PROGRESSIVE EDUCATION SOCIETY'S
MODERN COLLEGE OF ENGINEERING, PUNE
(An Autonomous Institute Affiliated to Savitribai Phule Pune University)

Department of First Year B.Tech.

Unit – 5: Magnetism, Superconductors and Nanomaterials

Importance of Magnetism, Superconductors and Nanomaterials in Engineering

Magnetism, superconductors, and nanomaterials are at the heart of modern engineering, driving innovation and shaping future technologies. Magnetism underpins critical applications such as electric motors, generators, magnetic levitation (maglev) trains, and data storage systems like hard drives. Medical imaging techniques, such as MRI, rely heavily on magnetic principles to provide non-invasive diagnostic tools.

Superconductors, which conduct electricity with zero resistance at low temperatures, have enabled groundbreaking technologies like highly efficient power grids, particle accelerators (e.g., the Large Hadron Collider), and maglev trains that offer faster, frictionless transportation. In the future, high-temperature superconductors could revolutionize energy storage, quantum computing, and ultra-sensitive sensors.

Nanomaterials, with their extraordinary properties at the nanoscale, have found applications in a wide range of fields. For instance, carbon nanotubes and graphene are transforming electronics with faster, smaller, and more energy-efficient devices. Nanoparticles are revolutionizing medicine through targeted drug delivery, while nanostructured catalysts enhance the efficiency of chemical reactions in industries and environmental solutions like water purification. Future trends include the integration of magnetic materials in spintronics for next-generation data storage, superconducting materials in quantum computing, and nanomaterials in energy harvesting and biomedical applications. Together, these technologies promise a future of sustainable and highly efficient engineering solutions across aerospace, healthcare, energy, construction, and beyond.

Subtopics in Unit – 5

Magnetism, Superconductors & Nanomaterials	**5.1. Introduction to magnetism** *5.1.1. Types of magnetism* *5.1.2. Magnetic properties of materials* *5.1.3. Magnetic domains and hysteresis* *5.1.4. Applications of magnetism* **5.2. Introduction to superconductivity** *5.2.1. Explanation of superconductivity with resistivity vs. temperature graph* *5.2.2. Characteristics of superconductors* **5.3. History of superconductivity** **5.4. Meissner Effect** **5.5. Types of superconductors** *5.5.1. Type I* *5.5.2. Type II* **5.6. Applications of superconductivity** **5.7. Introduction to nanomaterials** *5.7.1. Classifications of nanomaterials* **5.8. Quantum confinement** *5.8.1. Types of quantum confinement* **5.9. Surface-to-volume ratio** **5.10. Comparison between bulk and nanomaterials** **5.11. Optical properties of nanomaterials** **5.12. Magnetic properties of nanomaterials** **5.13. Applications of nanomaterials**

Magnetism

5.1. Introduction to Magnetism

Magnetism is a fundamental property of matter that arises from the motion of electric charges and the intrinsic magnetic moments of elementary particles. It plays a vital role in many areas of science and technology, influencing how materials interact with magnetic fields. It is the phenomenon by which materials exert attractive or repulsive forces on other materials due to their magnetic properties.

Sources of Magnetism:

1. **Orbital Motion of Electrons:** Electrons moving around the nucleus create tiny current loops, which generate magnetic fields.
2. **Intrinsic Magnetic Moment of Electrons (Spin):** Electrons behave like tiny magnets due to their spin, a quantum property.
3. **Nuclear Magnetic Moments:** Protons and neutrons also have magnetic moments, but their contribution is much weaker than that of electrons.

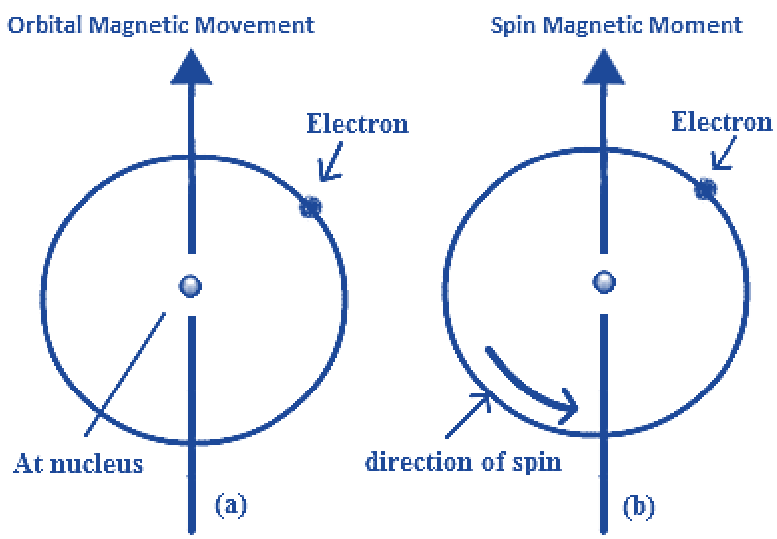


Figure 5.1. Orbital motion of electrons and their spin rotation.[1]

5.1.1 Types of Magnetism

a. Diamagnetic Materials

- **Properties:**
  - Weakly repel external magnetic fields.
  - Magnetic susceptibility (χ) is negative.
  - Examples: Copper, gold, bismuth.
- **Mechanism:**

  Diamagnetism arises from the induced current loops in atoms opposing the external magnetic field.

b. Paramagnetic Materials

- **Properties:**
  - Weakly attracted to external magnetic fields.
  - Magnetic susceptibility (χ) is small and positive.
  - Examples: Aluminum, platinum, and oxygen.
- **Mechanism:**

  Paramagnetism arises from the alignment of unpaired electron spins with the external magnetic field.

c. Ferromagnetic Materials

- **Properties:**
  - Strongly attracted to external magnetic fields.
  - Retain magnetization even after the field is removed (hysteresis).
  - Examples: Iron, cobalt, nickel.
- **Mechanism:**

  Ferromagnetism is due to the alignment of magnetic domains—regions with uniformly aligned magnetic moments.

d. Antiferromagnetic Materials

- **Properties:**
  - Magnetic moments of atoms or ions align in opposite directions, canceling each other out.
  - No net magnetization.
  - Examples: Manganese oxide (MnO).
- **Mechanism:**

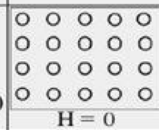
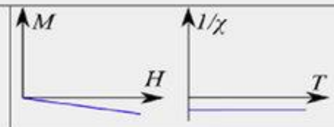
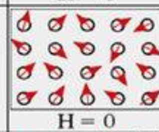
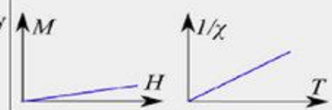
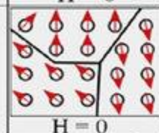
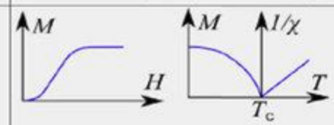
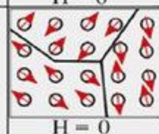
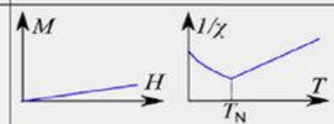
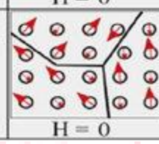
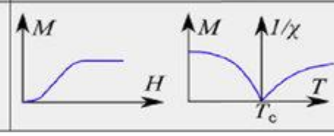
  Antiferromagnetism arises from quantum mechanical exchange interactions between adjacent atoms.

e. Ferrimagnetic Materials

- **Properties:**
  - Magnetic moments of atoms align in opposite directions but do not cancel completely, resulting in net magnetization.
  - Examples: Magnetite (Fe_3O_4), ferrites.
- **Mechanism:**

  Ferrimagnetism occurs due to unequal opposing magnetic moments in a material.

Table 5.1. Types of magnetism.[2]

Magnetism	Examples	Magnetic behaviour
Diamagnetism	Bi, Si, Cu, inert gases Susceptibility small and negative (-10^{-6} to -10^{-5})	 Atoms have no magnetic moments. 
Paramagnetism	Al, O_2, MnBi Susceptibilty small and positive (10^{-5} to 10^{-3})	 Atoms have randomly oriented magnetic moments. 
Ferromagnetism	Fe, Ni, Co, Gd Susceptibility large (generally > 100)	 Atoms are organized in domains which have parallel aligned magnetic moments. 
Antiferromagnetism	Cr, MnO, FeO Susceptibilty small and positive (10^{-5} to 10^{-3})	 Atoms are organized in domains which have antiparallel aligned moments. 
Ferrimagnetism	Fe_3O_4, $MnFe_2O_4$, $NiFe_2O_4$ Susceptibility large (generally > 100)	 Atoms are organized in domains which have a mixture of unequal antiparallel aligned moments. 

5.1.2 Magnetic Properties of Materials

a. Magnetic Susceptibility (χ)

- A measure of how a material responds to an applied magnetic field. It is a fundamental property that quantifies how much a material becomes magnetized in response to an applied magnetic field. It differs for various types of magnetism and reflects the magnetic behavior of materials. Here is an overview of magnetic susceptibility for the main types of magnetism:
- Defined as: $\chi = M/H$ where M is magnetization and H is the applied magnetic field.

Diamagnetism

- **Description**: Diamagnetic materials create a weak magnetic field in opposition to an applied magnetic field, resulting from the realignment of electron orbital motion.
- **Susceptibility**:
  - Small and **negative** ($\chi<0$).

  - Typical range: -10^{-6}-10^{-5}.
- **Example Materials**: Bismuth, copper, graphite, water.
- **Key Features**:
  - Independent of temperature.
  - Present in all materials but is often overshadowed by other types of magnetism if they exist.

Paramagnetism

- **Description**: Paramagnetic materials have unpaired electrons, causing magnetic moments to align partially with an external magnetic field.
- **Susceptibility**:
  - Small and **positive** ($\chi>0$).
  - Typical range: 10^{-6}-10^{-3}.
  - Follows **Curie's Law**: $\chi=C/T$, where C is the Curie constant and T is the absolute temperature.
- **Example Materials**: Aluminum, platinum, some transition metal salts.
- **Key Features**:
  - Increases at lower temperatures.
  - No permanent magnetization without an applied field.

