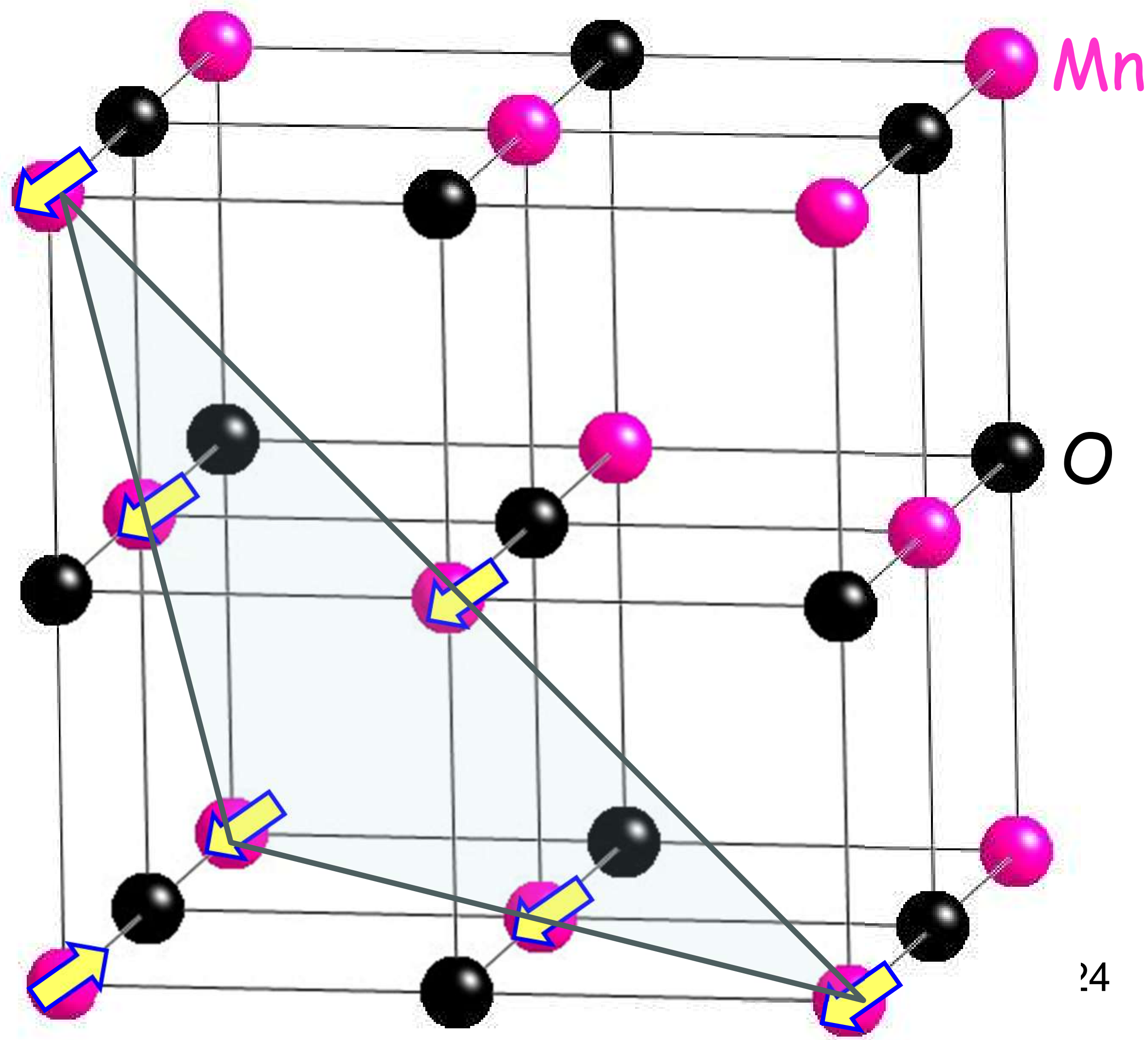
Example:

Magnetism of MnO

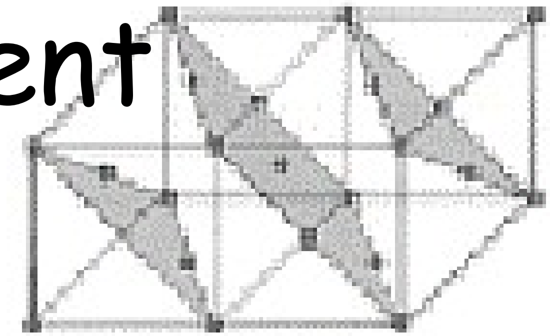
Corners and all of the face centers known as the face-center cubic crystal structure

Oxygen
in the centers of all edges and in the body center

Still an FCC crystal structure



Example spin alignment



Example:

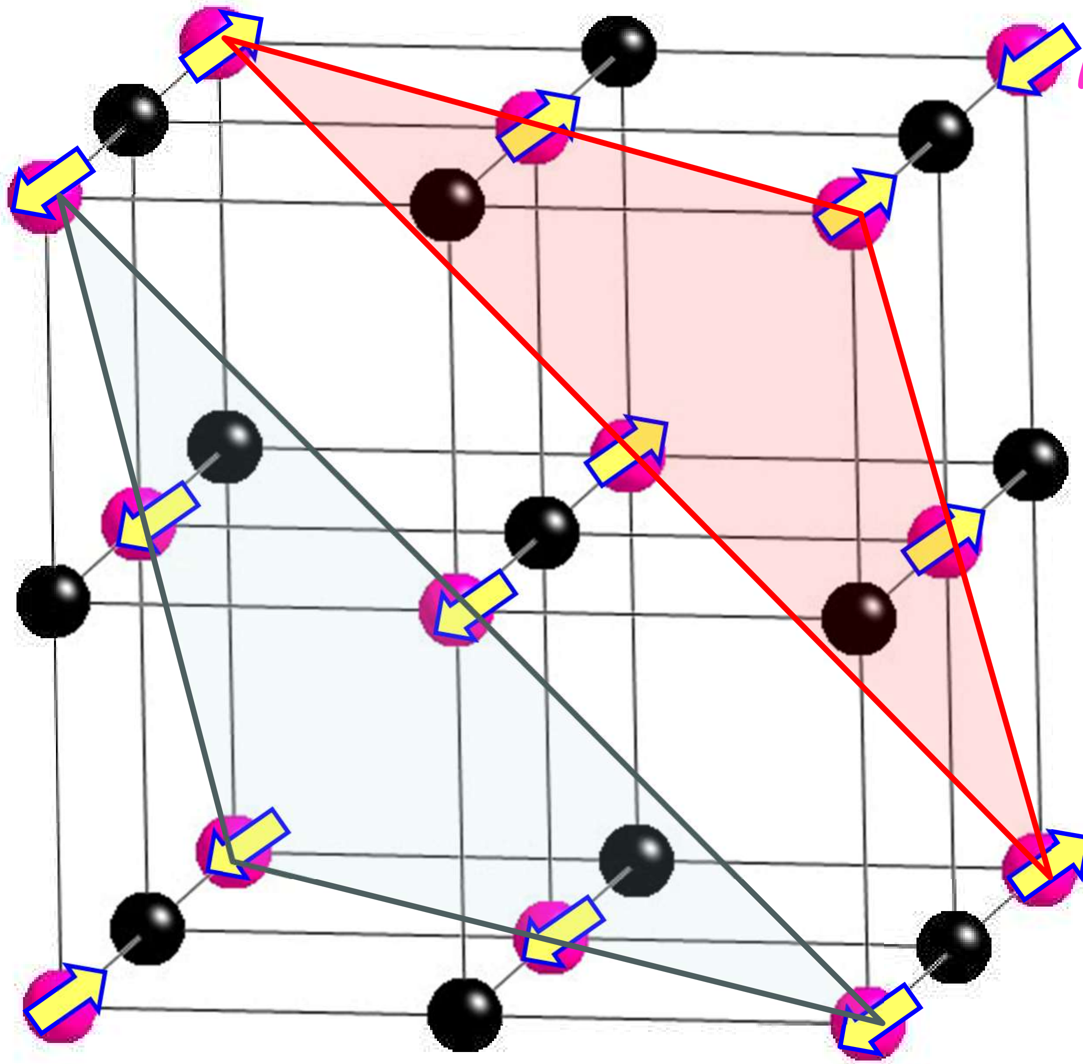
Magnetism of MnO

Mn^{2+} ions

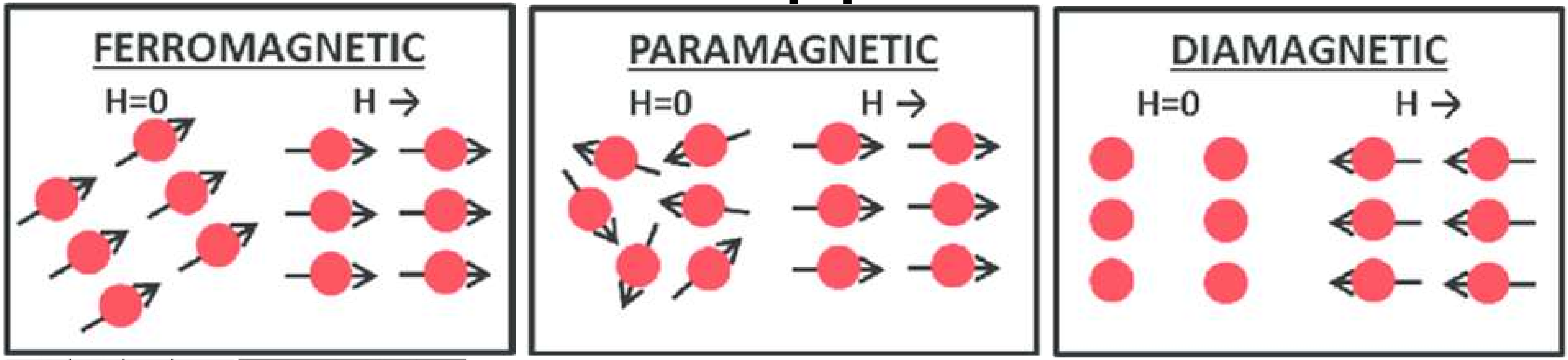
Corners and all of the face centers known as the face-center cubic crystal structure

