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**Materials Science for Engineers – ME232TB / ME242TB
Unit I**

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The Fundamentals of Materials -----6 Hours

The electronic structure of atoms, types of atomic and molecular bonds: ionic bond, covalent bond, metallic bond, secondary bonds, mixed bonding, hybridization.

Energy bands in metals, insulators, and semiconductors.

Basic crystallography. Defects and dislocations.

Types of materials: polymers, metals and alloys, ceramics, semiconductors, composites.



The fundamentals of materials cover the interdisciplinary relationship between a material's processing, structure, properties, and performance. Key topics include understanding the atomic and crystal structure, mechanical and thermal properties, different material classes like metals, ceramics, and polymers, and how factors such as crystal defects, diffusion, and phase transformations influence behaviour and allow for the design of materials for specific applications.

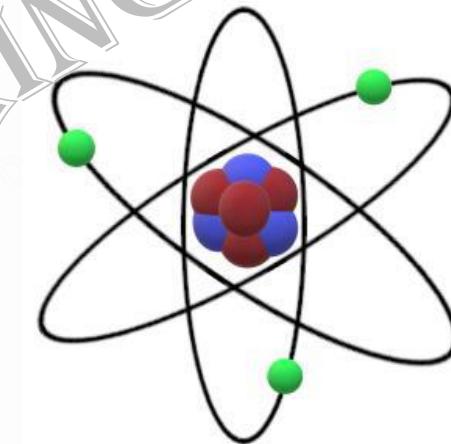
Materials are probably more deep-seated in our culture than most of us realize. Transportation, housing, clothing, communication, recreation, and food production - virtually every segment of our everyday lives is influenced to one degree or another by materials. Materials science involves investigating the relationships that exist between the structures and properties of materials.



The electronic structure of atoms

The **electronic structure of an atom** describes the arrangement of electrons in shells, subshells, and orbitals around the nucleus, which determines its chemical properties.

Electronic configuration of an atom : In the given figure **electrons** are green -coloured spheres are subatomic particles that carry a negative charge and orbit around the **nucleus** of an atom. The nucleus of an atom consists of **protons** (positive charge particle, red spheres) and **neutrons** (neutral charge particle, blue spheres).



Quantum numbers are a set of four numerical values (principal, azimuthal, magnetic, and spin quantum numbers) that describe the unique state of an electron in an atom, including its energy level, the shape and orientation of its orbital, and its intrinsic spin.

The electron configuration of an atom, follows specific rules such as Pauli's Exclusion Principle, Aufbau principle, Hund's rule, defining the number of electrons occupy each energy level and orbital.

Components of Electronic Structure

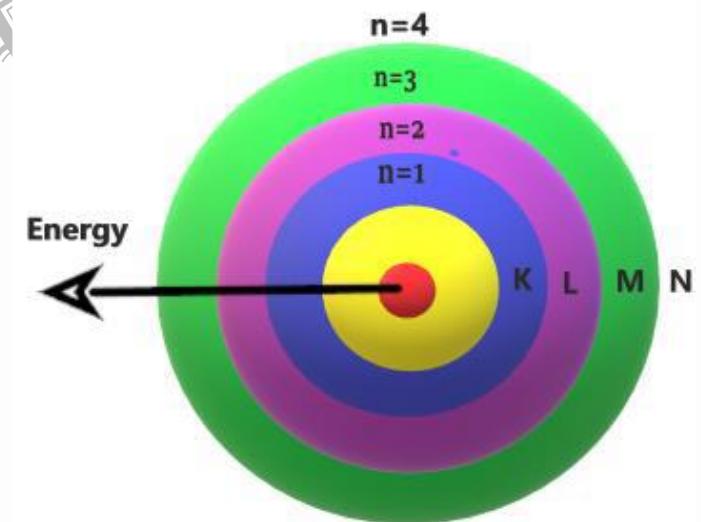
Principal Quantum Number (n) : It describes the electron's main energy level or shell of an electron and the approximate size of the electron's orbital. These are positive integers values correspond to higher energy levels and larger orbitals.

Energy levels or Electron Shells: Concentric energy levels where electrons orbit the nucleus. The innermost shells are filled first. These shells are labelled as K,L,M and so on.

Subshells (Orbitals): Within each shell, electrons are distributed into different subshells (s, p, d, f), each with its own shape and capacity for electrons.

Valence Electrons: The electrons in the outermost shell of an atom.

Shell No.	Shell Name	Sub Shell	Electrons	Total Electrons
1	K	1s	2	2
2	L	2s 2p	2 6	8
3	M	3s 3p 3d	2 6 10	18
4	N	4s 4p 4d 4f	2 6 10 14	32

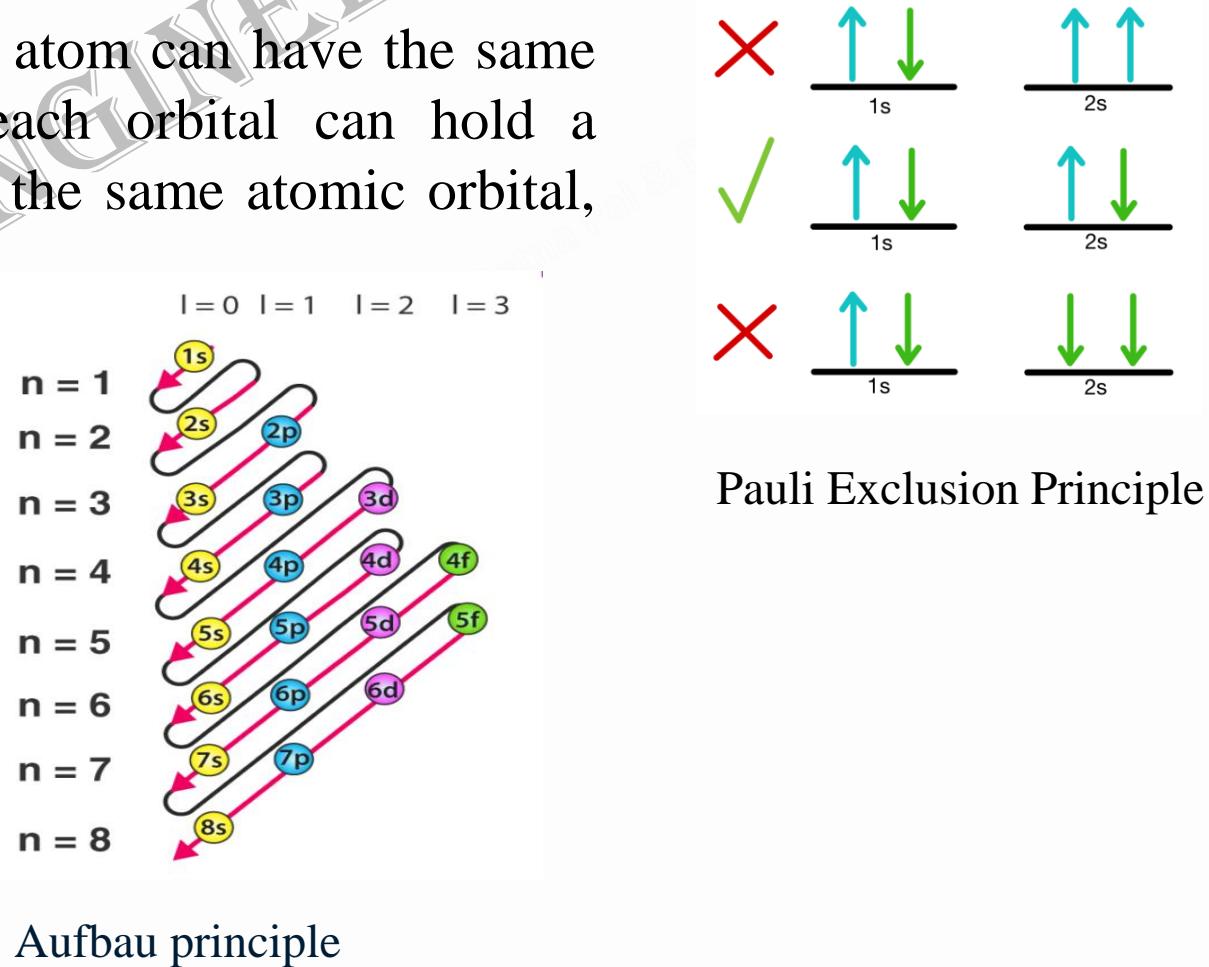


Principle of quantum number (n)

Spin Quantum Number: Represents the intrinsic angular momentum of an electron, known as its "spin". Which can be either $+1/2$ or $-1/2$. An electron can only spin in one of these two directions.

Pauli Exclusion Principle: No two electrons in an atom can have the same set of quantum numbers (n). This means that each orbital can hold a maximum of two electrons. If two electrons are in the same atomic orbital, they must have opposite spin.

Aufbau Principle: It states electrons fill the lowest energy orbitals first before moving to higher energy ones. This principle provides a step-by-step sequence for electron distribution, which determines an atom's electron configuration. The general order of filling is $1s$, $2s$, $2p$, $3s$, $3p$, $4s$, $3d$, $4p$, and so on, though there are exceptions for some elements like chromium and copper.



Hund's rule, also known as the **rule of maximum multiplicity**, states that electrons will occupy degenerate (equal energy) orbitals by filling each orbital singly before pairing up, and all unpaired electrons in a subshell will have the same spin.

This configuration results in the lowest energy state for an atom or molecule because it minimizes electron-electron repulsion and maximizes the total electron spin.

Hund's Rule

Filling Up of Electrons in 2p Orbitals

1s	2s	2p	2p	2p
↑ ↓	↑ ↓			
↑ ↓	↑ ↓	↑		
↑ ↓	↑ ↓	↑	↑	
↑ ↓	↑ ↓	↑	↑	↑
↑ ↓	↑ ↓	↑ ↓	↑	↑
↑ ↓	↑ ↓	↑ ↓	↑	↑
↑ ↓	↑ ↓	↑ ↓	↑ ↓	↑



Atomic and molecular bonds

Atomic and molecular bonds are interactions that hold atoms and molecules together. There are several types of bonds, each characterized by the way electrons are shared, transferred, or attracted between atoms.

Atomic bonding in solids may be considered in terms of attractive and repulsive forces and energies. The three types of primary bond in solids are **ionic, covalent, and metallic**.

For **ionic bonds**, electrically charged ions are formed by the transference of valence electrons from one atom type to another and forces are coulombic.

There is a sharing of valence electrons between adjacent atoms when bonding is **covalent**.

With **metallic bonding**, the valence electrons form a “sea of electrons” that is uniformly dispersed around the metal ion cores and acts as a form of glue for them.

In general, each of these three types of bonding arises from the tendency of the atoms to assume stable electron structures, like those of the **inert gases**, by completely filling the outermost electron shell.

Secondary or physical forces and energies are also found in many solid materials. They are weaker than the primary ones and influence the physical properties of some materials.



Ionic bond

Ionic bonds - It is always found in compounds that are composed of both metallic and non-metallic elements.

Atoms of a metallic element give up their valence electrons to the non-metallic atoms. In the process all the atoms acquire stable or inert gas configurations and, in addition, an electrical charge; that is, they become ions.

Sodium chloride (NaCl) is the classic ionic material. A sodium (Na 11) atom can assume the electron structure of neon (Ne 10) (and a net single positive charge) by a transfer of its one valence 3s electron to a chlorine atom (Cl 17). After such a transfer, the chlorine ion has a net negative charge and an electron configuration identical to that of argon (Ar 18). In sodium chloride, all the sodium and chlorine exist as ions.

This type of bonding is illustrated schematically in Figure. The attractive bonding forces are coulombic; that is, positive and negative ions, by virtue of their net electrical charge, attract one another.

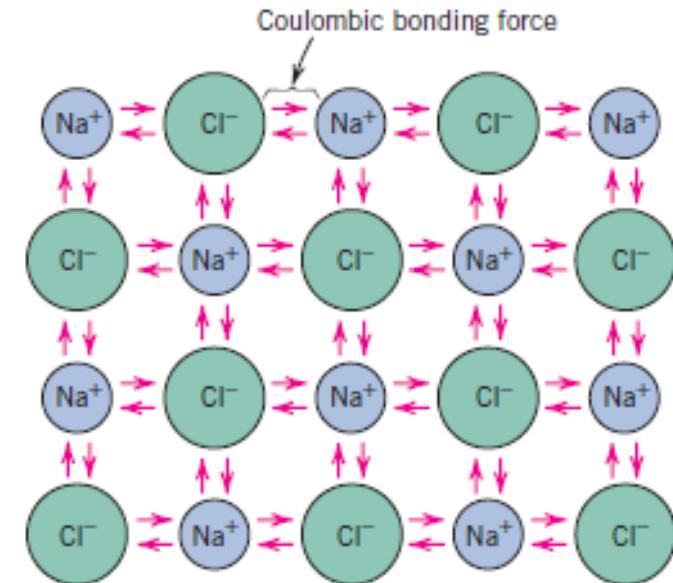


Figure Schematic representation of ionic bonding in sodium chloride (NaCl).



Covalent bond

Covalent bonds – In covalent bonding, stable electron configurations are assumed by the sharing of electrons between adjacent atoms. Two atoms that are covalently bonded will each contribute at least one electron to the bond, and the shared electrons may be considered to belong to both atoms.

Covalent bonding is schematically illustrated in the given figure for a molecule of methane (CH_4). The carbon atom (C 6) has four valence electrons, whereas each of the four hydrogen atoms (H 1) has a single valence electron.

Each hydrogen atom can acquire a helium electron configuration ($\text{He} 2$) (two 1s valence electrons) when the carbon atom shares with it one electron.

The carbon now has four additional shared electrons, one from each hydrogen, for a total of eight valence electrons, and the electron structure of neon ($\text{Ne} 10$).

The covalent bond is **directional**. It is between specific atoms and may exist only in the direction between one atom and another that participates in the electron sharing.

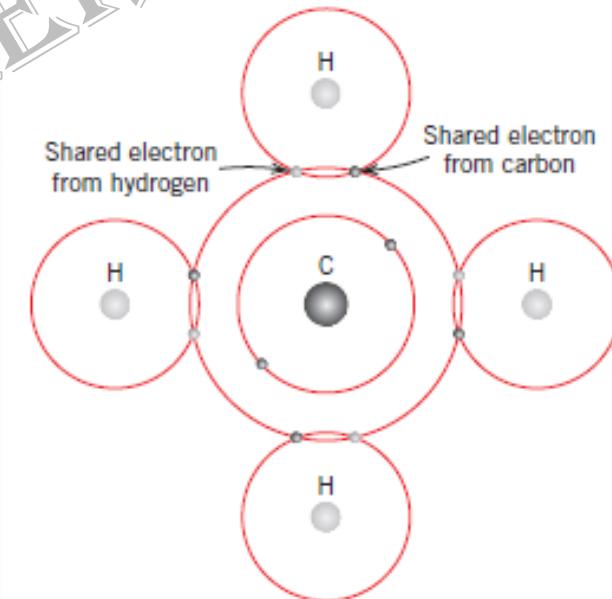


Figure : Schematic representation of covalent bonding in a molecule of methane (CH_4).