Ferromagnetism

- **Description**: Ferromagnetic materials have strong interactions between magnetic moments, leading to spontaneous alignment even without an external field.
- **Susceptibility**:
  - Very large and **positive** ($\chi\gg1$).
  - Below the **Curie temperature** (T_c), magnetic susceptibility is temperature-dependent but non-linear.
  - Above T_c, follows the **Curie-Weiss Law**: $\chi=C/(T-T_c)$
- **Example Materials**: Iron, cobalt, nickel.
- **Key Features**:

- High magnetization even without a field.
- Strong temperature dependence near T_c.

Antiferromagnetism

- **Description**: In antiferromagnetic materials, magnetic moments of adjacent atoms align antiparallel, canceling each other.
- **Susceptibility**:
  - Small and **positive** ($\chi>0$).
  - Peaks at the **Néel temperature** (T_N) and decreases both above and below T_N.
- **Example Materials**: Manganese oxide (MnO), hematite (Fe_2O_3).
- **Key Features**:
  - Weak net magnetization.
  - Transition to paramagnetism above T_N.

Superparamagnetism

- **Description**: Found in nanoscale particles of ferromagnetic or ferrimagnetic materials, where thermal energy causes randomization of magnetic moments.
- **Susceptibility**:
  - Large and **positive** ($\chi\gg1$).
  - Follows Curie-like behavior at low temperatures: $\chi=C/T$.
- **Example Materials**: Magnetic nanoparticles like Fe_3O_4 at nanoscale.
- **Key Features**:
  - No hysteresis; magnetization aligns instantly with the field.

b. Magnetic Permeability (μ)

- Indicates how easily a material can support the formation of a magnetic field.
- Defined as: $\mu=\mu_0(1+\chi)$, where μ_0 is the permeability of free space.

c. Magnetization (M)

- The magnetic moment per unit volume of a material.

- Defined as: M=Magnetic moment/Volume

5.1.3. Magnetic Domains and Hysteresis

a. Magnetic Domains:

- Magnetic materials are composed of regions called domains, where magnetic moments are aligned.
- In an unmagnetized material, the domains are randomly oriented, canceling the overall magnetization.
- When an external field is applied, domains align, resulting in magnetization.

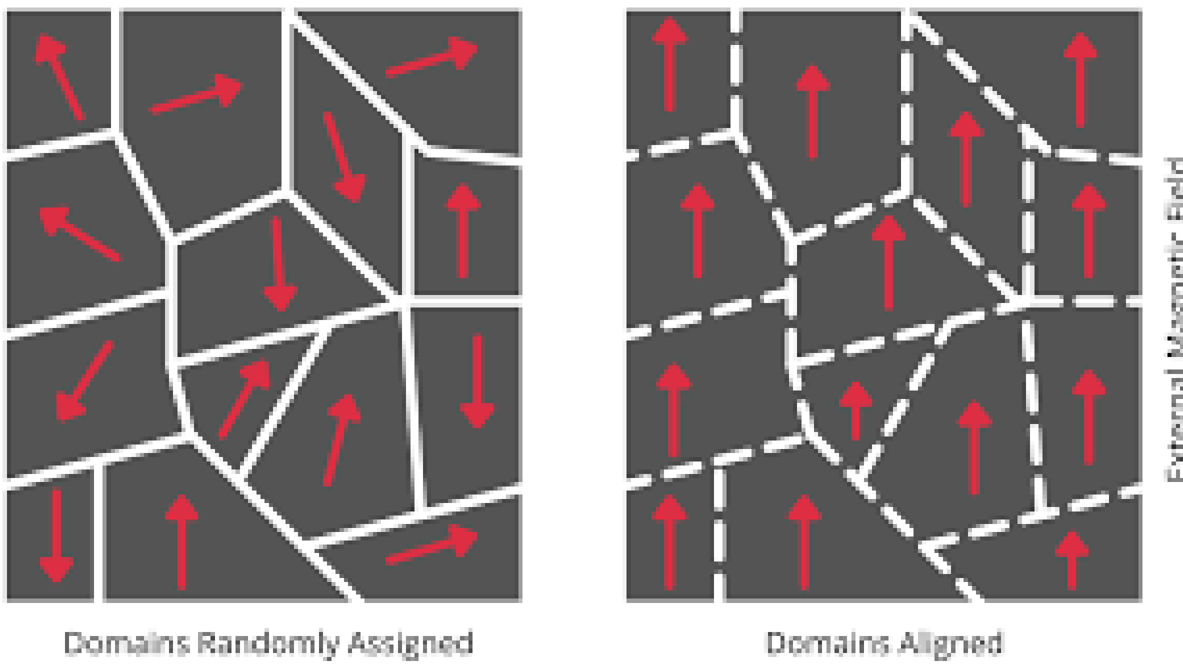


Figure 5.2. Magnetic domains of a ferromagnetic material line up when exposed to an external magnetic field.[3]

b. Hysteresis:

- Hysteresis refers to the lag between the magnetization of a material and the applied magnetic field.
- **Hysteresis Loop:**
    - A graph plotting magnetization (M) versus the applied field (H).

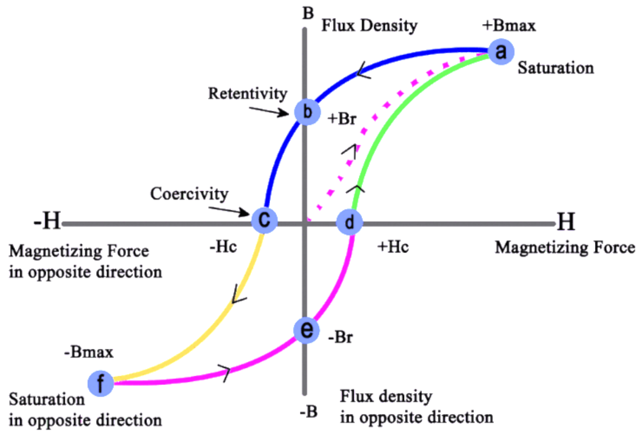


Figure 5.3. Hysteresis loop diagram.[4]

- Key Points on the Loop:
    1. **Remanence (M_r):** Residual magnetization when the field is reduced to zero.
    2. **Coercivity (H_c):** The reverse field needed to demagnetize the material.
    3. **Saturation Magnetization (M_s):** Maximum magnetization achieved in a strong field.

5.1.4. Applications of Magnetism

a. Data Storage:

- Magnetic materials are used in hard drives, tapes, and other storage devices.
- Data is stored as patterns of magnetized regions.

b. Electric Motors and Generators:

- Permanent magnets and electromagnets are critical in converting electrical energy to mechanical energy and vice versa.

c. Transformers and Inductors:

- Soft magnetic materials are used to guide and enhance magnetic fields in transformers and inductors, improving efficiency.

d. Magnetic Levitation (Maglev):

- Magnetic forces are used to levitate and propel trains, reducing friction and allowing high speeds.

e. Magnetic Resonance Imaging (MRI):

- MRI uses strong magnetic fields to produce detailed images of internal body structures.

f. Sensors and Actuators:

- Magnetic sensors detect changes in magnetic fields, used in compasses, position sensing, and robotics.

Superconductors

5.2. Introduction to Superconductivity

Superconductivity is a quantum mechanical phenomenon where certain materials exhibit **zero electrical resistance** and **complete expulsion of magnetic fields (Meissner effect)** below a characteristic temperature known as the **critical temperature (T_c)**.

Discovery of Superconductivity:

- Discovered by **Heike Kamerlingh Onnes** in 1911.
- Mercury was found to have **zero resistance** when cooled below 4.2 K.

5.2.1. Explanation of Superconductivity with Resistivity vs. Temperature Graph

The behavior of a superconductor is best explained through a **resistivity vs. temperature (**ρ-T**) graph**. The temperature dependence of a superconductor's resistance is illustrated in the figure 5.4.

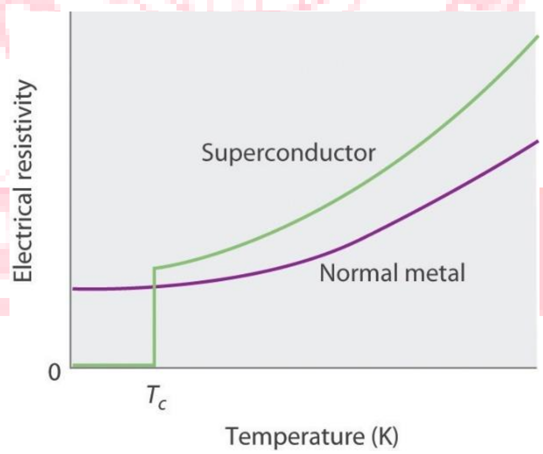


Figure 5.4. Electrical resistivity vs. temperature.[5]

As the temperature decreases, the resistance gradually reduces until, at the critical temperature, it suddenly becomes zero. At this point, the material achieves 100% conductivity.

Stages in the Graph

1. **Normal State (Above** Tc**)**: Resistivity decreases with decreasing temperature, as in a typical conductor.
2. **Transition to Superconducting State (At** Tc**)**: Resistivity drops sharply to **zero** over a narrow temperature range.
3. **Superconducting State (Below** Tc**)**: The material exhibits zero resistivity, enabling current to flow indefinitely without energy loss.

The critical temperature varies among different superconducting materials. For example:

- Mercury (Hg): 4.16 K
- Tin (Sn): 3.72 K
- Niobium Nitride (NbN): 16 K
- Indium (In): 3.4 K
- Lead (Pb): 7.2 K

5.2.2 Characteristics of Superconductors

1. Zero Electrical Resistance

- Definition: Below T_c, superconductors exhibit zero electrical resistance, meaning no energy is dissipated as heat.
- **Applications:**
  - Lossless energy transmission.
  - High-efficiency magnets in particle accelerators.

