

Stoichiometry

Student Learning Outcomes

After studying this chapter, students will be able to:

- State the formulae of common elements and compounds.
- Define molecular formula of a compound as the number and type of different atoms in one molecule
- Define empirical formula of a compound as the simplest whole number ratio of different atoms in a Molecule.
- Deduce the formula and name of a binary ionic compounds from ions given relevant information
- Deduce the formula of a molecular substance from the given structure of molecules.
- Use the relationship amount of substance = mass / molar mass to calculate number of moles, mass, molar mass, relative mass (atomic/molecular/formula) and number of particles
- Define mole as amount of substance containing Avogadro's number 6.02×10^{23} of particles
- Explain the relationship between a mole and Avogadro's constant.
- Construct chemical equations and ionic equations to show reactants forming products, including state symbols.
- Deduce the symbol equation with state symbols for a chemical reaction given relevant information.

Stoichiometry is an important concept in chemistry which helps us to calculate the amounts of reactants and products by using a balanced chemical equation. It is based on the law of conservation of mass which states that matter can neither be created nor destroyed. Therefore, the total mass of all the reactants must be equal to the total mass of all the products. The stoichiometric coefficient used to balance a chemical equation provides the mole ratio between reactants and products.

Stoichiometry is used in industry quite often to determine the amount of raw materials required to produce the desired amount of the products.

4.1 Chemical formula

Elements exist in different forms in this world. There are elements which exist in the form of aggregate of atoms. These elements are represented by their symbols alone, for example, Na, Ca, C, Fe, etc. On the other hand, elements like O_2 , N_2 , H_2 exist as discrete molecules in which their atoms are chemically bonded to each other. In ozone, three atoms of oxygen are bonded to each other, so its chemical formula is O_3 .

Similar to elements, chemical compounds also exist in different forms. Common salt i.e. sodium chloride exists in the form of ions which are bonded together in the form of a crystal. Since ratio between its ions is 1:1, sodium chloride is represented by a formula unit $NaCl$. Similarly, the other ionic compounds are represented by their formula units which show the minimum ratio present between their ions. Examples are $CaCl_2$, KBr and $BaCl_2$, etc.

Covalent compounds generally exist in discrete molecules in which atoms are bonded together. For example, water exists as molecules which are represented by the chemical formula H_2O . It shows that in one molecule of water two atoms of hydrogen are bonded to one atom of oxygen. Similarly, chemical compound, ammonia is represented by NH_3 and methane gas is represented by CH_4 . A chemical compound is thus, represented by a chemical formula which is called the molecular formula of that compound and which shows all the types of atoms bonded together in one molecule of that compound. Examples of covalent compounds are HCl , HF , H_2S , PH_3 , H_2O_2 , H_2SO_4 , CO_2 , CO , C_6H_6 , etc.

Exercise

How would you differentiate between the chemical formula of an element and that of a compound? Give examples. Write down the names of ionic and covalent compounds whose formulas have been given in this article.

4.2 Empirical Formula

Empirical Formula of a compound shows the simplest whole number ratio of atoms present in that compound. All the ionic compounds are represented by their empirical formulas. These formulas show the simplest ratio present between their ions. The empirical formula of calcium fluoride is CaF_2 which shows the ratio present between calcium and fluoride ions in its crystal.

For covalent chemical compounds, which exist as molecules, the empirical formulas may be different from their molecular formulas. For example, hydrogen

peroxide is represented by its molecular formula H_2O_2 ; its empirical formula will be HO . Similarly, a benzene molecule has C_6H_6 as its molecular formula; so its empirical formula will be CH . For water, the molecular formula and the empirical formula are both the same i.e. H_2O because there does not exist any minimum ratio between hydrogen and oxygen atoms.

Since an empirical formula does not tell us the actual number of atoms present in that compound, rather it represents the simplest ratio between atoms, it is possible that some compounds may have the same empirical formula. For example, both benzene (C_6H_6) and acetylene (C_2H_2) have the same empirical formula CH .

Exercise

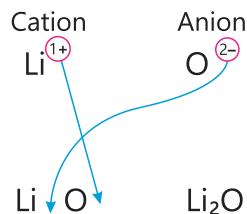
Give two examples of the compounds which have same empirical and molecular formulas.