Many non-metallic elemental molecules (H_2 , Cl_2 , F_2 , etc.) as well as molecules containing dissimilar atoms, such as CH_4 , H_2O , HNO_3 , and HF , are covalently bonded.

This type of bonding is found in elemental solids such as diamond (carbon), silicon, and germanium and other solid compounds composed of elements that are located on the right-hand side of the periodic table, such as gallium arsenide (GaAs), indium antimonide (InSb), and silicon carbide (SiC).

The number of covalent bonds that is possible for a particular atom is determined by the number of valence electrons.

For N valence electrons, an atom can covalently bond with at most $8 - N$ other atoms. For example, $N=7$ for chlorine, and $8 - N = 1$, which means that one Cl atom can bond to only one other atom, as in Cl_2 . Similarly, for carbon, $N = 4$, and each carbon atom has $8 - 4$, or four, electrons to share. Diamond is simply the three-dimensional interconnecting structure wherein each carbon atom covalently bonds with four other carbon atoms.



Metallic bond

Metallic bonding – It is a primary bonding, found in metals and their alloys. Metallic materials have one, two, or at most, three valence electrons. These valence electrons are not bound to any particular atom in the solid and are more or less free to drift throughout the entire metal.

They may be thought of as belonging to the metal as a whole, or forming a sea of electrons or an electron cloud. The remaining non-valence electrons and atomic nuclei form what are called ion cores, which possess a net positive charge equal in magnitude to the total valence electron charge per atom.

Given figure is a schematic illustration of metallic bonding. The free electrons shield the positively charged ion cores from mutually repulsive electrostatic forces, which they would otherwise exert upon one another.

Consequently the metallic bond is **non-directional** in character. In addition, these free electrons act as a glue to hold the ion cores together. Metallic bonding is found for all elemental metals.

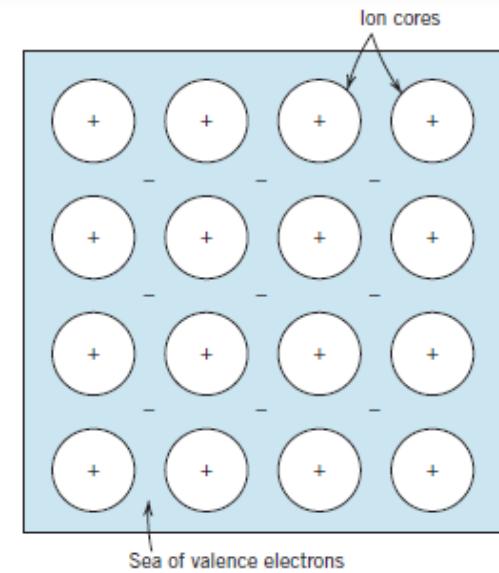


Figure: Schematic illustration of metallic bonding.



Secondary bonds

VAN DER WAALS BONDING

Secondary, van der Waals, or physical bonds are **weak** in comparison to the primary or chemical ones. Bonding energies are typically on the order of only 10 kJ/mol (0.1 eV/atom). Secondary bonding exists between virtually all atoms or molecules, but its presence may be obscured if any of the three primary bonding types is present. Secondary bonding is evidenced for the inert gases, which have stable electron structures, and, in addition, between molecules in molecular structures that are covalently bonded.

Secondary bonding forces arise from atomic or molecular **dipoles**. An electric dipole exists whenever there is some separation of positive and negative portions of an atom or molecule.

The bonding results from the coulombic attraction between the positive end of one dipole and the negative region of an adjacent one, as indicated in Figure. Dipole interactions occur between induced dipoles, between induced dipoles and polar molecules (which have permanent dipoles), and between polar molecules.

Hydrogen bonding, a special type of secondary bonding, is found to exist between some molecules that have hydrogen as one of the constituents.

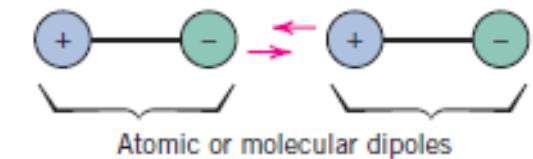


Figure: Schematic illustration of van der Waals bonding between two dipoles.



Fluctuating Induced Dipole Bonds

A dipole may be created or induced in an atom or molecule that is normally electrically symmetric; that is, the overall spatial distribution of the electrons is symmetric with respect to the positively charged nucleus, as shown in Figure a.

All atoms are experiencing constant vibrational motion that can cause instantaneous and short-lived distortions of this electrical symmetry for some of the atoms or molecules, and the creation of small electric dipoles, as represented in Figure b.

One of these dipoles can in turn produce a displacement of the electron distribution of an adjacent molecule or atom, which induces the second one also to become a dipole that is then weakly attracted or bonded to the first, this is one type of van der Waals bonding. These attractive forces may exist between large numbers of atoms or molecules, which forces are temporary and fluctuate with time.

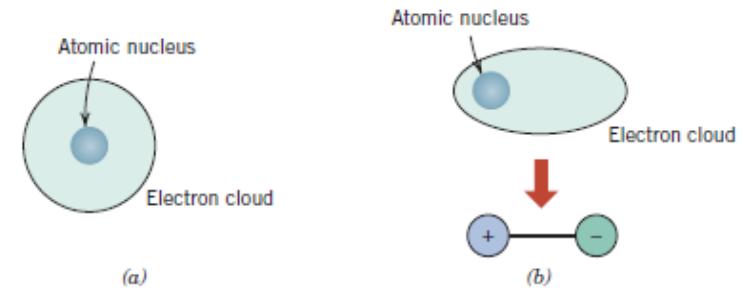


Figure: Schematic representations of (a) an electrically symmetric atom and (b) an induced atomic dipole.

Polar Molecule-Induced Dipole Bonds

Permanent dipole moments exist in some molecules by virtue of an asymmetrical arrangement of positively and negatively charged regions, such molecules are termed polar molecules.

The given figure is a schematic representation of a hydrogen chloride molecule, a permanent dipole moment arises from net positive and negative charges that are respectively associated with the hydrogen and chlorine ends of the HCl molecule.

Polar molecules can also induce dipoles in adjacent nonpolar molecules, and a bond will form as a result of attractive forces between the two molecules. Furthermore, the magnitude of this bond will be greater than for fluctuating induced dipoles.

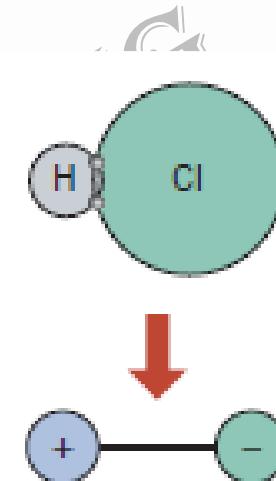


Figure: Schematic representation of a polar hydrogen chloride (HCl) molecule.

Permanent Dipole Bonds

Van der Waals forces will also exist between adjacent polar molecules. The associated bonding energies are significantly greater than for bonds involving induced dipoles.

The strongest secondary bonding type, the **hydrogen bond**, is a special case of polar molecule bonding.

It occurs between molecules in which hydrogen is covalently bonded to fluorine (as in HF), oxygen (as in H₂O), and nitrogen (as in NH₃).

For each H—F, H—O, or H—N bond, the single hydrogen electron is shared with the other atom.

Thus, the hydrogen end of the bond is essentially a positively charged bare proton that is unscreened by any electrons. This highly positively charged end of the molecule is capable of a strong attractive force with the negative end of an adjacent molecule, as demonstrated in Figure for HF.

In essence, this single proton forms a bridge between two negatively charged atoms. The magnitude of the hydrogen bond is generally greater than that of the other types of secondary bonds and may be as high as 51 kJ/mol (0.52 eV/molecule).

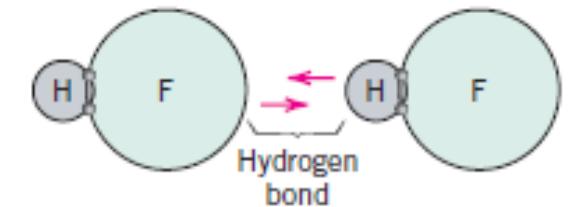


Figure: Schematic representation of hydrogen bonding in hydrogen fluoride (HF).



Mixed bonding

Mixed Bonding: Mixed bonding refers to a type of chemical bonding that combines characteristics of different bonding types, such as ionic, covalent, metallic, or hydrogen bonding. It occurs when there is a partial sharing or transfer of electrons between atoms.

Mixed bonding refers to the presence of **both ionic and covalent bonding** within a single compound or system. In such cases, part of the bonding between atoms involves the transfer of electrons (ionic bonding), while another part involves the sharing of electrons (covalent bonding).

This results in a hybrid structure where both types of interactions contribute to the compound's overall stability and properties.

An **example** of mixed bonding is seen in the compound **sodium hypochlorite (NaOCl)**, which is the active ingredient in household bleach. In NaOCl, the oxygen atom is more electronegative than the sodium atom. As a result, the oxygen atom attracts the shared electron pair in the covalent bond more strongly, creating a partial negative charge. The sodium atom, having lost an electron to oxygen, carries a partial positive charge. This partial transfer of electrons leads to an ionic character in the compound, while the sharing of the electron pair between oxygen and chlorine atoms contributes to the covalent character.

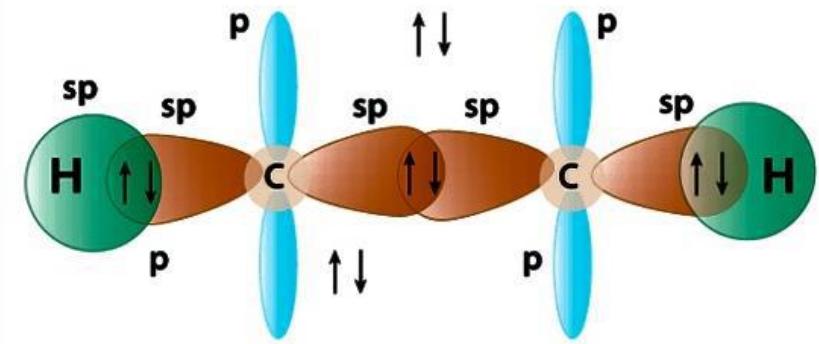
Calcium Carbonate (CaCO₃): The bond between calcium (Ca²⁺) and the carbonate ion (CO₃²⁻) is ionic. However, within the carbonate ion (CO₃²⁻), the carbon and oxygen atoms are bonded covalently.



Hybridization

Hybridization is the combination of atomic orbitals within an atom to form new, equivalent hybrid orbitals that are better suited for forming chemical bonds and determining molecular geometry. The most commonly encountered hybridization types are sp , sp^2 , and sp^3 hybridizations. Each hybridization type corresponds to a specific arrangement of electron domains around the central atom in a molecule.

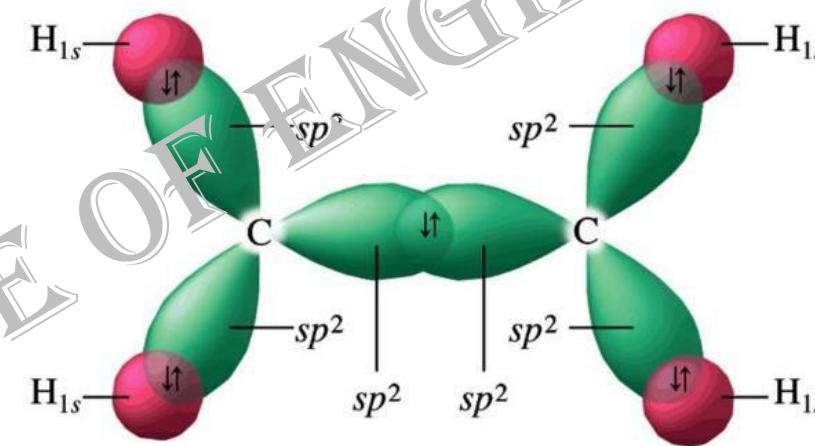
sp Hybridization: In sp hybridization, one ‘s’ orbital and one ‘p’ orbital from the central atom combine to form two sp hybrid orbitals. These hybrid orbitals are linearly oriented at an angle of 180° to each other. Examples of molecules that exhibit sp hybridization include linear molecules like BeCl_2 and linear carbon-containing molecules like acetylene (C_2H_2) shown in figure.



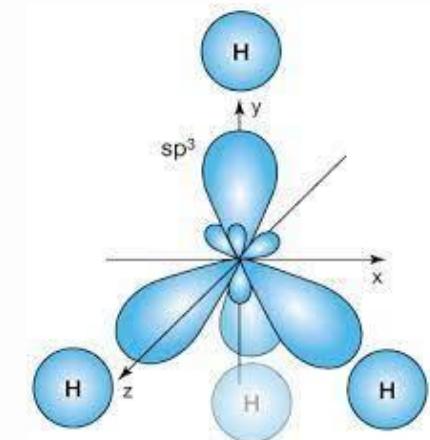
C_2H_2 sp hybridization

sp² Hybridization: In sp² hybridization, one ‘s’ orbital and two ‘p’ orbitals from the central atom combine to form three sp² hybrid orbitals. These hybrid orbitals are trigonally oriented in a plane, with angles of 120° between them. This type of hybridization is commonly observed in molecules with a trigonal planar geometry, such as boron trichloride (BCl₃) and molecules containing a carbon-carbon double bond, like ethylene (C₂H₄) shown in figure.

Sp³ Hybridization: In sp³ hybridization, one ‘s’ orbital and three ‘p’ orbitals from the central atom combine to form four sp³ hybrid orbitals. These hybrid orbitals are tetrahedrally oriented, with angles of approximately 109.5° between them. Examples of molecules exhibiting sp³ hybridization include methane (CH₄) as shown in figure and other molecules with a tetrahedral geometry.