2. Persistent Current

- Definition: A current in a superconducting loop can flow indefinitely without decay.

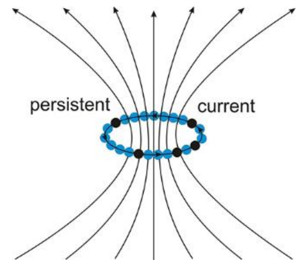


Figure 5.5. Persistent currents in superconductors.[5]

- Why?
  - Since there is no resistance, energy is conserved.
- Applications:
  - Persistent currents are used in highly sensitive magnetic field detectors like SQUIDs.

3. Critical Magnetic Field (H_c)

- Definition: Superconductivity is destroyed by sufficiently strong magnetic fields. The minimum value of the applied magnetic field required to destroy superconductivity is called the critical magnetic field (H_c) and is a function of temperature.
- Behavior:
  - Below H_c: The material is superconducting.
  - Above B_c: The material transitions to a normal conductive state ($H_c = 0$).
- Temperature Dependence:
  - H_c decreases as the temperature approaches T_c.

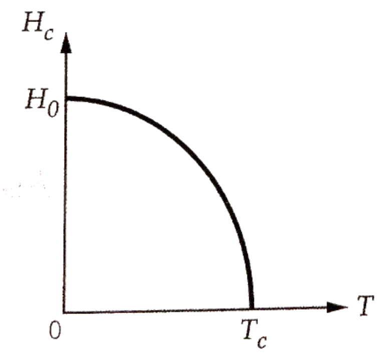


Figure 5.6. Temperature dependence of critical magnetic field.[6]

H_c can be represented as:

$$H_C = H_O\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

Where, H_o is the critical field at absolute zero.

therefore, there are two main characteristics of superconductors— perfect conductivity and perfect diamagnetism.

Numericals: Example and Practice Problems: Critical Magnetic Field

Worked-out Problem:

Example: Superconducting tin (Sn) has a critical temperature of 3.7 K at zero magnetic field and a critical field of 0.0306 T at 0 K. Find the critical field at 2 K.

Sol: To determine the critical magnetic field (H_C) of a superconductor at a given temperature, we use the following relationship derived from the empirical behavior of superconductors:

$$H_C = H_O\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

Where:

- H_C: Critical field at temperature T.
- H_0: Critical field at absolute zero (T=0).

- T: Temperature at which we want to find the critical field.
- T_c: Critical temperature at zero magnetic field.

Given Data

- T_c=3.7 K
- H_0=0.0306 T
- T=2 K

Calculation

Substituting the given values into the formula:

$$H_C = 0.0306\left[1 - \left(\frac{2}{3.7}\right)^2\right]$$

$$\text{Hence, } H_C = 0.0217\ T$$

Final Answer

The critical field at 2 K is approximately: 0.0217 T.

Problems:

5.1. Calculate the critical current for a wire of lead having a diameter of 1 mm at 4.2 K. Critical temperature of lead is 7.18 K and H_C at 0 K is 6.5×10^4 A/m. (Ans: I_C=134.33 A)

5.2. The critical temperature for lead is 7.2 K. However, at 5 K it loses its superconductivity when subjected to a magnetic field of 3.3 ×10^4 A/m. Find the maximum value of critical magnetic field which will allow the metal to retain its superconductivity at 0 K. (Ans: H_0= 6.37 ×10^4 A/m).

5.3. Superconducting lead (Pb) has a critical temperature of 7.2 K at zero magnetic field and a critical field of 0.0803 T at 0 K. Find the critical field at 5 K. (Ans: $H_C = 0.0416\ T$)

5.4. Calculate the critical current for a wire of tin (Sn) having a diameter of 0.5 mm at 2.5 K. The critical temperature of tin is 3.7 K, and the critical field at 0 K is 4.8×10^4 A/m. (Ans: I_C= 40.99 A)

5.3. History of Superconductivity

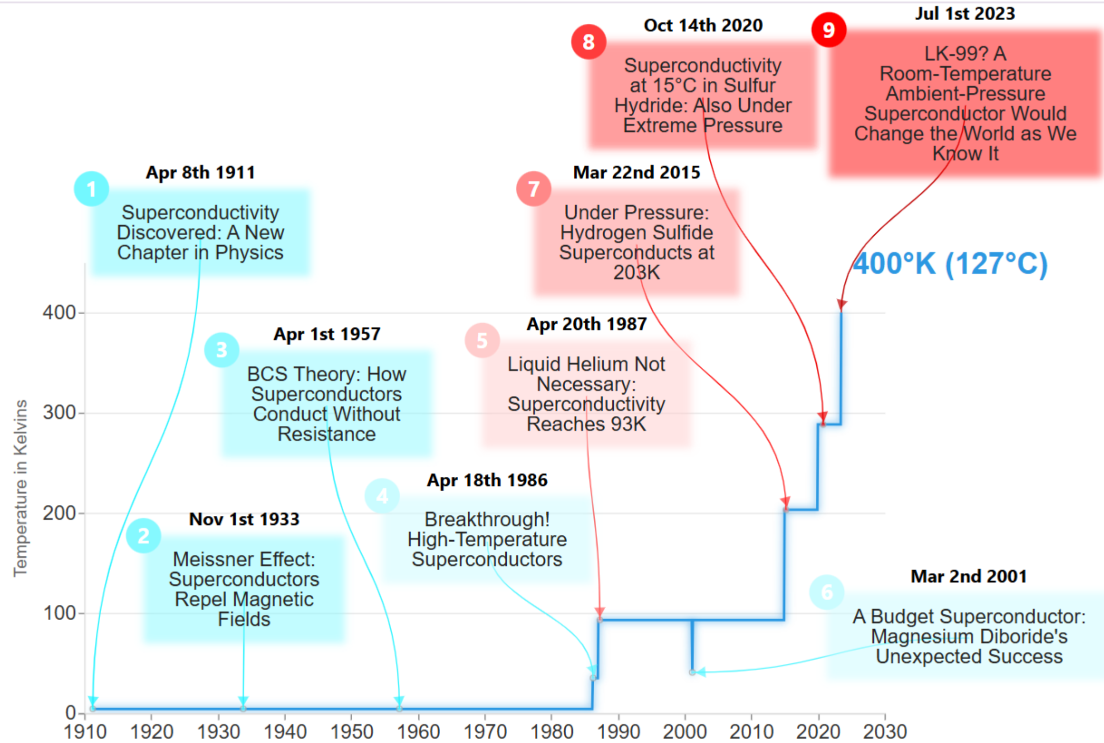


Figure 5.7. A history of superconductivity.[7]

Superconductivity Discovered: A New Chapter in Physics

On **8 April 1911**, Kamerlingh Onnes found that at 4.2 K the resistance in a solid mercury wire immersed in liquid helium suddenly vanished. He immediately realized the significance of the discovery: electricity could flow through it perfectly, without any loss of energy.

He reported that "Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state". He published more articles about the phenomenon, initially referring to it as "supraconductivity" and, only later adopting the term "superconductivity".

He won the Nobel Prize in Physics two years later, in 1913.

Meissner Effect: Superconductors Repel Magnetic Fields

Discovered by **Walther Meissner and Robert Ochsenfeld**, the Meissner Effect shows that when superconducting materials are cooled below a critical temperature, not only they conduct electricity without resistance but also exhibit 'diamagnetism,' repelling magnetic fields. This stands in contrast to 'ferromagnetism', where materials are attracted to magnetic fields. Like a commercial magnet.

In the case of the Meissner Effect, the superconductor pushes out the magnetic field from its interior, acting like a perfect shield against magnetism.

This discovery was fundamental in understanding superconductivity, showing that it involves more than just perfect electrical conduction; it also involves a special interaction with magnetic fields.

BCS Theory: How Superconductors Conduct Without Resistance

John Bardeen, Leon Cooper, and John Robert Schrieffer described how electrons in a superconductor form pairs, known as **Cooper pairs**, that move together through the lattice structure of the material without scattering off impurities or lattice vibrations. This pairing mechanism leads to a state where electrical resistance becomes exactly zero below a critical temperature.

The BCS Theory was groundbreaking in its ability to explain the previously mysterious phenomenon of superconductivity and remains a cornerstone of quantum many-body theory.

It earned the trio the Nobel Prize in Physics in 1972.

Breakthrough! High-Temperature Superconductors

A landmark discovery made by J. Georg Bednorz and K. Alex Müller, who identified a new class of ceramic materials that exhibited superconductivity at temperatures as high as **35 Kelvin (K).**

This was a significant advancement from previously known superconductors, which required much colder temperatures to operate. Their discovery of high-temperature superconductivity in lanthanum-based copper oxide (La_2CuO_4) initiated an intense wave of research into similar materials.

The breakthrough opened new possibilities for applications of superconductivity and earned Bednorz and Müller the Nobel Prize in Physics the following year, in 1987.

Liquid Helium Not Necessary: Superconductivity Reaches 93K

The discovery of superconductivity at 93 Kelvin in a **yttrium barium copper oxide** compound by physicists Paul Chu, Maw-Kuen Wu, and colleagues represented a major milestone.

This temperature was above the boiling point of liquid nitrogen (77 K), a coolant that is both inexpensive and widely available. As a result, the costs and complexities associated with cooling superconductors were significantly reduced.

This made high-temperature superconductors more practical for applications such as medical imaging (MRI), power transmission, transportation (including maglev trains), and scientific research instruments, driving further innovation and development in these fields.

A Budget Superconductor: Magnesium Diboride's Unexpected Success

In 2001 a research group led by Jun Akimitsu discovered that magnesium diboride exhibited superconducting properties at 39 Kelvin. This was notable because magnesium diboride is a simple and inexpensive compound, unlike many other high-temperature superconductors that require complex structures and costly materials.

The relatively high critical temperature of 39 K, combined with the ease of production, made magnesium diboride an attractive candidate for various industrial applications, such as in the manufacturing of superconducting cables and magnets.

