Fundamentals of Solid State Physics

Magnetic Properties

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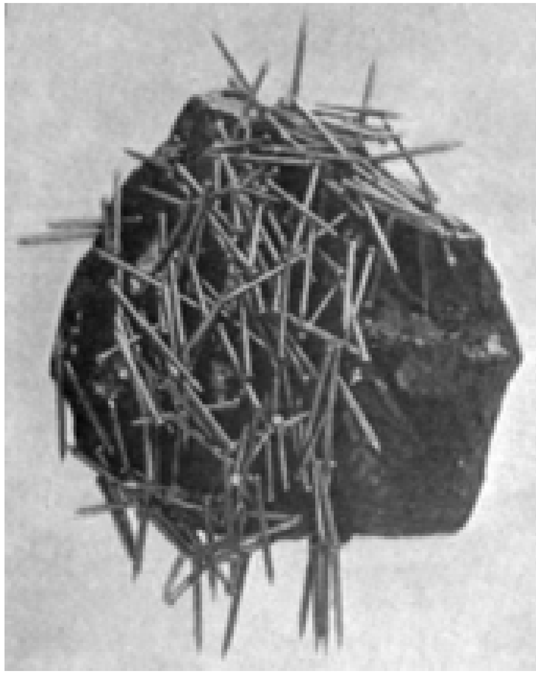
This Class

- Introduction (Week 1)
- Materials and Crystal Structures (Week 2–3)
- Electronic Properties (Week 4–12)
- Thermal Properties (Week 13)
- Optical Properties (Week 14)
- **Magnetic Properties (Week 15)**
  - Origin of Magnetics
  - Diamagnetism, Paramagnetism, Ferromagnetism
  - Superconductivity

References

- https://cse.umn.edu/irm/1-definitions-and-units
- https://www.britannica.com/science/magnetism/Magnetic-properties-of-matter

History of Magnetism



lodestone
磁铁矿
Greek
600 B.C.

compass
司南
China
1100 A.D.

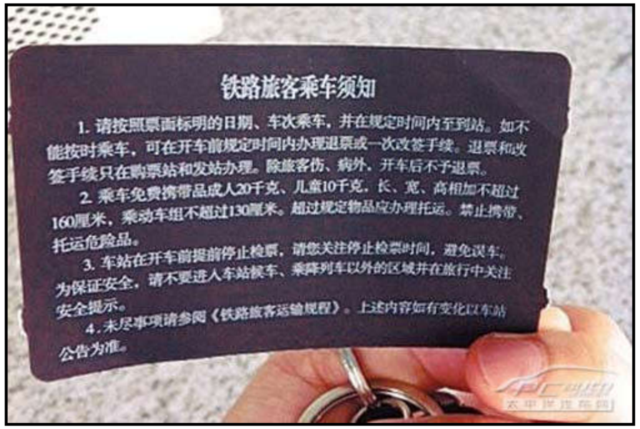
Wikipedia

Applications of Magnetism

Compass

Hard Drive

Wind Turbine



ID ticket

MagLev 磁悬浮

MRI

Nobel Prizes in Magnetism

- 1902 Zeeman effect
- 1943 Magnetic moment of proton
- 1944 Magnetics of atomic nuclei
- 1952 Nuclear magnetic resonance (NMR)
- 1955 Magnetic moment of electron
- 1970 anti-ferromagnetism and ferri-magnetism
- 1972 BCS theory of superconductivity
- 2007 Giant magnetoresistance
- ...

incomplete list ...

Outline

- Maxwell's Equations
  - *H*, *B*, *M*, μ_r
  - Magnetic Susceptibility 磁化率 χ
- Origin of magnetism
  - spin of electrons, orbital angular momentum, external field
  - nuclear magnetic momentum
- Types of magnetism
  - Diamagnetism 抗磁性
  - Paramagnetism 顺磁性
  - Ferromagnetism 铁磁性
  - Antiferromagnetism 反铁磁性
  - Ferrimagnetism 亚铁磁性

Electrodynamics

- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

Constitutive Relations

本构关系

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}$$

$\varepsilon_0\ \varepsilon_r$ - **Permittivity (dielectric constant)**

ε_r **= 1 for vacuum**

ε_0 **= 8.85*10^{-12} F/m**

$\mu_0 \mu_r$ - **Permeability**

μ_r **= 1 for vacuum**

μ_0 **= 4π*10^{-7} H/m**

Electrodynamics

- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

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Constitutive Relations
本构关系

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}$$

For magnetic materials

$\mu_r \neq 1$

Electrodynamics

- **Maxwell's Equations**

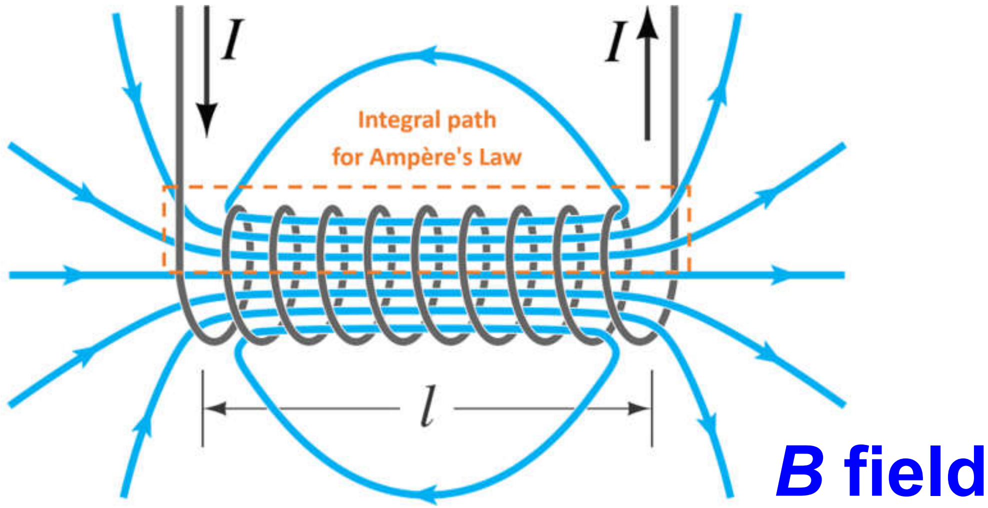
$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

Solenoid (螺线管)



$$\mathbf{B} = \mu_0 \mu_r n I$$

Electromagnet: Magnetic field is produced by electric currents. (Ampere's law)

Electrodynamics

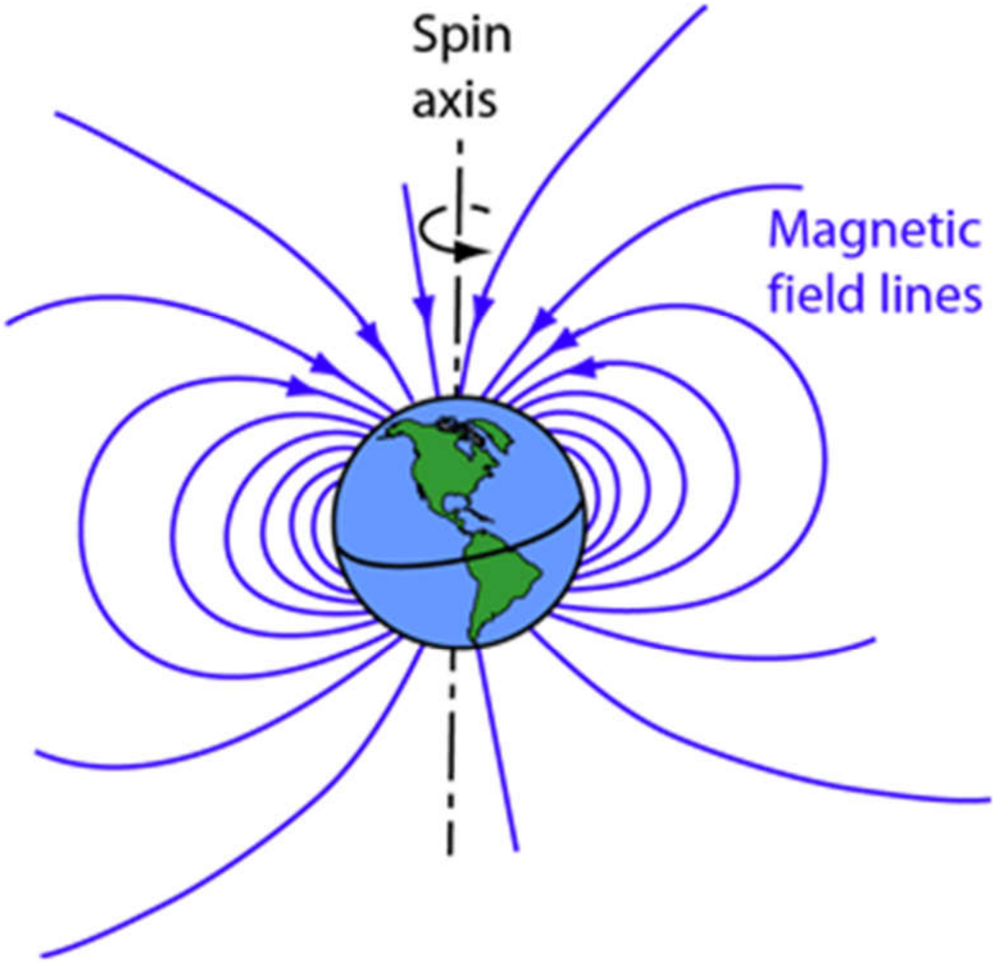
- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$



Our earth is a big electromagnet

Electrodynamics

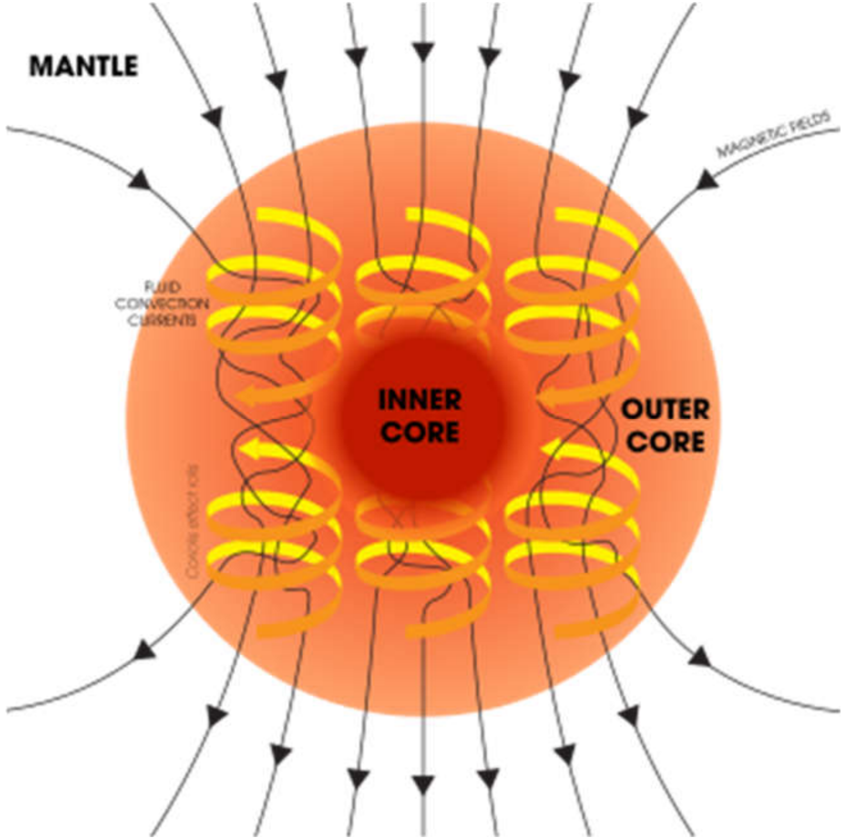
- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$