C₂H₄ sp² hybridization



C₂H₄ sp³ hybridization



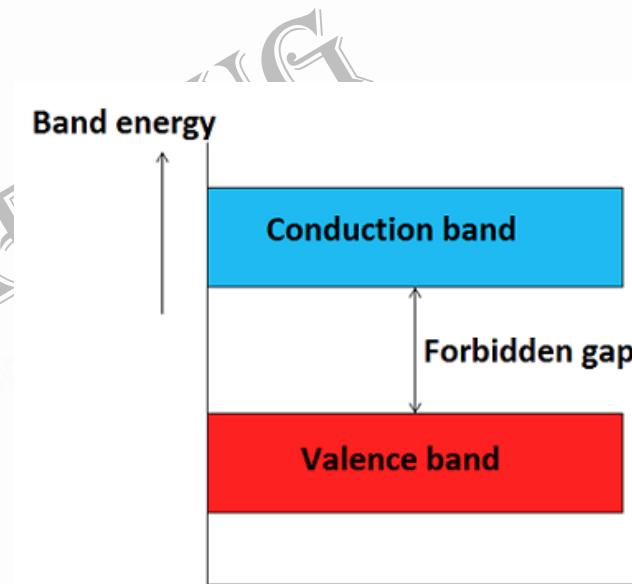
Energy Bands

Energy bands in solids are ranges of continuous energy that electrons can occupy. These energy bands formed when isolated atomic energy levels overlap in a solid material.

These bands are categorized into three

- Valence band** - This band is at a lower energy level and is filled with the valence electrons of the atoms in the solid. Electrons in the valence band are tightly bound to their atoms and are generally not free to move, so they do not conduct electricity.
- Conduction band** - This band is located at a higher energy level than the valence band. It can be partially or completely empty. Electrons in the conduction band are free to move throughout the solid, allowing for electrical conductivity.
- Forbidden band or band gap** - This is the region of energy between the valence band and the conduction band where electrons are not allowed to exist. The energy difference is called the band gap.

The size of this band gap determines whether a solid is a conductor (small or no gap), a semiconductor (small gap), or an insulator (large gap).



Bands in solids

Classification of Solids by Band Structure

The size of the band gap determines the material's electrical properties:

Conductors: In conductors, the valence and conduction bands either overlap, or there is a very small or no forbidden gap, allowing electrons to move easily between them and conduct electricity.

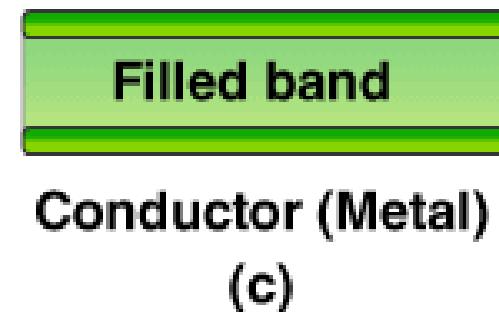
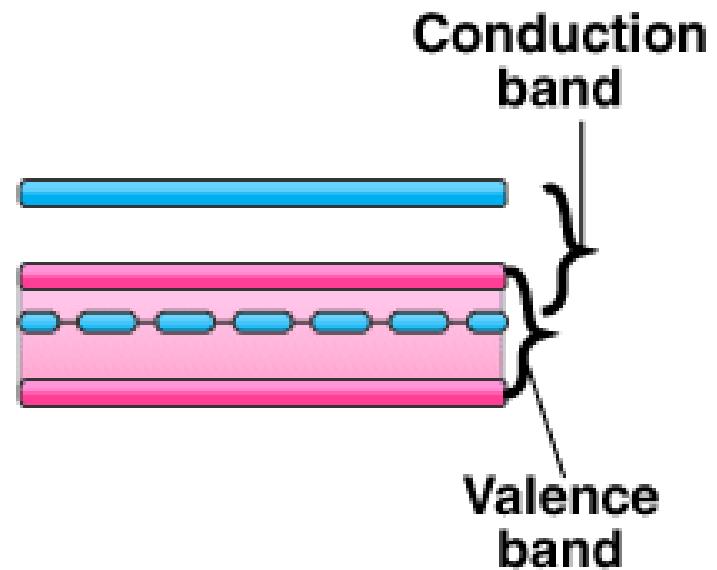
Insulators: Insulators have a very large band gap, requiring a substantial amount of energy for an electron to jump from the valence band to the conduction band. Therefore, they are poor conductors of electricity.

Semiconductors: Semiconductors have a band gap that is smaller than an insulator's but larger than a conductor's. Electrons can move to the conduction band with a moderate amount of energy, making them capable of conducting electricity, though less effectively than metals.

In metals, the valence and conduction energy bands **overlap**, or the conduction band is partially filled, creating a continuous band of allowed energy states.

This overlap or partial filling allows valence electrons to move freely into the higher-energy, unoccupied states of the conduction band.

When an electric field is applied, resulting in the high electrical conductivity characteristic of metals.



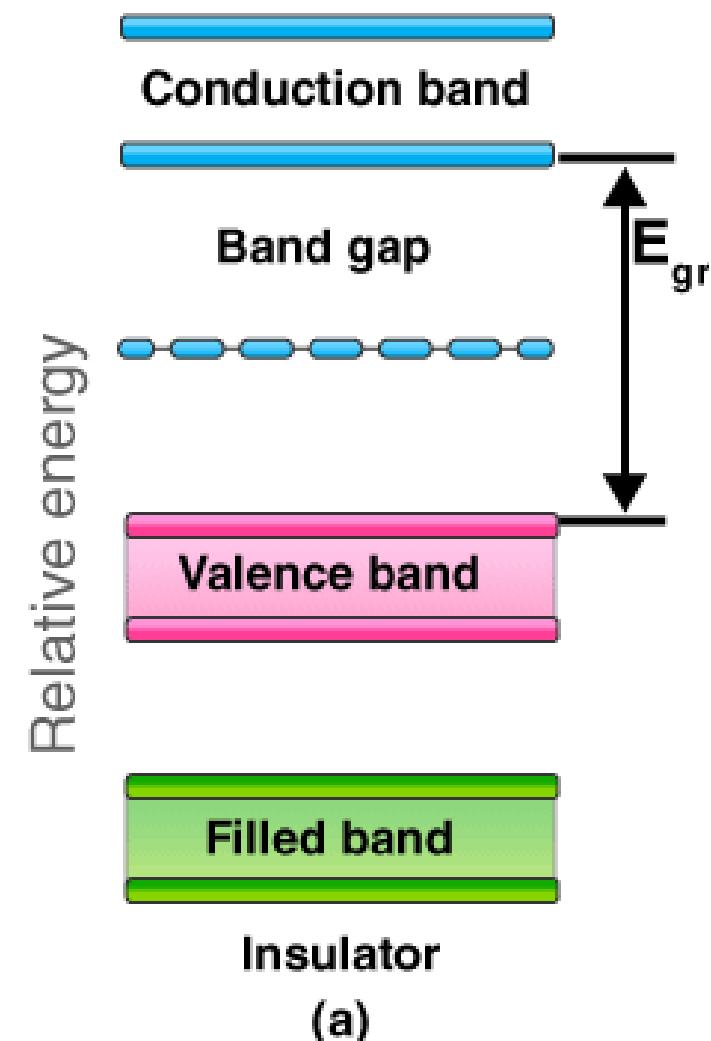
Energy bands in Insulators

Go, change the world

In an **insulator**, energy bands are characterized by a large energy gap (band gap, E_g) between the fully filled valence band and the empty conduction band, typically greater than 3 eV.

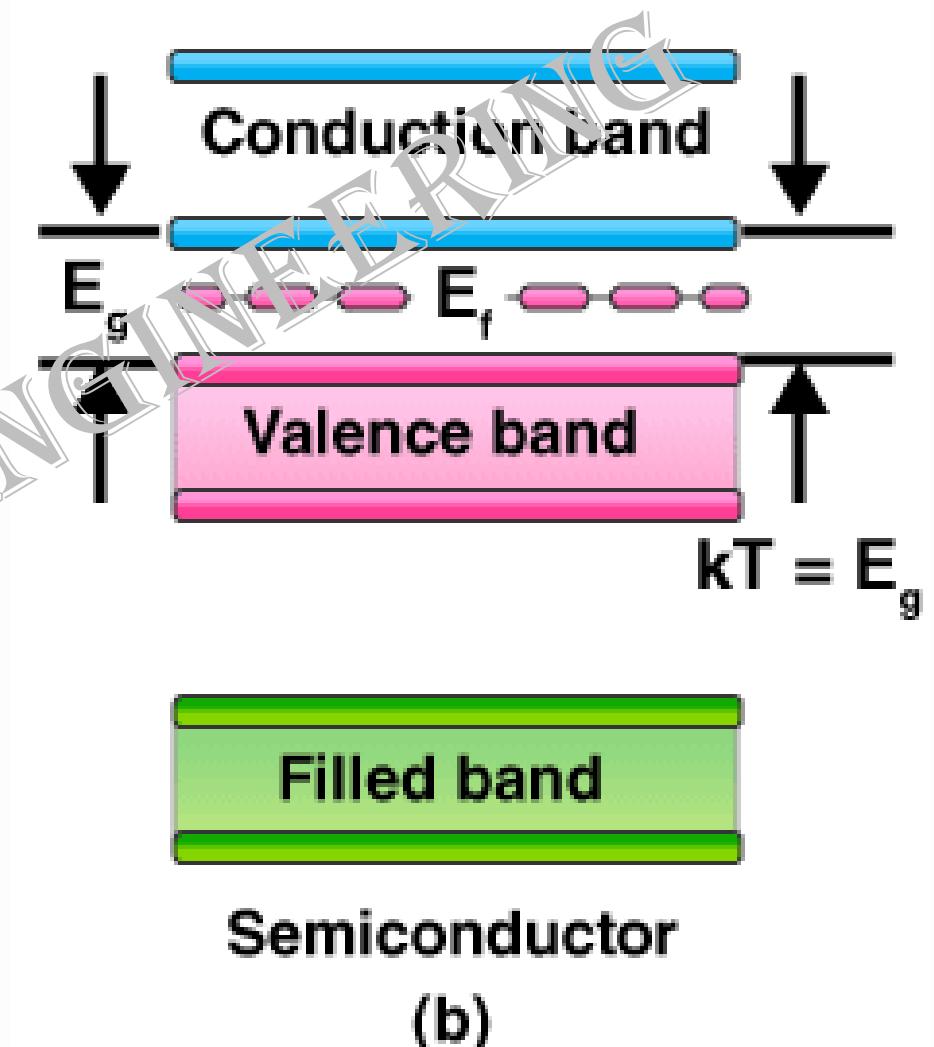
This substantial energy gap makes it nearly impossible for electrons to gain enough energy to cross into the conduction band, resulting in a lack of free charge carriers and therefore, extremely poor electrical conductivity under normal conditions.

Because a significant amount of energy is required to excite electrons across the large gap, very few electrons are available to move and conduct electricity.



Energy bands in **semiconductors** define their electrical properties, consisting of the valence band (lower energy, where electrons are bound), the conduction band (higher energy, where electrons are free to conduct), and the band gap (the forbidden energy range between them).

Unlike conductors, the small band gap in semiconductors allows electrons to gain enough energy to jump from the valence band to the conduction band, enabling a controllable flow of current and making them useful in electronic devices.





Basic crystallography

Fundamental Concepts of solid materials

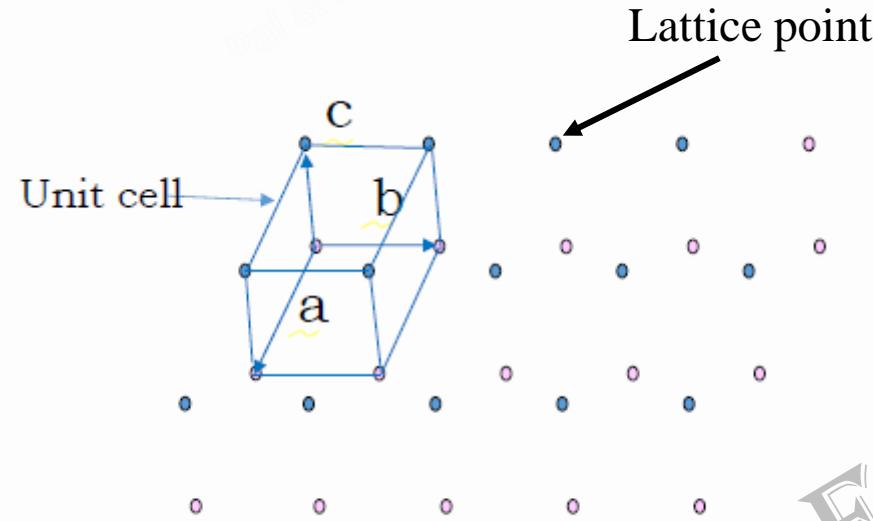
Solid materials may be classified according to the regularity with which atoms or ions are arranged with respect to one another. A **crystalline** material is one in which the atoms are situated in a repeating or periodic array over large atomic distances, that is, long-range order exists, such that upon solidification, the atoms will position themselves in a repetitive three-dimensional pattern, in which each atom is bonded to its nearest-neighbour atoms.

All metals, many ceramic materials, and certain polymers form crystalline structures under normal solidification conditions.

For those that do not crystallize, this long-range atomic order is absent; these **noncrystalline or amorphous** materials.

Some of the properties of crystalline solids depend on the **crystal structure** of the material, the manner in which atoms, ions, or molecules are spatially arranged.

Space Lattice: An infinite array of points in 3D space in which each point is identically located with respect to other

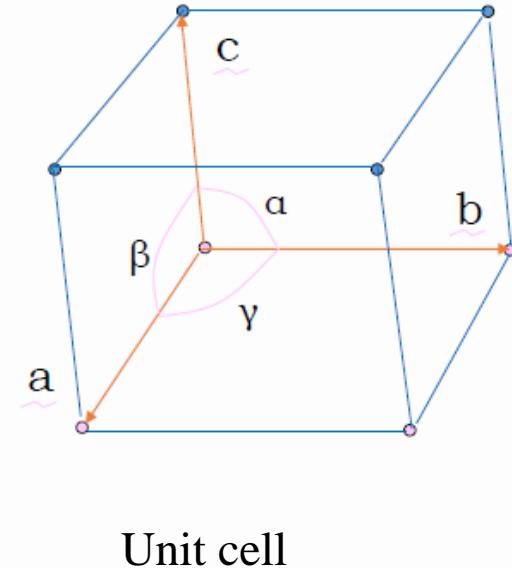


Lattice parameters: that define the shape and size of a unit cell in a crystal lattice.

a , b , and c and α , β , γ are the lattice parameters of the unit cell.

Lattice - infinite, perfectly periodic array of points in a space

Unit cell: smallest repetitive volume which contains the complete lattice pattern of a crystal. It is the smallest building block of a crystal and is representative unit of the repetitive motifs in the crystal structure.