4.3 Chemical Formulas of Binary Ionic Compounds

In order to write down the formula of an ionic compound, first identify the cations and anions and the number of charges present on them. Finally combine the two ions together to form an electrically neutral compound.

If you know the name of binary ionic compound, you can write its chemical formula. Start by writing symbol of cation with its charge. Then write the symbol of anion with its charge and find out how many of these ions are needed to give an electrically neutral compound. For example, write down the formula of lithium oxide. The symbol of lithium cation with its single positive charge is Li^+ . The symbol of anion is O^{2-} .

Let us now apply crisscross method to write the formula. In this method, the numerical value of each of the ion charges is crossed over to become the subscript of the other ion. Signs of the charges are then dropped.



Write down the formula of Aluminium oxide.



Write down the formula of Magnesium nitride.



Table (4.1) shows some important atoms, their ions and the charges on the ions



Interesting Information!

The composition of all the chemical products we use in our lives, such as shampoos, perfumes, soaps and fertilizers are formed using stoichiometric calculations. Without stoichiometry the chemical industry does not exist.

Table (4.1) Atoms and their Cations and Anions

Atoms and their Cations with charges		Atoms and their Anions and Cations with charges	
Atom	Charge	Atom	Charge
H	H ¹⁺	O	O ²⁻
Na	Na ¹⁺	N	N ³⁻
Li	Li ¹⁺	Cl	Cl ¹⁻
K	K ¹⁺	Br	Br ¹⁻
Mg	Mg ²⁺	I	I ¹⁻
Ca	Ca ²⁺	Cu	Cu ¹⁺ , Cu ²⁺
Ba	Ba ²⁺	Fe	Fe ²⁺ , Fe ³⁺
Zn	Zn ²⁺	Sn	Sn ²⁺ , Sn ⁴⁺
Al	Al ³⁺	Ni	Ni ²⁺

4.4 Chemical Formulas of Compounds

Molecular formula of a compound can be found out if we know its empirical formula. To calculate the empirical formula of a compound, you need to determine the simplest whole-number ratio of atoms in the compound. This can be done by using experimental data on the mass percent composition of the compound. Molecular formula is then calculated by the following relationship.

$$\text{Molecular formula} = n (\text{Empirical Formula})$$

$$\text{Where } n = \frac{\text{Molar Mass}}{\text{Empirical Formula mass}}$$

For example, the empirical formula of hydrogen peroxide is HO. Its molar mass is 34. Its molecular formula will then be

$$n = \frac{34}{17} = 2$$

$$\text{Molecular formula} = (\text{HO})_2 = \text{H}_2\text{O}_2$$

If for a compound the value of n is one, then its molecular formula is the same as its empirical formula.

Exercise

Write down the names of three such compounds which have different empirical and molecular formulas.

Sample Problem:

Empirical formula of a compound is CH . Its molecular mass is 78 g mol^{-1} . Find out its molecular formula.

Solution:

$$\begin{aligned}\text{Empirical Formula} &= \text{CH} & \text{Molecular mass} &= 78 \text{ g mol}^{-1} \\ \text{Molecular formula} &= n(\text{Empirical formula}) \\ n &= \text{molar mass} / \text{empirical formula mass} \\ &= \frac{78}{13} = 6 \\ \text{Molecular Formula} &= (\text{CH})_6 = \text{C}_6\text{H}_6\end{aligned}$$

Exercise

1. The empirical formula of a compound is CH_2O . Its molar mass is 180 g mol^{-1} . Determine its molecular formula.
2. The empirical formula of a compound is CH_2O . Its molar mass is 60 g mol^{-1} . Determine its molecular formula.

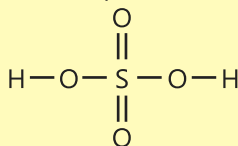
4.5 Deduce the molecular formula from the structural formula

In order to deduce the molecular formula from the structural formula the following steps are taken.

1. Write down the structural formula of the compound.
2. Count the number of atoms of each type in the structural formula.
3. Write the symbols of all the elements.
4. Write the total number of atoms of each kind as a subscript.
5. Remove the subscript 1.