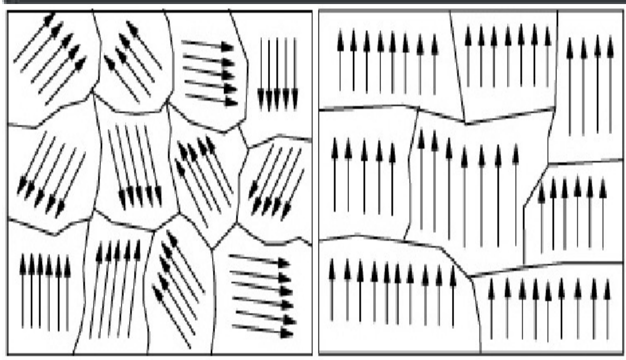
O^{2-} ions
in the centers of all edges and in the body center

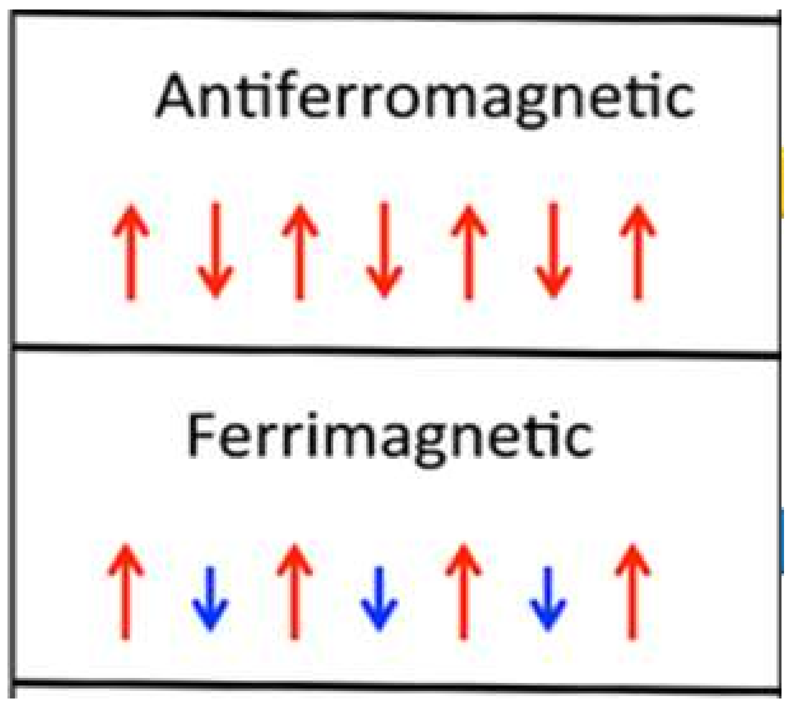
Still an FCC crystal structure



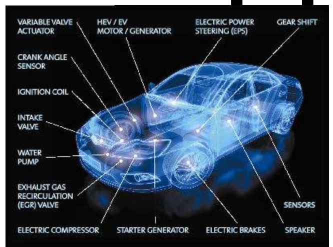
Different Magnets Have Different Applications







Applications



Ferromagnets

- Motors and generators
- Transformers
- Magnetic storage
- Electromagnets

Diamagnets

- MRI machines
- Magnetic shielding
- Magnetic levitation (Maglev)

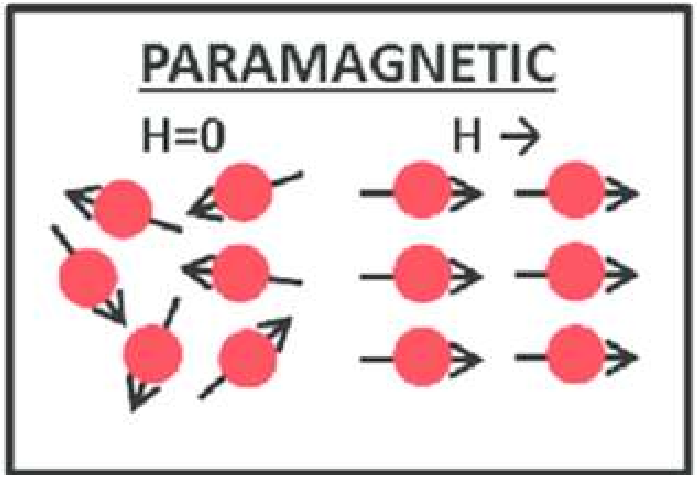
Paramagnets

- magnetic separation for (recycling, foodprocessing)
- some catalytic processes, where their weak magnetism facilitates chemical reactions

Antiferromagnets/Ferrimagnets

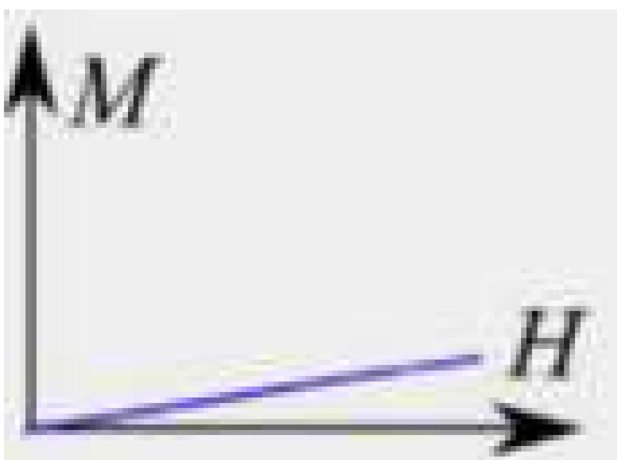
- Hard disk drives/memory
- Magnetic sensors
- Spintronics: a field focusing on using electron spin for information processing.

How does the magnetization vary as you apply a magnetic field H?



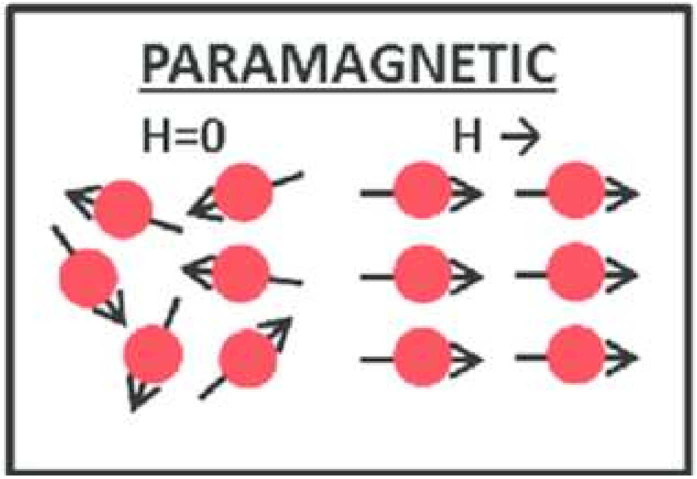
What do you expect at zero field?

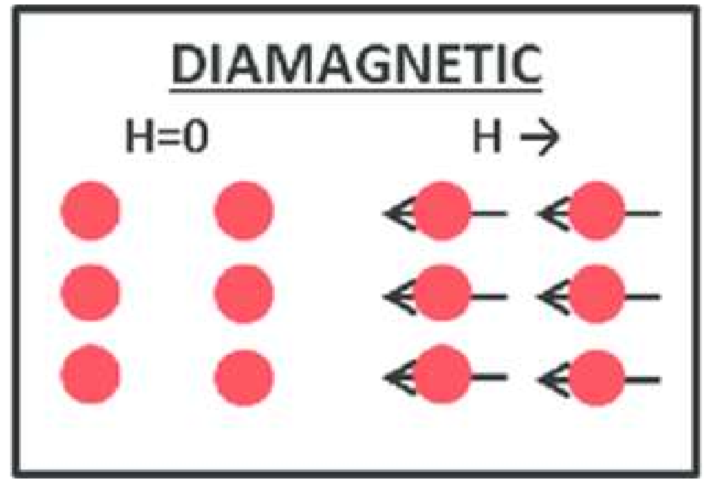
What if you apply a small field?