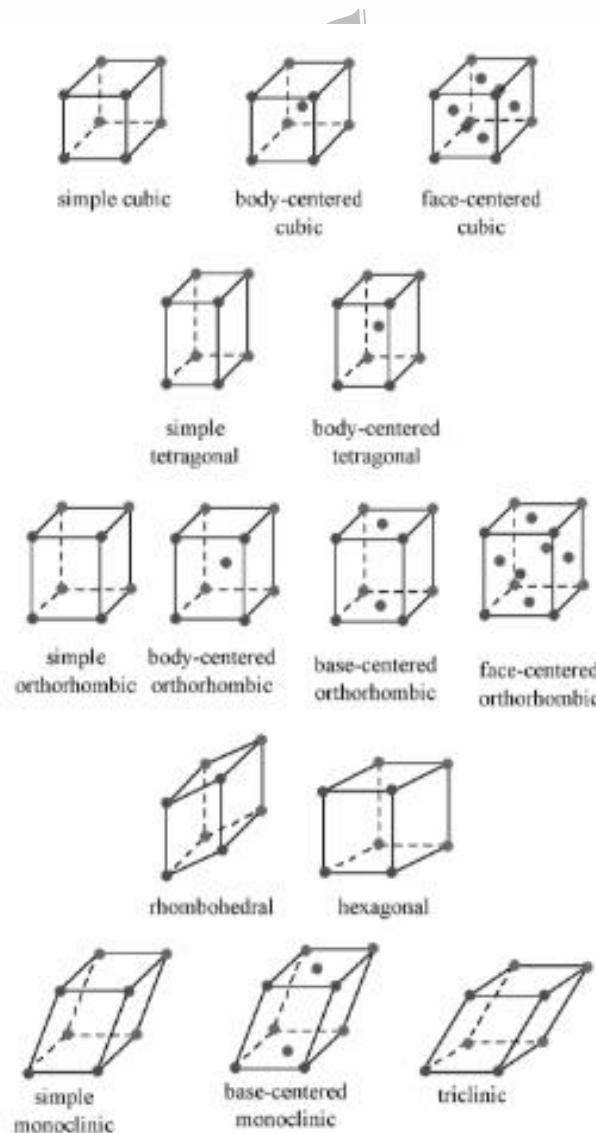
Crystal Systems : A crystal system is a fundamental classification of crystalline solids based on the symmetry and shape of their internal lattice structure.

There are seven distinct crystal systems: **Cubic, Tetragonal, Orthorhombic, Monoclinic, Triclinic, Hexagonal, and Trigonal (or Rhombohedral).**

Each system is defined by specific rules for the lengths of the unit cell's axes (a, b, c) and the angles (α, β, γ) between them, determining the overall symmetrical arrangement of atoms or molecules within the crystal.

Bravais lattices : Combining these crystal systems with different lattice point centering (primitive, body-centered, face-centered, or end-centered) results in the unique 14 Bravais lattices.

Seven crystal systems and their Bravais lattices are given in the figure.



Cubic unit cells are the repeating three-dimensional cubes in a crystal lattice, with the main types being the simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC) structures.

These units differ in the arrangement of atoms within the cube: SC has atoms only at the corners, BCC has atoms at the corners and one in the body center, and FCC has atoms at the corners and one on each face of the cube.

1. Simple Cubic (SC) Unit Cell

Atom Arrangement: Atoms are located only at the eight corners of the cube.

Atoms Per Unit Cell: One atom, as each corner atom is shared by eight unit cells ($8 \text{ corners} \times 1/8 \text{ atom} = 1 \text{ atom}$).

Coordination Number: Six, meaning each atom touches six other atoms.

Packing Efficiency: Approximately 52%, meaning only about half the volume is filled by atoms.

2. Body-Centered Cubic (BCC) Unit Cell

Atom Arrangement: Atoms at the eight corners and one additional atom at the very center of the cube.

Atoms Per Unit Cell: Two atoms (1 atom from the 8 corners and 1 atom fully within the center).

Coordination Number: Eight, as each corner atom touches the central atom, and the central atom touches eight corner atoms.

3. Face-Centered Cubic (FCC) Unit Cell

Atom Arrangement: Atoms at the eight corners and one atom at the center of each of the six faces of the cube. Also known as Cubic Close Packed (CCP).

Atoms Per Unit Cell: Four atoms (1 atom from the 8 corners and 1/2 atom from each of the 6 faces).

Coordination Number: Twelve, as each atom touches twelve other atoms.

Packing Efficiency: Approximately 74%, the highest for the common cubic structures.

Co-ordination number: For metals, in an unit cell, each atom has the same number of nearest-neighbor or touching atoms, which is termed as coordination number.

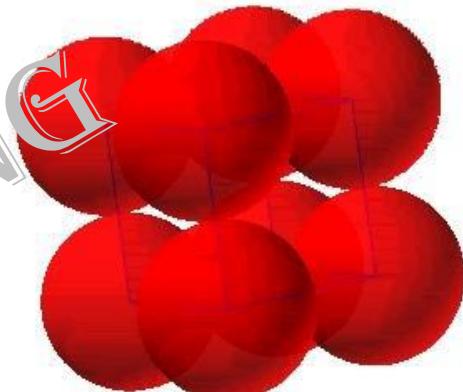
Atomic Packing Factor (APF): The APF is the sum of the sphere volumes of all atoms within a unit cell, divided by the unit cell volume.

$$\text{APF} = \frac{\text{volume of atoms in a unit cell}}{\text{total unit cell volume}}$$

Simple Cubic (SC) Unit Cells

Go, change the world

A simple cubic (SC) structure is a crystal structure where atoms are located only at the eight corners of a cube, resulting in one atom per unit cell. It is the most basic type of cubic crystal structure, though it's a loosely packed system that is rarely found in nature, with polonium (Po) being a notable exception.



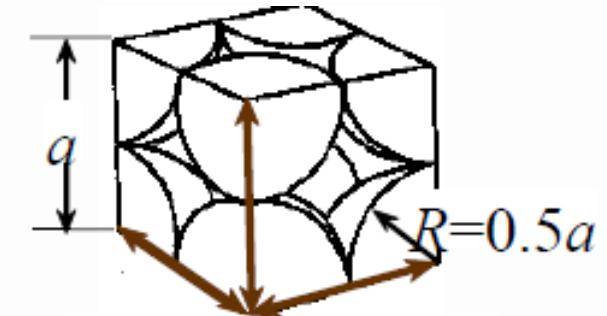
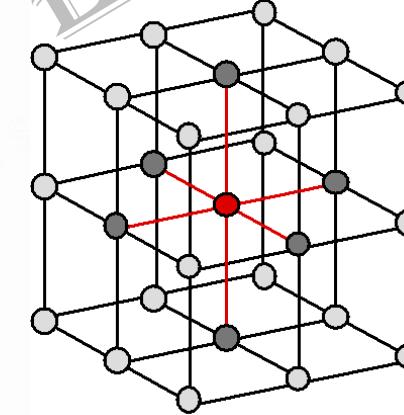
Coordination No. = 6 (# nearest neighbors)

Unit cell contains(8 (corners) x 1/8) = 1 atom/unit cell

At close-packed directions $a = 2R$

$$APF = \frac{\frac{atoms}{unit\ cell} \times volume\ per\ atom}{volume\ per\ unit\ cell}$$

$$APF = \frac{1 \times \frac{4}{3} \pi (0.5a)^3}{a^3}$$



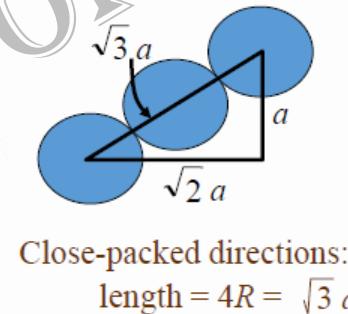
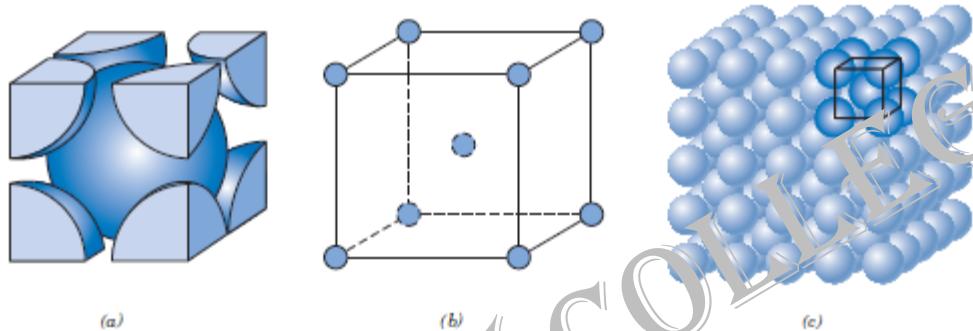
APF for a simple cubic structure = 0.52 = 52%
Example : Polonium (Po)

The Body-Centered Cubic Crystal Structure : A common metallic crystal structure has a cubic unit cell with atoms located at all eight corners and a single atom at the cube center. This is called a **body-centered cubic (BCC)** crystal structure.

A collection of spheres depicting this crystal structure is shown in Figure *c*, whereas Figures *a* and *b* are diagrams of BCC unit cells with the atoms.

Center and corner atoms touch one another along cube diagonals, and unit cell length a and atomic radius R are related through $4R = \sqrt{3}a$.

Examples : Chromium, iron, molybdenum, tantalum, tungsten exhibit a BCC structure.



Close-packed directions:
length = $4R = \sqrt{3}a$

$$APF = \frac{\frac{atoms}{unit\ cell}}{\frac{volume}{atom}} = \frac{2}{\frac{4}{3}\pi(\sqrt{3}a/4)^3} \times \frac{a^3}{\frac{volume}{unit\ cell}}$$

Coordination No. = 8

Unit cell contains 8 (corner) $\times 1/8 + 1$ centre = 2 atom/unit cell
and at close-packed directions $4R = \sqrt{3}a$

APF for a BCC structure = $0.68 = 68\%$

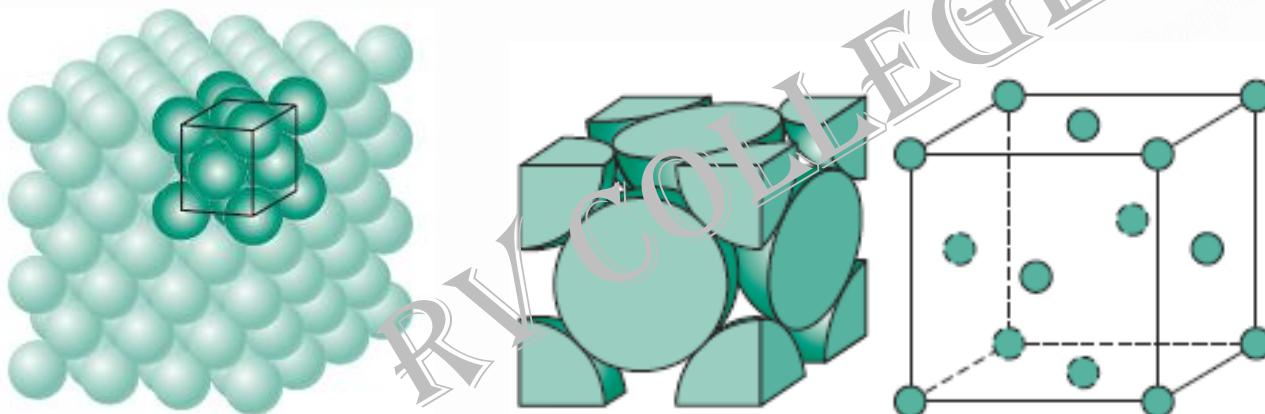
The Face-Centered Cubic (FCC) Crystal Structure : The crystal structure found for many metals has a unit cell of cubic geometry, with atoms located at each of the corners and the centers of all the cube faces. It is aptly called the face-centered cubic (FCC) crystal structure.

Figure shows the aggregate of atoms of FCC unit cell, along with a hard-sphere model for the FCC unit cell. These spheres or ion cores touch one another across a face diagonal. The cube edge length a and the atomic radius R are related through $4R = \sqrt{2}a$

Examples : Al, Cu, Au, Pb, Ni, Pt, Ag

Coordination No. = 12

Unit cell contains 8 (corner) x $1/8$ + 6 (faces) x $1/2$
 $\equiv 4$ atom/unit cell



$$\text{APF} = \frac{\frac{4}{3} \pi (\sqrt{2}a/4)^3}{a^3}$$

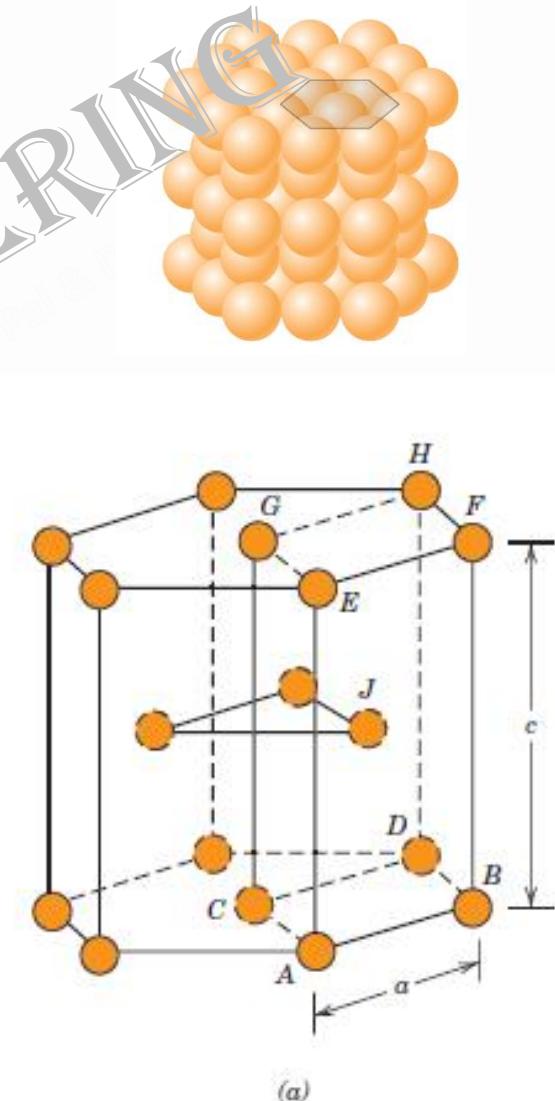
APF for a FCC structure = 0.74 = 74 %

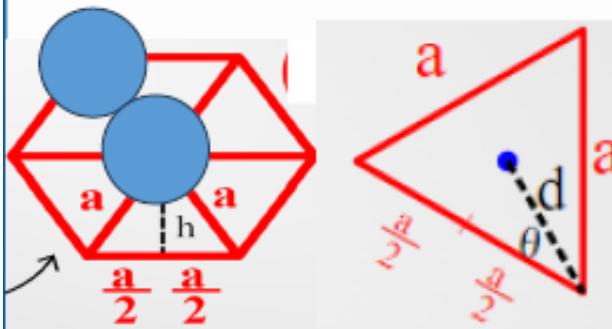
Assemblage of several Hexagonal Closed Pack (HCP) unit cells is presented in Figure.