Sample Problem:

Write down the molecular formula of sulphuric acid. Its structural formula is:

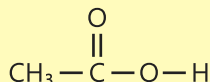


It has 2 H, 1 S and 4 O atoms.

Its molecular formula will be H_2SO_4

Sample Problem:

Write down the molecular formula of acetic acid. Its structure formula is:

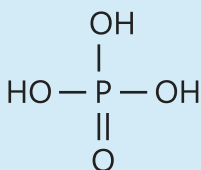


It has 2C, 4H, 2O atoms

Its molecular formula will be $\text{C}_2\text{H}_4\text{O}_2$

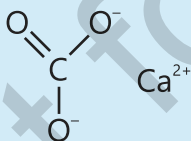
Exercise

1. Find out the molecular formula of phosphoric acid, Its structural formula is:



2. Determine the molecular formula of n – propyl alcohol. Its structural formula is $\text{CH}_3 - \text{CH}_2 - \text{CH}_2 - \text{OH}$

3. Write down the formula of calcium carbonate. Its structural formula is:



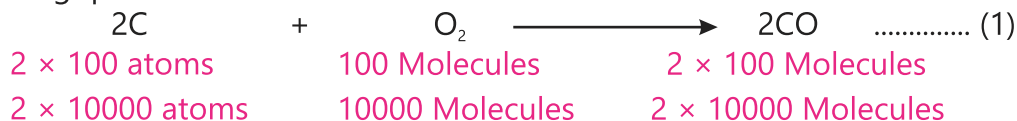
4.6 Avogadro's Number (N_A)

In a chemical reaction, large number of atoms or molecules of reactants react to give the products. We would very much like to know the mass ratio in which the reactants react. For this purpose, we would also like to express these masses of reactants in grams. To achieve this objective, we need to transform the concepts of chemical formula and atomic mass units into such concepts which may lead us to know the masses of reacting elements and compounds in grams. Avogadro, an Italian scientist, helped us to achieve this objective in the following way.

Let us consider the following reaction in which two atoms of carbon react with a molecule of oxygen to produce two molecules of CO.



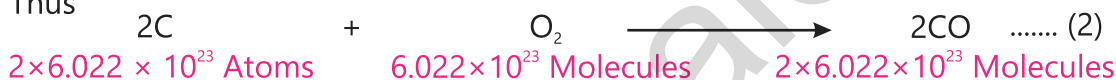
Since it is not possible to account for the masses of individual atoms or molecules because these are very small particles, we increase the number of reacting species as written below.



Increasing the number of reacting atoms or molecules will not change the ratio in which these are reacting or are being formed.

Increasing the number of reacting species, however, has not solved the problem because this number is still very small. We should increase this number to such a value whereby it is convenient for us to calculate their masses.

Thus



6.022×10^{23} is a huge number and we have selected this because

$$1.00 \text{ g} = 6.022 \times 10^{23} \text{ amu}$$

Now the amounts of reactants and products in the forementioned equations can be written as follows.

$$2 \times 6.022 \times 10^{23} \times (12.0 \text{ amu}) = 24.00 \text{ g carbon atoms}$$

$$6.022 \times 10^{23} \times (32.0 \text{ amu}) = 32.00 \text{ g oxygen molecules}$$

$$2 \times 6.022 \times 10^{23} \times (28.0 \text{ amu}) = 2 \times 28.00 \text{ g carbon monoxide molecules}$$

The mass ratio between the reactants and those of products will then become



You must have realized that starting from a simple equation we have developed such ratio of masses of the reacting species which can conveniently be used in the laboratory.

According to the above-mentioned equation, 24 g of carbon contains $2 \times 6.022 \times 10^{23}$ atoms of carbon, 32 g of oxygen contains 6.02×10^{23} molecules of oxygen and 56 g of carbon monoxide contains $2 \times 6.022 \times 10^{23}$ of its molecules.

The number 6.022×10^{23} is called Avogadro's number after the name of an Italian chemist Amedeo Avogadro. Avogadro's number is the number of units in one mole of a substance. This number is represented as N_A .