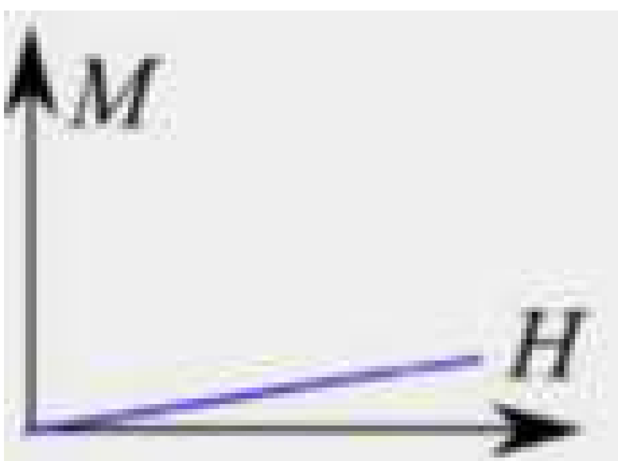


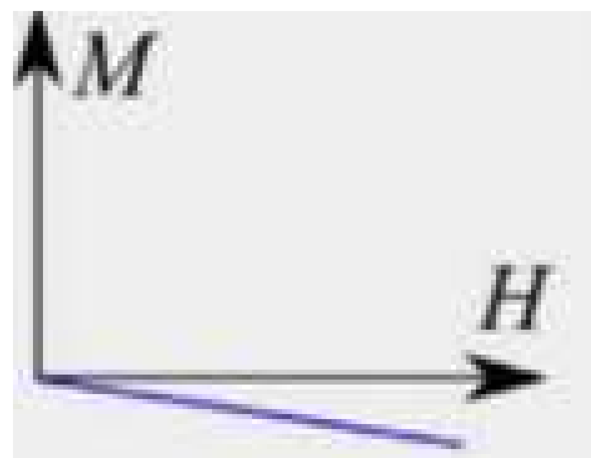
An antiferromagnet has a similar but smaller field dependence. Any idea why?

How do you think a diamagnet varies with a magnetic field H?

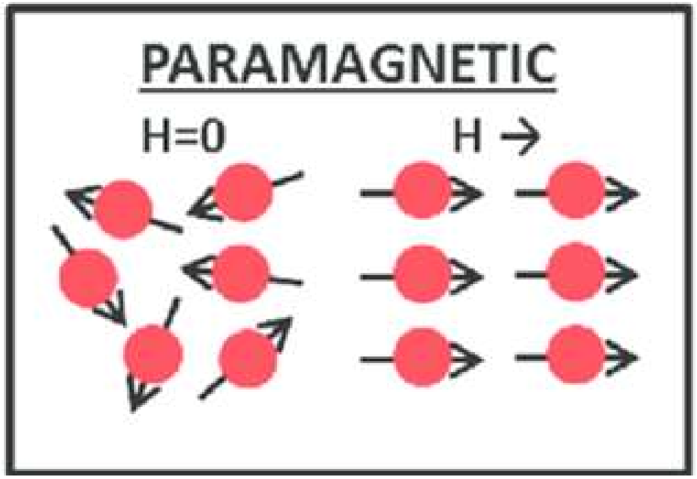


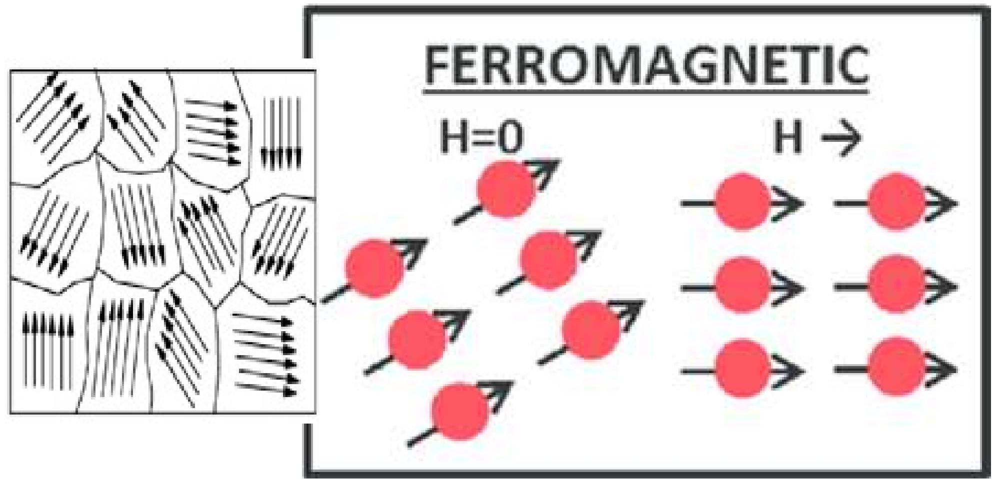


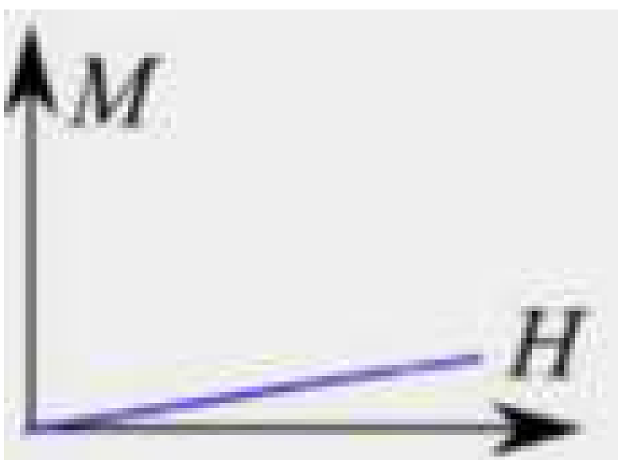


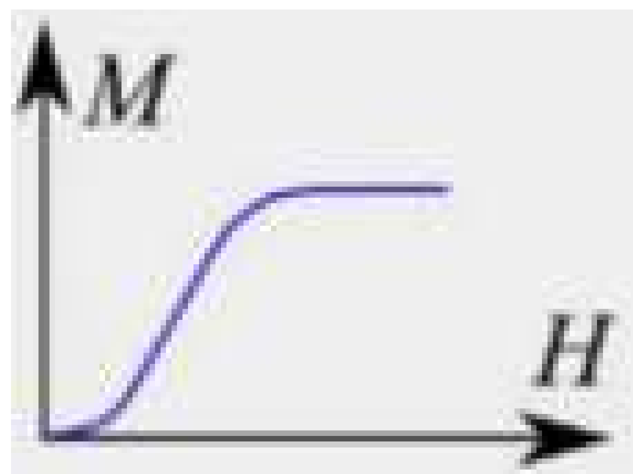


How do you think a ferromagnet varies with a magnetic field H?

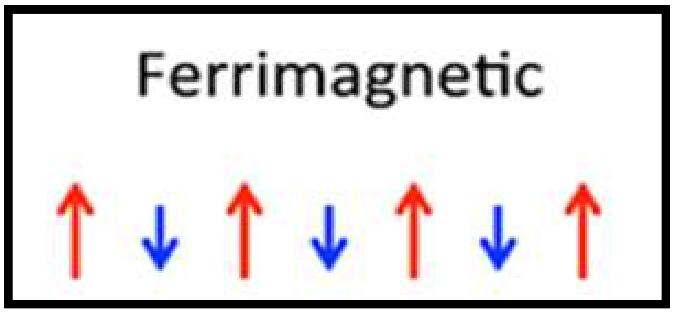


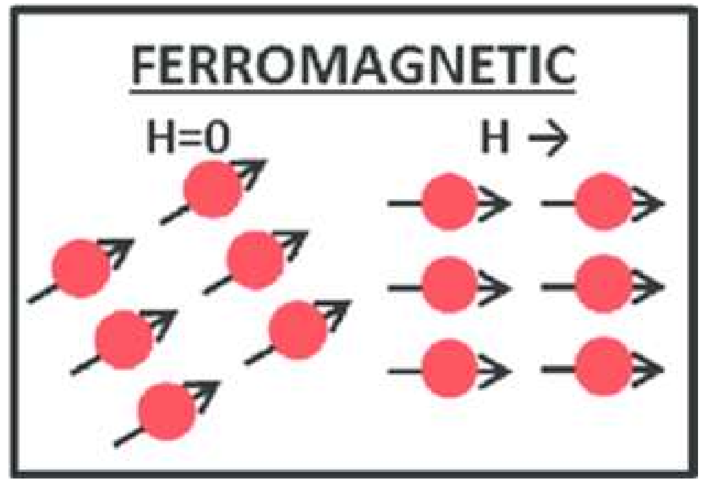




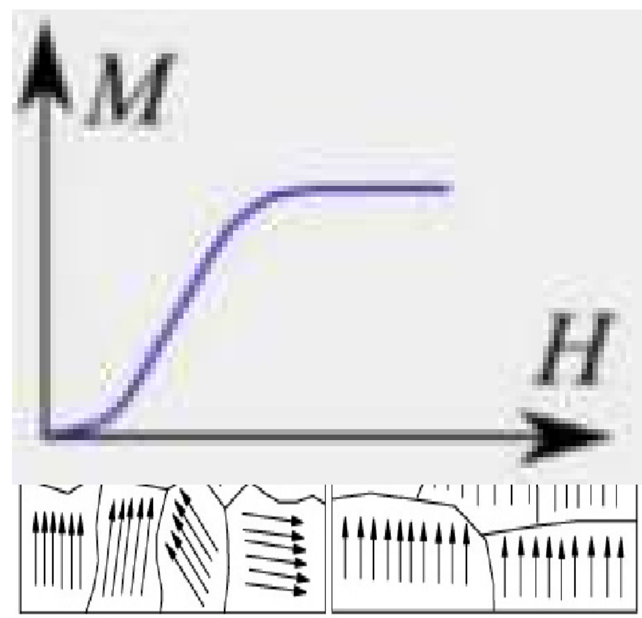


How do you think a ferrimagnet varies with a magnetic field H?