The top and bottom faces of the unit cell consist of six atoms that form regular hexagons and surround a single atom in the center. Another plane that provides three additional atoms to the unit cell is situated between the top and bottom planes. The atoms in this midplane have as nearest neighbors atoms in both of the adjacent two planes. The equivalent of six atoms is contained in each unit cell, one-sixth of each of the 12 top and bottom face corner atoms, one-half of each of the 2 centre face atoms, and all 3 midplane interior atoms.

If a and c represent, respectively, the short and long unit cell dimensions of Figure, the ratio should be 1.633, however, for some HCP metals this ratio deviates from the ideal value.

The **coordination number** and the **atomic packing factor** for the HCP crystal structure are 12 and 0.74, respectively. The HCP metals include cadmium, magnesium, titanium, and zinc.





12 atoms on the corners with $1/6$ of their volume inside the unit cell = $12 \times 1/6 = 2$ atoms

3 atoms inside the cell, with 100 % of their volume inside the unit cell = 3 atoms

2 atoms on the faces, with $\frac{1}{2}$ of their volume inside the unit cell = $2 \times \frac{1}{2} = 1$ atom

Total atoms = 6 atoms per cell

Volume of the 6 atoms = $6 \times 4/3 \pi r^3 = 8 \pi r^3$

Volume of the HCP = Area of the hexagon x height of the prism

Area of triangle = $\frac{1}{2}$ Base * height = $\frac{1}{2} a \frac{\sqrt{3}}{2} h$

$$h = \sqrt{a^2 - \frac{a^2}{4}} = \frac{\sqrt{3}}{2} a$$

$$\text{Area of triangle} = \frac{1}{2} a \frac{\sqrt{3}}{2} a = \frac{\sqrt{3}}{4} a^2$$

$$\text{Area of Hexagon} = \text{Hexagon made of 6 triangle} = 6 \times \frac{\sqrt{3}}{4} a^2 = \frac{3\sqrt{3}}{2} a^2$$

$$\theta = 30^\circ$$

$$d = \frac{a}{2 \cos \theta} = \frac{a}{\sqrt{3}}$$

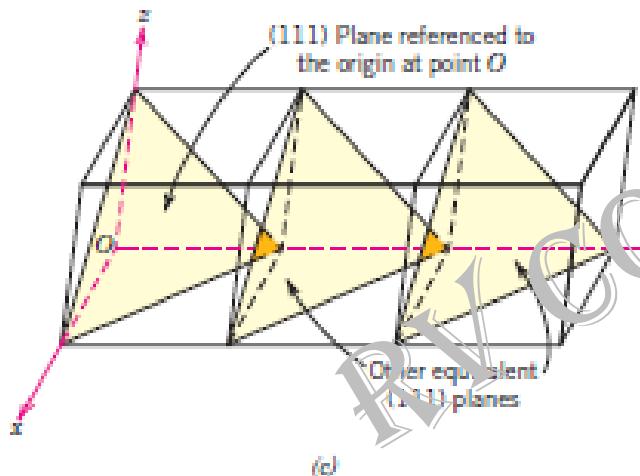
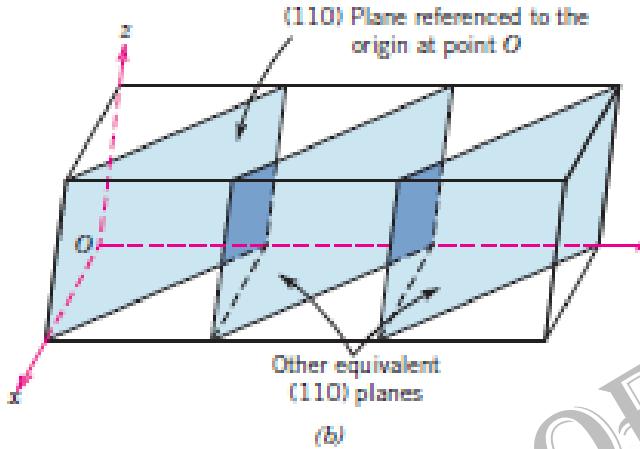
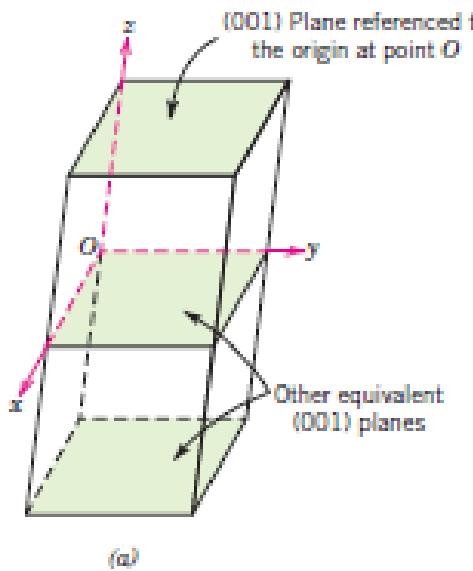
$$c = \sqrt{\frac{8}{3}} a \text{ or } 4 \sqrt{\frac{2}{3}} r$$

$$\frac{c}{2} = a^2 - d^2 = a^2 - \frac{a}{\sqrt{3}}$$

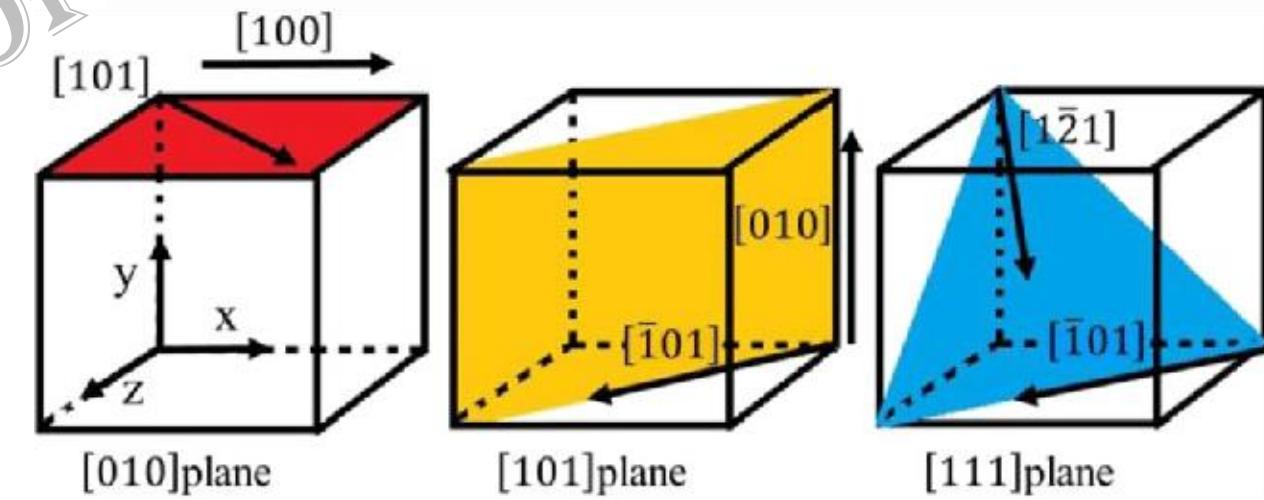
$$\text{Volume of unit cell} = \text{area of hexagon} \times c = \frac{3\sqrt{3}}{2} a^2 \times \sqrt{\frac{8}{3}} a$$

Volume of unit cell = $24 \sqrt{2} r^3$

Atomic packing factor = $\frac{\text{volume of atoms}}{\text{volume of unit cell}} = \frac{8 \pi r^3}{24 \sqrt{2} r^3} = \frac{\pi}{3\sqrt{2}} = 74\%$



Link for Crystallographic planes and directions
<https://youtu.be/fUV9v-bdF1k>





Defects and Dislocations

Thus far it has been tacitly assumed that perfect order exists throughout crystalline materials on an atomic scale. However, such an idealized solid does not exist, all contain large numbers of various defects or **imperfections**. As a matter of fact, many of the properties of materials are profoundly sensitive to deviations from crystalline perfection, the influence is not always adverse, and often specific characteristics are deliberately fashioned by the introduction of controlled amounts or numbers of particular defects. Crystalline defect refers to a lattice irregularity having one or more of its dimensions on the order of an atomic diameter.

Classification of crystalline imperfections is frequently made according to geometry or dimensionality of the defect. Several different imperfections are discussed in this chapter, including point defects (those associated with one or two atomic positions), linear (or one-dimensional) defects, and interfacial defects, or boundaries, which are two-dimensional. Impurities in solids are also discussed, because impurity atoms may exist as point defects. Finally, techniques for the microscopic examination of defects and the structure of materials are briefly described.

CRYSTAL IMPERFECTIONS

A useful classification of defects is on the basis of their Dimensionality

0D: Point defects - Vacancy, self interstitials, impurities (interstitials and substitutional), Frenkel and Schottky defect.

1D: Line defects - Edge and Screw dislocation

2D: Planer defects - Grain boundary, stacking faults, tilt, twist and twin boundary

3D: Volume defects - Voids, porosity, cracks, inclusions, precipitation, second phase

Crystal Imperfections

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VACANCIES - The simplest of the point defects is a **vacancy**, or vacant lattice site, from which an atom is missing (Figure). All crystalline solids contain vacancies and it is not possible to create such a material that is free of these defects.

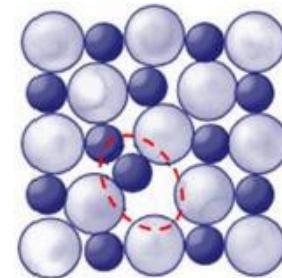
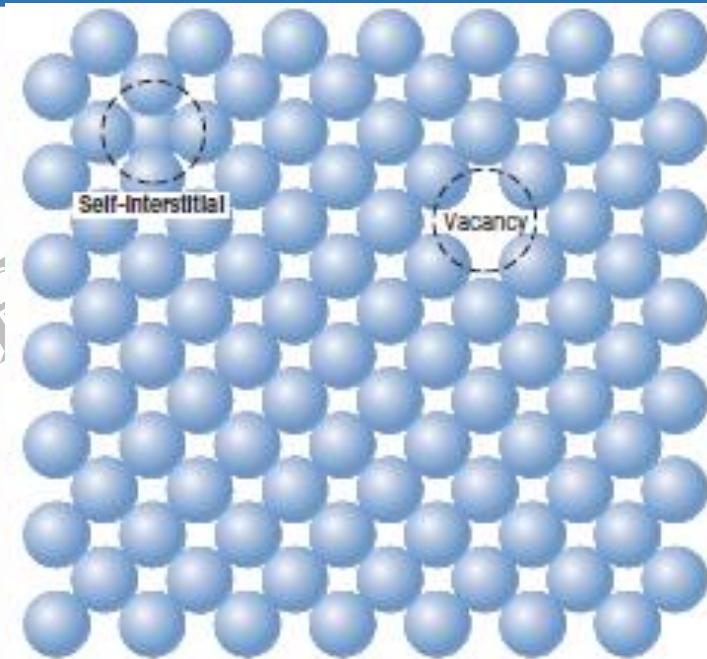
A **self-interstitial** is an extra atom from the crystal that occupies an interstitial site (a small void space that under ordinary circumstances is not occupied, shown in Figure).

In metals, a self-interstitial introduces relatively large distortions in the surrounding lattice because the atom is substantially larger than the interstitial position in which it is situated. Consequently, the formation of this defects are significantly lower than the vacancies.

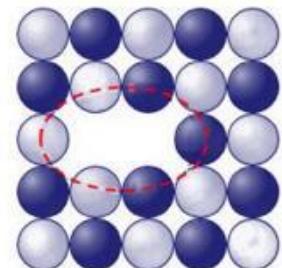
In ceramic materials, point defects occur in pair to maintain the electroneutrality.

Frenkel defect : A cation vacancy and a cation interstitials

Schottky defect : A cation – anion vacancy pair



Frenkel defect



Schottky defect

Impurities in Solids

Most familiar metals are not highly pure, and they are alloys, in which impurity atoms have been added intentionally to impart specific characteristics to the material. Ordinarily, alloying is used in metals to improve mechanical strength and corrosion resistance.

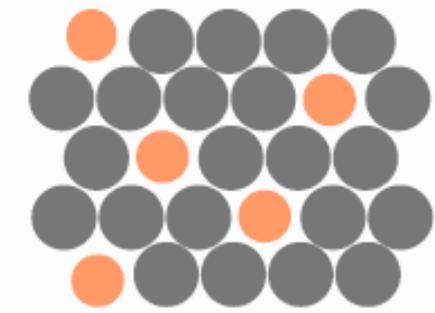
The addition of impurity atoms to a metal will result in the formation of a **solid solution**. *Solvent* represents the element or compound that is present in the greatest amount; on occasion, solvent atoms are also called *host atoms*. Solute is used to denote an element or compound present in a minor concentration.

A **solid solution** forms when, as the solute atoms are added to the host material, the crystal structure is maintained and no new structures are formed. A solid solution is compositionally homogeneous the impurity atoms are randomly and uniformly dispersed within the solid.

Impurity point defects are found in solid solutions, of which there are two types: **substitutional** and **interstitial**.

For the substitutional type, solute or impurity atoms replace or substitute for the host atoms (Figure). The factors determine the degree to which the solute dissolves in the solvent atoms are following

1. Atomic size factor
2. crystal structure
3. electronegativity
4. valences

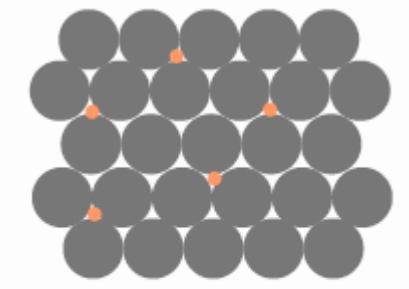


Substitutional solid soln.
(e.g., Cu in Ni)

Factors for formation of **substitutional solid solution**

1. Atomic size factor - The difference in atomic radii between the two atom types is less than about 15%.
2. Crystal structure - The crystal structures for metals of both atom types must be the same.
3. Electronegativity - The more electropositive one element and the more electronegative the other, the higher possibility is that they will form an intermetallic compound instead of a substitutional solid solution.
4. Valences - A metal will have more of a tendency to dissolve another metal of higher valence than one of a lower valence.

For **interstitial** solid solutions, impurity atoms fill the voids or interstices among the host atoms (Figure). For metallic materials that have relatively high atomic packing factors, interstitial positions are relatively small. Consequently, the atomic diameter of an interstitial impurity must be substantially smaller than that of the host atoms.