4.7 The Mole and Molar Mass

Avogadro's number has an immense significance in Chemistry and the quantity of a substance containing Avogadro's number of particles (N_A) is called **a Mole**. Mole is a number like a dozen or a gross. A dozen of oranges means 12

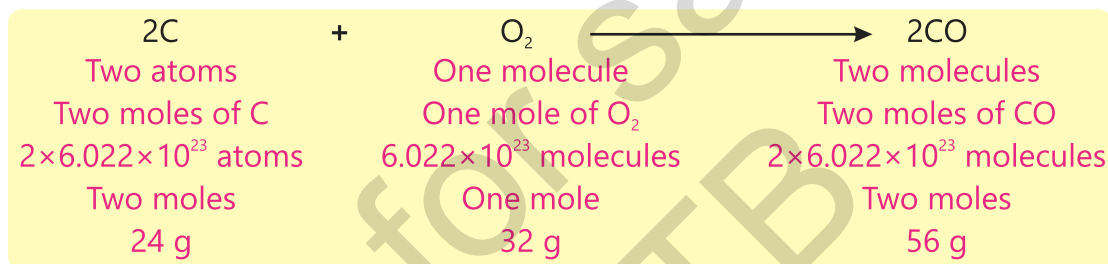
oranges. Similarly, a mole of a substance means its 6.022×10^{23} particles which can be atoms, molecules or ions. When we use the term mole of a substance, we must also refer to what type of particles are present in this substance. The following examples will help you to understand the concept clearly.

A mole of carbon atoms contains 6.022×10^{23} atoms and weighs 12 g.

A mole of oxygen molecules (O_2) contains 6.022×10^{23} molecules and weighs 32g. A mole of sodium chloride ($NaCl$) consists of 6.022×10^{23} of its formula units and its mass is 58.5 g.

The mass of one mole of a substance is called Molar mass. The molar mass of hydrogen atoms refers to the mass of one mole of hydrogen atoms and its value is 1.008 g. Similarly the molar mass of hydrogen molecules will be 2.016 g.

The chemical equation discussed in the previous article will now be understood in the following way.



Interesting Information!

Mole is important because atoms and molecules are so small that they can not be counted. The mole concept allows us to count atoms and molecules by weighing macroscopically small amounts of matter.

Exercise

Calculate the molar masses of the following compounds
 H_3PO_4 , SiO_2 , $C_{12}H_{22}O_{11}$, N_2O_4 , $MgCO_3$

Sample Problems:

Determine the molar masses of the following compounds in $g\ mol^{-1}$.

(a) H_2SO_4 (Sulphuric acid)

(b) $C_6H_{12}O_6$ (Glucose)

(a) H_2SO_4

Atomic mass of H = 1

Atomic mass of S = 32

Atomic mass of O = 16

Add the contribution of each atom

$$2(1) + 1(32) + 4(16) = 98\ g\ mol^{-1}$$

(b) $C_6H_{12}O_6$

Atomic mass of C = 12

Atomic mass of H = 1

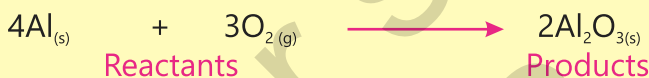
Atomic mass of O = 16

Add the contribution of each atom

$$6(12) + 12(1) + 6(16) = 180\ g\ mol^{-1}$$

4.8 Chemical Equations and Chemical Reactions

To understand a chemical change and to study the different factors which control it, has always been a focal point in the efforts of chemists. To achieve these objectives, we should have an appropriate way of representing a chemical change. Fortunately, the chemists have developed a very suitable way of representing a chemical change in terms of symbols of elements and formulas of compounds. **Representing a chemical change in this way is called a chemical equation.** A chemical equation tells us the elements or compounds which are reacting and those which are being produced as a result of a chemical change. The reacting substances are called as **reactants** while those being produced are called **products**. It is customary to write the reactants on the left-hand side and the products on the right-hand side. An arrow head drawn from reactants to products separates the two. The following example will help you to understand these points clearly.



The following points must be kept in mind while writing a chemical equation.