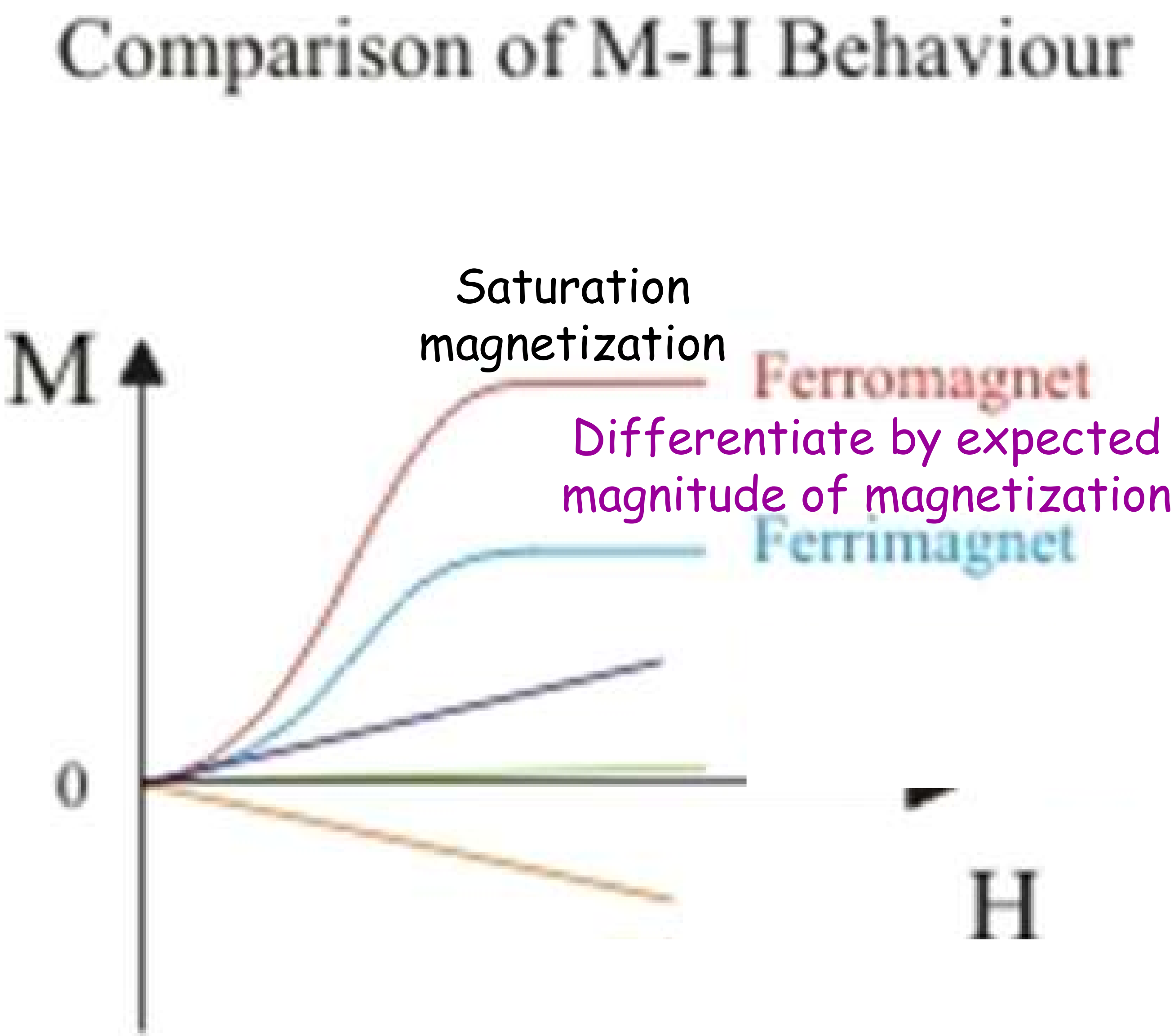


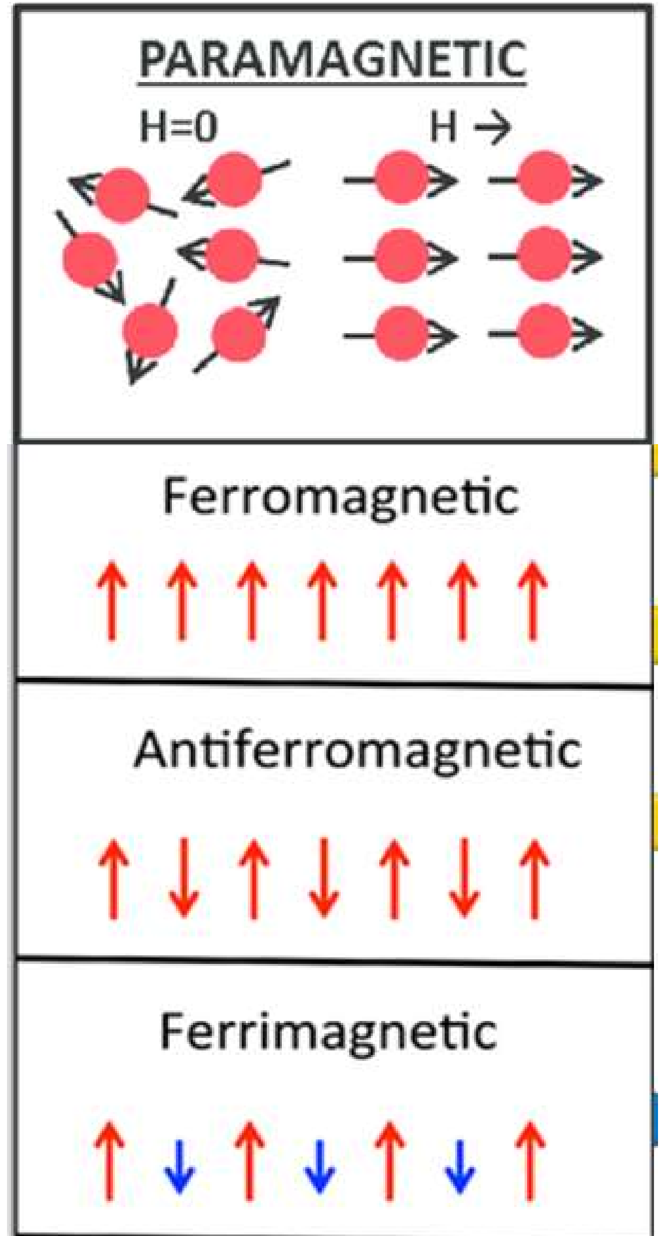
It looks a lot like a ferromagnet but the magnetization is not as large.



Magnetization versus H field can differentiate many but not all types of magnetism

Label these.