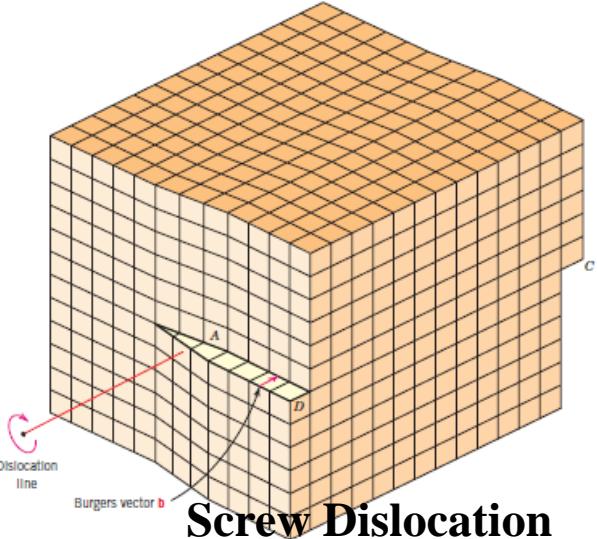
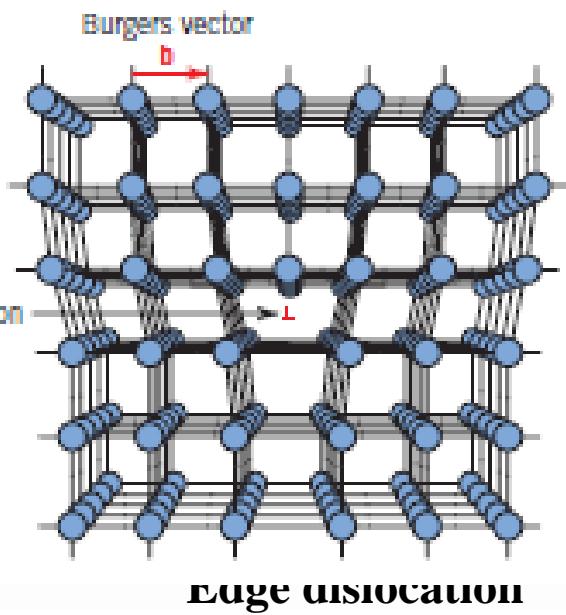
Interstitial solid soln.
(e.g., C in Fe)

Edge dislocation - A dislocation is a linear or one-dimensional defect in which an extra half plane of atoms, terminates within the crystal. This is termed an **edge dislocation** (Figure). In an edge dislocation, extra half-plane of atoms inserted in a crystal structure. Burger vector ‘ b ’ is perpendicular to dislocation line.

Edge dislocations are represented by ‘ \perp ’ or ‘ T ’ depending on whether the incomplete plane starts from the top or from the bottom of the crystal.

These two configurations are referred to as positive and negative edge dislocations respectively.

Screw Dislocation - In this dislocation, the atoms are displaced in two separate planes perpendicular to each other shown in Figure. The Burgers Vector is parallel to the screw dislocation line. It is denoted by ‘ \circlearrowright ’.



Comparison between Edge and Screw Dislocations



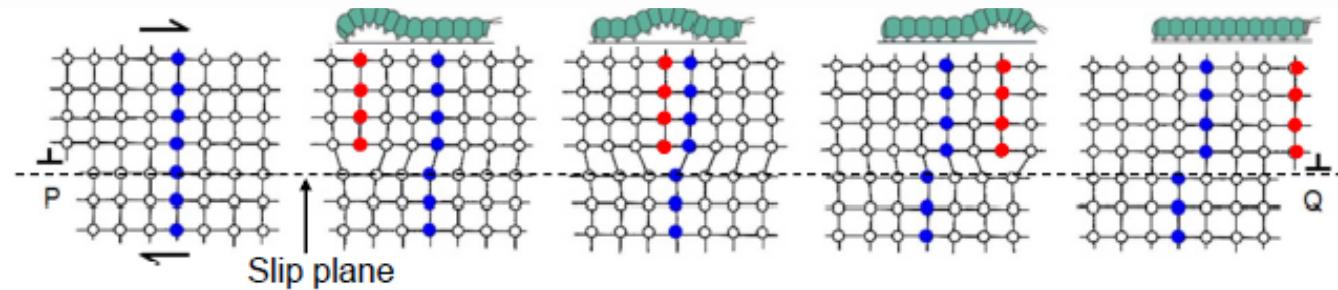
Edge Dislocation	Screw Dislocation
An edge dislocation is formed by the linear movement of a complete set of atomic planes, with the insertion of one extra half plane of atoms.	A screw dislocation is formed by the angular movement of a partial set of atomic planes on one side along a line.
The movement of a set of atoms occurs on a slip line that is perpendicular to the movement.	The movement of a set of atoms occurs along a line (dislocation line) that is parallel to the movement.
The Burger vector is perpendicular to the edge dislocation line.	The Burger vector is parallel to the screw dislocation line.
The displaced atomic planes are arranged in steps like a staircase manner.	The displaced atomic planes are arranged in a spiral staircase or screw manner.
Above the slip line with the extra half plane of atoms, it has region of compressive strain, while the bottom part has a region of tensile strain.	Around the screw dislocation, there is a region of shear strain (with stored energy).
An edge dislocation is denoted by the symbol ‘  ’	A screw dislocation is denoted by the symbol ‘  ’.

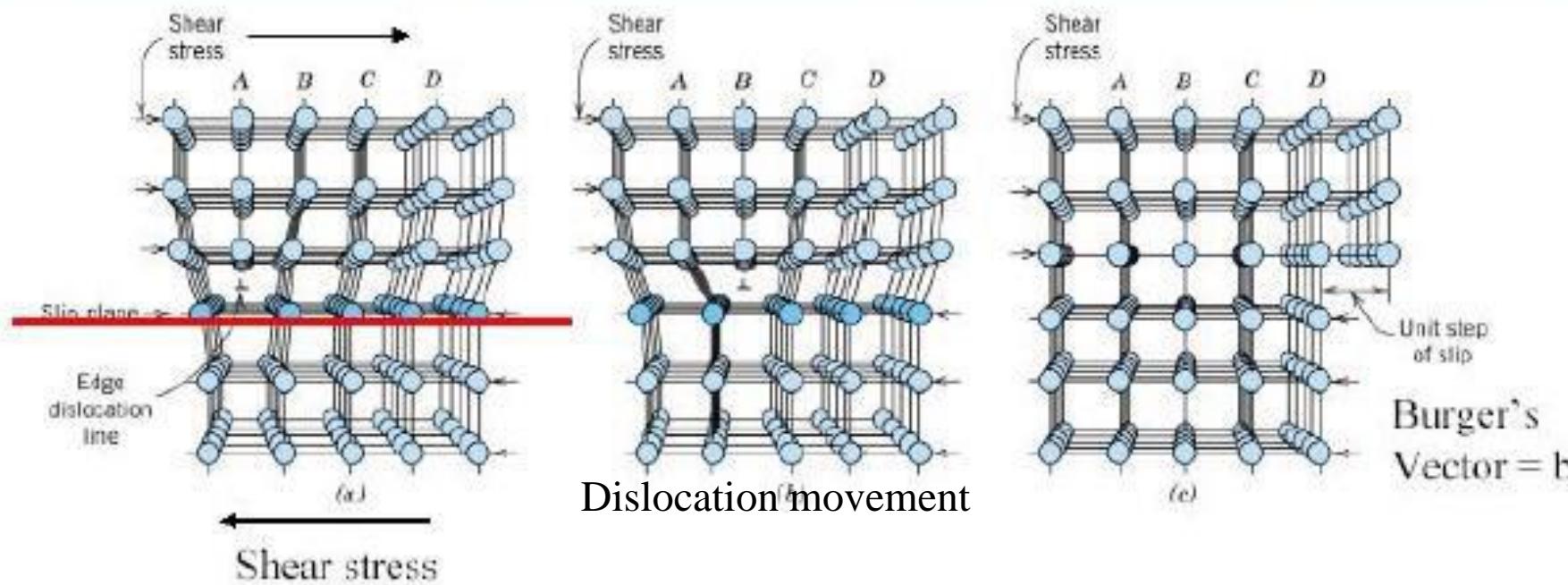
Dislocation movement and deformation

When a shear force is applied to a material, dislocations move. Real materials contain a lot of dislocations, which are introduced during solidification, heat treatments and manufacturing techniques. Dislocation motion requires the successive movement (slip) of a half plane of atom along the slipping plane. Bond across the slipping planes are broken and made in succession. The movement of dislocations produces a slip step of one Burger vector or one interatomic distance, which cause plastic deformation in crystalline materials.

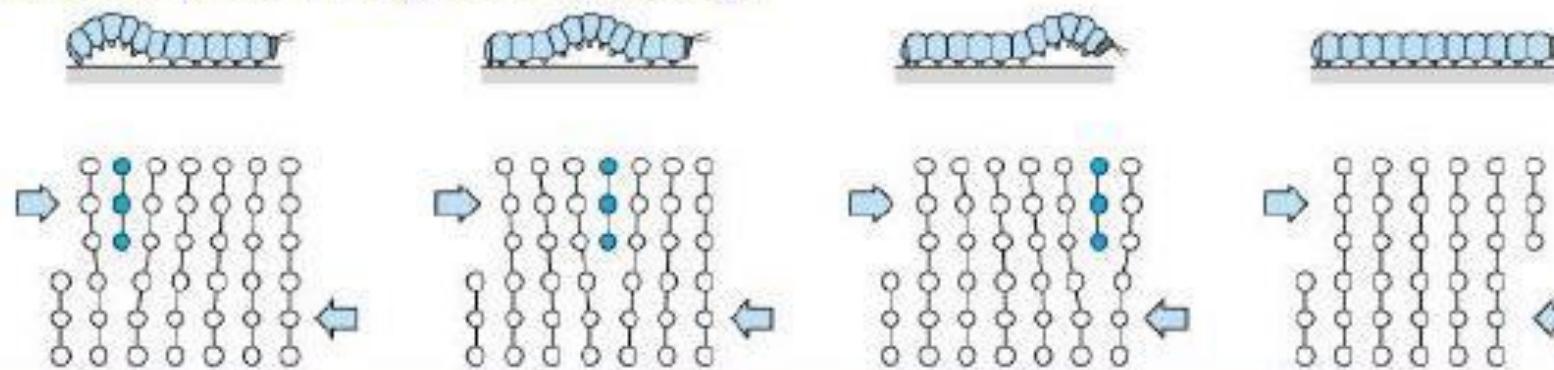
Dislocations move in steps. The edge dislocation at P moves to Q in steps as depicted by the red (half plane) and blue atoms. This movement is analogous to movement of a caterpillar. When the half-plane reaches a free surface it produces a slip step. Edge dislocations can move only on the slip plane, while screw dislocations do not have a fixed glide plane.

Since plastic deformation takes place by movement of dislocations, any hindrance to their motion will increase the strength of metals.

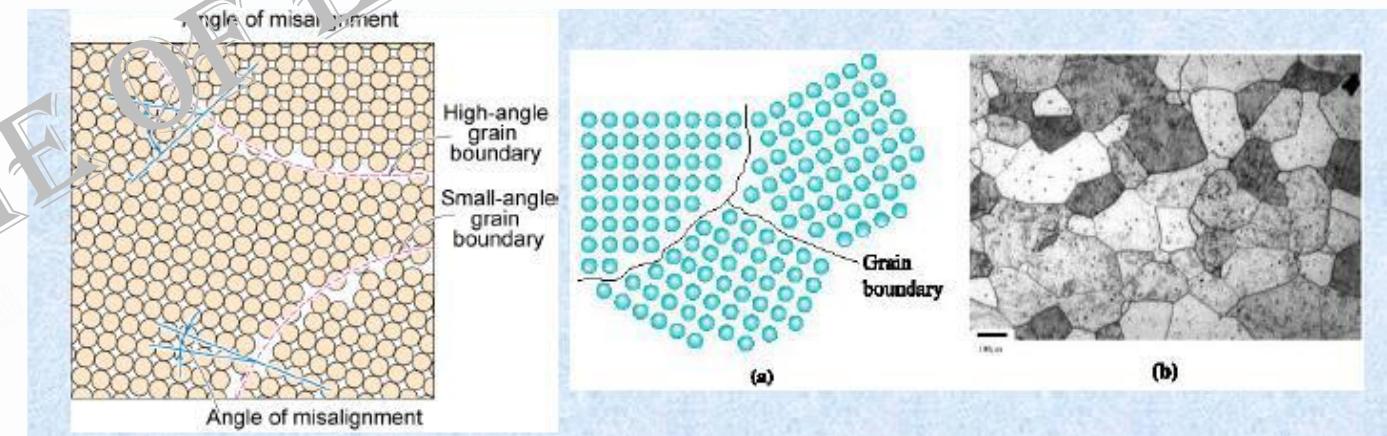
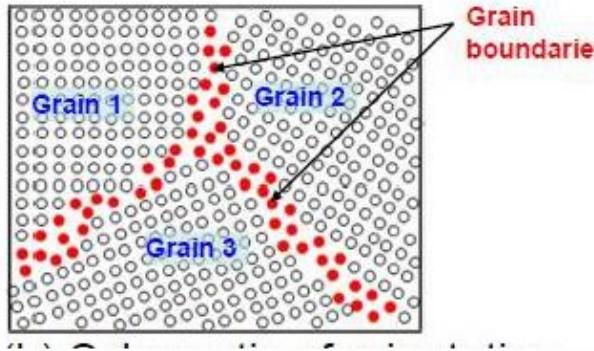




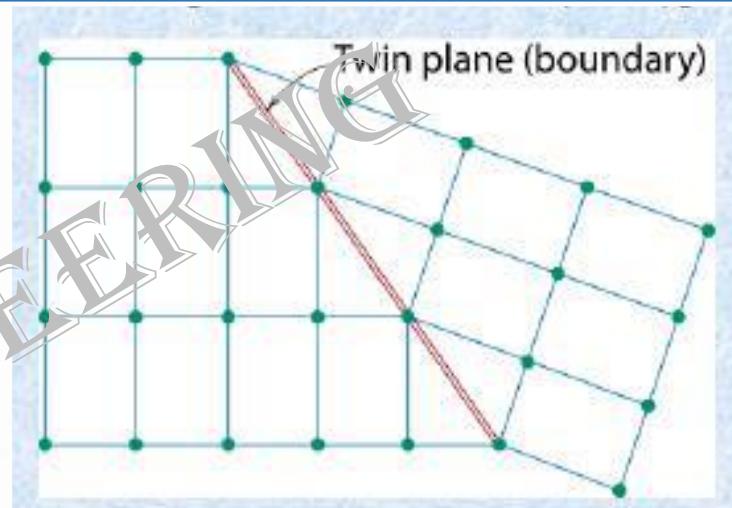
The caterpillar or rug-moving analogy



Grain Boundaries - They are the boundaries between crystals, with a change in crystal orientation across them. They are produced by the solidification process and impede dislocation motions. Presence of grain boundaries imparts strength in the metals.



