Applied Chemistry

Chemical Bonding, Hybridization, and Solutions

1. Types of Chemical Bonding

A chemical bond is the force of attraction that holds two or more atoms together in a molecule or compound. Atoms form chemical bonds mainly in order to attain a stable electronic configuration, usually resembling that of the nearest noble gas, by either transferring, sharing, or delocalising their valence electrons. Depending on the mechanism by which this stability is achieved, chemical bonds are classified into several types, described below.

1.1 Ionic (Electrovalent) Bond

An ionic bond is formed by the complete transfer of one or more valence electrons from a metal atom (which loses electrons to form a positively charged cation) to a non-metal atom (which gains electrons to form a negatively charged anion). The resulting oppositely charged ions are then held together by strong electrostatic forces of attraction, forming an ionic compound. Ionic compounds are typically formed between elements with a large difference in electronegativity, generally between a metal and a non-metal.

1.2 Covalent Bond

A covalent bond is formed by the mutual sharing of one or more pairs of valence electrons between two atoms, usually both non-metals, such that each atom attains a stable electronic configuration. Depending on the number of electron pairs shared, covalent bonds may be single, double, or triple bonds. Covalent bonds are typically formed between elements with similar or comparable electronegativities.

1.3 Metallic Bond

A metallic bond is the force of attraction that holds atoms together in a metal, arising from the electrostatic attraction between positively charged metal ions, arranged in a regular lattice structure, and a surrounding “sea” of freely moving, delocalised valence electrons that are not associated with any particular atom. This delocalisation of electrons accounts for many characteristic properties of metals, including their high electrical and thermal conductivity, malleability, and ductility.

1.4 Hydrogen Bond

A hydrogen bond is a relatively weak type of bond (much weaker than ionic, covalent, or metallic bonds) that forms due to the electrostatic attraction between a hydrogen atom, which is covalently bonded to a small, highly electronegative atom (typically fluorine, oxygen, or nitrogen), and a lone pair of electrons on a nearby electronegative atom, either within the same molecule or in a neighbouring molecule. Hydrogen bonding is responsible for many important properties of substances such as water, including its unusually high boiling point, and plays a crucial role in the structure of biological molecules such as DNA and proteins.

The four types of chemical bonding, along with examples of each, are summarised below:

Type of Bond	Formation	Examples
Ionic (Electrovalent) Bond	Formed by the complete transfer of one or more electrons from a metal atom to a non-metal atom, resulting in oppositely charged ions held together by electrostatic force of attraction	NaCl (sodium chloride), MgO (magnesium oxide), $CaCl_2$ (calcium chloride), KBr (potassium bromide)
Covalent Bond	Formed by the mutual sharing of one or more pairs of electrons between two atoms, usually between two non-metal atoms	H_2 (hydrogen), Cl_2 (chlorine), H_2O (water), CH_4 (methane), CO_2 (carbon dioxide)
Metallic Bond	Formed by the electrostatic attraction between positively charged metal ions (arranged in a lattice) and a surrounding "sea" of freely moving, delocalised valence electrons	Copper (Cu), Iron (Fe), Aluminium (Al), Sodium (Na), and other metals and alloys
Hydrogen Bond	A relatively weak bond formed due to the electrostatic attraction between a hydrogen atom (covalently bonded to a highly electronegative atom such as F, O, or N) and a lone pair of electrons on a nearby electronegative atom	Water (H_2O), Hydrogen fluoride (HF), Ammonia (NH_3), and biological molecules such as DNA and proteins

2. Hybridization

Hybridization is the concept of mixing (or combining) atomic orbitals of comparable energy within an atom, to form a new set of equivalent orbitals, called hybrid orbitals, which are then used by the atom to form covalent bonds with other atoms. Hybrid orbitals have shapes and energies different from the pure atomic orbitals from which they are formed, and they are oriented in space in specific geometric arrangements that minimise electron pair repulsion, thereby determining the overall shape of the resulting molecule.

The type of hybridization exhibited by a central atom in a molecule, along with the resulting molecular geometry, bond angle, and example, is summarised in the table below:

Type of Hybridization	Orbitals Mixed	Geometry	Bond Angle	Example
sp	One s + one p orbital	Linear	180°	$BeCl_2$ (beryllium chloride)
sp^2	One s + two p orbitals	Trigonal planar	120°	BF_3 (boron trifluoride)
sp^3	One s + three p orbitals	Tetrahedral (regular)	109.5°	CH_4 (methane)
sp^3 (with one lone pair)	One s + three p orbitals	Pyramidal (distorted tetrahedral)	≈107°	NH_3 (ammonia)
sp^3 (with two lone pairs)	One s + three p orbitals	Bent / angular (distorted tetrahedral)	≈104.5°	H_2O (water)

2.1 sp Hybridization — Example: $BeCl_2$

In the beryllium chloride ($BeCl_2$) molecule, the central beryllium atom undergoes sp hybridization, mixing one s orbital and one p orbital to form two equivalent sp hybrid orbitals. These two hybrid orbitals are oriented at 180° to each other, resulting in a linear molecular geometry for $BeCl_2$, with the two chlorine atoms positioned on either side of the central beryllium atom.