The discovery pushed forward further research into simple compounds as potential superconductors.

Under Pressure: Hydrogen Sulfide Superconducts at 203 K

In 2015 hydrogen sulfide was discovered to superconduct at 203 Kelvin (K) under high pressures of around 150 gigapascals. For reference, diamonds are formed at pressures between 5 and 15 gigapascals!

This temperature set a new record for high-temperature superconductivity, significantly exceeding previous limits.

Researchers, including Mikhail Eremets and his team, achieved this by compressing the hydrogen, possibly forming a metallic phase of hydrogen sulfide.

The discovery of superconductivity in such a simple compound at relatively high temperatures provided important insights into the nature of superconductors and led to further investigation into hydrogen-rich materials.

Superconductivity at 15 °C in Sulfur Hydride: Also Under Extreme Pressure

In 2020, a team led by Dr. Ranga Dias and Dr. Ashkan Salamat achieved a significant milestone in superconductivity by creating a sulfur hydride compound that superconducted at 15 °C (59 °F), or 288 Kelvin (K). This temperature marked the highest ever recorded for superconductivity and was a substantial step toward room-temperature superconductivity.

The discovery was made under extreme pressures of around 267 gigapascals, utilizing a hydrogen sulfide compound doped with carbon. The researchers' work opened new possibilities for understanding unconventional superconductors and brought attention to the potential of hydrogen-based materials for high-temperature superconductivity.

LK-99? A Room-Temperature Ambient-Pressure Superconductor Would Change the World as We Know It

The excitement over LK-99, a purported room-temperature, ambient-pressure superconductor discovered by South Korean physicists, has stirred both enthusiasm and skepticism within the scientific community.

This breakthrough could herald a new era of technological advancements, including more efficient electricity transmission, faster-charging batteries, practical nuclear fusion energy, and scalable quantum computing. If real, a room-temperature superconductor would be a transformative innovation on par with the 1947 invention of the transistor.

However, mixed results in attempts to replicate the discovery have created an atmosphere of uncertainty. The implications of a room-temperature superconductor are immense, but as of today, the reality of LK-99 remains a tantalizing question mark.

5.4. Meissner Effect

The **Meissner effect** is a unique property of superconductors (Figure 5.2). The magnetic flux originally present in the specimen is ejected from the specimen when placed in the weak magnetic field and cooled below a critical temperature (T_c). This behavior differentiates superconductors from ordinary conductors, where magnetic fields can exist inside.

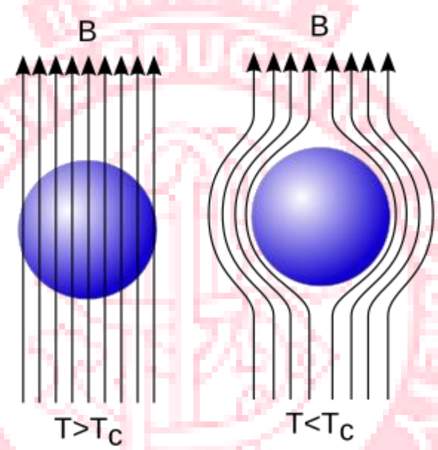


Figure 5.8. Diagram of the Meissner effect. Magnetic field lines, represented as arrows, are excluded from a superconductor when it is below critical temperature.[8]

1. **Above Critical Temperature ($T>T_c$):** The material behaves as a normal conductor, and magnetic fields can penetrate it freely.

2. **Below Critical Temperature ($T<T_c$):** The material transitions into a superconducting state, and magnetic fields are expelled from its interior. This happens regardless of whether the field was present before cooling.

3. **Perfect Diamagnetism:** The superconductor generates surface currents that oppose and cancel the external magnetic field inside the material, resulting in B=0 within the superconductor.

Mechanism of Meissner Effect:

- When a material transitions into a superconducting state, its electrons form "Cooper pairs", which behave as a single quantum entity.
- These pairs produce persistent currents at the surface of the material.
- The currents create a magnetic field that exactly cancels the external field inside the superconductor, leading to the expulsion of the field.

Mathematical Representation:

The relationship between magnetic induction (B), external field (H), and magnetization (M) is given by:

$$B=\mu_0(H+M)$$

For a perfect diamagnet (superconductor in the Meissner state or when the temperature T of the specimen is lowered below its critical temperature T_c):

$$B=0$$

$$\Rightarrow \mu_0(H+M) = 0$$

$$\Rightarrow M = -H$$

This shows that the superconductor generates a magnetization that exactly opposes the applied field.

Susceptibility (χ) is given by:

$$\chi = M/H$$

$$\Rightarrow \chi = -1$$

As the relative permeability, $\mu_r = 1+ \chi$

$$\Rightarrow \mu_r = 0$$

This indicated perfect diamagnetism.

Meissner effect cannot be explained by assuming that the superconductor is a perfect conductor with zero electrical conductivity. The electric field is given by:

$$E = \frac{V}{l} = \frac{IR}{l} = \frac{IR}{l} \times \frac{A}{A}$$

$$= \frac{RA}{l} \times \frac{I}{A}$$

$$\therefore E = \rho J$$

Where, $\rho = resistivity, J = current\ density$

If ρ becomes zero for a finite current density J, then E=0.

From Maxwell's equations,

$$\nabla \times \vec{E} = \frac{-d\vec{B}}{dt}$$

As, E=0, $\frac{-d\vec{B}}{dt} = 0$

Hence, $\vec{B} = 0$

In a regular conductor, the magnetic flux remains unchanged when it is cooled below the critical temperature. This behavior contradicts the Meissner effect, which states that the magnetic flux inside a superconductor must be expelled and reduced to zero. This shows that a superconductor is not simply a perfect conductor; it has unique properties. Because of the Meissner effect, superconductors strongly repel external magnetic fields, enabling fascinating phenomena like magnetic levitation.

5.5. Types of Superconductors

Superconductors are classified based on their behavior in the presence of magnetic fields.

5.5.1. Type I Superconductors (Soft Superconductors)

- **Definition:** Superconductors that exhibit a complete Meissner effect and have a single critical magnetic field (H_c). These are superconductors that completely expel magnetic fields (perfect diamagnetism) when cooled below their T_c and exhibit a sharp transition to the superconducting state.

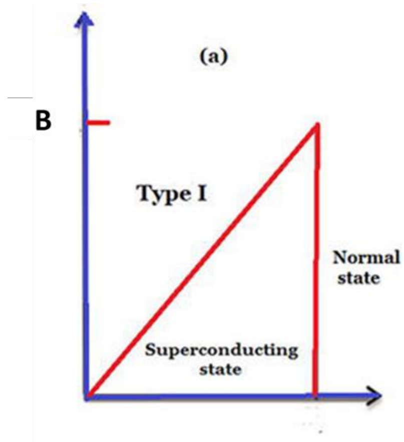


Figure 5.9. Type- I superconductor.[9]

- **Properties**:

a) Critical Magnetic Field (H_c):

- Type 1 superconductors exhibit a single critical magnetic field, H_c.
- If the applied magnetic field exceeds H_c, the material abruptly transitions to the normal (non-superconducting) state.

b) Meissner Effect:

- Perfectly expel magnetic fields from their interior below T_c, demonstrating complete diamagnetism.

c) Sharp Transition:

- The transition from the superconducting state to the normal state is abrupt with respect to temperature or magnetic field changes.

d) Coherence Length:

- The coherence length (ξ) is relatively large, typically on the order of tens to hundreds of nanometers.

e) Soft Superconductors:

- Due to their sensitivity to magnetic fields, they are often called "soft" superconductors.

- **Applications**:
    - Limited practical use due to their low critical temperatures and sensitivity to magnetic fields.
    - Mostly used in scientific research to understand fundamental superconducting phenomena.
- **Examples**:
    - Lead (Pb), Mercury (Hg), Tin (Sn), alloys.

5.5.2. Type II Superconductors (Hard Superconductors)

- **Definition:** Superconductors that allow partial penetration of magnetic fields between two critical field values (H_{c1} and H_{c2}).

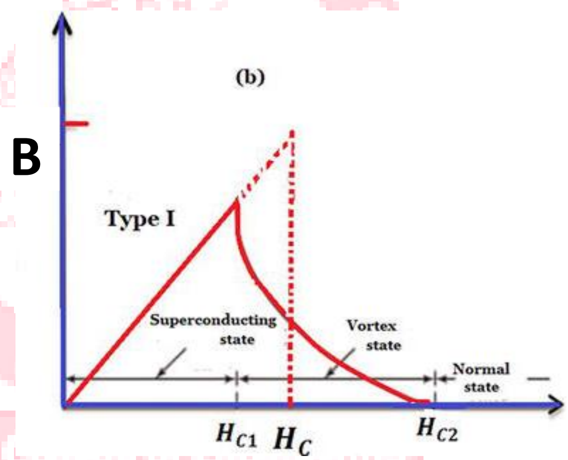


Figure 5.10. Type- II superconductor.[5]

- **Characteristics:**
    1. Exhibit a "mixed state" where magnetic flux penetrates as quantized lines (vortices).
    2. Found in alloys and compounds like niobium-titanium (NbTi) and niobium-tin (Nb_3Sn).
    3. Operate under higher magnetic fields and temperatures compared to Type I.

- **Critical Field Behavior:**
  - $H<H_{c1}$: Perfect diamagnetism (Meissner effect).
  - $H_{c1}<H<H_{c2}$: Mixed state with magnetic flux lines penetrating.
  - $H>H_{c2}$: Material becomes normal.
- **Applications:**

  Widely used in high-field applications such as MRI, particle accelerators, and Maglev trains.

Table 5.2. Comparison of Type I and Type II Superconductors

Property	Type I Superconductors	Type II Superconductors
Behavior in Magnetic Field	Sharp transition	Gradual transition
Critical Field(s)	Single Hc	Two (H_{c1} and H_{c2})
Magnetic Field Penetration	No penetration	Partial penetration in mixed state
Material Type	Pure metals	Alloys and compounds
Applications	Limited	High-performance applications

5.6. Applications of Superconductors

Superconductors have significant applications in technology due to their ability to carry current without resistance and generate powerful magnetic fields.

a. Maglev Technology

Maglev (Magnetic Levitation) Trains:

- Superconductors are used to create strong magnetic fields that interact with tracks for levitation and propulsion.
- The train is lifted above the track, eliminating friction and enabling high speeds.