Twin Boundary – A twin boundary is a special type of grain boundary across which there is a specific mirror lattice symmetry. Atoms on one side of the boundary are located in mirror-image positions of the atoms on the other side.



The region of material between these boundaries is appropriately termed a twin. Twins result from atomic displacements that are produced from applied mechanical shear forces (mechanical twins), and also during annealing heat treatments following deformation (annealing twins).

Twinning occurs on a definite crystallographic plane and in a specific direction, both of which depend on the crystal structure. Annealing twins are typically found in metals that have the FCC crystal structure, whereas mechanical twins are observed in BCC and HCP metals.

Volume defects in metals are three-dimensional flaws like pores, cracks, inclusions, and precipitates that occupy a significant volume within the crystal lattice. These defects, often introduced during processing, can act as stress concentrators and weaken the material, but can also be intentionally added for strengthening through methods like dispersion hardening.

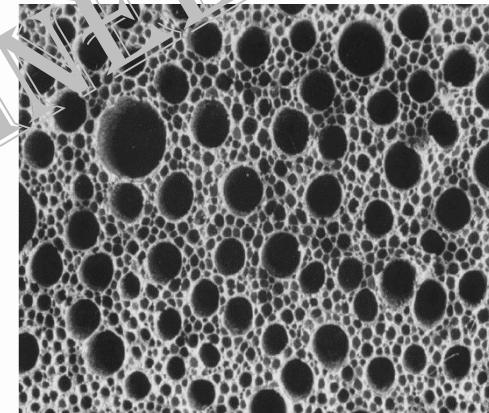
Types of volume defects

Pores and voids: Empty spaces within the metal, often formed during solidification or gas entrapment. They reduce the density and can weaken the material.

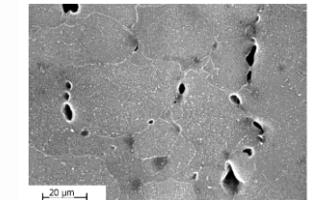
Cracks: Fractures or voids that extend through the material, acting as significant stress risers.

Inclusions: Foreign particles or impurities trapped within the metal, which can include slag from welding or other processing steps.

Precipitates: Small particles of a second phase introduced into the metal to increase its strength. These can be intentionally added to disrupt the movement of dislocations.



Pores



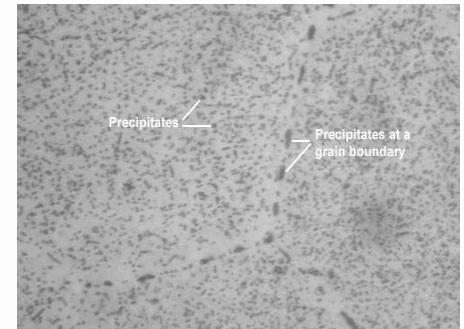
Voids



Cracks



Inclusions

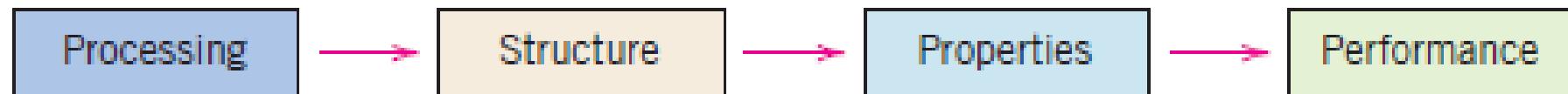


Precipitates



Types of materials

Materials engineering is, on the basis of structure–property correlations, designing or engineering the structure of a material to produce a pre-determined set of properties for right selection of materials. The interrelationship between processing, structure, properties, and performance is as depicted in the schematic diagram. The relationships of these four components, the structure of a material will depend on how it is processed. Furthermore, a material's performance will be a function of its properties.

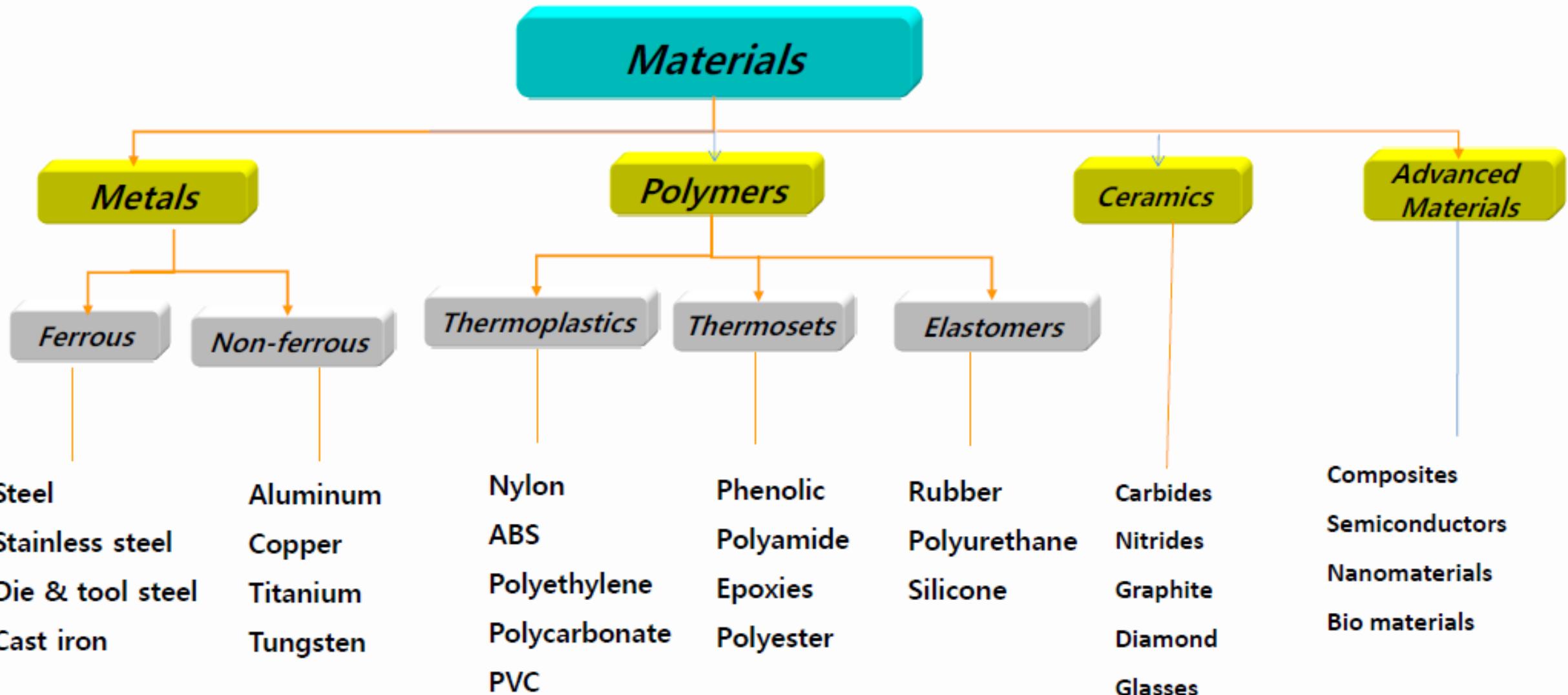


Solid materials have been classified into three basic categories: **metals, ceramics, and polymers**. This scheme is based primarily on chemical composition and atomic structure. Most materials fall into one distinct group or another.

In addition, there are composites, which are engineered combinations of two or more different materials. Another category is advanced materials, those used in high-technology applications, such as semiconductors, biomaterials, smart materials, and nano-engineered materials.

Materials - Classification

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Metals and Alloys

Metals - Materials in this group are composed of one or more metallic elements (e.g., iron, aluminium, copper, titanium, gold, and nickel), and also non-metallic elements (e.g., carbon, nitrogen, and oxygen) in relatively small amounts. Atoms in metals and their alloys are arranged in a very orderly manner and in comparison to the ceramics and polymers, are relatively dense.

With regard to **mechanical characteristics**, these materials are relatively stiff and strong, yet are ductile (i.e., capable of large amounts of deformation without fracture), and are resistant to fracture, which accounts for their widespread use in structural applications.

Metallic materials have large numbers of non localized electrons. These electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons. For example, metals are extremely good conductors of electricity and heat, and are not transparent to visible light. A polished metal surface has a lustrous appearance. In addition, some of the metals (i.e., Fe, Co, and Ni) have desirable magnetic properties.



Objects that are made of metals and metal alloys (from left to right): silverware (fork and knife), scissors, coins, a gear, a ring, and a nut and bolt.

Lustre: Metals have a shiny appearance and reflect light.

Electrical & Thermal Conductivity: They are excellent conductors of both heat and electricity because of free-moving electrons.

Malleability: Metals can be hammered or pressed into thin sheets.

Ductility: They can be drawn into thin wires.

Sonorous: Metals produce a ringing sound when struck.

High Melting & Boiling Points: Most metals have high melting and boiling points, making them useful in high-temperature environments.

Strength & Hardness: Metals are generally strong, tough, and durable, though some, like sodium and potassium, are soft enough to be cut with a knife. **Density:** Most metals are heavier than non-metals. **React with oxygen to form basic oxides.**

Construction: Iron and steel create structural beams, frames, and reinforced concrete for buildings and bridges. Other metals like aluminium are used for window frames and roofing.

Transportation: Aluminium alloys are essential for aircraft and automobile bodies and engine parts due to their lightweight properties. Steel is used for car bodies and boat hulls, while metals are also used in railway and rocket construction.

Electrical Systems: Copper's excellent conductivity makes it ideal for electrical wires, cables, and components in electronic devices and appliances.

Household Goods & Utensils: Metals like iron, copper, and stainless steel are used to make kitchen utensils, appliances, and cookware.

Medicine: Biocompatible metals such as stainless steel, titanium, and nickel are used in medical implants and devices like syringes, scalpels, and catheters.

Packaging: Aluminium foil is a popular packaging material for food storage, thanks to its ability to protect contents.

Corrosion Protection: Zinc is used to galvanize steel to prevent rusting, and other alloys like stainless steel, which contains chromium and nickel, resist corrosion in various applications.

Industrial Equipment: Metals are critical for various industrial machinery, tools, and equipment due to their strength and durability.

Jewellery : Metals are used in jewelry for their aesthetic appeal, durability, and ability to be shaped into intricate designs. Gold, silver, platinum, and palladium are popular precious metals for fine jewelry due to their beauty and resistance to corrosion. Other metals like titanium, tungsten, and stainless steel are used for their unique properties, such as extreme strength and affordability, especially in modern and costume jewelry.



Ceramics

Ceramics - Ceramics are compounds between metallic and non-metallic elements. They are most frequently oxides, nitrides, and carbides.

For example, common ceramic materials include aluminum oxide (or alumina, Al_2O_3), silicon dioxide (or silica, SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4). Traditional ceramics - those composed of clay minerals (i.e., porcelain), as well as cement and glass.

With regard to mechanical behaviour, ceramic materials are relatively stiff and strong - stiffnesses and strengths are comparable to those of the metals. In addition, they are typically very hard. Historically, ceramics have exhibited extreme brittleness (lack of ductility) and are highly susceptible to fracture. However, newer ceramics are being engineered to have improved resistance to fracture. These materials are used for cookware, cutlery, and even automobile engine parts. Furthermore, ceramic materials are typically insulated to the passage of heat and electricity i.e., have low electrical conductivities, and are more resistant to high temperatures and harsh environments than metals and polymers.

With regard to optical characteristics, ceramics may be transparent, translucent, or opaque and some of the oxide ceramics (e.g., Fe_3O_4) exhibit magnetic behaviour.



Objects made of ceramic materials - scissors, a china teacup, a building brick, a floor tile, and a glass vase.

Mechanical Properties - Hardness: Ceramics are very hard, making them resistant to scratching and abrasion. **Strength:** They possess high compressive strength, meaning they can withstand pressure.

Brittleness: This is a key characteristic; ceramics have low ductility, are easily fractured, and have poor impact resistance. **Wear Resistance:** Due to their hardness, ceramics exhibit good wear resistance.

Thermal Properties - Refractory: Ceramics can withstand very high temperatures, making them useful in high-temperature applications. **High Melting Point:** They have relatively high melting points. **Low Thermal Conductivity:** Most ceramics are poor conductors of heat, serving as effective thermal insulators. **Low Thermal Expansion:** They tend to have minimal changes in size with temperature fluctuations.

Chemical Properties - Chemical Stability & Inertness: Ceramics are very resistant to corrosion and chemical attack, making them ideal for harsh environment. **Oxidation Resistance:** They are resistant to oxidation.

Electrical Properties - Electrical Insulators: Ceramics typically lack free electrons, making them excellent electrical insulators. **Electrical Semiconductivity:** Some ceramics can be modified to have semiconducting properties, expanding their use in electronics.

Traditional Applications - Construction and Architecture: Decorative elements like wall tiles, as well as structural components such as sanitary ware, roof tiles, and various building materials. **Tableware and Cookware:** Earthenware, pottery, and high-temperature-resistant ceramics are used for dinnerware, cooking utensils, and kitchen appliances like stoves and ovens.

Electronics and Electrical Applications - Insulators: Their excellent electrical insulation properties make them ideal for use in capacitors, resistors, and various circuit boards. **Components:** Ceramics are used to make spark plugs, heating elements, and sensors due to their high thermal and electrical properties.

Aerospace and Defence - High-Temperature Components: Ceramic composites are used in aerospace for heat shields, rocket nozzles, and jet engine turbine blades. **Lightweight Applications:** Their low weight and high strength make them suitable for a variety of components in space shuttles and other aerospace applications.

Biomedical and Dental Fields - Implants and Prosthetics: Bioceramics like hydroxyapatite are used for artificial joints, dental implants, and as bone substitutes. **Dental Restorations:** Materials like zirconia and porcelain are used for dental crowns, bridges, and braces due to their strength and natural appearance.

Industrial Applications - Cutting Tools and Abrasives: High-tech ceramics such as silicon carbide and tungsten carbide are used as cutting tools and abrasives. **Filters and Bearings:** Porous ceramics serve as filter elements in chemical and environmental technologies, while self-lubricating ceramic bearings are used in industrial machinery. **Refractories:** Materials that can withstand high temperatures are crucial for lining furnaces and kilns in the chemical and other high-temperature industries.



Polymers

Polymers - Polymers include the familiar plastic and rubber materials. Many of them are organic compounds that are chemically based on carbon, hydrogen, and other non-metallic elements (i.e., O, N, and Si).