1. A chemical equation must obey the law of conservation of mass. This means that no atom should be destroyed or produced during a chemical change. The total number and the type of atoms must remain the same during a chemical change. Thus the total number and kind of atoms on both sides of the equation must be equal or the chemical equation must be balanced.
2. The formulas of elements and compounds must be written correctly.
3. A chemical equation must determine the correct mole ratio among the reactants, the products and between the reactants and the products.
4. A chemical equation must also point out the direction in which the change is proceeding.
5. It is a usual practice to show the normal **physical states** of reactants and products as a subscript. Solid, liquid and gas are symbolized as s, l and g respectively. Aqueous (aq) represents the solvated ion.

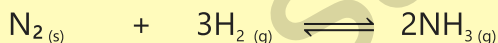
A chemical equation can, however, only be written if all the previous mentioned points are experimentally verified. For example, the nature of the products and their correct formulas must first be ascertained before writing a chemical equation. After the experimental verification of all the information about a chemical change, we should now be able to write a correct chemical

equation. The following equation has been written keeping in view all the points mentioned above.



According to this chemical equation, zinc reacts with sulphuric acid to give zinc sulphate and hydrogen gas. This chemical equation further tells us the mole ratio not only between reactants or products but also between reactants and products. According to the equation, one mole of zinc reacts with one mole of sulphuric acid to produce one mole of zinc sulphate and one mole of hydrogen gas.

Sometimes a chemical reaction moves both ways. In other words, the reactants react to give the products and the products, in turn, react to give the reactants back. Such reactions are called as **reversible reactions** and are indicated by (\rightleftharpoons) sign, e.g.:



Reaction involving ions may also be shown in the form of chemical equation. Both AgNO_3 and NaCl are ionic compounds and are soluble in water. When they are mixed in water, they react to form products.

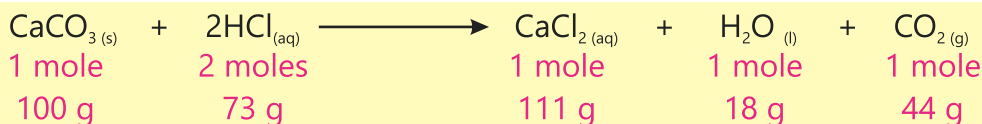


AgCl being insoluble comes out of the aqueous solution in the form of a precipitate.

4.9 Calculations Based on Chemical Equation

A complete and balanced chemical equation tells us the mole ratio or molar mass ratio between the reactants and the products. With the help of this ratio, we can find out the molar masses of the products provided we know the molar masses of the reactants. Similarly the molar masses of the reactants can also be found out if we know the molar masses of the products.

For example, the following equation tells us that one mole (100 g) of calcium carbonate reacts with two moles (73 g) of hydrochloric acid to produce one mole (111 g) of CaCl_2 , one mole (18 g) of water and one mole (44 g) of carbon dioxide.



The total masses of the reactants are equal to the total masses of the products.

Example 1

25g of limestone (CaCO_3) reacts with an excess of hydrochloric acid according to the above equation. How much calcium chloride (CaCl_2) will be produced?

Solution Mass of $\text{CaCO}_3 = 25 \text{ g}$ Molar mass of $\text{CaCO}_3 = 100 \text{ g mol}^{-1}$

Mass of CaCl_2 product = ? Molar mass of $\text{CaCl}_2 = 111 \text{ g mol}^{-1}$

According to the equation

100 g of limestone reacts to produce calcium chloride = 111 g

1 g of limestone will react to produce calcium chloride = $\frac{111}{100} \text{ g}$

25 g of limestone will react to produce calcium chloride = $\frac{111}{100} \times 25$
= 27.75g

Example 2

1.80 moles of ethyl alcohol, when burnt in air completely, will utilize how many moles of oxygen gas? Also calculate the number of moles of CO_2 produced.

Solution No. of moles of ethyl alcohol = 1.80

No. of moles of oxygen needed = ?