The dynamo mechanism

Electrodynamics

- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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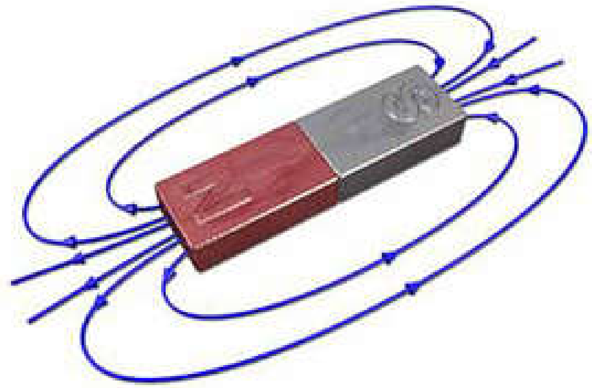
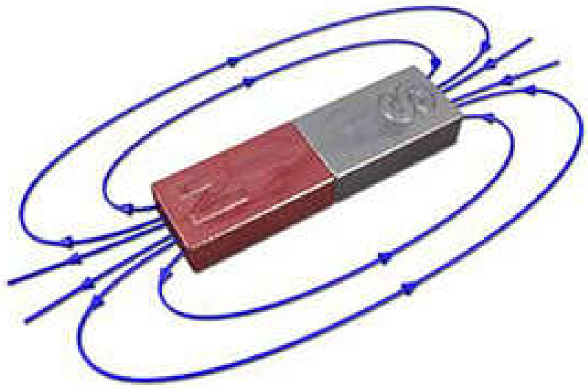
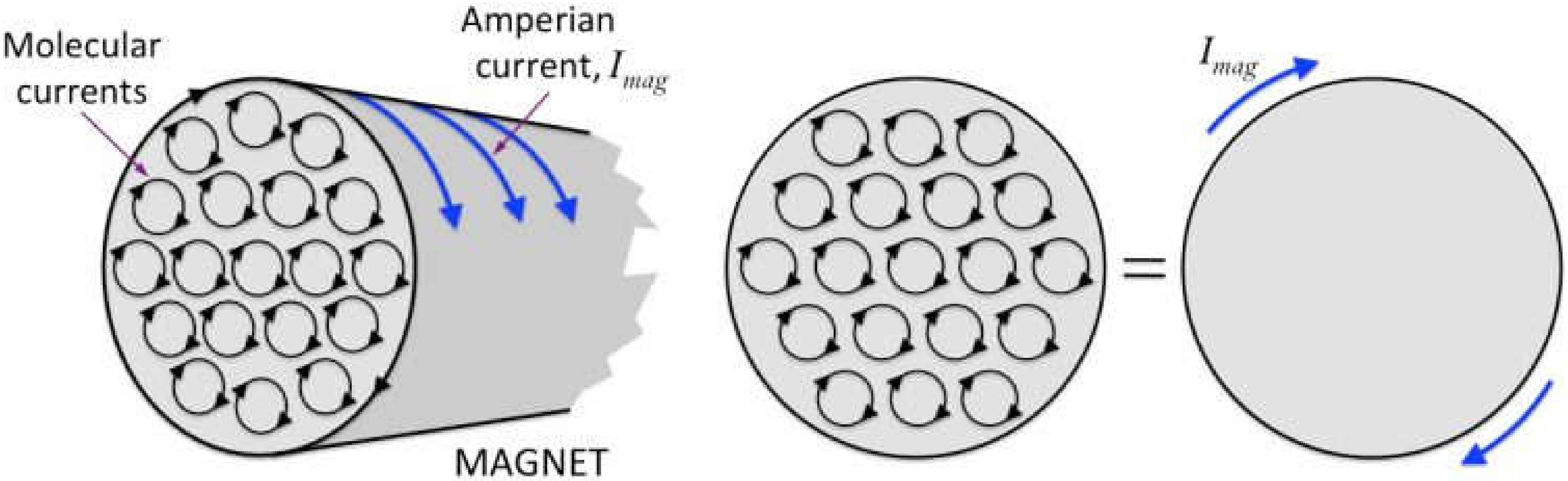


How about magnetic materials?

Origin of Magnetism - Old Theory

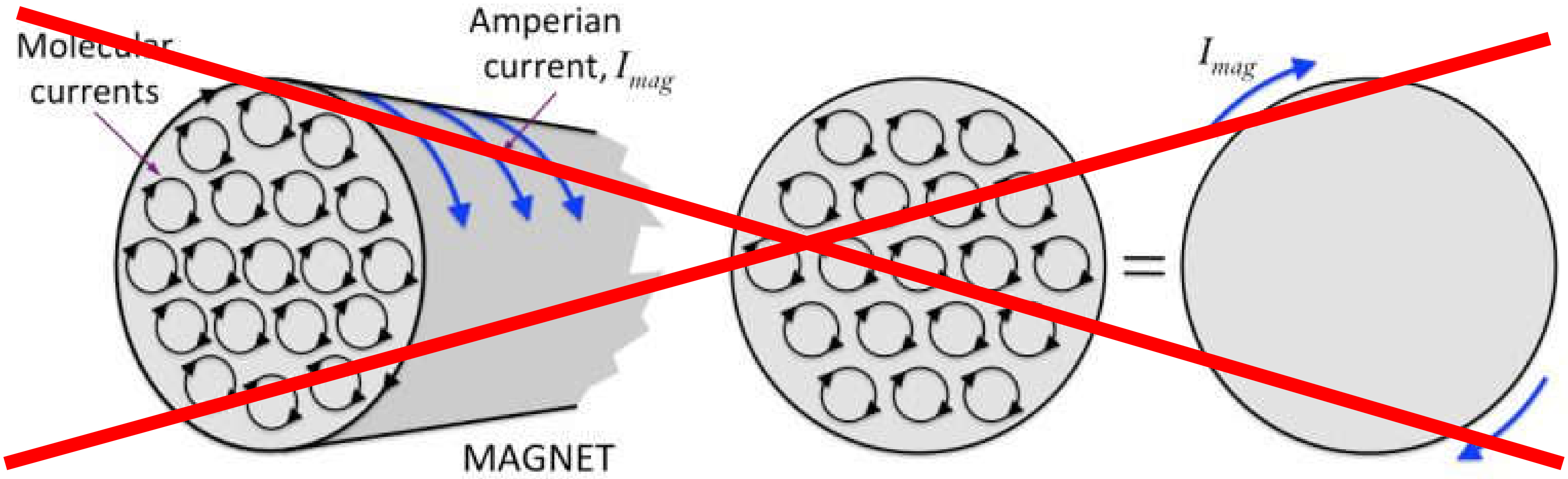
- **Ampere 安培, 1826**
  - **Molecular Currents 分子电流假说**
  - **"magnetism is electricity in motion"**





Origin of Magnetism - Old Theory

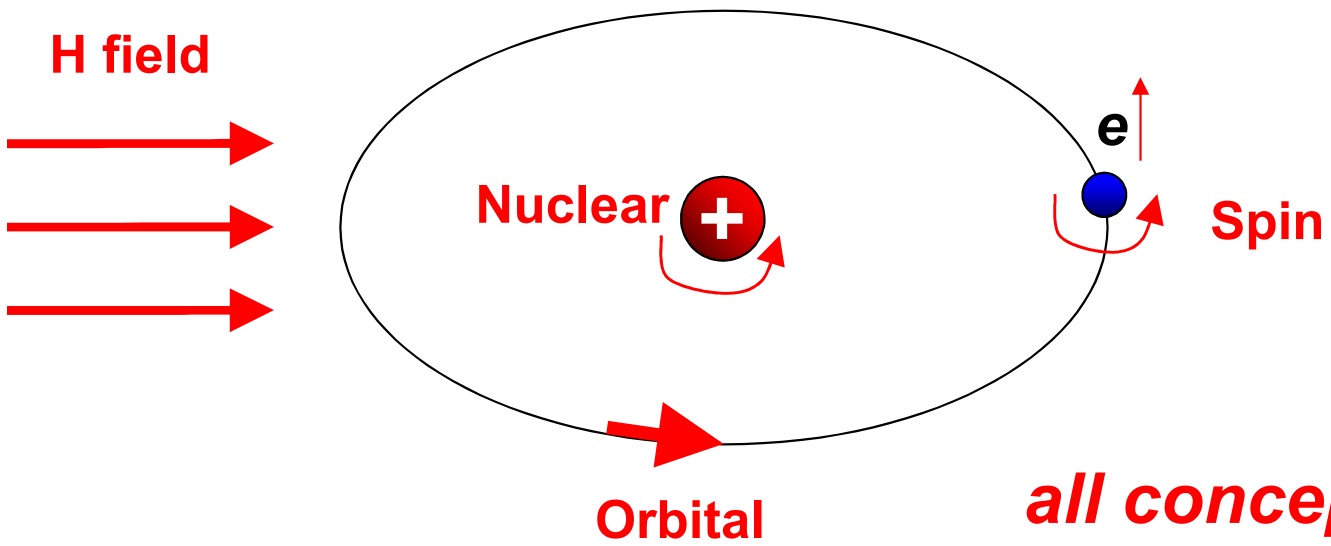
- **However,**
  - **There are no "molecular currents" at all**
  - **For a steady solid, all the magnetic moments cancel out**



We can only understand magnetism with quantum mechanics

Origin of Magnetism - Modern Theory

- **Magnetic moment of atoms**
  - spin of electrons
  - orbital angular momentum
  - external magnetic field
  - magnetic momentum of nuclei (10^{-3} times smaller than that from electrons)



all concepts are quantum mechanics based

Magnetic Properties

- For magnetic materials, $\mu_r \neq 1$

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} = \mu_0 (1 + \chi) \mathbf{H} = \mu_0 (\mathbf{H} + \mathbf{M})$$

$$\chi = \mu_r - 1 \qquad \mathbf{M} = \chi \mathbf{H}$$

- ***B*** **- Magnetic induction 磁感应强度**
- ***H*** **- Magnetic field 磁场强度**
- ***M*** **- Magnetization 磁化强度**
- χ **- Magnetic Susceptibility 磁化率**

Types of Magnetism

- χ - Magnetic Susceptibility 磁化率

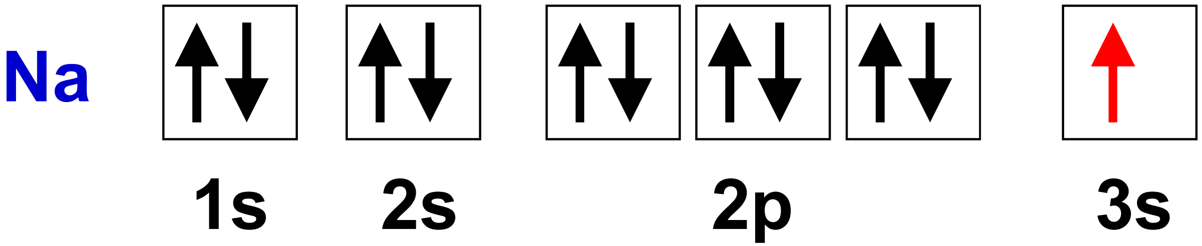
$$\mathbf{M} = \chi \mathbf{H}$$

Diamagnetism 抗磁性	$\chi < 0$	$\sim 10^{-6}$
Paramagnetism 顺磁性	$\chi > 0$	$10^{-4} \sim 10^{-5}$
Ferromagnetism 铁磁性	$\chi >> 0$	$> 10^{-2}$