They have very large molecular structures, often chainlike in nature, that often have a backbone of carbon atoms. Some of the common and familiar polymers are polyethylene (PE), nylon, poly(vinyl chloride) (PVC), polycarbonate (PC), polystyrene (PS), and silicone rubber.

These materials have low densities, whereas their mechanical characteristics are dissimilar to the metallic and ceramic materials. They are not as stiff nor as strong as these other material types. However, on the basis of their low densities, many times their stiffness and strengths on a per-mass basis are comparable to the metals and ceramics.

In addition, many of the polymers are extremely ductile and pliable (plastic), which means they are easily formed into complex shapes. In general, they are relatively inert chemically and unreactive in a large number of environments.

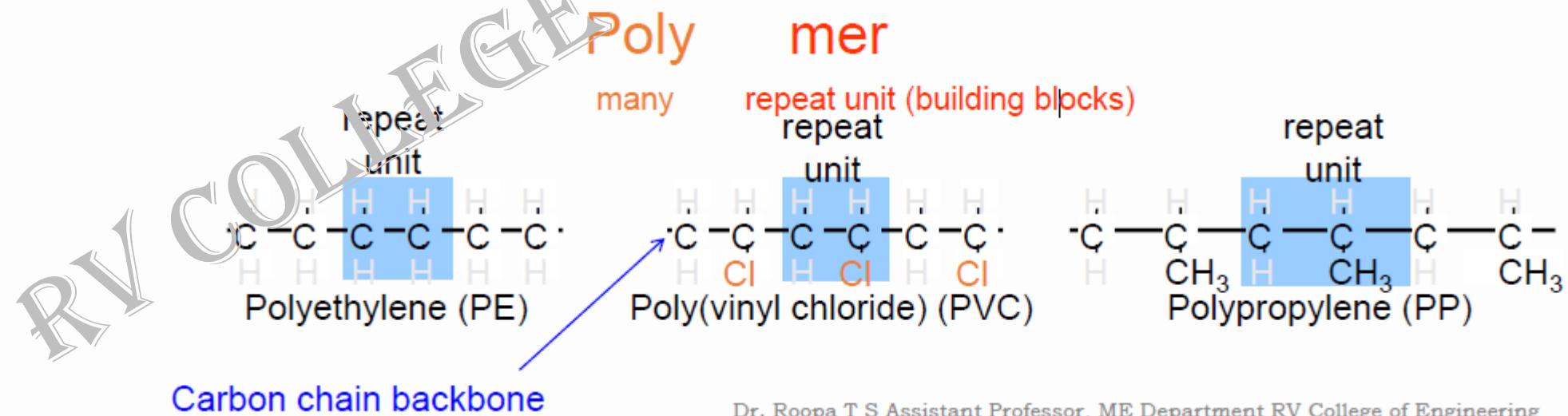
One major drawback to the polymers is their tendency to soften and/or decompose at modest temperatures, which, in some instances, limits their use. Furthermore, they have low electrical conductivities and are nonmagnetic.



Objects made of polymers

Polymers are compound consisting of long-chain molecules, each molecule made up of repeating units connected together. Polymer of high molecular weight derived either by the **addition** of any smaller molecules, as polyethylene, or by the **condensation** of many smaller molecules with the elimination of water, alcohol, or the like, as nylon. There may be thousands, even millions of units in a single polymer molecule as shown in the figure. Most polymers are based on carbon and are therefore considered organic chemicals

- **Natural polymers:** amber, wool, silk and natural rubber have been used for centuries.
- **Synthetic polymers:** synthetic rubber, phenol formaldehyde resin (or Bakelite) neoprene, nylon, polyvinyl chloride, polystyrene, polyethylene, silicone.



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Polymers can be separated into following three categories consists of plastics (1 and 2) and rubbers (3)

- 1.Thermoplastic polymers (e.g Polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene, and polyethylene terephthalate (PET)).
- 2.Thermosetting polymers (e.g Bakelite, epoxy resin, silicone, polyurethane, phenolic resin, melamine resin, and urea-formaldehyde)
- 3.Elastomers (e.g natural rubber, silicone, nitrile rubber, and polyurethane, as well as synthetic rubbers such as Styrene-Butadiene Rubber (SBR) and EPDM rubber).

Characteristics of Polymers

1. Polymers have long chain structures. The individual molecule of a polymer is very large, i.e., it may consists of thousands of similar small molecules, all bonded together covalently.
- 2.All polymers have one thing common, i.e., carbon, which further bonds with hydrogen, nitrogen, halogens or other organic or inorganic substances.
- 3.Although, polymer's structure may be crystalline in simple materials but generally they are non-crystalline solids at room temperatures. Polymers pass through a viscous stage during formation
- 4.Polymers have light weight and they can be easily fabricated and shaped.
- 5.They are poor conductors of electricity and their thermal conductivity is also low.
6. Polymers are resistant to chemical attack and decay.

Mechanical Properties - Strength: Polymers display a wide range of strengths, from low-strength to high-strength materials, depending on their molecular structure. **Elasticity:** Many polymers can stretch and deform under load and return to their original shape, a characteristic known as elastic behaviour. **Toughness:** Polymers can be tough, meaning they can undergo significant deformation before breaking. **Viscoelasticity:** Some polymers show a permanent, viscous deformation under load, which is a combination of viscous and elastic behaviour.

Chemical Properties - Reactivity: Polymers have strong covalent bonds within their chains, which contributes to their low reactivity and resistance to chemicals. **Intermolecular Forces:** The presence of intermolecular forces like hydrogen bonds and dipole-dipole interactions influence a polymer's flexibility and strength.

Biodegradability: Some natural polymers are biodegradable, while most synthetic polymers are not.

Electrical and Optical Properties - Conductivity: Many polymers are poor conductors of heat and electricity, acting as electrical insulators. **Optical Properties:** Polymers can be transparent, coloured, or opaque depending on their structure and additives.

Packaging: Polymers are used for films, containers, and bottles for food and general packaging.

Clothing & Textiles: They form synthetic fibers for clothing, sportswear, and other textile products.

Construction: Polymers are found in building materials, flooring, windows, pipes, and as adhesives and sealants.

Automotive & Transportation: Lightweight polymer components in vehicles improve fuel efficiency.

Electronics: Polymers are used in electronic components like organic LEDs (OLEDs), solar cells, and insulation.

Medical: They are used for wound dressings, artificial skin, artificial limbs, drug delivery, blood bags, and as dental polymers.

Household Goods: Polymers are found in everyday items such as buckets, kitchenware, toys, and appliance casings.

Cosmetics: They act as film formers, stabilizers, and skin-conditioning agents in cosmetics.

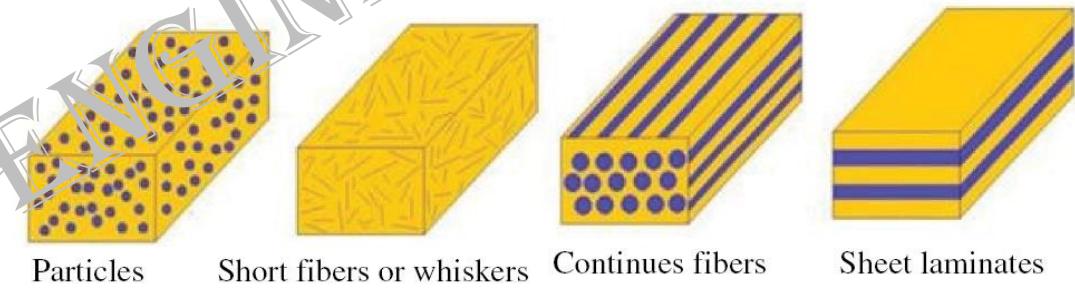
Paints & Adhesives: Many paints, varnishes, and adhesives are polymer-based.



Composites

Composite materials are engineered materials made from two or more distinct constituent materials with different physical or chemical properties, resulting in a new material with unique, often enhanced properties, like greater strength or lighter weight.

Composite materials are composed of just two phases - one is termed the **matrix**, which is continuous and surrounds the other phase, often called the **dispersed phase**. The properties of composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase. Dispersed phase geometry means the shape of the particles and the particle size, distribution, and orientation.



Classification by Matrix Material

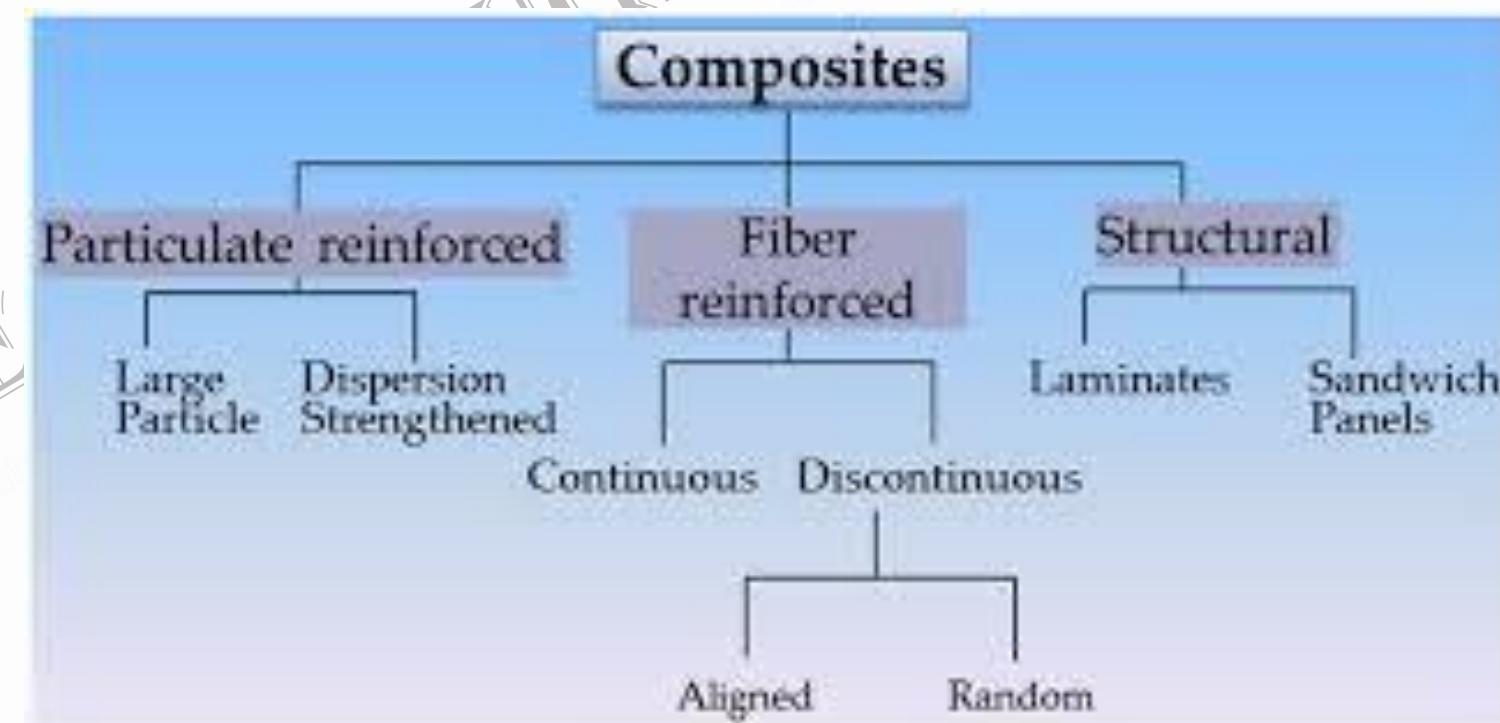
This classification focuses on the material that binds the reinforcing phase together.

Polymer Matrix Composite (PMCs): A polymer serves as the matrix material.

Metal Matrix Composites (MMCs): A metal or metal alloy is the matrix.

Ceramic Matrix Composites (CMCs): A ceramic material forms the matrix.

Classification by Reinforcements



Properties of Composite Materials

- High Strength-to-Weight Ratio
- Corrosion and Chemical Resistant
- Better Fatigue and Impact Resistance
- Design Flexibility and Moulding capabilities
- Durability and Longevity
- Tailorable Properties

Limitations

high cost, brittleness, difficult and costly repairs, and challenges with disposal and recycling. Sensitive to temperature and UV radiation, which can cause degradation, and their complex structure makes them hard to analyze and join with other materials.

Applications - Due to their tailored properties, composite materials are essential in various fields:

Aerospace: For lighter, stronger aircraft and spacecraft components.

Construction: In buildings for strength and durability.

Sports Equipment: For high-performance equipment such as bicycles and tennis rackets.

Automotive: In vehicles to reduce weight and improve fuel efficiency.



Semiconductors

Semiconductors are materials with electrical conductivity between conductors and insulators, a property that can be controlled by external factors like temperature, light, and doping to achieve specific functions like switching, amplification, and energy conversion.

These versatile properties are the foundation of modern electronics, enabling applications such as transistors, diodes, integrated circuits, solar cells, LEDs, and sensors, which are crucial in computers, smartphones, renewable energy, healthcare, and communication.

Properties

Intermediate Conductivity

Sensitivity to External Conditions: Their electrical properties are highly responsive to temperature, light, and applied electric fields.

Doping: The deliberate addition of impurities (dopants) to the semiconductor material significantly alters its conductivity, allowing for custom control of electrical current flow.

Holes and Electrons: Current conduction in semiconductors involves both the movement of electrons and "holes" (vacancies left by electrons).

Band Gap: The presence of an energy gap (band gap) determines how easily electrons can move, and this can be modified through doping.

Semiconductors are categorized into two primary types:

Intrinsic semiconductors, which are pure materials like silicon or germanium, and extrinsic semiconductors, which are intrinsic semiconductors with added impurities through doping.

Extrinsic semiconductors are further divided into n-type semiconductors, which have an excess of free electrons, and p-type semiconductors, which have an excess of "holes" (electron vacancies)

Intrinsic Semiconductors

Definition: These are pure semiconductor materials, such as silicon (Si) or germanium (Ge), without any added impurities.

Characteristics: At absolute zero, they behave like insulators, but at higher temperatures, thermal energy breaks some covalent bonds, creating an equal number of free electrons and holes.

Conductivity: Their conductivity is low and is highly dependent on temperature.

Extrinsic Semiconductors

Definition: These are intrinsic semiconductors that have been doped with a specific amount of impurities to control their electrical conductivity.

Purpose: The addition of impurities creates a significantly higher number of charge carriers (electrons or holes), making the material more conductive.

N-type Semiconductors: Formed by doping with pentavalent (Group V) impurities like phosphorus, arsenic, or antimony. These impurities contribute extra electrons, leading to an excess of negative charge carriers.

P-type Semiconductors: Created by doping with trivalent (Group III) impurities like boron, gallium, or indium. These impurities result in a deficit of electrons, creating an abundance of positive charge carriers called holes.

The End