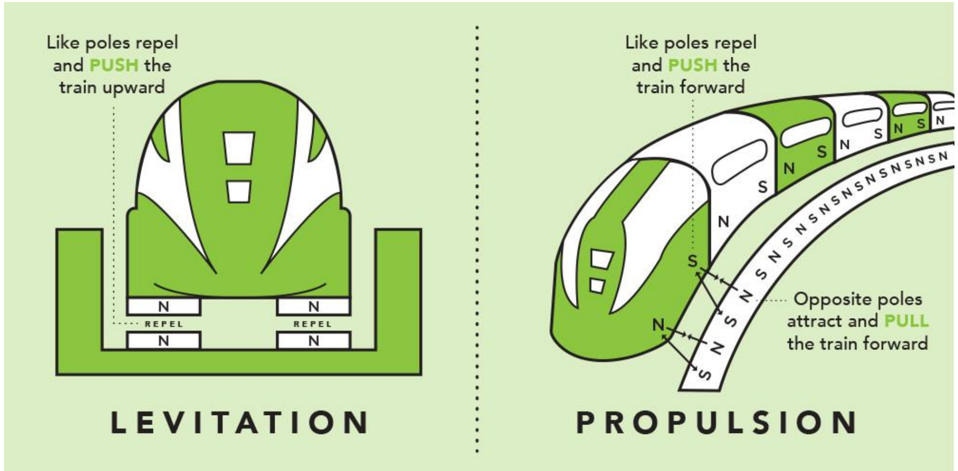


Figure 5.11. Mechanism involved in Maglev trains.[9]

How it Works:

- Magnetic fields generated by superconductors repel or attract the magnetic rails, creating levitation.
- Linear motors are used for propulsion, controlled by adjusting the magnetic field's direction.

Advantages:

1. Speeds of over 600 km/h are achievable.
2. No mechanical friction, resulting in quieter and smoother rides.
3. Energy efficiency and reduced maintenance costs.

Superconductors used in maglev trains:

- Niobium-titanium alloy: A superconducting wire made from this alloy is cooled to -452°F using liquid helium to achieve a stable state of superconductivity.
- Rare-earth barium-copper-oxide (REBCO): A high-temperature superconductor that can be used to create a superconducting bulk magnet.

b. Transmission Lines

Superconductors are used to design efficient power transmission lines.

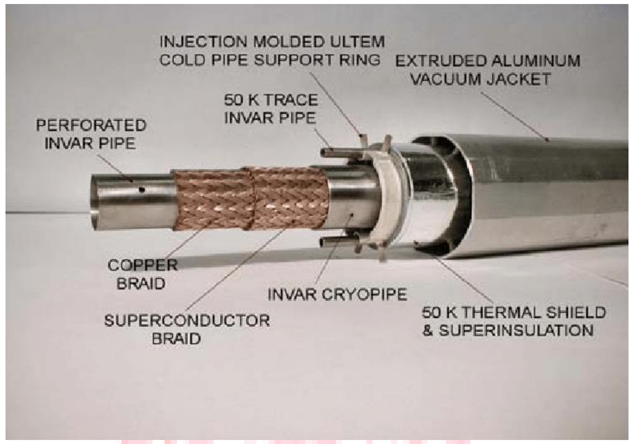


Figure 5.12. High efficiency transmission lines.[10]

Advantages:

1. **Zero Resistance:** No energy is lost as heat, improving efficiency.
2. **Compact Design:** Superconducting cables can carry high current densities, making them smaller and lighter.
3. **Long-Distance Efficiency:** Ideal for transmitting power across large distances.

Challenges:

1. Requires continuous cooling to maintain superconductivity.
2. High initial installation costs.

Superconductors used in transmission lines:

- $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO): Has a critical temperature of –160 °C
- $YBa_2Cu_3O_7$ (YBCO): Has a critical temperature of –180 °C
- MgB_2: Has a critical temperature of –235 °C

c. Magnetic Resonance Imaging (MRI)

Role of Superconductors:

MRI machines use superconducting magnets to generate strong and stable magnetic fields for medical imaging.

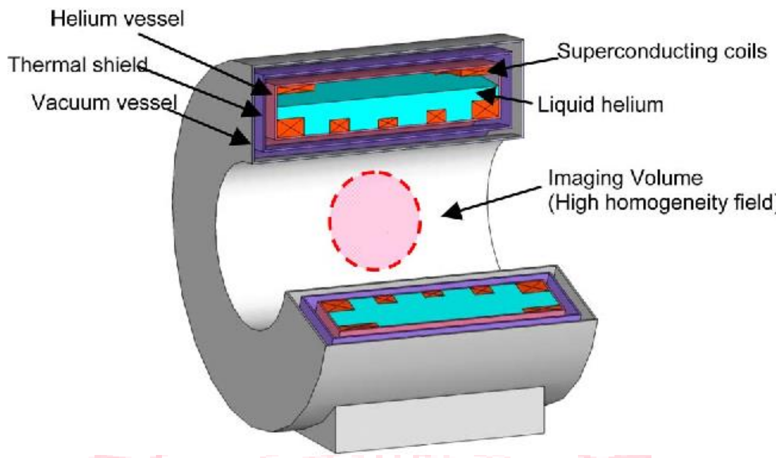


Figure 5.13. Super-Stable Superconducting MRI Magnet.[11]

How MRI Works:

- The magnetic field aligns hydrogen nuclei in the body.
- Radio waves disturb this alignment, and the nuclei emit signals as they relax back to their original state.
- These signals are processed to create detailed internal images.

Advantages of Superconductors in MRI:

1. Generate high-strength magnetic fields essential for imaging.
2. Operate with minimal energy loss due to zero resistance.
3. Reliable and consistent performance for long periods.

Applications of MRI:

- Diagnosing brain, spinal cord, and soft tissue abnormalities.
- Non-invasive and radiation-free imaging.

Superconductors used in MRI machine:

- Niobium-titanium (NbTi)
- Niobium-tin (Nb_3Sn)
- Vanadium-galium (V_3Ga)
- Magnesium-diboride (MgB_2)

Nanomaterials

5.7. Introduction to Nanomaterials

Nanomaterials are materials with structural components smaller than 100 nanometers (nm) in at least one dimension. They exhibit unique properties—mechanical, optical, electrical, and chemical—due to their nanoscale dimensions. These characteristics distinguish them from their bulk counterparts, making them a vital part of modern nanotechnology. Their unique behavior arises from the dominance of surface atoms, quantum effects, and their high surface-to-volume ratio.

5.7.1. Classification of Nanomaterials

Nanomaterials are categorized based on their dimensionality, structure, and composition:

A. Based on Dimensionality

1. **Zero-dimensional (0D)**: Nanoparticles, quantum dots.
    - All dimensions are confined.
    - Example: Gold nanoparticles, carbon dots.
2. **One-dimensional (1D)**: Nanorods, nanowires.
    - Confined in two dimensions, free in one dimension.
    - Example: Titanium dioxide nanorods.
3. **Two-dimensional (2D)**: Nanosheets, graphene, MoS_2.
    - Free movement in two dimensions.
4. **Three-dimensional (3D)**: Nanocomposites, porous materials.
    - Bulk nanostructured materials with nanoscale features.

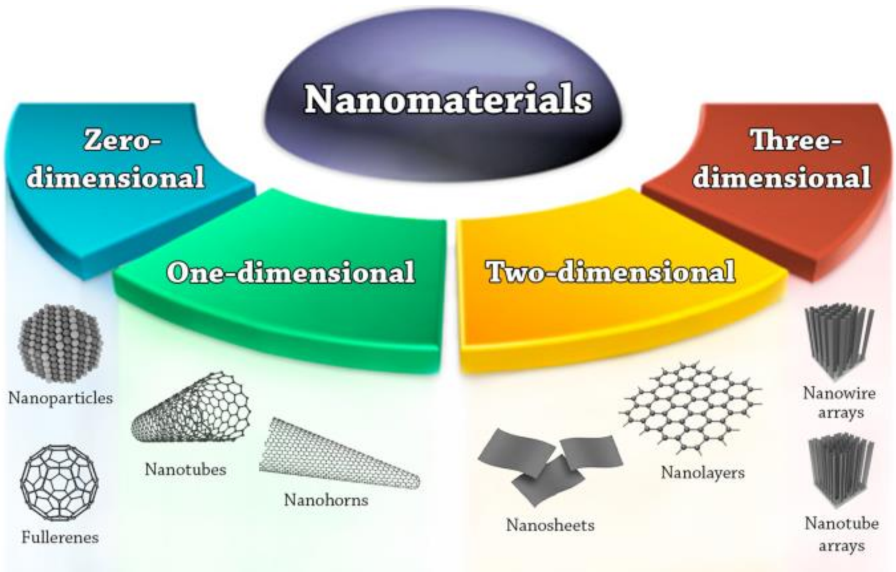


Figure 5.14. Classification of nanomaterials based on dimensionality.[12]

B. Based on Composition

1. **Metallic Nanomaterials**: Gold, silver, aluminum oxide nanoparticles.
2. **Semiconducting Nanomaterials**: Silicon nanowires, quantum dots.
3. **Polymeric Nanomaterials**: Nanofibers, dendrimers.
4. **Ceramic Nanomaterials**: Zirconia, silica nanoparticles.
5. **Carbon-based Nanomaterials**: Fullerenes, graphene, carbon nanotubes.

C. Based on Origin

1. **Natural Nanomaterials**: Proteins, viruses, volcanic ash.
2. **Engineered Nanomaterials**: Synthesized in laboratories for specific applications.