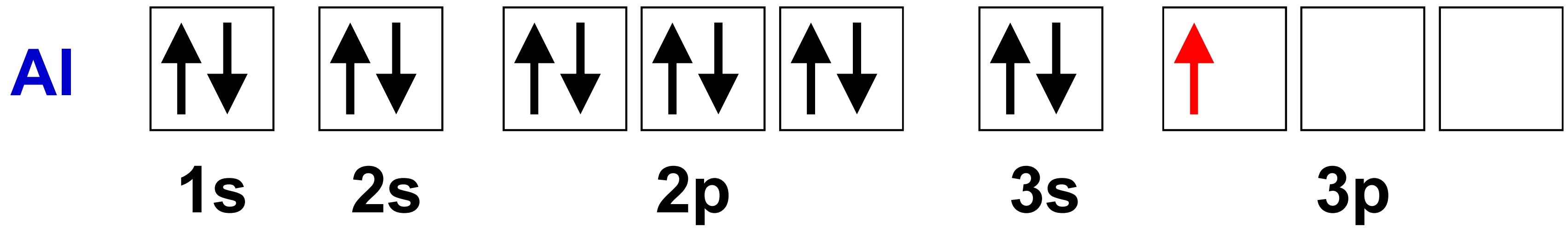
Paramagnetism 顺磁性

- Originated from *unpaired electrons*

  - **Sodium (Na)** [$1s^2$ $2s^2$ $2p^6$] $3s^1$

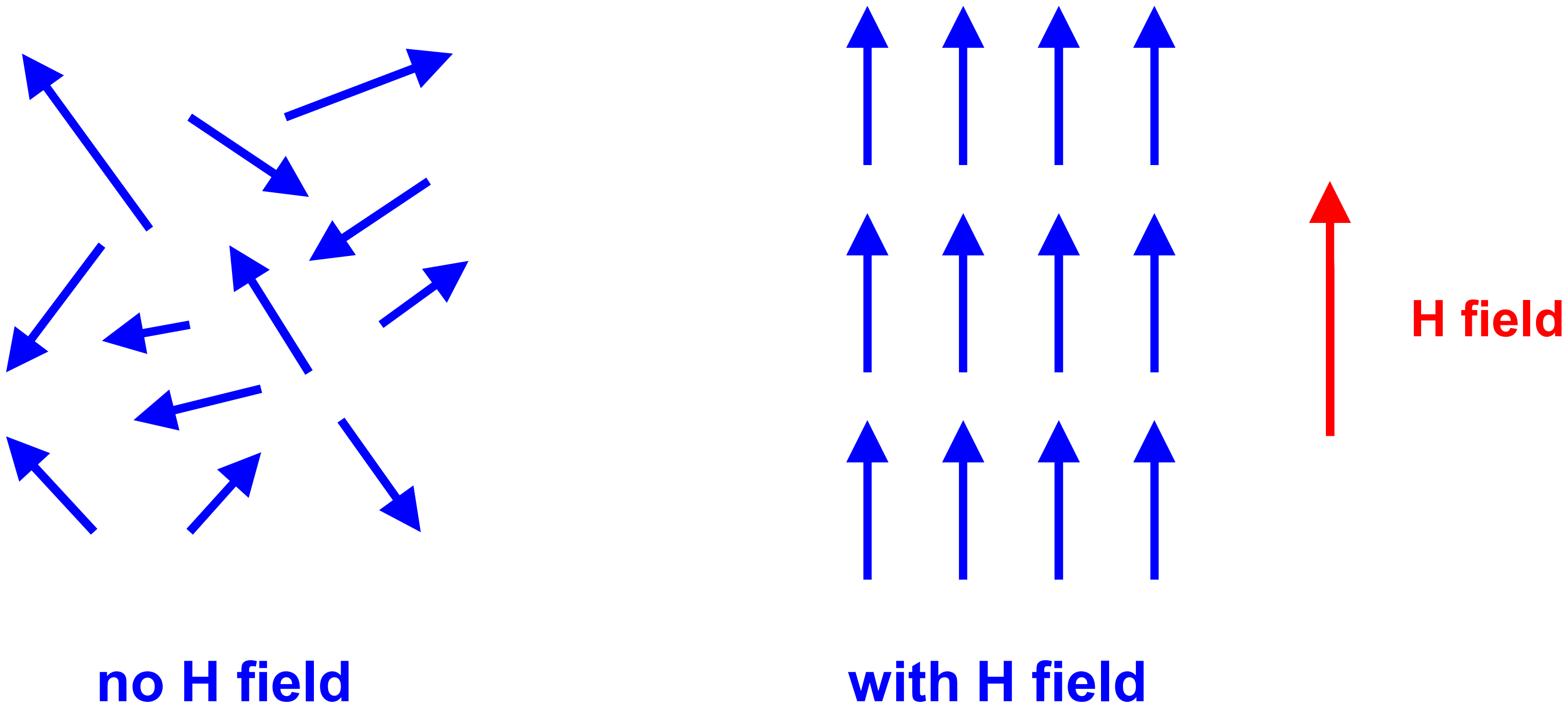


  - **Aluminum (Al)** [$1s^2$ $2s^2$ $2p^6$] $3s^2$ $3p^1$



Paramagnetism 顺磁性

- Originated from *unpaired electrons*



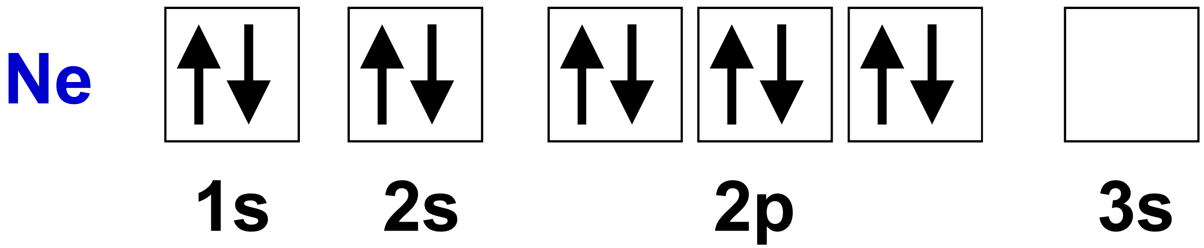
$$\mathbf{M} = \chi \mathbf{H}$$

Diamagnetism 抗磁性

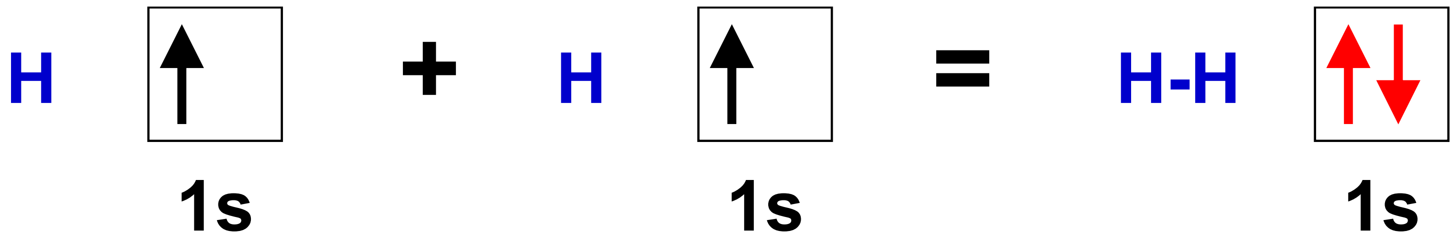
- Originated from *paired electrons*

  - He, Ne, Ar, ...

Detailed analysis requires quantum mechanics

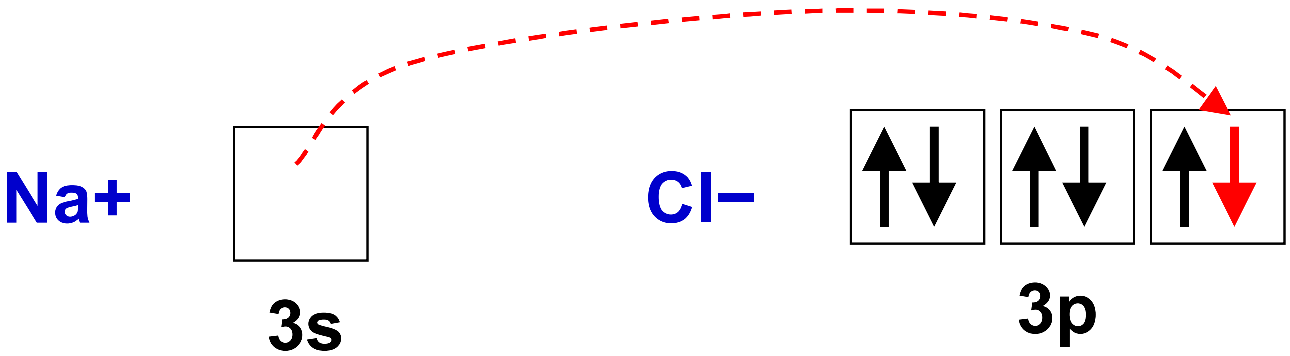


  - H_2, N_2, ...



Diamagnetism 抗磁性

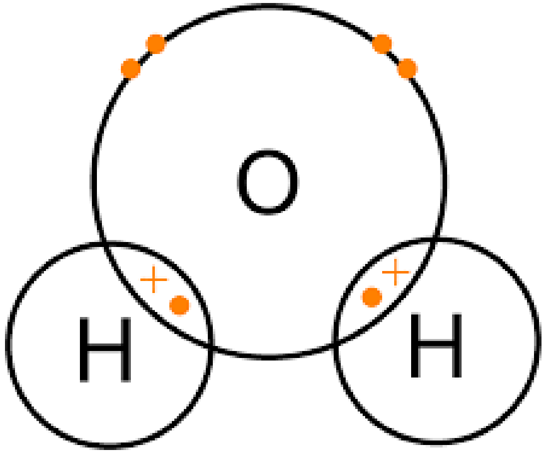
- Originated from *paired electrons*
  - NaCl = Na^+Cl^-