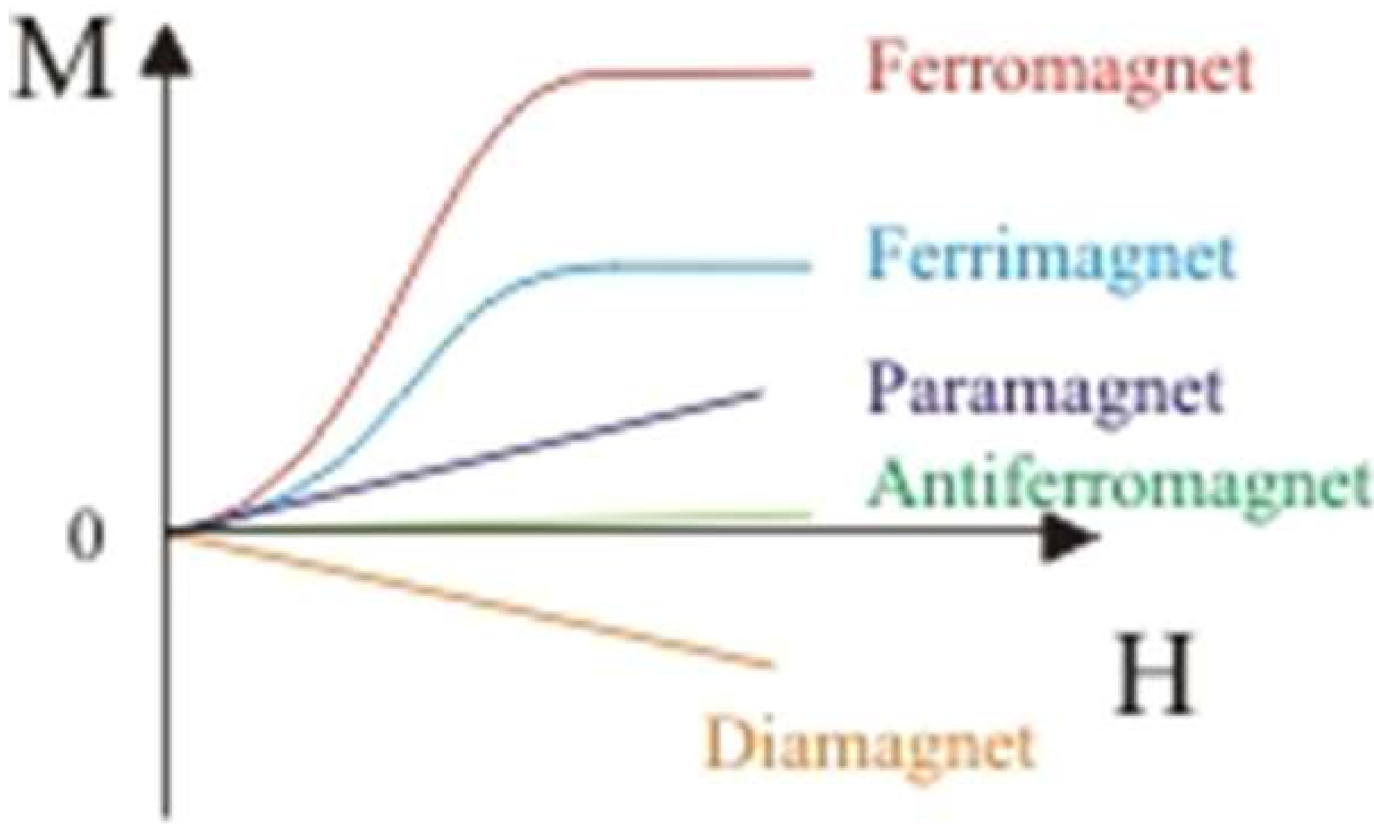




Magnetic materials can sometimes change the type of magnetism they exhibit, depending on the temperature

Why might that matter?

So, you could measure M vs H for many temperatures



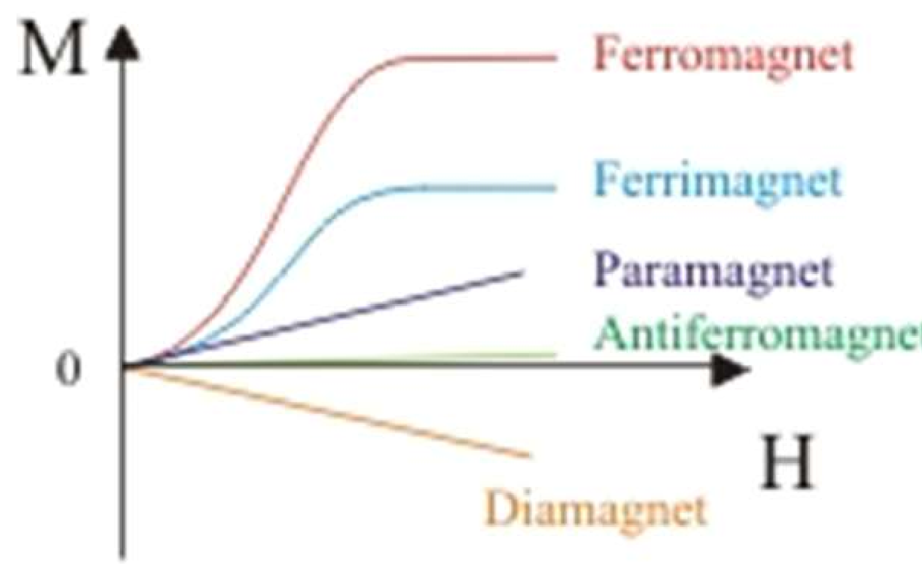
OR you could measure M vs temperature for a specific H field.

What even is magnetization?

- Magnetization **M** is defined as the magnetic moment **m** per unit volume V,

$$\mathbf{M} = \mathbf{m}/V$$

- A **magnetic moment m** is a measure of how strongly something acts like a tiny magnet.



Formula relating M and H

- When an applied magnetic field **H** is applied to a material, the response is called its magnetic induction **B**. As we've seen, in some cases, it can be linear.
- **Permeability** μ_0 ($4\pi \times 10^{-7}$ T·m/A) tells how strong a magnetic field you get in empty space when you have a given magnetization. It's like the 'stiffness' of space to magnetic fields. Just like the permittivity ε_0 tells you how electric fields behave in empty space.

$\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$ (cgs units) $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$ (SI units)

	Symbol	cgs units	Conversion	SI units
Magnetic flux density	B	gauss	10^{-4}	tesla (T)
Magnetic field strength	H	oersted	$10^3/(4\pi)$	A/m
Volume magnetization	M	emu/cm^3	10^3	A/m
Magnetic moment	m	emu	10^{-3}	A m^2

Most people prefer SI, but often reported in cgs

Magnetic Susceptibility χ

- What kind of magnet a material is does not depend on the magnetization, but instead how it varies when a magnetic field is applied.
- Thus, it is common to plot **M** versus **H**. The ratio of **M** to **H** is called the magnetic susceptibility

$$\chi = \mathbf{M} / \mathbf{H}$$

$$\chi = \frac{M}{H}$$

Where,

χ = Magnetic Susceptibility

M = Magnetization

H = Magnetic Field strength

In temperature studies, it's sometimes easier to plot something rather than magnetization (M)

Magnetization = magnetic moment per unit volume

$$\chi = \frac{M}{H}$$

Where,

χ = Magnetic Susceptibility

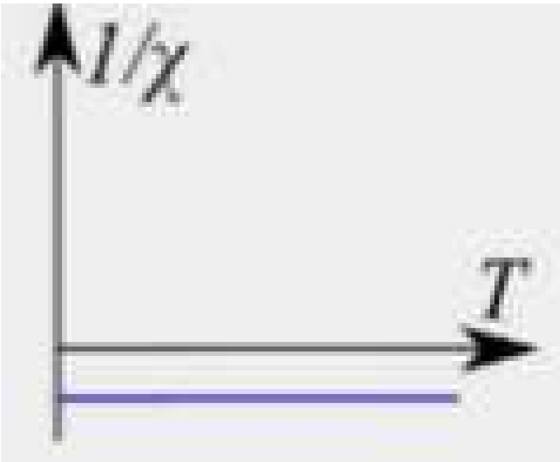
M = Magnetization

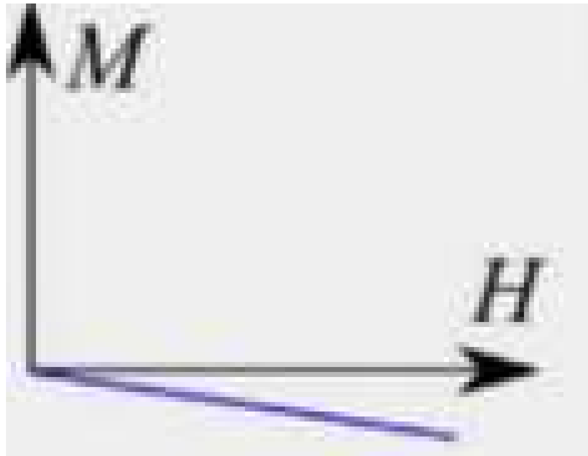
H = Magnetic Field strength

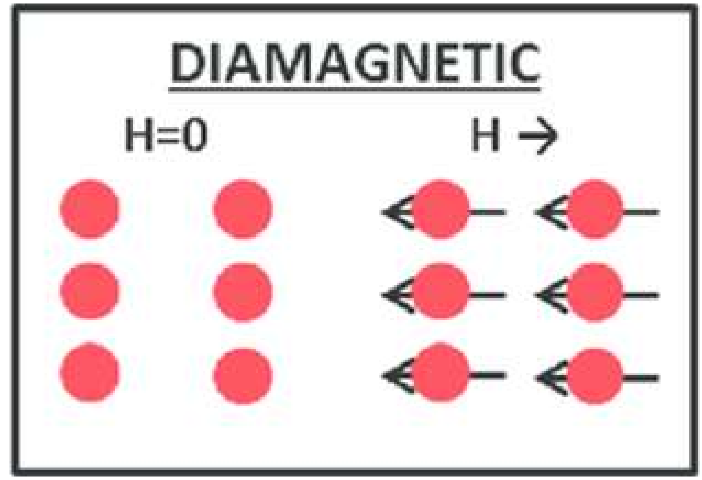
The magnetization and magnetic susceptibility χ are proportional to each other

<u>WARNING</u>: Susceptibility χ or even $1/\chi$ are commonly plotted to interpret the magnetic behavior. Related.