5.8. Quantum Confinement

Quantum confinement is a phenomenon that occurs when the dimensions of a material are reduced to the nanoscale, typically less than the de Broglie wavelength of electrons (on the order of a few nanometers). At this scale, the movement of electrons is restricted, and their energy levels become quantized, leading to unique optical, electronic, and magnetic properties. In bulk materials, electrons can move freely, and their energy levels are continuous. However, when the size of a material approaches the nanoscale, the following occur:

1. **Spatial Restriction**:
   - Electrons are confined in one or more dimensions.
   - This confinement alters their wave-like behavior, governed by quantum mechanics.
2. **Quantized Energy Levels**:
   - The continuous energy bands of bulk materials split into discrete energy levels.
   - The smaller the size of the material, the larger the spacing between energy levels.
3. **Effect on Properties**:
   - Changes in optical absorption and emission (e.g., quantum dots emit different colors based on size).
   - Altered electrical and thermal conductivity.

5.8.1. Types of Quantum Confinement

Quantum confinement depends on how many dimensions are restricted:

1. **Zero-Dimensional (0D)**:
   - Electrons are confined in all three dimensions.
   - Example: Quantum dots.
   - Property: Emission wavelength depends on dot size.
2. **One-Dimensional (1D)**:
   - Electrons are confined in two dimensions but free in one.
   - Example: Nanowires or nanorods.
   - Property: Directional conductivity.
3. **Two-Dimensional (2D)**:
   - Electrons are confined in one dimension but free in two.
   - Example: Thin films or quantum wells.
   - Property: Modified electronic band structure.

4. **Three-Dimensional (Bulk)**:
   - No confinement; electrons move freely in all directions.

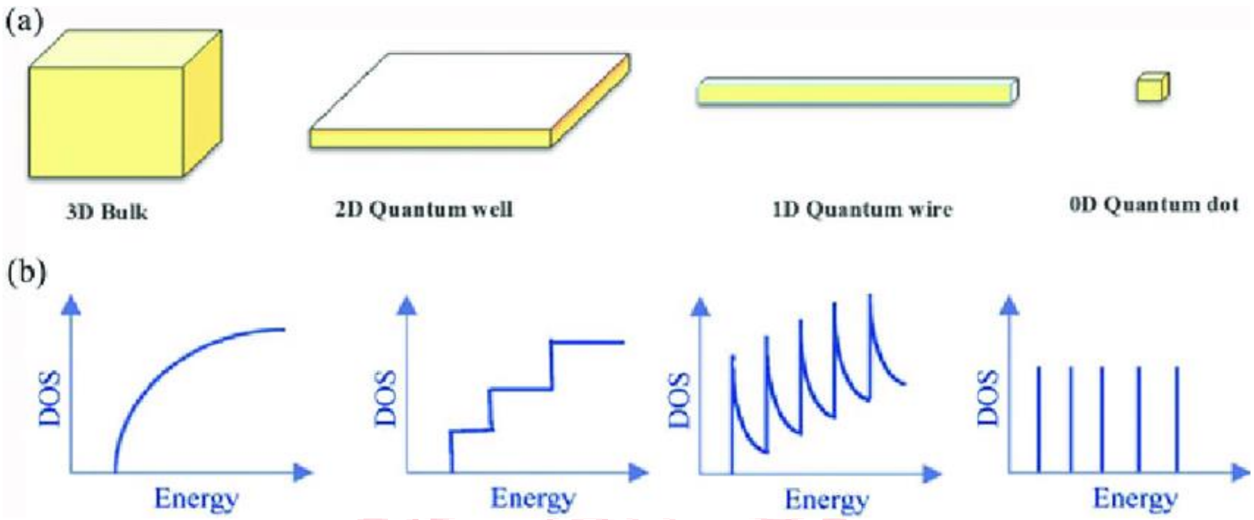


Figure 5.15. Types of quantum confinement in nanomaterials.[13]

For a three-dimensional quantum system (bulk), the density of states (DoS) g(E) describes the number of available quantum states per unit energy interval.

Density of States (DoS), $g(E)=(2\cdot \sqrt{2}\cdot m^{1/2}\cdot E^{-1/2})/h^3$

Where:

- g(E): Density of states (per unit energy interval).
- m: Effective mass of the electron.
- E: Energy of the state.
- h: Planck's constant.

Quantum confinement directly impacts the density of states:

- As the dimensionality decreases, the density of states transitions from continuous (bulk) to discrete (quantum dots).
- This discrete energy level structure leads to size-dependent optical and electronic properties, such as the color tunability of quantum dots.

5.9. Surface-to-Volume Ratio

The **surface-to-volume ratio** is the ratio of an object's surface area to its volume. It is a measure of how much surface area is exposed compared to the material's total volume.

For a general shape:

Surface-to-Volume Ratio (S/V)=Surface Area/Volume

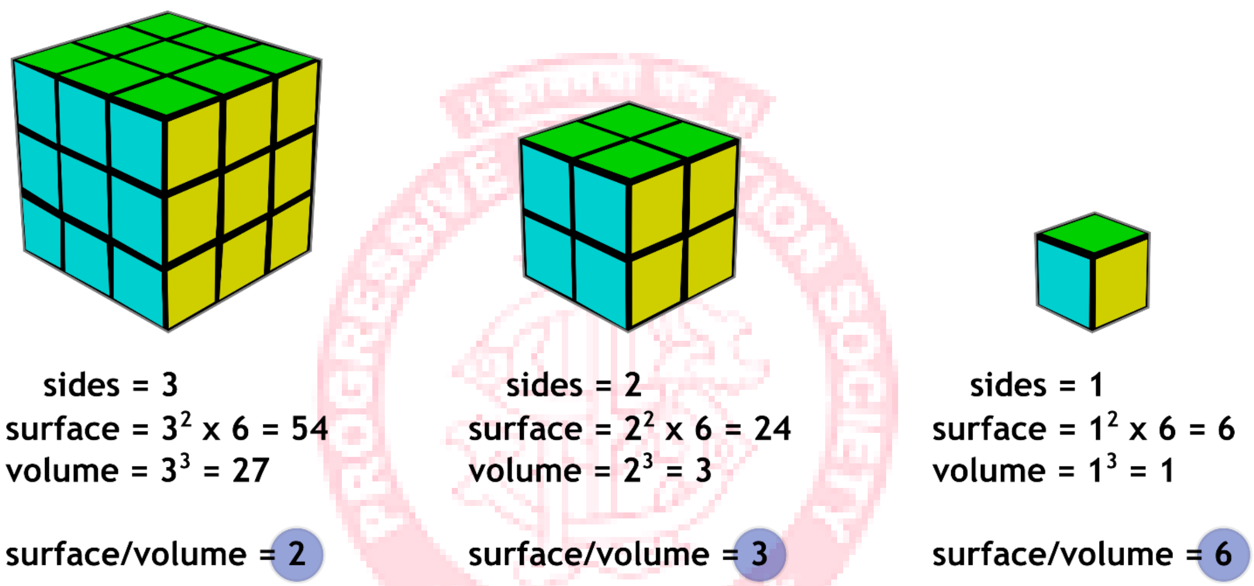


Figure 5.16. As particle size gets smaller, the surface area to volume ratio gets larger. Nanoparticles are almost all surface![14]

Nanomaterials have extremely high S/V ratios compared to bulk materials. This characteristic directly impacts their properties:

1. **Chemical Reactivity**:
   - More atoms or molecules are present on the surface in nanomaterials.
   - Higher surface area allows more interactions with the surrounding environment, making them highly reactive.
2. **Mechanical Strength**:
   - Increased surface area strengthens the interactions between grains in nanomaterials, leading to enhanced mechanical properties.

3. **Thermal and Electrical Properties**:
   - Heat and electron transport behave differently due to surface effects.
4. **Catalytic Efficiency**:
   - Catalysts made from nanoparticles have a larger number of active sites, improving efficiency.

Examples of S/V Ratio Effects

1. **Bulk vs. Nano Comparison (Spherical Particles)**:
   - Bulk particle (1 cm diameter):
     - Surface Area: 12.57 cm^2, Volume: 4.19 cm^3
     - S/V = 3 cm^{-1}
   - Nanoparticle (10 nm diameter):
     - Surface Area: 3.14×10^{-12} cm^2
     - S/V = 6×10^8 cm^{-1}

   The S/V ratio increases dramatically for smaller particles.

2. **Catalysis**:
   - Platinum nanoparticles in catalytic converters are more efficient than bulk platinum due to the increased surface area.
3. **Drug Delivery**:
   - Nanoparticles used in drug delivery systems can easily interact with biological systems due to their high surface area.

5.10. Comparison between Bulk and Nanomaterials

Table 5.3. Comparison of bulk and nanoparticles

Property	Bulk Materials	Nanomaterials
Size	Macro or micro scale (larger than 100 nm).	Nanoscale (1–100 nm in at least one dimension).
Surface Area to Volume Ratio	Low surface area to volume ratio.	High surface area to volume ratio, leading to enhanced reactivity and unique properties.
Mechanical Properties	Relatively lower strength and hardness.	Enhanced strength, hardness, and flexibility (e.g., carbon nanotubes).
Optical Properties	Optical properties depend on material composition and bulk structure.	Size-dependent optical properties due to quantum confinement (e.g., quantum dots).
Electronic Properties	Continuous energy bands.	Discrete energy levels due to quantum confinement.
Thermal Properties	Normal thermal conductivity and heat capacity.	Enhanced or reduced thermal conductivity, depending on material type and structure.
Magnetic Properties	Bulk magnetic behavior depends on domain size.	Superparamagnetism in nanoparticles due to single magnetic domains.
Chemical Properties	Lower reactivity due to fewer surface atoms.	High reactivity due to a larger proportion of surface atoms.
Surface Plasmon Resonance (SPR)	Not observed.	Observed in metallic nanoparticles (e.g., gold, silver).
Applications	General applications in structural, mechanical, and optical fields.	Specialized applications in medicine, energy, electronics, and catalysis.