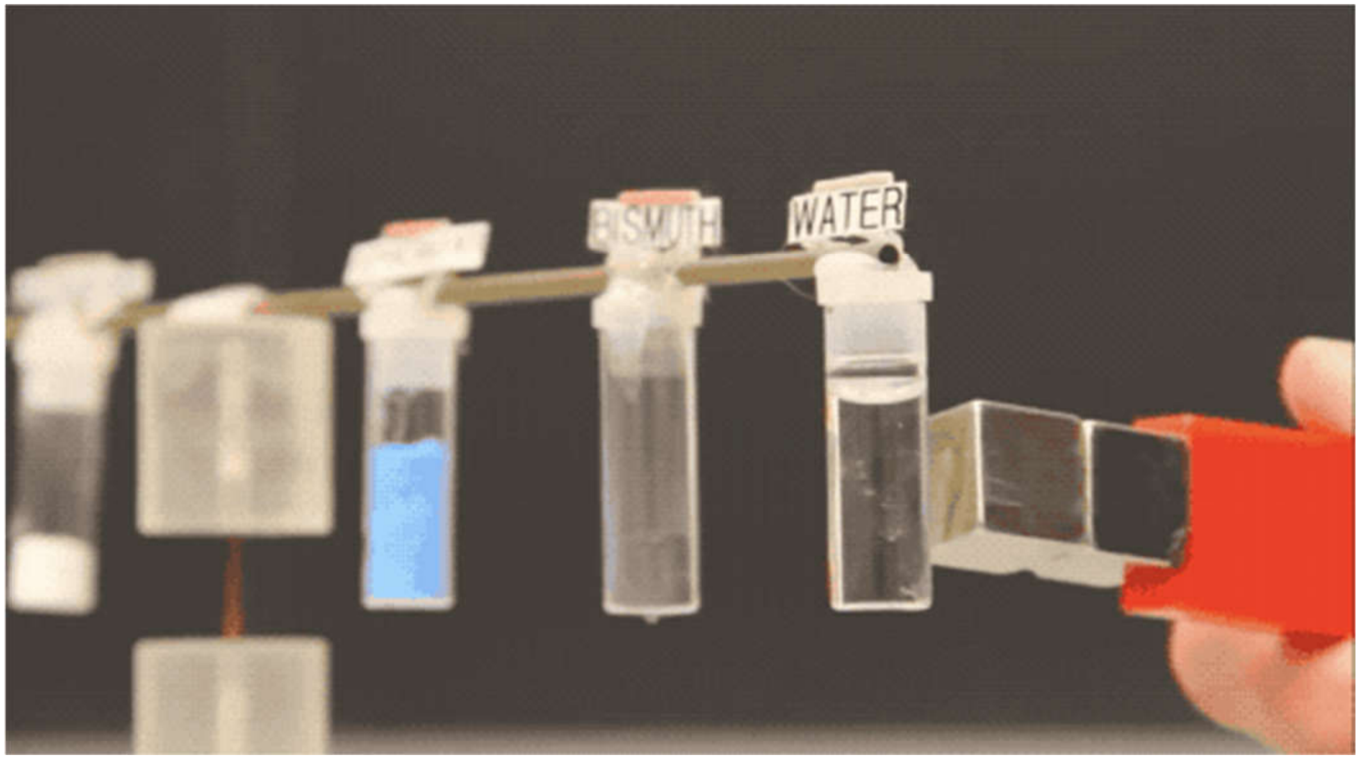


  - Silicon crystal

Diamagnetism 抗磁性

- Water (H_2O) is diamagnetic
  - All electrons are paired





http://demoweb.physics.ucla.edu/content/para-and-dia-magnetism

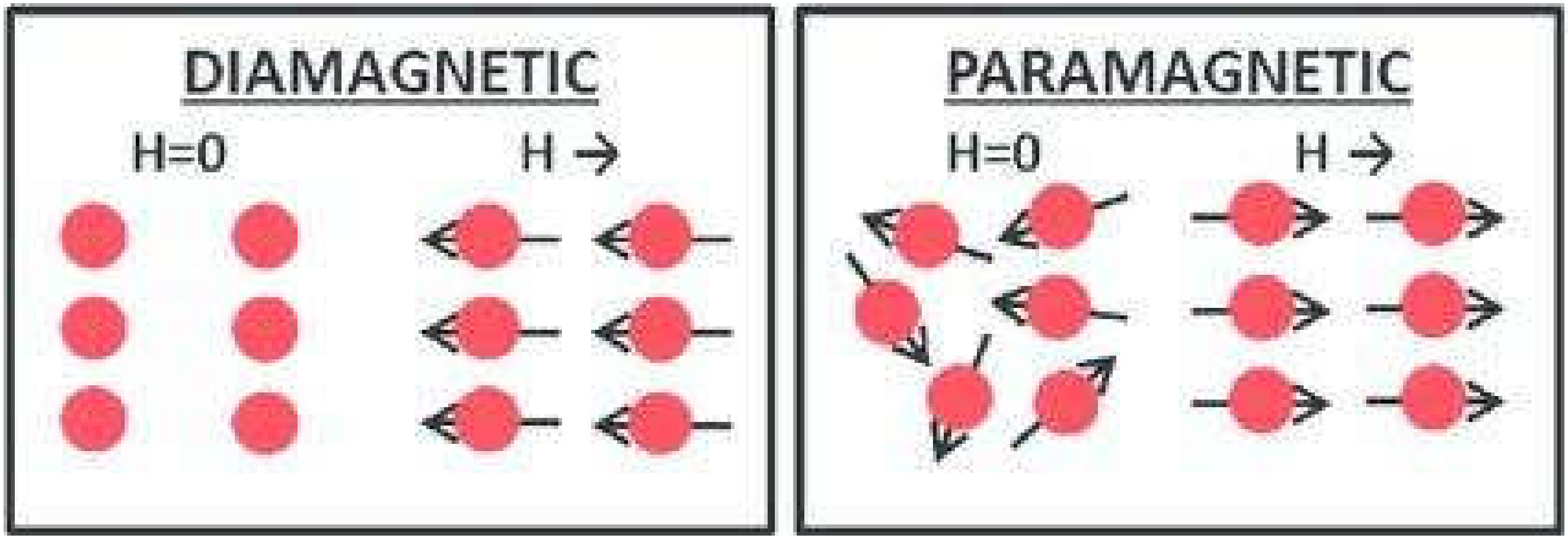
Diamagnetism 抗磁性

- **Water (H_2O) is diamagnetic**
  - **A frog is lifted by a strong magnetic field (*H* = 10 T)**

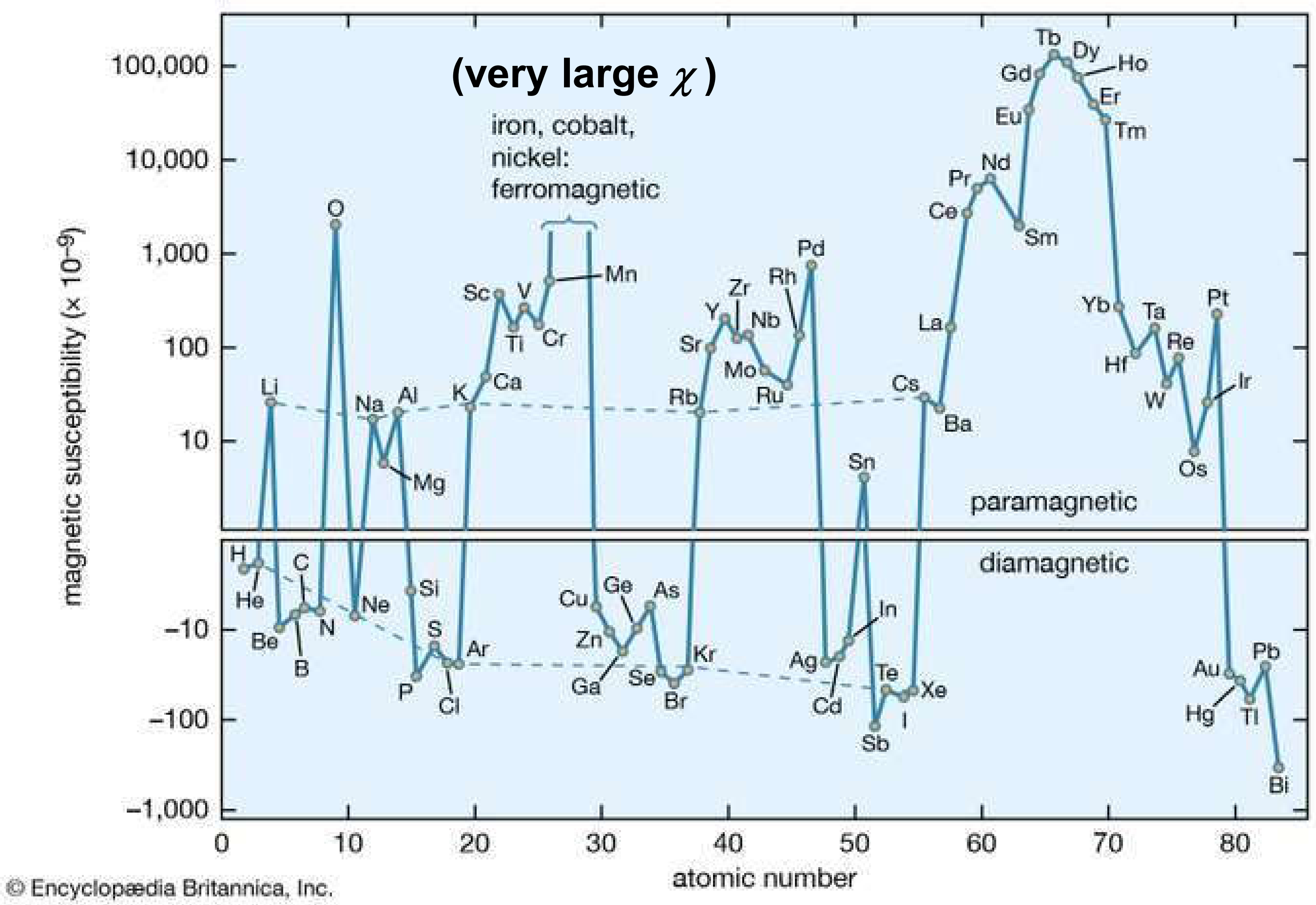
A. Geim, *Phys. Today* **51,** 9, 36 (1998)