Diamagnetism







$$\chi = \frac{M}{H}$$

Where,

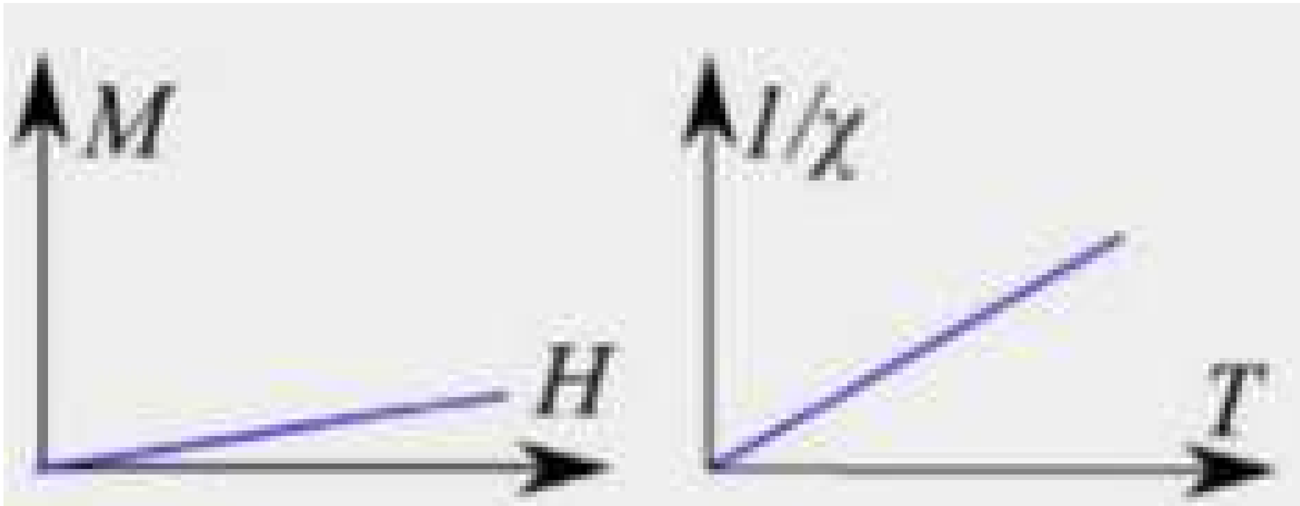
χ = Magnetic Susceptibility

M = Magnetization

H = Magnetic Field strength

In a diamagnet, the magnetization and magnetic susceptibility (which are proportional to each other) are temperature independent!

Paramagnetism, linear



$$\chi = \frac{M}{H}$$

Where,

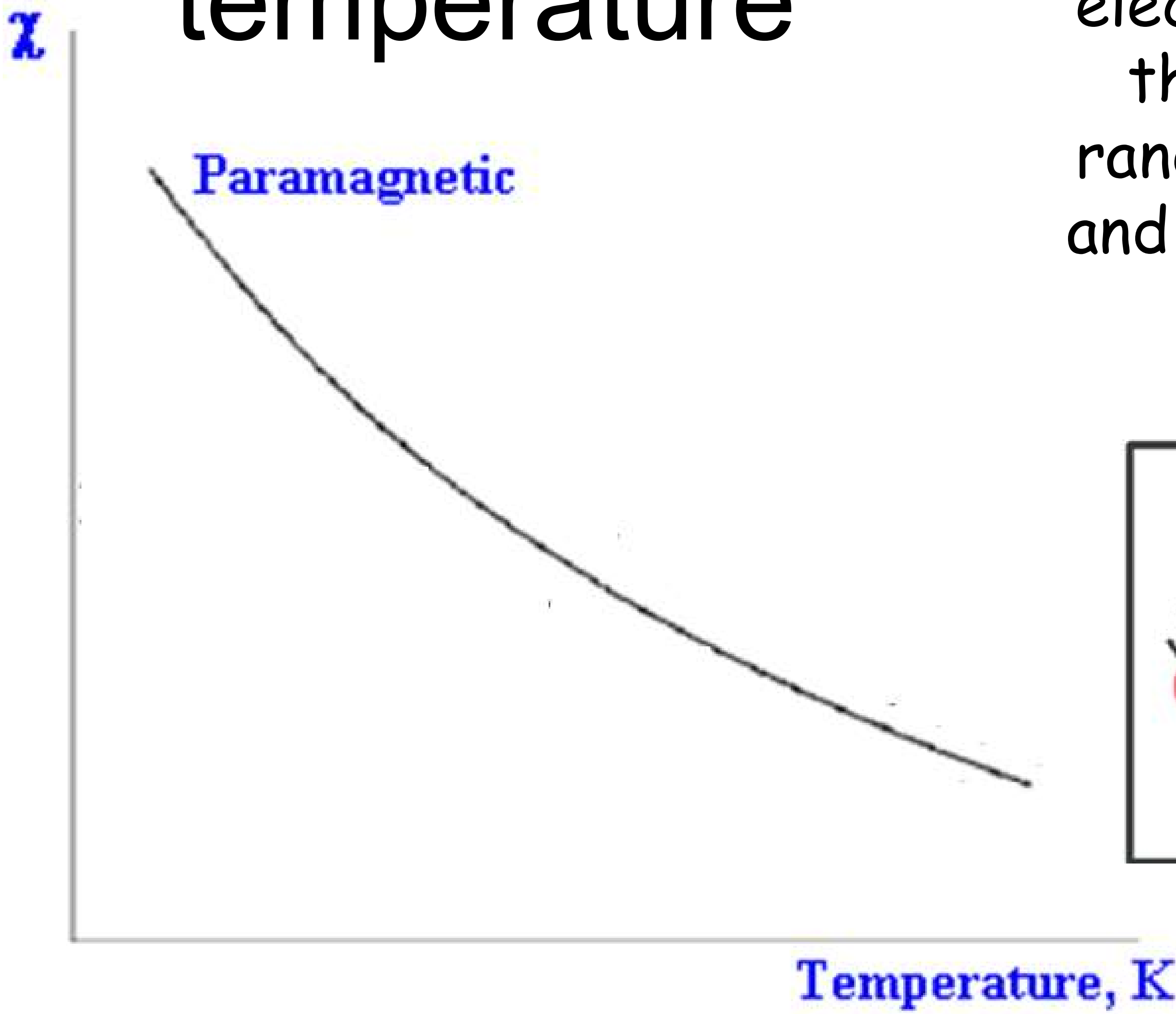
χ = Magnetic Susceptibility

M = Magnetization

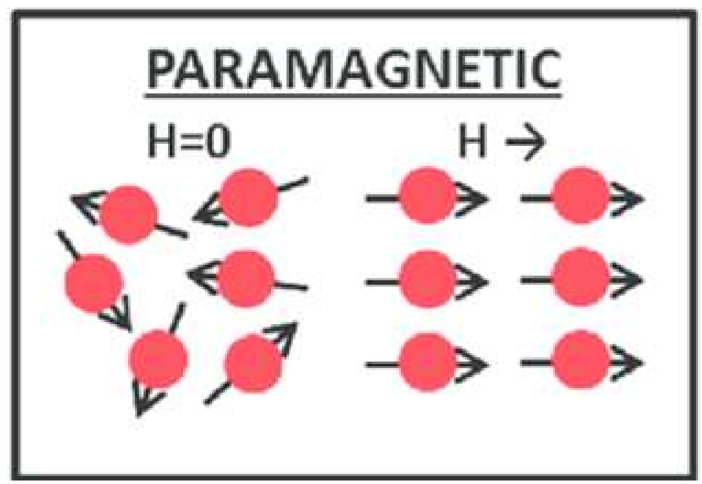
H = Magnetic Field strength

If $1/\chi$ is linear, what would χ vs temperature look like?