2.2 sp^2 Hybridization — Example: BF_3

In the boron trifluoride (BF_3) molecule, the central boron atom undergoes sp^2 hybridization, mixing one s orbital and two p orbitals to form three equivalent sp^2 hybrid orbitals. These three hybrid orbitals lie in the same plane, oriented at 120° to one another, resulting in a trigonal planar molecular geometry for BF_3, with the three fluorine atoms positioned symmetrically around the central boron atom.

2.3 sp^3 Hybridization — Examples: CH_4, NH_3, H_2O

In the methane (CH_4) molecule, the central carbon atom undergoes sp^3 hybridization, mixing one s orbital and three p orbitals to form four equivalent sp^3 hybrid orbitals. These four hybrid orbitals are oriented at 109.5° to one another, pointing towards the corners of a regular tetrahedron, resulting in a tetrahedral molecular geometry for CH_4, with all four hydrogen atoms bonded to the central carbon atom.

The nitrogen atom in ammonia (NH_3) and the oxygen atom in water (H_2O) also undergo sp^3 hybridization; however, in these molecules, one or two of the four sp^3 hybrid orbitals are occupied by lone pairs of electrons instead of being used to form bonds with other atoms:

- In NH_3, one of the four sp^3 hybrid orbitals contains a lone pair, while the remaining three form bonds with three hydrogen atoms, resulting in a pyramidal molecular shape, with a bond angle of approximately 107° (slightly less than the ideal 109.5°, due to the greater repulsion exerted by the lone pair compared to a bonded pair).
- In H_2O, two of the four sp^3 hybrid orbitals contain lone pairs, while the remaining two form bonds with two hydrogen atoms, resulting in a bent (angular) molecular shape, with a bond angle of approximately 104.5° (further reduced from the ideal tetrahedral angle, due to the even greater repulsion exerted by two lone pairs).

3. Structure of Diamond and Graphite

Diamond and graphite are both naturally occurring allotropes of carbon, meaning they are different structural forms of the same element, carbon, but they exhibit strikingly different physical properties due to differences in the hybridization of carbon and the resulting arrangement of atoms within each structure.

Property	**Diamond**	**Graphite**
Hybridization of carbon	sp^3	sp^2
Structure	Each carbon atom is tetrahedrally bonded to four other carbon atoms, forming a rigid, three-dimensional network	Each carbon atom is bonded to three other carbon atoms in a plane, forming flat hexagonal layers, with weak forces holding the layers together
Bonding	Strong covalent bonds in all three dimensions	Strong covalent bonds within each layer; weak van der Waals forces between layers
Physical property	Extremely hard; poor conductor of electricity	Soft and slippery (layers slide over each other); good conductor of electricity due to delocalised electrons within each layer

Common use	Cutting tools, abrasives, jewellery	Lubricant, pencil "lead", electrodes

This comparison illustrates an important general principle in chemistry: the physical and chemical properties of a substance are determined not only by its chemical composition, but also significantly by the type of bonding and the structural arrangement of its constituent atoms.

4. Solution — Idea of Solute, Solvent and Solution

A solution is a homogeneous mixture formed when one or more substances (solutes) are completely and uniformly dissolved in another substance (the solvent), such that the resulting mixture has a uniform composition and appearance throughout.

- Solute: The substance that is dissolved in a solution, and which is generally present in a smaller quantity compared to the solvent.
- Solvent: The substance in which the solute is dissolved, and which is generally present in a larger quantity, giving the solution its overall physical state (solid, liquid, or gas).
- Solution: The resulting homogeneous mixture formed when a solute is dissolved in a solvent, such as salt dissolved in water (forming a saline solution) or sugar dissolved in water (forming a sugar solution).

5. Methods to Express the Concentration of a Solution

The concentration of a solution refers to the amount of solute present in a given quantity of solvent or solution. Since different applications require concentration to be expressed in different ways, several methods are commonly used in chemistry, summarised in the table below:

Method	**Formula**	**Description**
Molarity (M)	M = Number of moles of solute / Volume of solution (in litres)	The number of moles of solute dissolved per litre of solution; SI-related unit is mol/L
Parts per Million (ppm)	ppm = (Mass of solute / Mass of solution) × 10^6	Used to express the concentration of very dilute solutions, such as trace impurities or pollutants

Mass Percentage (% w/w)	Mass % = (Mass of solute / Mass of solution) × 100	The mass of solute present in 100 units of mass of the solution
Volume Percentage (% v/v)	Volume % = (Volume of solute / Volume of solution) × 100	The volume of solute (liquid) present in 100 units of volume of the solution; commonly used for liquid-liquid solutions
Mole Fraction (x)	$x_1 = n_1 / (n_1 + n_2)$	The ratio of the number of moles of one component to the total number of moles of all components present in the solution; dimensionless

Among these, molarity is the most widely used method of expressing concentration in chemical laboratory work, since it directly relates the number of moles of solute (which determines the number of reacting particles) to a conveniently measurable volume of solution, making it particularly useful for calculations involving chemical reactions and titrations.