A. Geim
Nobel Prize in 2010
Ig Nobel Prize in 2001
(搞笑诺贝尔奖)

Diamagnetism vs. Paramagnetism

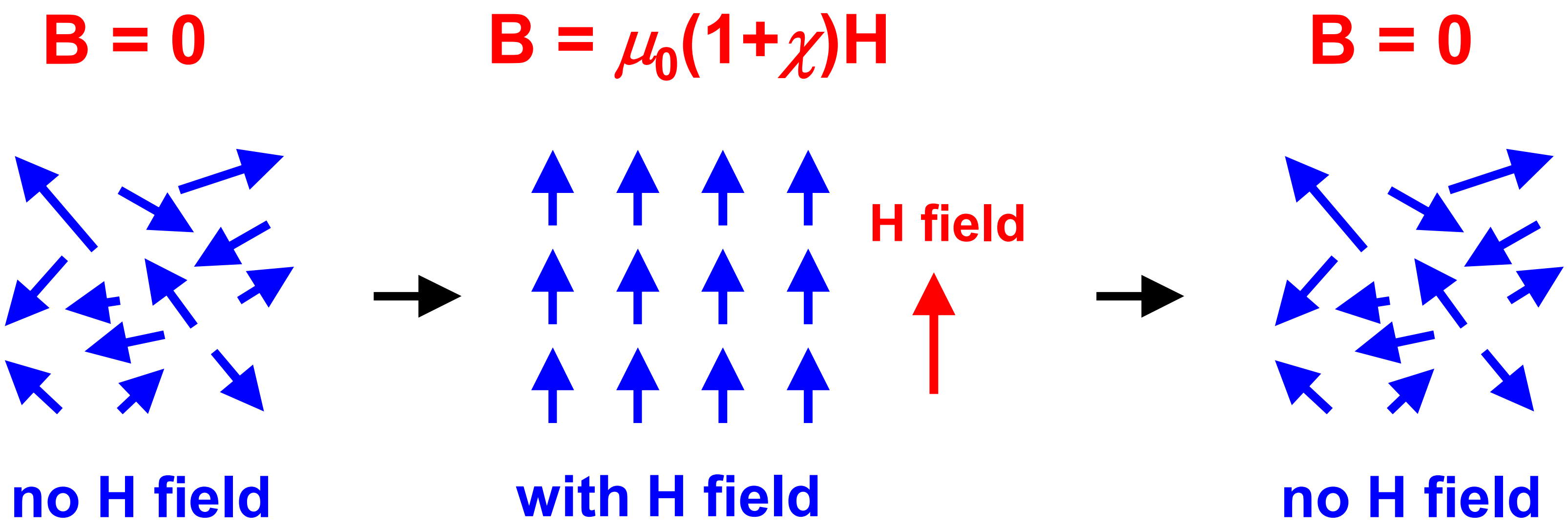


Diamagnetism vs. Paramagnetism



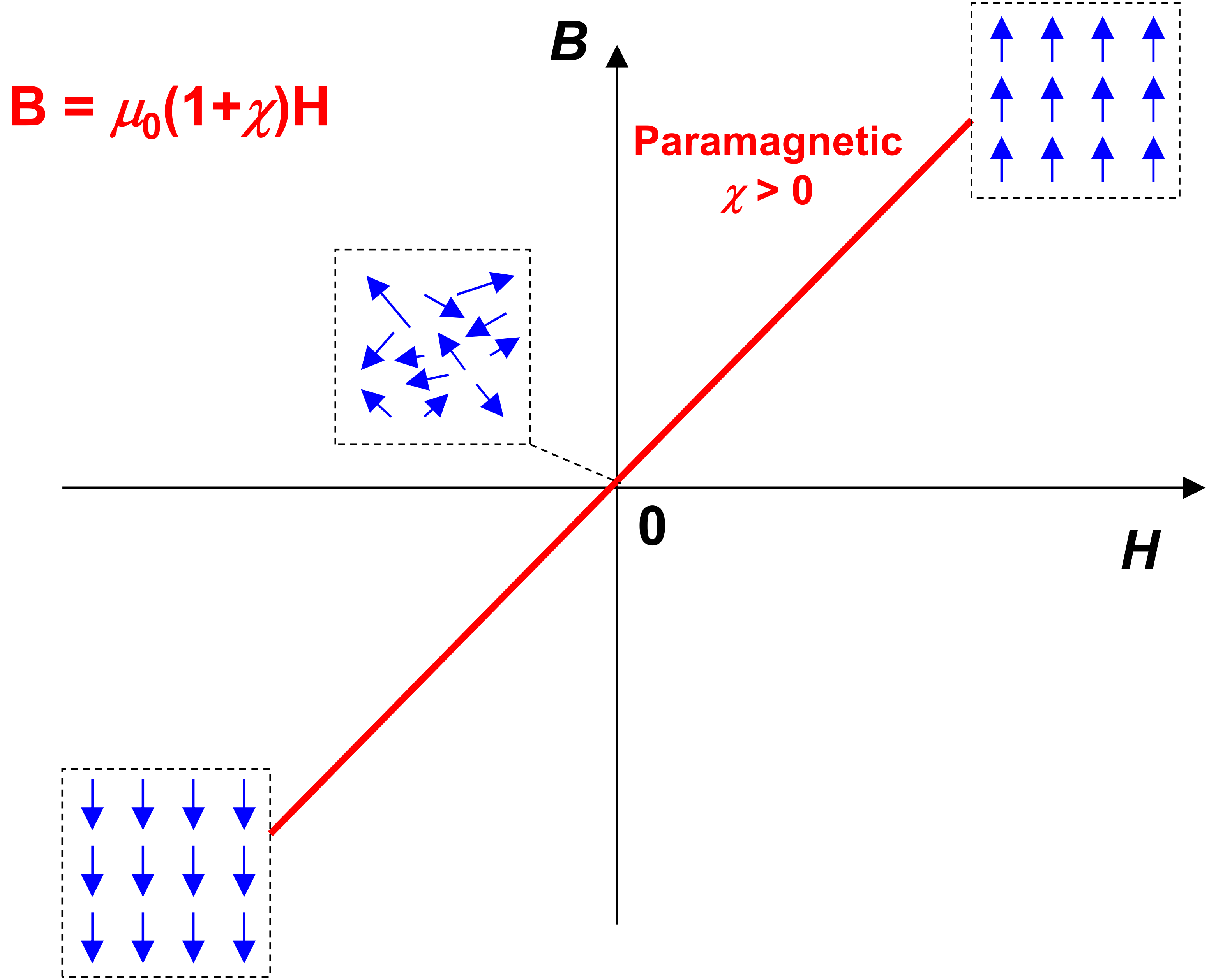
Magnetization Curve 磁化曲线

- B vs. H



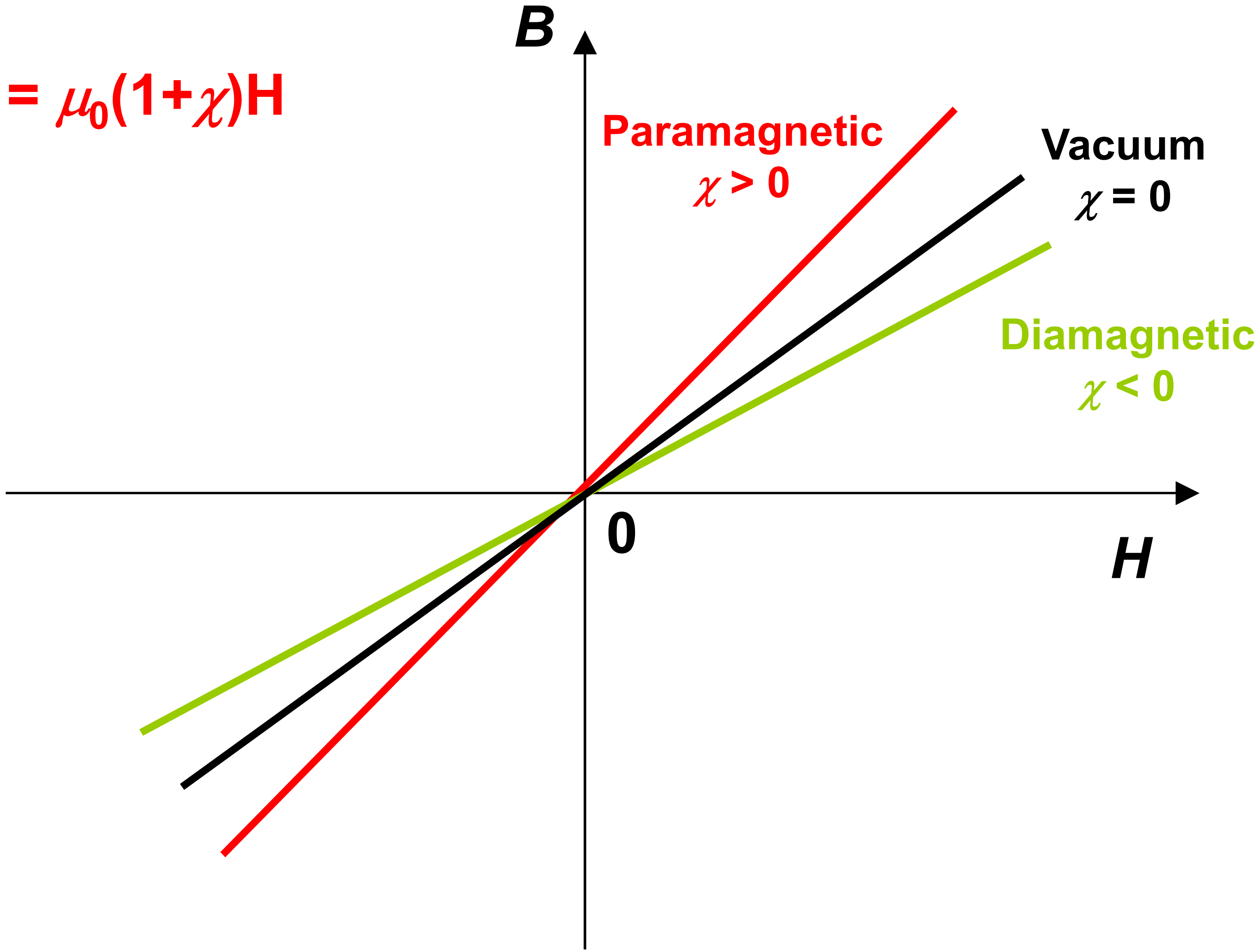
Paramagnetism

Magnetization Curve 磁化曲线



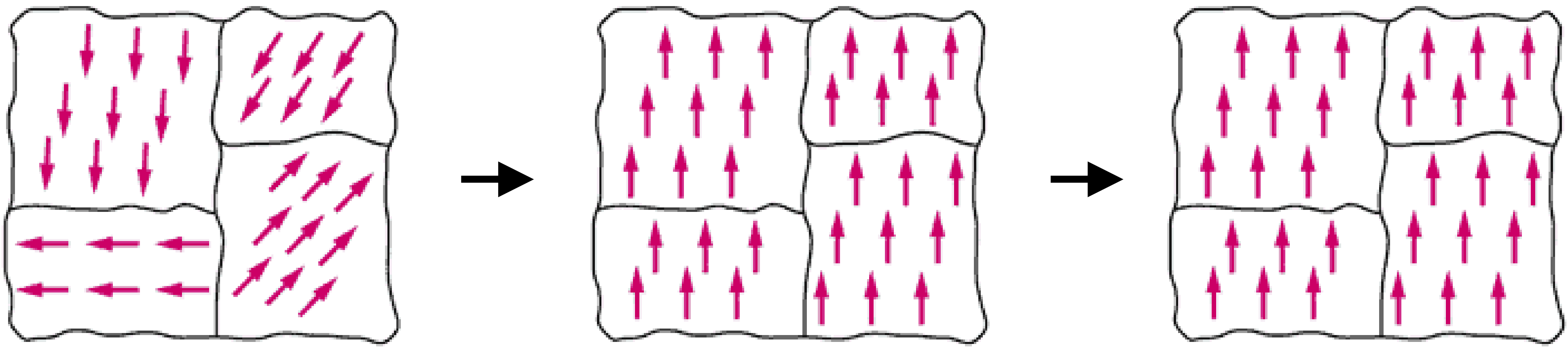
Magnetization Curve 磁化曲线

$B = \mu_0(1+\chi)H$



Ferromagnetism 铁磁性

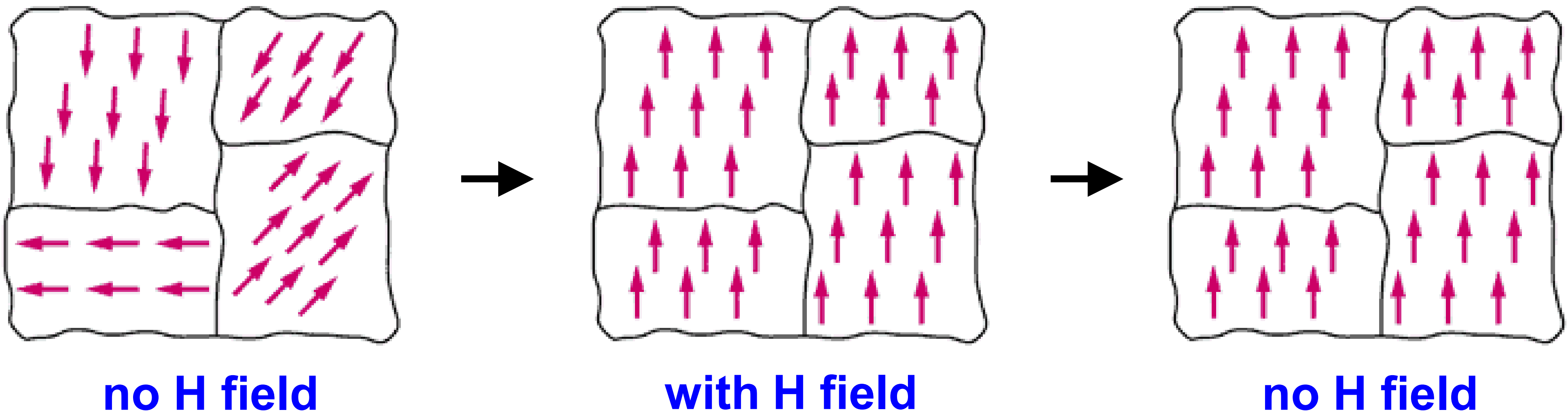
- **When *H* = 0, magnetic domains (磁畴) form with spontaneous magnetization (自发磁化)**
- **Magnetization remains when H is removed**