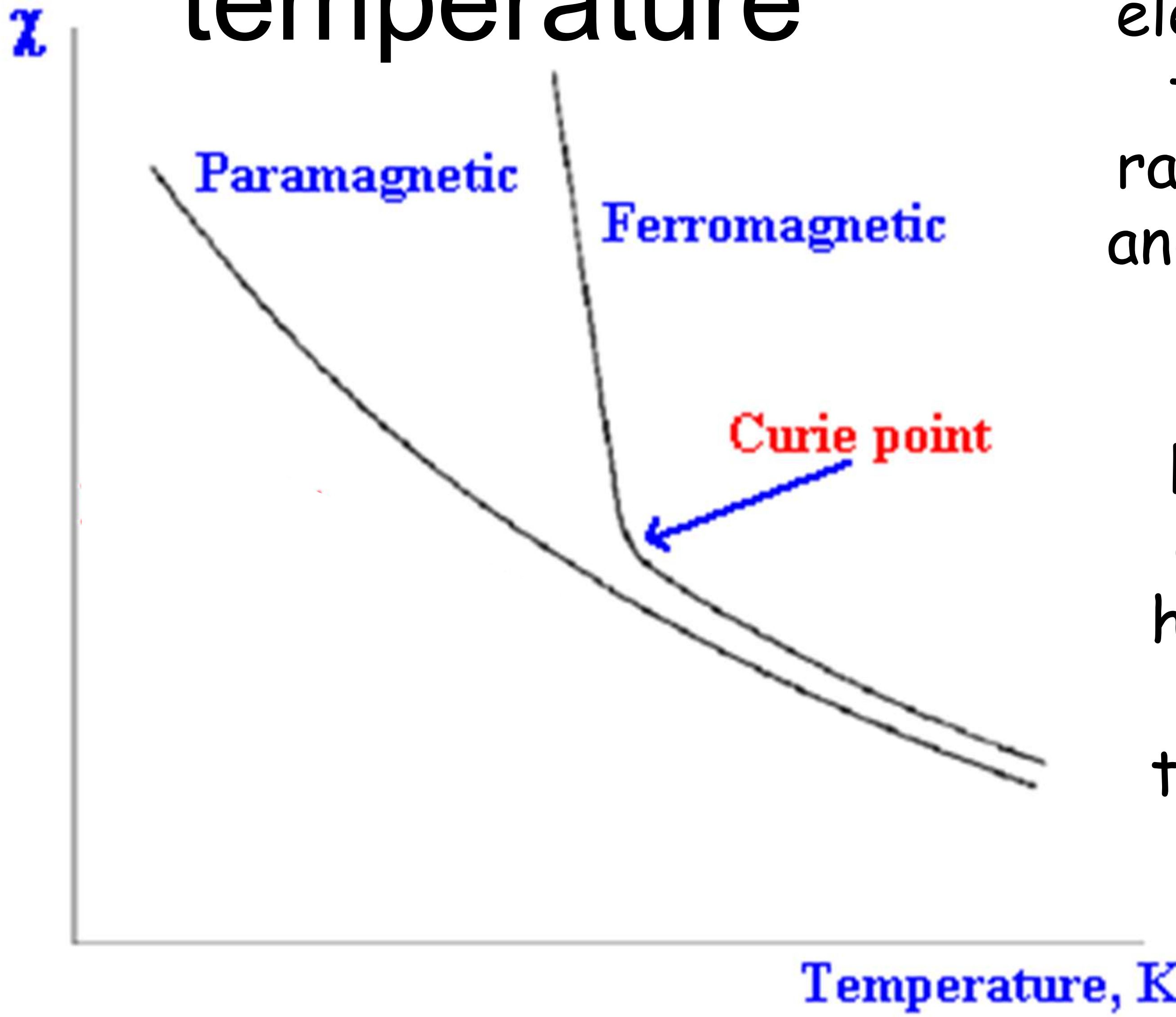
Magnetic susceptibility vs temperature



As the temperature increases the electrons gain enough thermal energy to randomize their spins and the magnetization decreases.



Magnetic susceptibility vs temperature



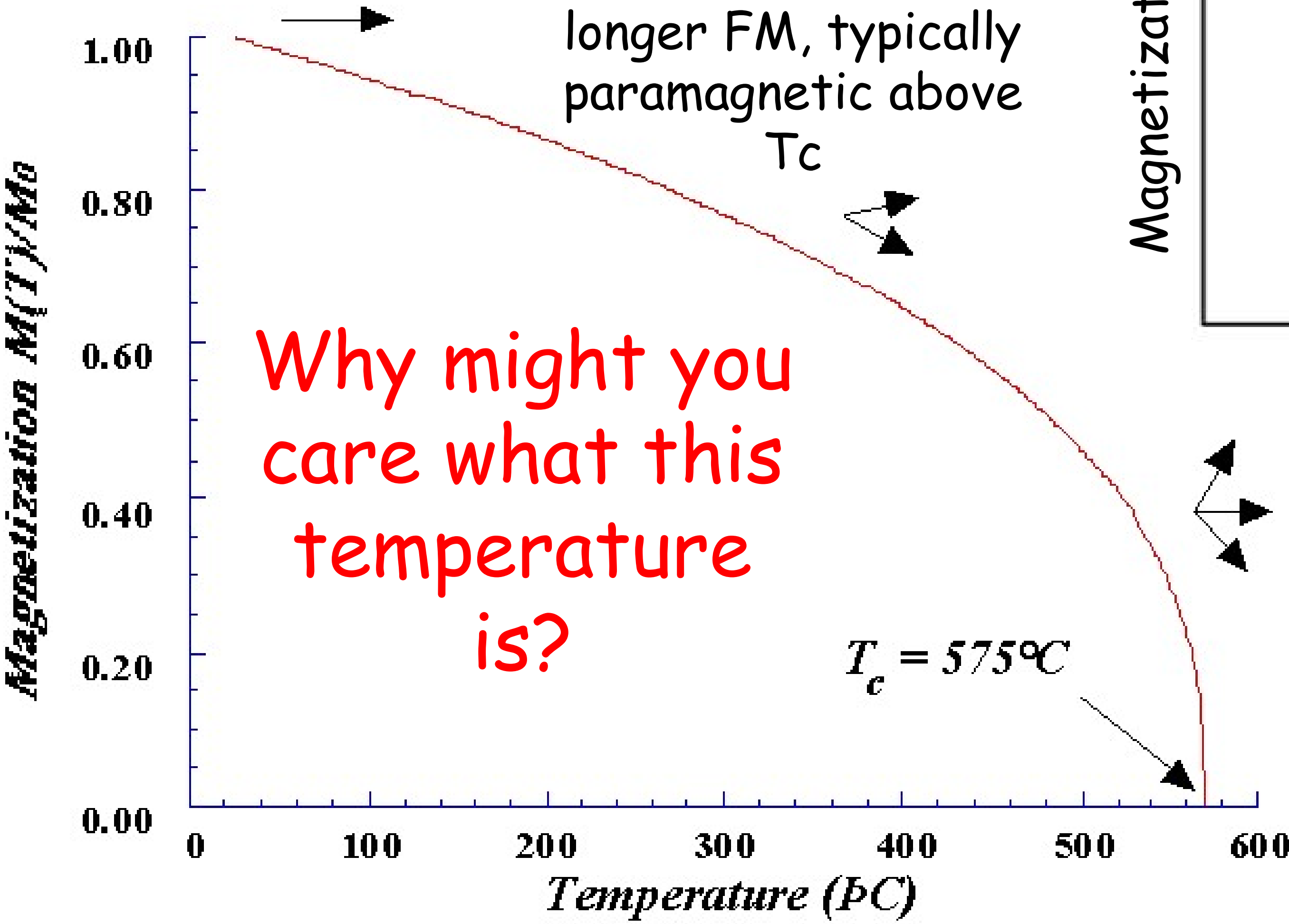
For both paramagnets and ferromagnets, as the temperature increases the electrons gain enough thermal energy to randomize their spins and the magnetization decreases.

Ferromagnets and antiferromagnets have weird kinks at their ordering temperatures from which they both switch to paramagnets.

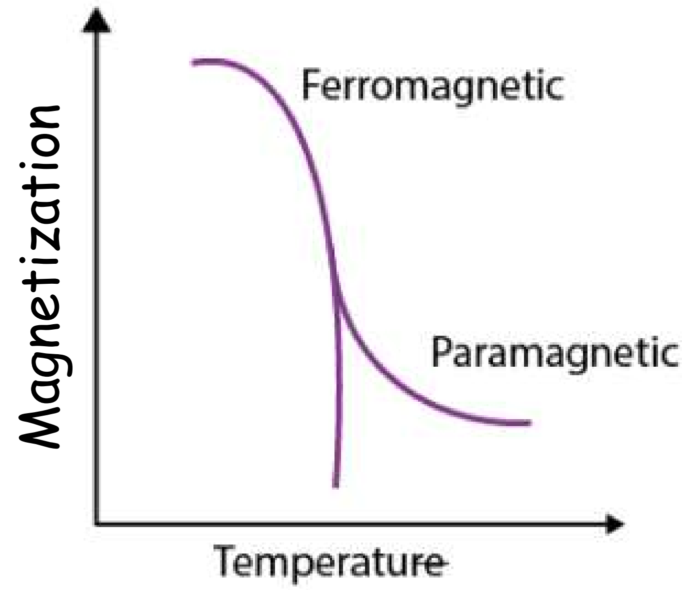
Ferromagnet with Temperature

Ferromagnets have a quantum mechanical effect that prefers alignment of the electron spin, but enough thermal energy can overcome this effect.

Curie Temperature above which no longer FM, typically paramagnetic above Tc



Why might you care what this temperature is?