5.11. Optical Properties of Nanomaterials

Nanomaterials exhibit unique optical properties due to their nanoscale size, where quantum effects dominate. One more reason is due to the quantization of energy levels resulting from their reduced dimensions. These properties arise from their interaction with light and are markedly different from those of bulk materials, and are closely tied to the concept of energy levels in quantum mechanics. Factors influencing optical behavior include quantum confinement, surface plasmon resonance, and size-dependent effects.

In bulk materials, energy levels are so closely spaced that they form continuous energy bands, such as the valence band and conduction band. However, as the size of the material decreases to the nanoscale, the energy levels become discrete due to quantum confinement. This occurs because the movement of electrons is restricted in one or more dimensions, effectively trapping them in a small space. As the size of a nanoparticle decreases, the energy gap between discrete levels increases. Smaller particles require higher energy photons for electronic transitions, which shifts their optical properties.

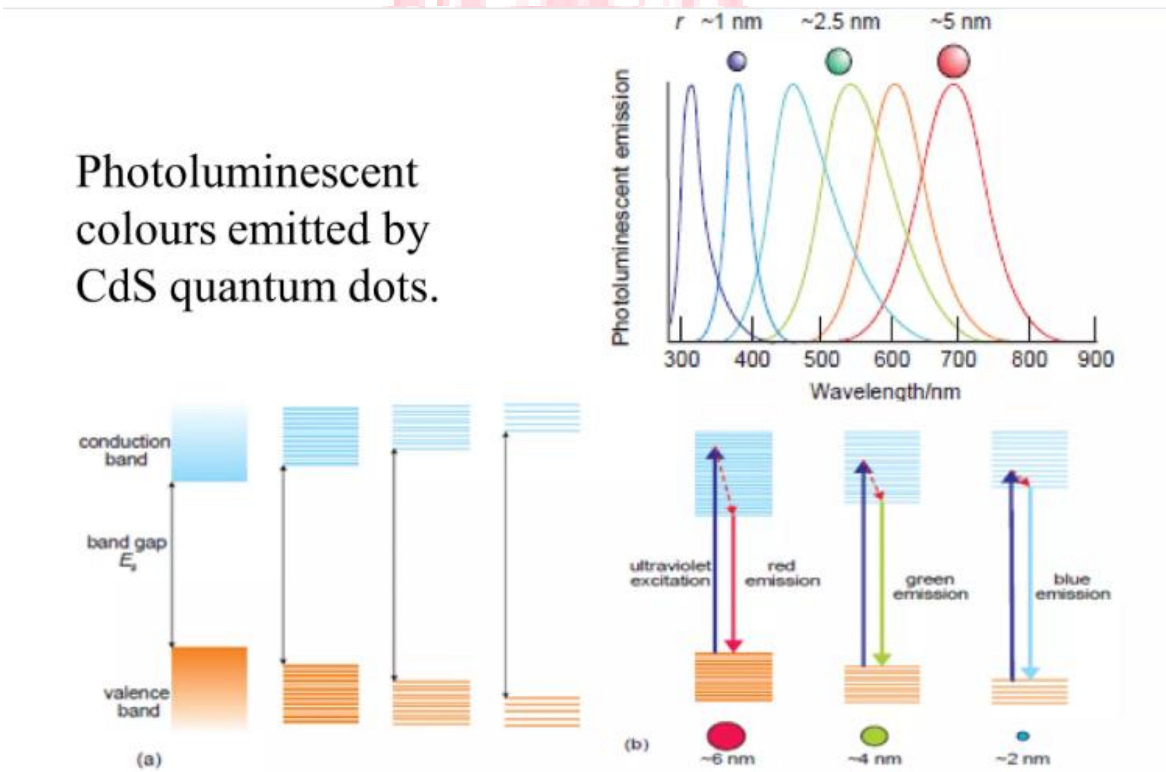


Figure 5.17. PL colors emitted by CdS QDs.[15]

Nanomaterials interact with light differently than bulk materials due to their discrete energy levels.

- **Absorption:** When a photon with energy matching the gap between two energy levels strikes the nanomaterial, an electron can be excited to a higher energy level. For nanoparticles, this gap depends on their size, composition, and shape.
- **Emission (Fluorescence):** When the excited electron returns to a lower energy state, it releases energy in the form of light. The wavelength of the emitted light depends on the energy difference between the levels.

The size of the nanoparticle directly influences its optical properties:

- **Blue Shift:** Smaller nanoparticles have a larger energy gap, causing absorption and emission of shorter wavelengths (higher energy, blue light).
- **Red Shift:** Larger nanoparticles have a smaller energy gap, leading to absorption and emission of longer wavelengths (lower energy, red light).

This phenomenon is observable in materials like quantum dots, where their color changes with particle size.

Applications of Nanomaterial Optical Properties

The unique optical behavior of nanomaterials makes them suitable for various applications:

- **Quantum Dots in Displays:** Size-tunable colors are used in high-resolution displays.
- **Biomedical Imaging:** Nanoparticles provide bright and stable fluorescent signals.
- **Photocatalysis:** Enhanced light absorption improves the efficiency of photocatalytic reactions.

Table 5.4. Comparison of Balk and nano materials based on the optical phenomenon.

Property	Bulk Material	Nanomaterial
Energy Levels	Continuous bands	Discrete, size-dependent levels
Bandgap	Fixed	Tunable with size
Absorption/Emission	Fixed wavelengths	Size-tunable wavelengths

Excitons	Weakly bound	Strongly bound
Surface Effects	Negligible	Dominant

5.12. Magnetic Properties of Nanomaterials

The magnetic properties of nanomaterials differ significantly from those of bulk materials due to their reduced size, increased surface-to-volume ratio, and quantum effects. These properties are influenced by the material's dimensions, composition, and surface interactions.

Magnetic Properties of Nanomaterials

1. **Superparamagnetism**
   - When the size of magnetic nanoparticles becomes comparable to the size of a single magnetic domain (10–50 nm for many materials), they exhibit superparamagnetic behavior.

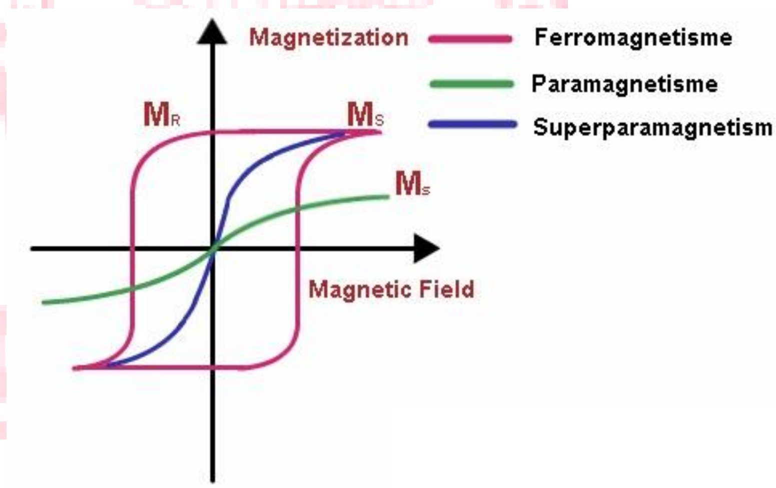


Figure 5.18. **Magnetic hysteresis in different types of magnetism**[16]

   - **What Happens?**
     - The entire nanoparticle acts as a single magnetic domain.
     - Thermal energy (k_BT) becomes sufficient to overcome magnetic anisotropy, causing spontaneous magnetization flipping.
   - **Key Characteristics**:
     - No remanence or coercivity when the external magnetic field is removed.

- Strong magnetic response to an external magnetic field.

2. **Magnetic Anisotropy**
   - Nanoparticles exhibit higher magnetic anisotropy than bulk materials due to surface effects and shape.

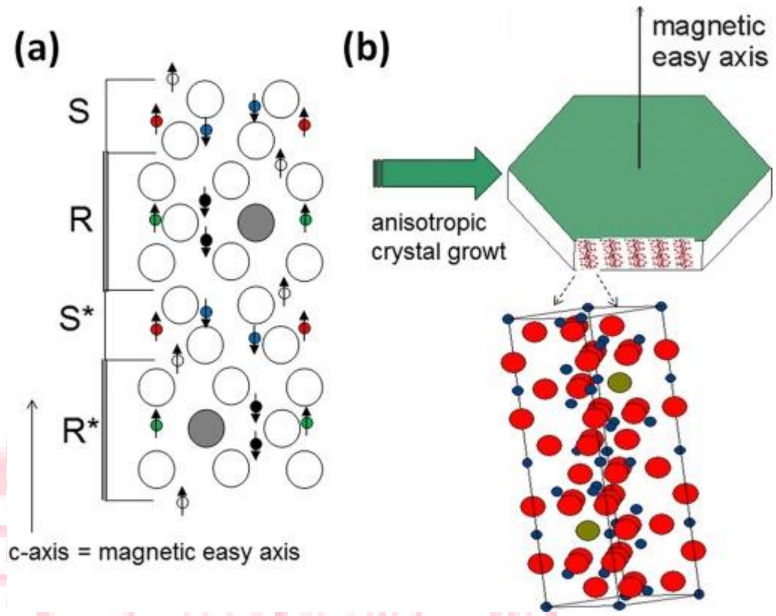


Figure 5.19. **Magnetic anisotropy.** [17]

   - **What Happens?**
     - Magnetic properties depend on particle orientation.
   - **Impact**:
     - Enables tuning of magnetic behavior for specific applications like magnetic storage.

3. **Enhanced Magnetic Moments**
   - Surface atoms in nanoparticles experience reduced coordination, leading to unpaired spins and enhanced magnetic moments.