no H field → **with H field** → **no H field**

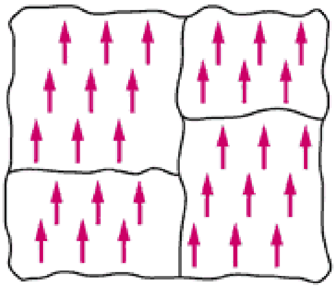
Ferromagnetism 铁磁性

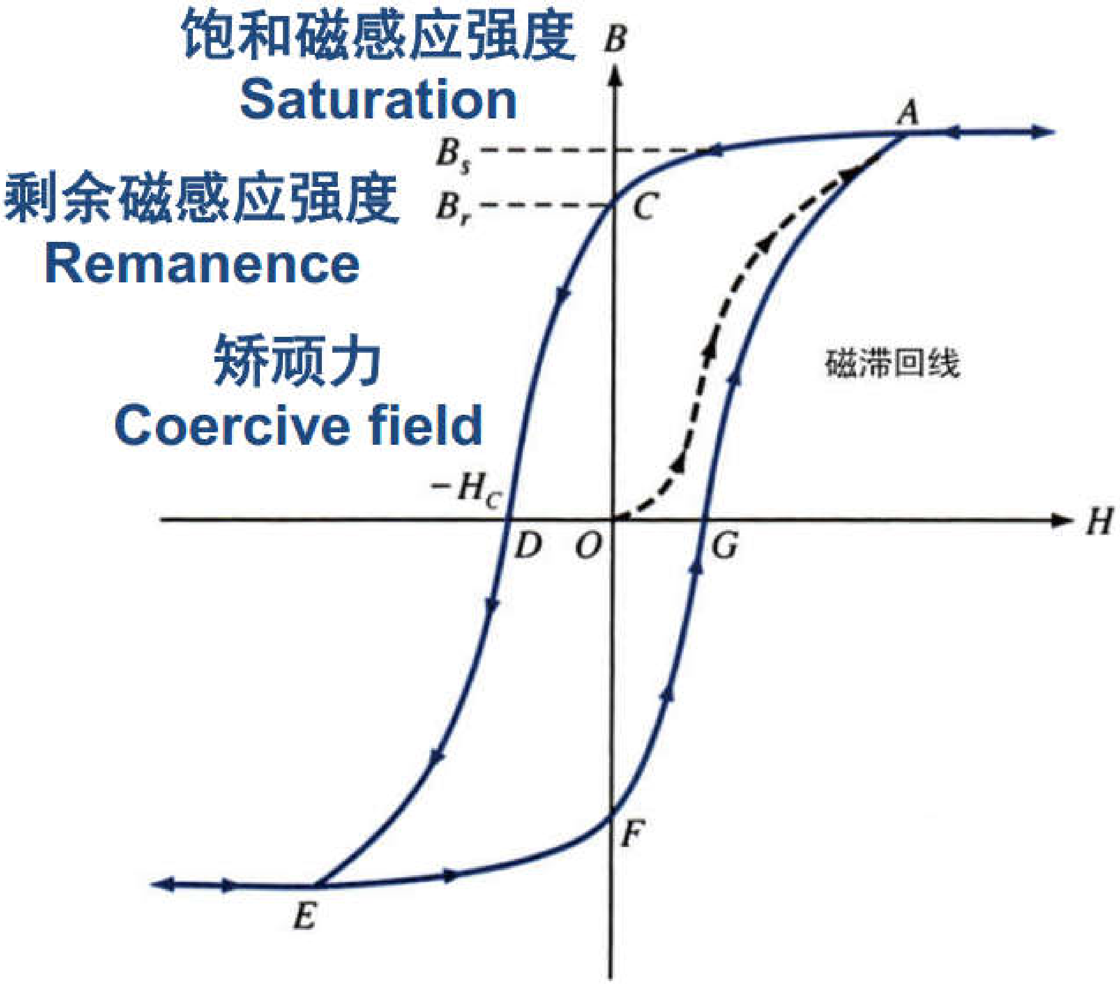
- **Permanent Magnet (永磁体)**
  - Fe, Co, Ni (铁，钴，镍)
  - Alloys: NdFeB (钕铁硼), SmCo (钐钴)



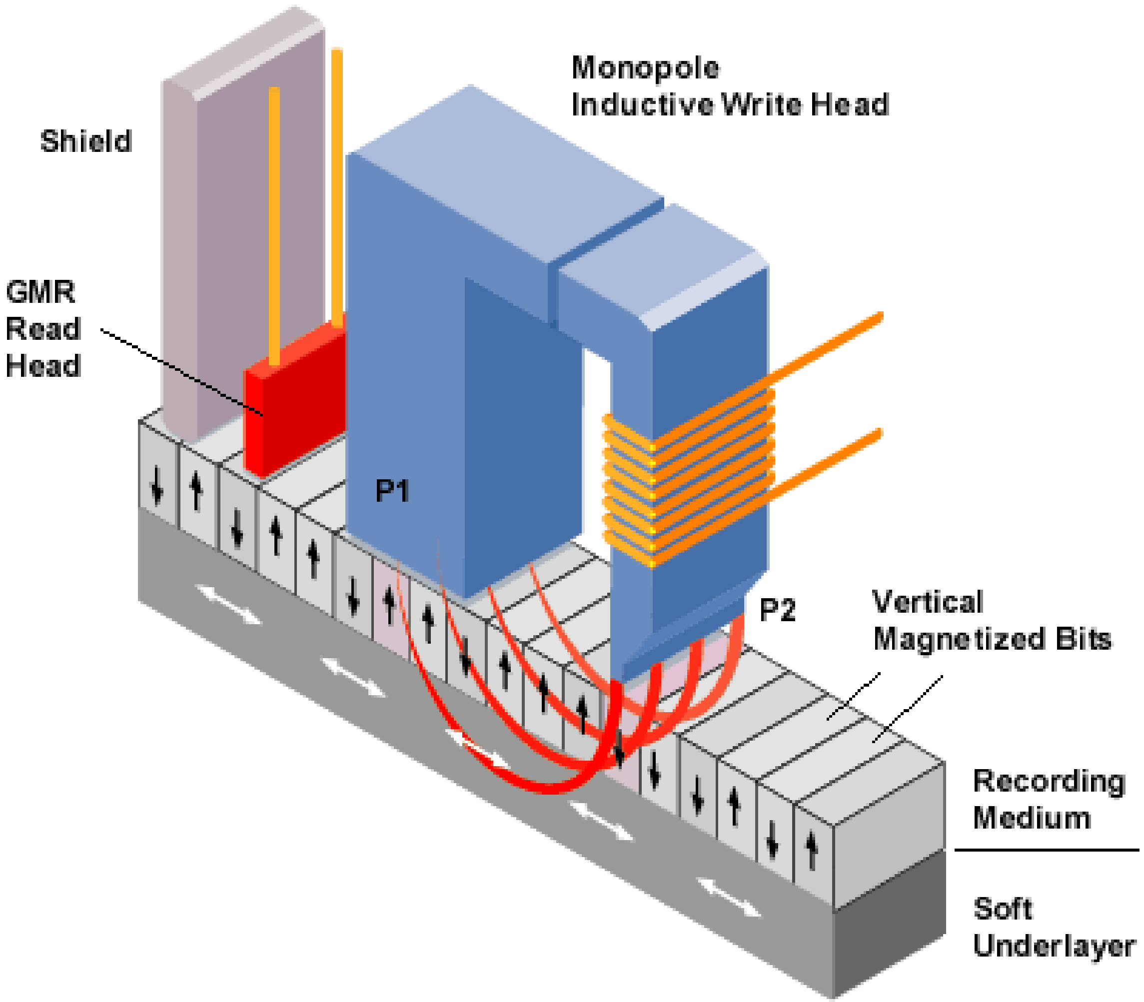
Ferromagnetism 铁磁性

- **B-H curve forms a hysteresis loop (磁滞回线)**





Magnetic recording



https://encyclopedia2.thefreedictionary.com/Perpendicular+magnetic+recording

Magnetic Tape 磁带

Hard Drive 硬盘

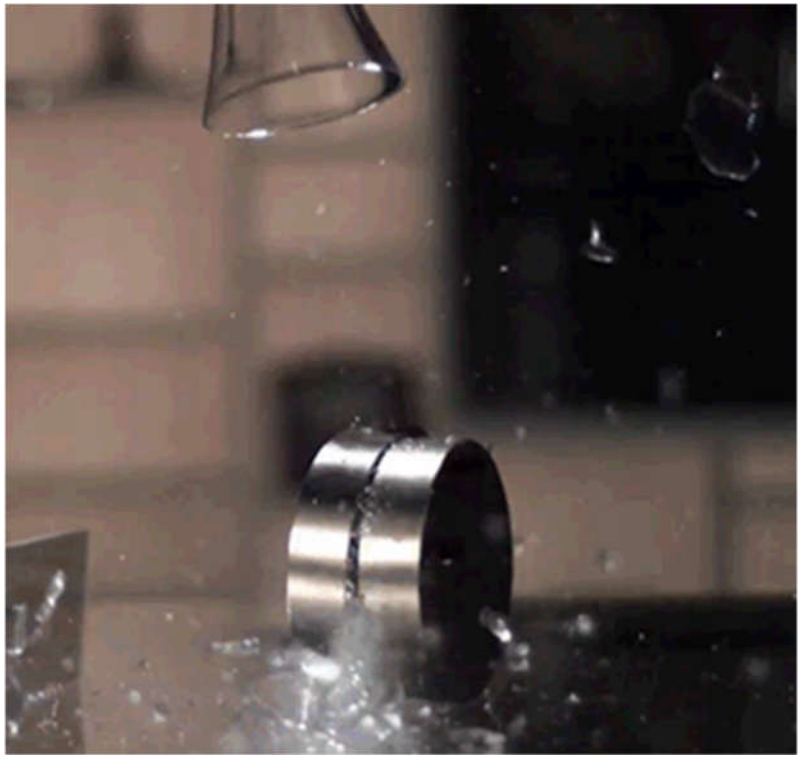
Evolution of Data Storage

Hard Drive 硬盘

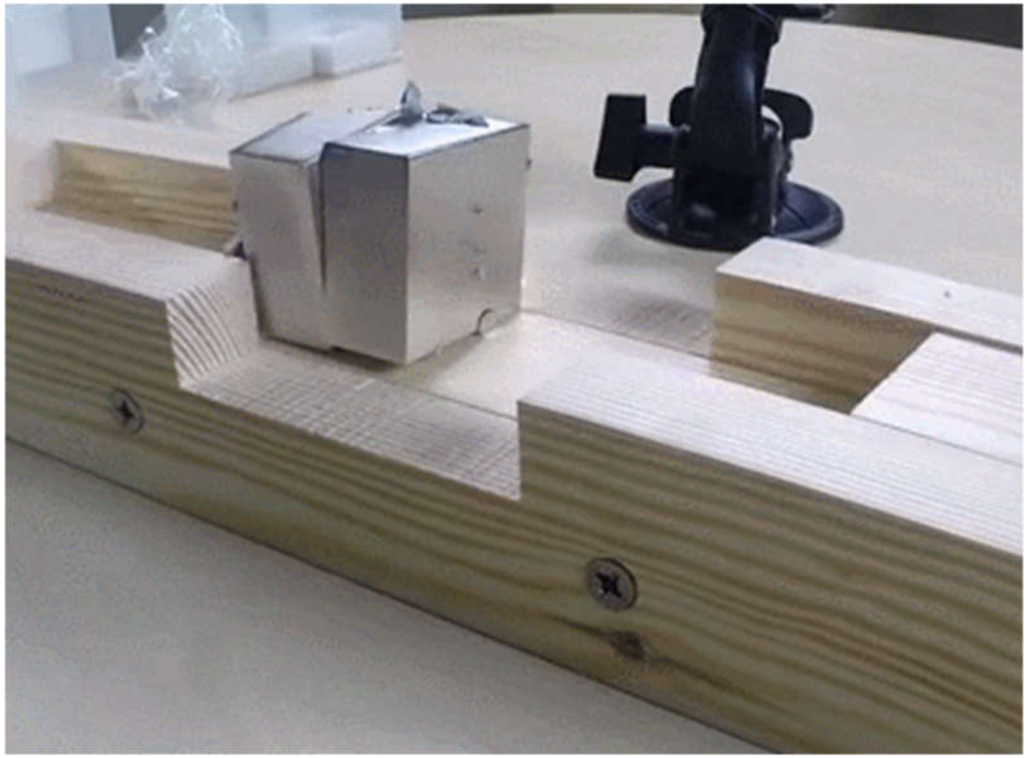
5 MB
IBM 1956

> 1 TB
Today

Ferromagnets can be Powerful



Be cautious!