Worked Example:
Calculate the molarity of a solution prepared by dissolving 5.85 g of sodium chloride (NaCl, molar mass 58.5 g/mol) in enough water to make 500 mL of solution.

Solution: Number of moles of NaCl = Mass / Molar mass = 5.85 / 58.5 = 0.1 mol. Volume of solution = 500 mL = 0.5 L. Molarity, M = Moles of solute / Volume of solution (in litres) = 0.1 / 0.5 = 0.2 mol/L. The molarity of the solution is 0.2 M.

6. Multiple Choice Questions (MCQs)

Answer the following questions by selecting the most appropriate option.

1. An ionic bond is formed by:
A) Mutual sharing of electrons
B) Complete transfer of electrons from one atom to another
C) Overlap of orbitals only
D) Delocalisation of electrons over a metal lattice

2. Which of the following is an example of a covalent compound?
A) NaCl
B) MgO
C) H_2O

D) KBr

3. The metallic bond arises due to the attraction between:

A) Two non-metal atoms sharing electrons

B) Positive metal ions and a sea of delocalised electrons

C) Two oppositely charged ions

D) A hydrogen atom and a lone pair of electrons

4. Hydrogen bonding is commonly observed in which of the following molecules?

A) CH_4

B) H_2O

C) CCl_4

D) N_2

5. The type of hybridization present in $BeCl_2$ is:

A) sp

B) sp^2

C) sp^3

D) sp^3d

6. The type of hybridization present in BF_3 is:

A) sp

B) sp^2

C) sp^3

D) sp^3d^2

7. The type of hybridization present in CH_4 is:

A) sp

B) sp^2

C) sp^3

D) sp^3d

8. The molecular geometry of $BeCl_2$, based on sp hybridization, is:

A) Linear

B) Trigonal planar

C) Tetrahedral

D) Pyramidal

9. The bond angle in a molecule with sp^2 hybridization (such as BF_3) is approximately:

A) 90°

B) 109.5°

C) 120°

D) 180°

10. The shape of the NH_3 molecule is:

A) Linear

B) Trigonal planar
C) Pyramidal
D) Bent

11. The shape of the H_2O molecule is:

A) Linear
B) Tetrahedral
C) Trigonal planar
D) Bent (angular)

12. In diamond, each carbon atom is:

A) sp hybridized and linearly bonded
B) sp^2 hybridized and bonded to three other carbon atoms
C) sp^3 hybridized and tetrahedrally bonded to four other carbon atoms
D) Not hybridized at all

13. Graphite is a good conductor of electricity because:

A) It has ionic bonding
B) It contains delocalised electrons that can move within each layer
C) It has no covalent bonds
D) It is a metal

14. Molarity of a solution is defined as:

A) Moles of solute per kilogram of solvent
B) Moles of solute per litre of solution
C) Grams of solute per litre of solvent
D) Moles of solvent per litre of solution

15. Mole fraction of a component in a solution is defined as the ratio of:

A) Mass of that component to the total mass of solution
B) Moles of that component to the total moles of all components in the solution
C) Volume of that component to the total volume
D) Moles of that component to the moles of solvent only

Answer Key

1. B) Complete transfer of electrons from one atom to another | 2. C) H_2O | 3. B) Positive metal ions and a sea of delocalised electrons | 4. B) H_2O | 5. A) sp | 6. B) sp^2 | 7. C) sp^3 | 8. A) Linear | 9. C) 120° | 10. C) Pyramidal | 11. D) Bent (angular) | 12. C) sp^3 hybridized and tetrahedrally bonded to four other carbon atoms | 13. B) It contains delocalised electrons that can move within each layer | 14. B) Moles of solute per litre of solution | 15. B) Moles of that component to the total moles of all components in the solution

7. Broad / Long Answer and Numerical Questions

1. Define ionic bond, covalent bond, metallic bond, and hydrogen bond, giving one example of a compound for each type.

2. Explain the formation of an ionic bond with reference to the formation of sodium chloride (NaCl) from sodium and chlorine atoms.

3. Explain the concept of hybridization. Describe sp, sp^2, and sp^3 hybridization, giving one example of each along with the resulting molecular geometry.

4. Explain the shape and hybridization of the $BeCl_2$ molecule.

5. Explain the shape and hybridization of the BF_3 molecule.

6. Explain the shape and hybridization of the CH_4, NH_3, and H_2O molecules, and explain why their bond angles differ from the ideal tetrahedral angle in the case of NH_3 and H_2O.

7. Describe the structure and bonding in diamond, and explain why diamond is extremely hard.

8. Describe the structure and bonding in graphite, and explain why graphite is soft, slippery, and a good conductor of electricity.

9. Define solute, solvent, and solution. Explain the different methods used to express the concentration of a solution: molarity, ppm, mass percentage, volume percentage, and mole fraction.

10. Calculate the molarity of a solution prepared by dissolving 5.85 g of sodium chloride (NaCl, molar mass 58.5 g/mol) in enough water to make 500 mL of solution.