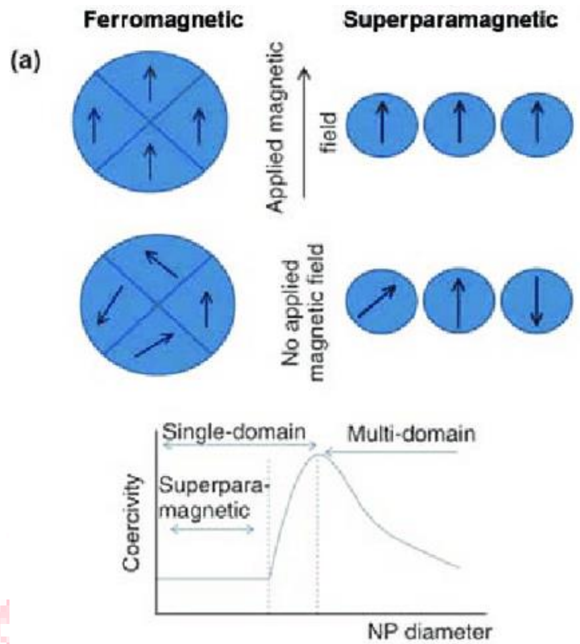


Figure 5.20. **Magnetic moment and domains in magnetic materials.**[18]

- Example: Magnetic moments in iron oxide nanoparticles can exceed those in bulk iron oxide.

4. **Exchange Bias Effect**
   - Observed in magnetic nanoparticles with a core-shell structure (e.g., antiferromagnetic core and ferromagnetic shell).
   - **Impact**:
     - Enhances magnetic stability, useful for data storage.

Table 5.5. Comparison of Balk and nano materials based on the magnetic properties.

Property	Bulk Material	Nanomaterial
Magnetic Domains	Multiple domains with domain walls.	Single domain (in small nanoparticles).
Coercivity	Lower coercivity.	Increased coercivity due to size effects.
Superparamagnetism	Not observed.	Observed in nanoparticles <50 nm.
Magnetic Saturation	Depends on material properties.	Can be tuned by size and shape.

Applications of Magnetic Nanomaterials

1. **Biomedical Applications**:
   - **Magnetic Resonance Imaging (MRI)**:
     - Superparamagnetic iron oxide nanoparticles (SPIONs) act as contrast agents.
   - **Drug Delivery**:
     - Magnetic nanoparticles are guided to target tissues using external magnetic fields.
   - **Hyperthermia Therapy**:
     - Magnetic nanoparticles generate localized heat to kill cancer cells under an alternating magnetic field.
2. **Data Storage**:
   - Nanomaterials like cobalt or iron nanoparticles are used to fabricate high-density magnetic storage devices.
   - Enhanced anisotropy and superparamagnetic effects improve performance.
3. **Sensors**:
   - Giant magnetoresistance (GMR) or tunneling magnetoresistance (TMR) sensors are based on magnetic nanostructures for precise detection of magnetic fields.
4. **Catalysis**:
   - Magnetic nanoparticles are used as recyclable catalysts in chemical reactions.
5. **Environmental Applications**:
   - Used in water purification for removing contaminants through magnetic separation.

Table 5.6. Comprehensive chart of application of magnetic nanoparticles.

Field	Application	Details	Examples
Electronics	**Nanoelectronics**	Miniaturization of devices and advanced transistors.	Carbon nanotube (CNT) transistors, graphene-based field-effect transistors.
	Memory Storage	High-density storage with improved speed and reliability.	Quantum dot flash memory, phase-change materials.
	Conductors and Interconnects	Ultra-thin, highly conductive nanomaterials for circuits.	Graphene, silver nanowires in touchscreens.
	Display Technology	Brighter, energy-efficient displays with vibrant colors.	Quantum Dot LEDs (QLEDs), flexible transparent displays using indium tin oxide (ITO).
	Energy Storage	Enhanced capacity and stability in batteries and supercapacitors.	Silicon nanoparticles for Li-ion batteries, graphene-based supercapacitors.
	Sensors	High sensitivity and precision in detecting gases and biomolecules.	Metal oxide gas sensors (ZnO, SnO_2), gold nanoparticle-based biosensors.
Automobiles	**Lightweight Materials**	High-strength nanocomposites reduce weight and improve fuel efficiency.	Polymer nanocomposites with CNTs or graphene for body panels and bumpers.
	Catalysis in Engines	Nanoparticles enhance catalytic efficiency, reducing emissions.	Platinum, palladium, and rhodium nanoparticles in catalytic converters.
	Coatings and Surface Treatments	Durable coatings for scratch resistance and self-cleaning surfaces.	Titanium dioxide (TiO_2) for hydrophobic surfaces, anti-scratch nanocoatings.

	Energy Storage	Improved battery performance and energy storage for electric vehicles (EVs).	Nanostructured anodes (silicon nanoparticles), graphene-enhanced supercapacitors.
	Sensors for Smart Vehicles	Nanomaterial-based sensors improve performance and enable autonomous features.	Tire pressure sensors, LiDAR, and pollution-monitoring gas sensors.
	Heat Management	Enhanced cooling efficiency with nanofluids and thermal coatings.	Aluminum oxide (Al_2O_3) nanoparticles in coolants, thermal nanocoatings in radiators.

Physical Parameters Influencing Magnetic Properties

1. **Particle Size**:
    - Below a critical size, particles exhibit single-domain behavior.
    - Size reduction can lead to superparamagnetism.
2. **Shape and Surface**:
    - Anisotropic shapes like rods or discs can enhance specific magnetic properties.
3. **Composition**:
    - Doping nanoparticles with elements like cobalt or nickel alters magnetic behavior.

5.13. Applications of Nanomaterials

Field	Application	Details	Examples
Electronics	**Nanoelectronics**	Miniaturization of devices and advanced transistors.	Carbon nanotube (CNT) transistors, graphene-based field-effect transistors.
	Memory Storage	High-density storage with improved speed and reliability.	Quantum dot flash memory, phase-change materials.
	Conductors and Interconnects	Ultra-thin, highly conductive nanomaterials for circuits.	Graphene, silver nanowires in touchscreens.
	Display Technology	Brighter, energy-efficient displays with vibrant colors.	Quantum Dot LEDs (QLEDs), flexible transparent displays using indium tin oxide (ITO).
	Energy Storage	Enhanced capacity and stability in batteries and supercapacitors.	Silicon nanoparticles for Li-ion batteries, graphene-based supercapacitors.
	Sensors	High sensitivity and precision in detecting gases and biomolecules.	Metal oxide gas sensors (ZnO, SnO_2), gold nanoparticle-based biosensors.

Field	Application	Details	Examples
Automobiles	**Lightweight Materials**	High-strength nanocomposites reduce weight and improve fuel efficiency.	Polymer nanocomposites with CNTs or graphene for body panels and bumpers.
	Catalysis in Engines	Nanoparticles enhance catalytic efficiency, reducing emissions.	Platinum, palladium, and rhodium nanoparticles in catalytic converters.
	Coatings and Surface Treatments	Durable coatings for scratch resistance and self-cleaning surfaces.	Titanium dioxide (TiO_2) for hydrophobic surfaces, anti-scratch nanocoatings.
	Energy Storage	Improved battery performance and energy storage for electric vehicles (EVs).	Nanostructured anodes (silicon nanoparticles), graphene-enhanced supercapacitors.
	Sensors for Smart Vehicles	Nanomaterial-based sensors improve performance and enable autonomous features.	Tire pressure sensors, LiDAR, and pollution-monitoring gas sensors.
	Heat Management	Enhanced cooling efficiency with nanofluids and thermal coatings.	Aluminum oxide (Al_2O_3) nanoparticles in coolants, thermal nanocoatings in radiators.

Questions:

1. Describe the origin of magnetism.
2. Discuss the types of magnetism.
3. What is magnetic susceptibility?
4. What are some of the magnetic properties of materials?
5. Discuss magnetic domain and hysteresis.
6. What is critical field in terms of superconductivity?
7. Explain Meissner effect.
8. What is superconductivity?
9. What is perfect diamagnetism in superconductors?
10. What is persistent current in superconductors?
11. Discuss applications of superconductivity.
12. Discuss some of the properties of nanomaterials.
13. Why do nanomaterials exhibit different physical properties than their bulk counterparts?
14. Discuss optical properties of nanoparticles.
15. Discuss magnetic properties of nanoparticles.
16. Discuss the applications of nanomaterials in electronics and automobile industries.

References

1. https://www.researchgate.net/publication/225835286_Application_of_Mineral_Magnetic_Techniques_to_Paleolimnology#pf4
2. https://www.sciencedirect.com/topics/chemistry/diamagnetic-material
3. https://eepower.com/technical-articles/understanding-the-different-properties-of-diamagnetic-paramagnetic-and-ferromagnetic-materials/
4. https://electricalacademia.com/electromagnetism/hysteresis-loop-magnetization-curve/
5. https://link.springer.com/article/10.1140/epjb/e2019-90577-0

6. https://www.researchgate.net/figure/Temperature-dependence-of-the-critical-magnetic-field-H-c-T_fig1_333785479
7. https://www.contextualize.ai/mpereira/a-history-of-superconductivity-d69301e8
8. https://en.wikipedia.org/wiki/Meissner_effect
9. https://www.energy.gov/articles/how-maglev-works
10. https://www.eetimes.com/are-superconducting-power-lines-still-a-viable-option/
11. https://www.semanticscholar.org/paper/Super-Stable-Superconducting-MRI-Magnet-Operating-Yamamoto Konii/32d9fb5bf37eae48a631d0b979066a74d950dc45
12. https://jnanobiotechnology.biomedcentral.com/articles/10.1186/s12951-022-01477-8
13. https://www.researchgate.net/figure/llustration-of-quantum-confinement-effect-125_fig3_331868642
14. https://sustainable-nano.com/2014/09/23/nano-sensors-small-size-big-impact/
15. https://www.sciencedirect.com/topics/materials-science/optical-property-of-nanomaterials
16. https://mappingignorance.org/2014/03/05/superparamagnetic-nanoparticles-and-the-separation-problem/
17. https://www.sciencedirect.com/science/article/abs/pii/S0079642518300331
18. https://www.researchgate.net/figure/Superparamagnetic-versus-ferromagnetic-particles-in-A-the-absence-and-B-presence-of_fig1_232274423