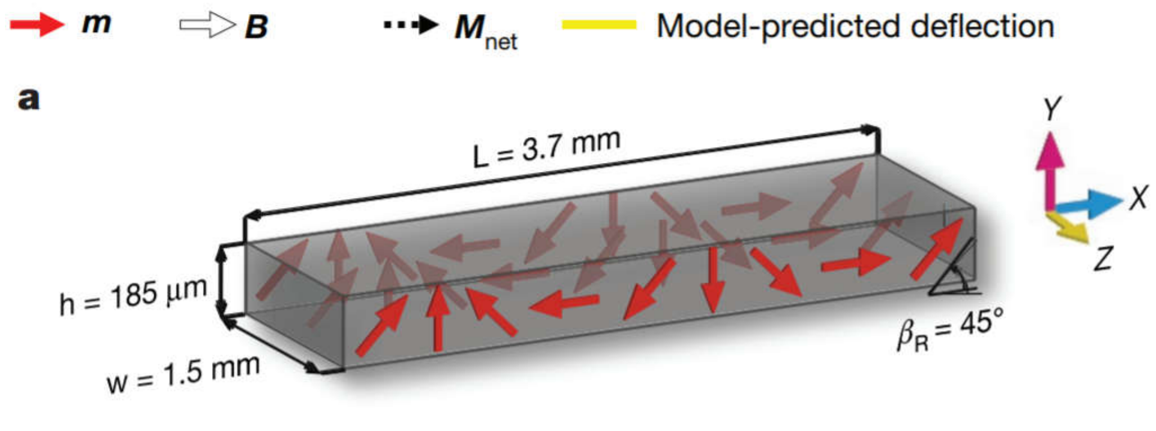


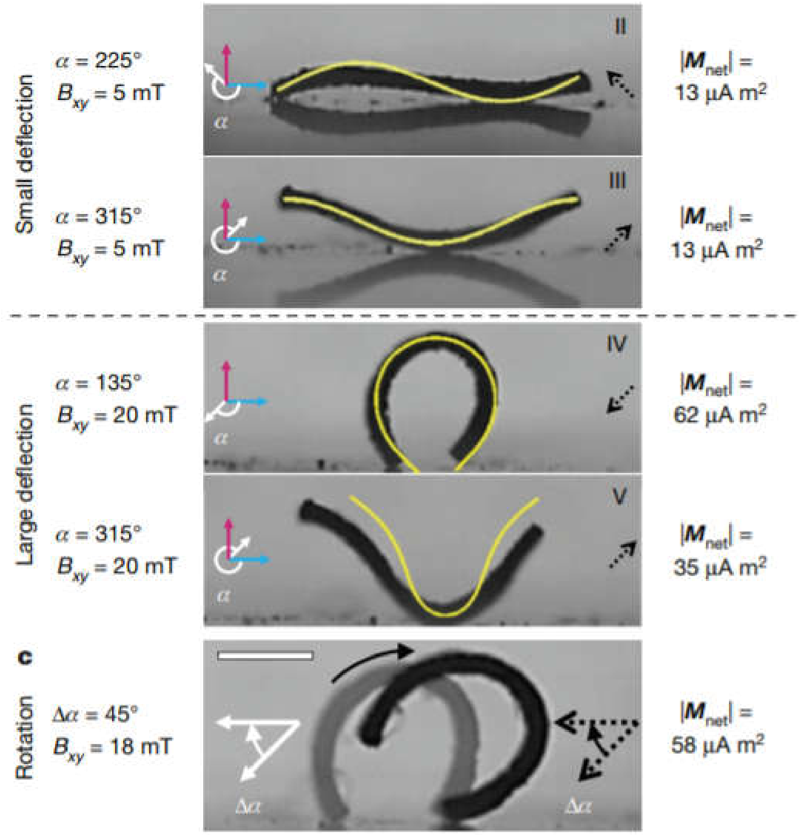
https://wonderfulengineering.com/these-15-magnet-gifs-will-show-you-the-power-of-magnetism/

Mini Magnetic Robot

Small-scale soft-bodied robot with multimodal locomotion

Wenqi Hu[1]*, Guo Zhan Lum[1]*, Massimo Mastrangeli[1] & Metin Sitti[1]



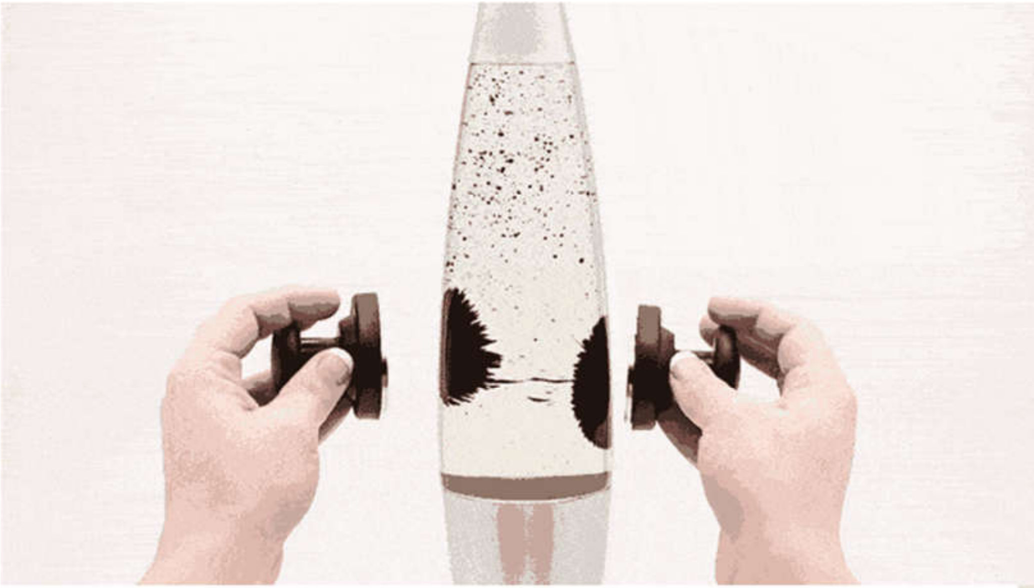


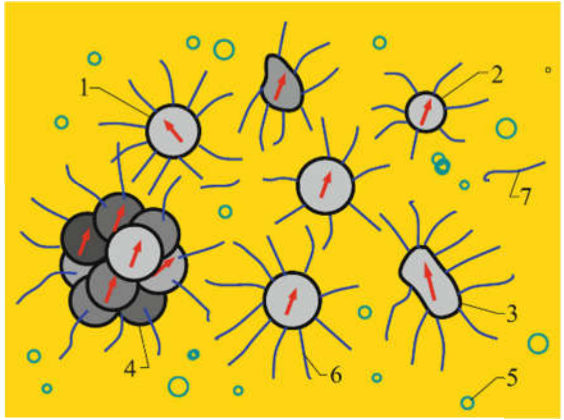
Video

W. Hu, et. al., *Nature* **554**, 81 (2018)

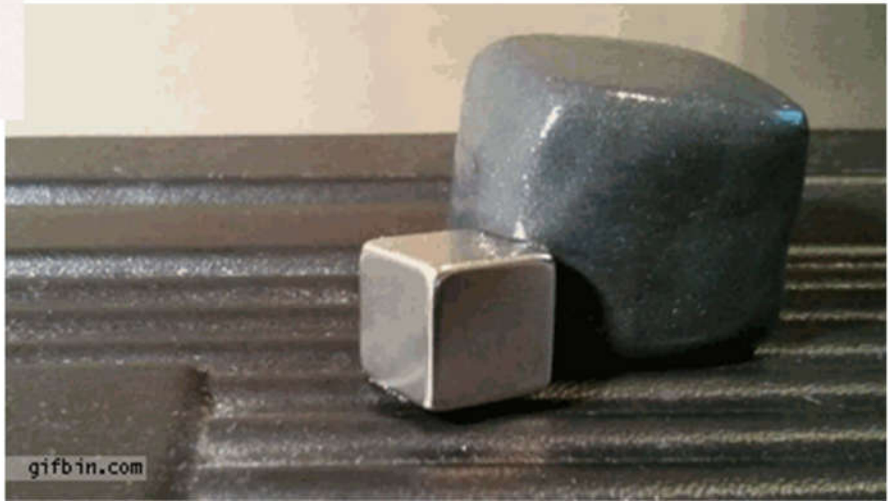
Ferrofluid 铁磁流体

- A liquid with ferromagnetic particles





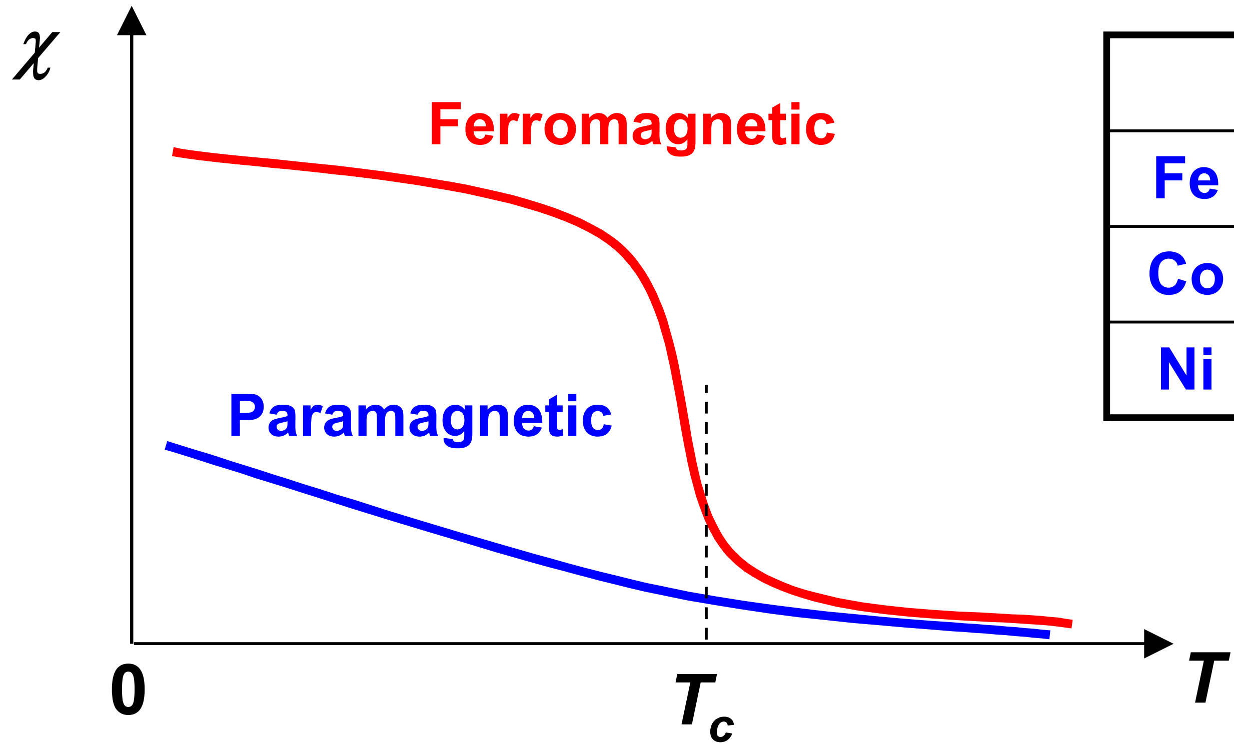
https://link.springer.com/chapter/10.1007/978-3-319-94427-2_1



https://wonderfulengineering.com/these-15-magnet-gifs-will-show-you-the-power-of-magnetism/