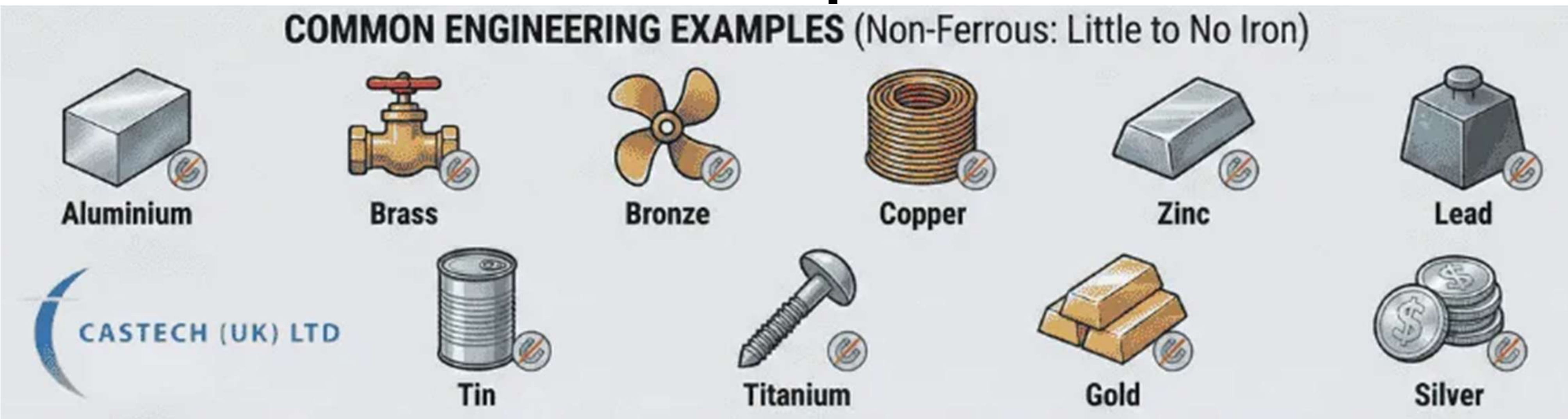


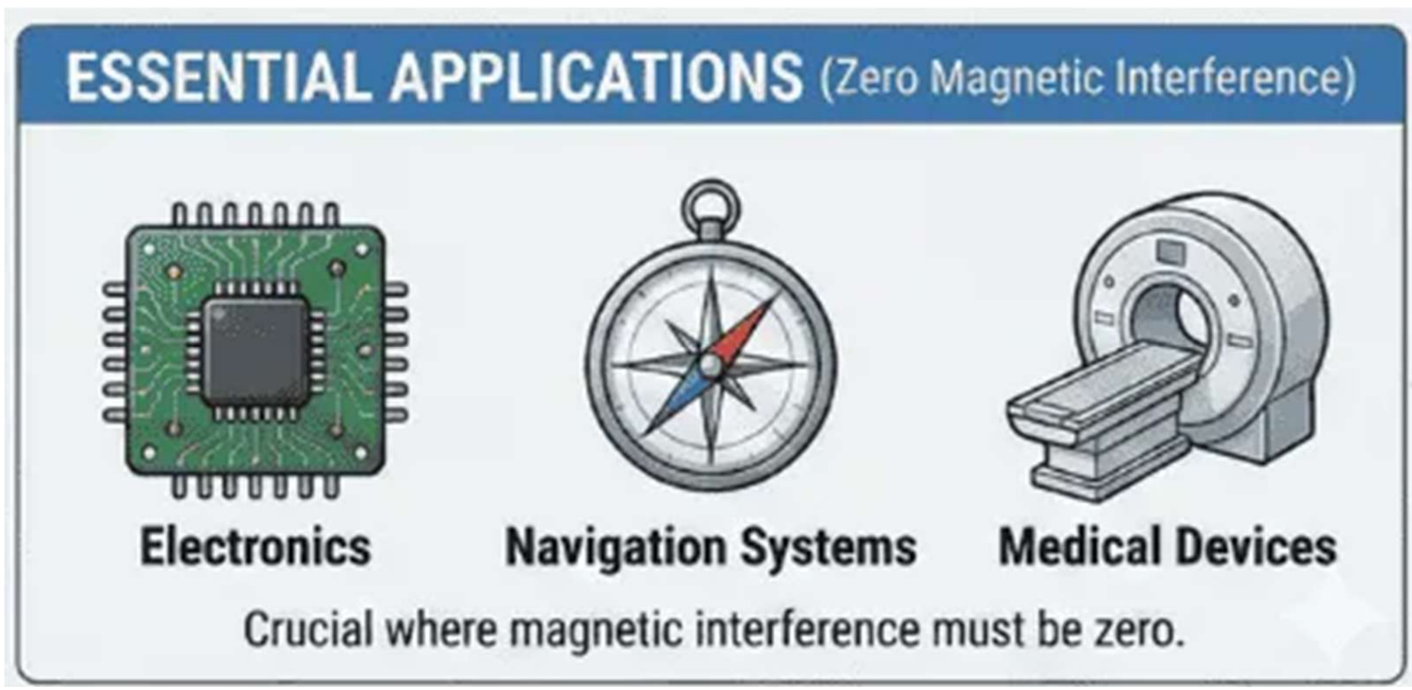
Cutoff is frequently not this sharp (H field can affect)

Visualizing Magnetic Field Lines

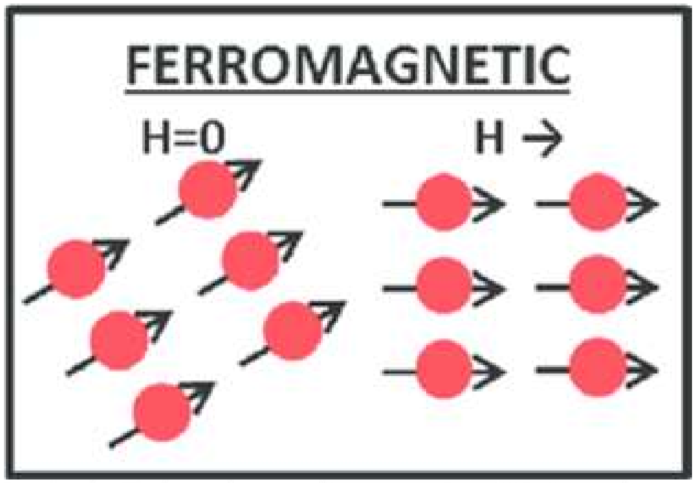
- Visualizing Magnetic Field Lines - Activity - TeachEngineering

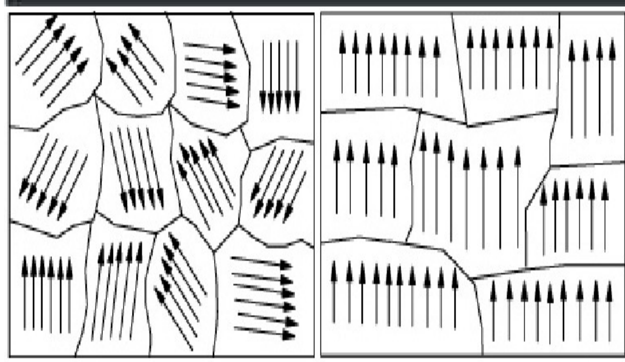
Important non-magnetic examples



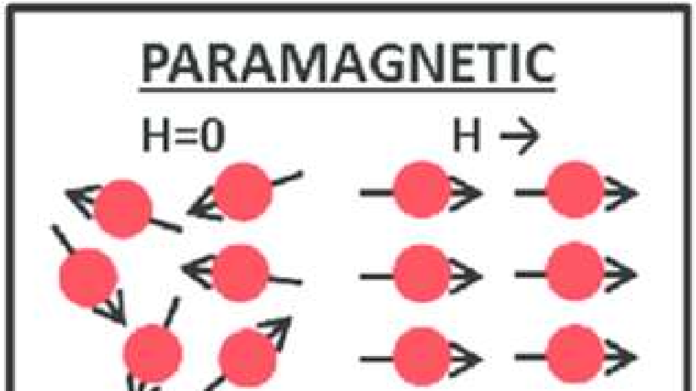


Examples of Each Magnetism

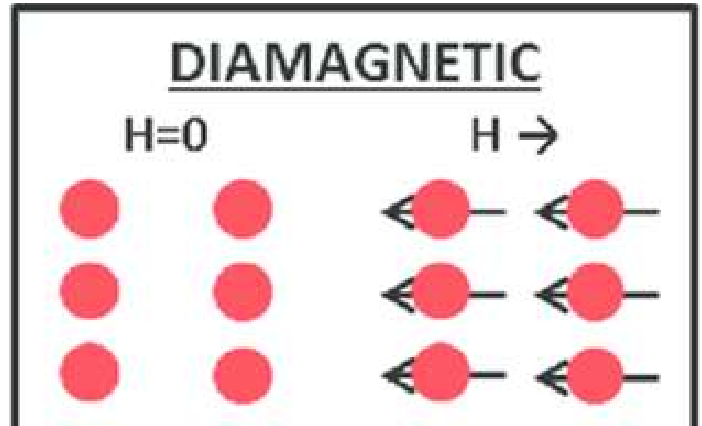




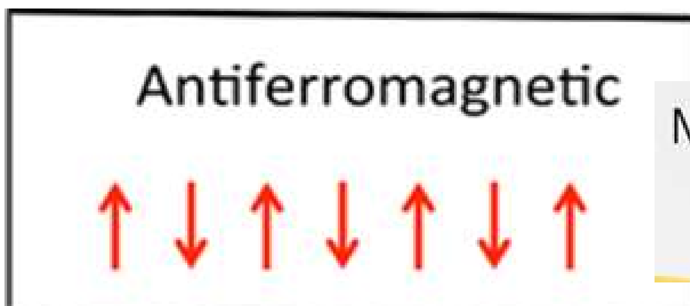
Iron, Cobalt, Nickel,
Gadolinium, Dysprosium,
Erbium, Holmium
$LaSrMnO_3$



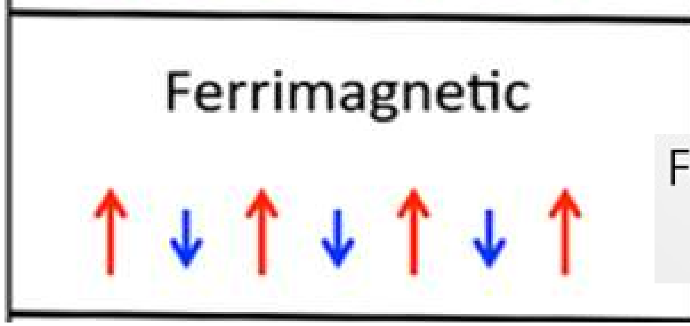
Platinum, Aluminum, Air,
Sodium, Tin, Oxygen,
Hydrogen
Titanium



Copper, Mercury, Bismuth,
Zinc, Magnesium, Gold,
Silicon, Phosphorus, Water,
Graphite, Proteins



MnO, FeO, CoO, $FeMn$, NiO,
MnS, MnF_2
$LaMnO_3$, $SrMnO_3$



Fe_3O_4, $PbFe_{12}O_{19}$, $BaFe_{12}O_{19}$,
$BaO{\cdot}6Fe_2O_3$, $SrO{\cdot}6Fe_2O_3$