Temperature Effect

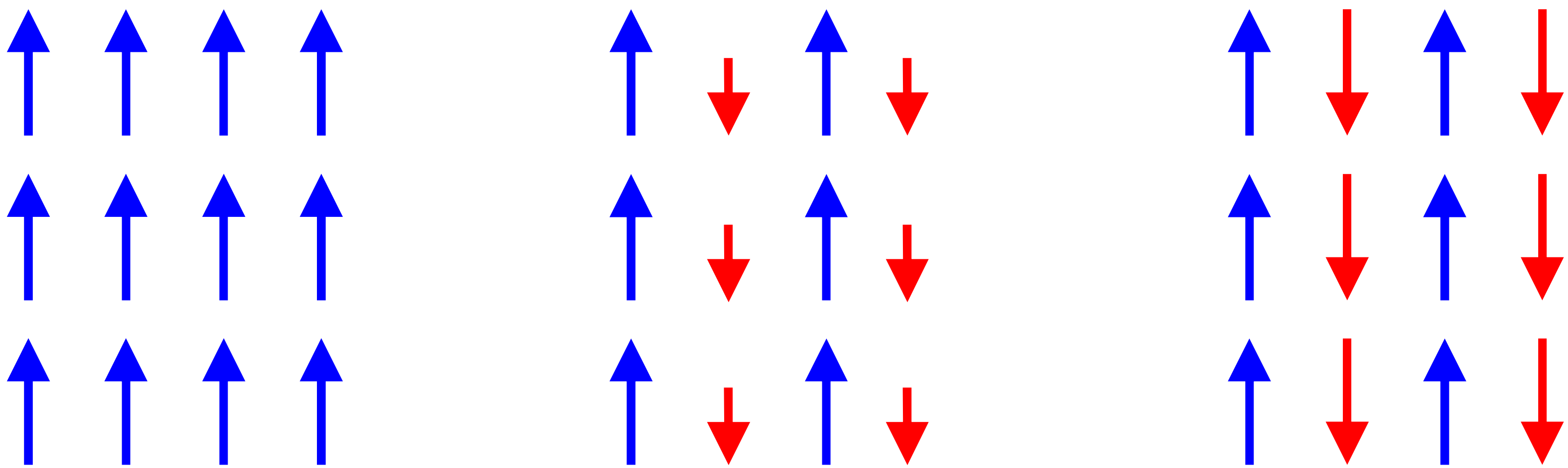
- Magnetization decreases with temperature, because of increased thermal fluctuation
- Ferromagnet becomes paramagnet when $T > T_c$
- T_c - Curie Temperature 居里温度



	T_c (°C)
Fe	770
Co	1110
Ni	350

Antiferromagnetism and Ferrimagnetism

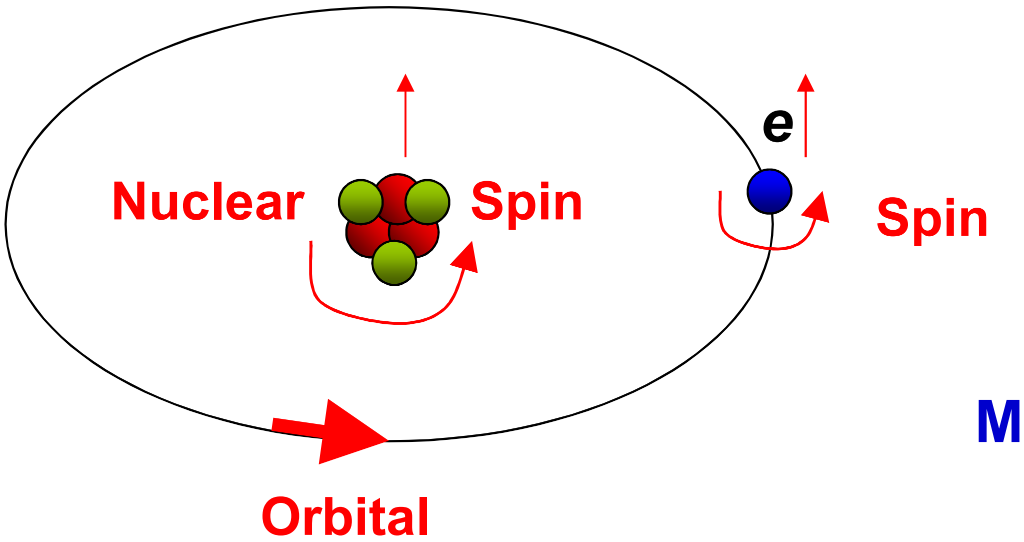
- **Ferri**magnetism 亚铁磁性
- **Antiferro**magnetism 反铁磁性



Ferromagnetic	Ferrimagnetic	Antiferromagnetic
$\chi_1 >> 0$	$\chi_2 < \chi_1$	$\chi_3 << \chi_1$

Magnetic Properties of Nuclei

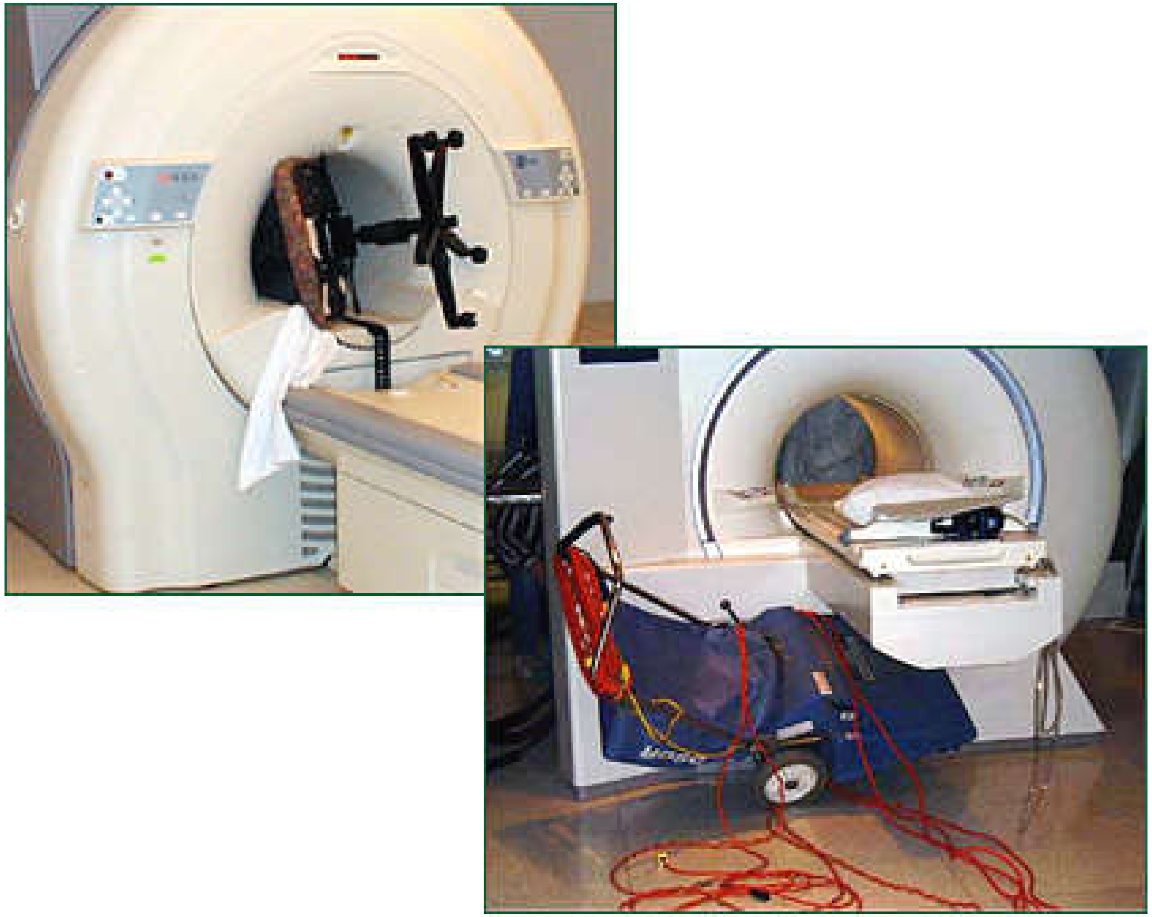
- Protons (质子) and Neutrons (中子) in the nuclei also have spins that generate magnetic moments
- Nuclei with odd numbers of protons and neutrons have a net magnetic moment
- χ is much smaller (< 1/1000) than those of electrons

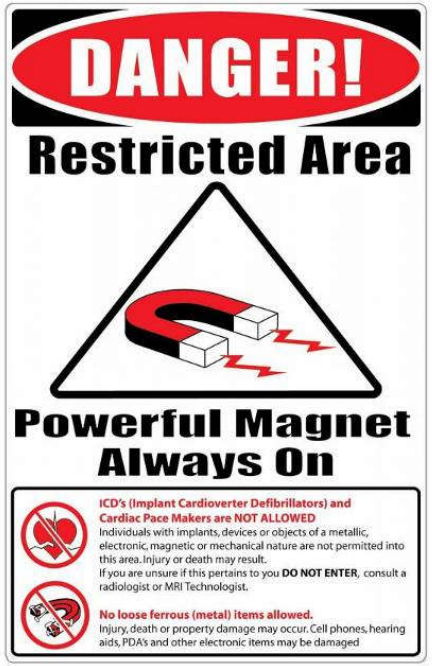


Magnetic Resonance Imaging (MRI)
核磁共振成像
detect ^1H atoms

Be cautious when doing MRI

- **Very strong magnetic field**





Summary

- **Maxwell's Equations**
  - ***H*, *B*, *M*, μ_r**
  - **Magnetic Susceptibility 磁化率 χ**
- **Origin of magnetism**
  - **spin of electrons, orbital angular momentum, external field**
  - **nuclear magnetic momentum**
- **Types of magnetism**
  - **Diamagnetism 抗磁性**
  - **Paramagnetism 顺磁性**
  - **Ferromagnetism 铁磁性**
  - **Antiferromagnetism 反铁磁性**
  - **Ferrimagnetism 亚铁磁性**

Thank you for your attention