The balanced chemical equation for the reaction will be



According to this equation

One mole of ethyl alcohol, when completely burnt, needs oxygen = 3 moles

1.8 moles of ethyl alcohol, upon burning, will need oxygen = $\frac{3}{1} \times 1.8$
= 5.4 moles

1 mole of ethyl alcohol produces moles of CO_2 = 2.0

1.8 mol of ethyl alcohol will produce = $\frac{2}{1} \times 1.8$
= 3.6 moles

Example 3

Aluminium metal reacts with oxygen to produce aluminium oxide. How many grams of oxygen will be required to react completely with 0.3 moles of aluminium?

Solution Moles of Al = 0.3 Grams of O₂ used = ?

The balanced chemical equation for the reaction.



According to this equation

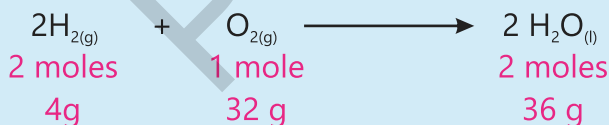
4 moles of aluminium need oxygen	= 3.0 moles
1.0 mole of aluminium will need oxygen	= $\frac{3}{4}$
0.3 moles of aluminium will need oxygen	= $\frac{3}{4} \times 0.3$
	= 0.225 moles
1 mole of oxygen (O ₂) has molar mass	= 32 g
0.225 mole of oxygen (O ₂) will have molar mass	= 32 × 0.225
	= 7.2 g

Example 4

How many molecules of water will be produced if we react 5 g of hydrogen gas with excess of oxygen gas?

Solution Mass of H₂ used = 5g Molecules of water produced = ?

The balanced chemical equation for the reaction:



According to this equation

4 g of hydrogen produce H ₂ O	= 36 g of H ₂ O
5 g of hydrogen will produce H ₂ O	= $\frac{36}{4} \times 5$ = 45g of H ₂ O
18g (1 mole) of H ₂ O contain molecules	= 6.022 × 10 ²³
36g of H ₂ O contain molecules	= 6.022 × 10 ²³ × 2
	= 12.04 × 10 ²³
45g of H ₂ O contain	= $\frac{45}{36} \times 12.04 \times 10^{23}$
	= 1.505 × 10 ²⁴ molecules

Key Points

1. Molecular formula of an element or a compound shows the actual number of atoms present in the molecule of the element or a compound.
2. The formula of a compound which gives the minimum ratio present between its atoms is called its Empirical formula. All the ionic compounds and some of the covalent compounds are represented by their empirical formulas.
3. Chemical formula of a binary ionic compounds can be written if you know their names and the charges present on the ions.
4. Chemical formula of a compound is n times its empirical formula where n is the ratio of molar mass to empirical formula mass.
5. Avogadro's number has been calculated to know the mass ratio of reactants and products in a chemical reaction. The value of this number is 6.022×10^{23} .
6. The quantity of an element or a compound, which contains Avogadro's number of particles, is called a Mole and the mass of a substance present in it is called the Molar Mass.
7. A chemical equation tells the reacting and producing elements or compounds in a chemical reaction. It also tells the mole ratio between reactants or products and between reactants and products. A chemical equation must be balanced and should show the correct formulas of all the participating elements and compounds.
8. The mole ratio between reactants and products as shown by a chemical equation enables us to find out the mass ratio of these substances. A chemical equation is used to calculate the masses of the reactants as well as the products, which take part in a chemical reaction.

Exercise



1. **Tick(✓) the correct answer.**
 - (i) How many atoms are present in one gram of H_2O ?
 - (a) 1002×10^{23} atoms
 - (b) 6.022×10^{23} atoms
 - (c) 0.334×10^{23} atoms
 - (d) 2.004×10^{23} atoms
 - (ii) Which is the correct formula of calcium phosphide?
 - (a) CaP
 - (b) CaP_2
 - (c) Ca_2P_3
 - (d) Ca_3P_2
 - (iii) How many atomic mass units (amu) are there in one gram?
 - (a) 1 amu
 - (b) 10^{23} amu
 - (c) 6.022×10^{23} amu
 - (d) 6.022×10^{22} amu
 - (iv) Structural formula of 2-hexene is $\text{CH}_3 - \text{CH} = \text{CH} - (\text{CH}_2)_2 - \text{CH}_3$. What will be its empirical formula?
 - (a) C_2H_2
 - (b) CH
 - (c) C_6H_{12}
 - (d) CH_2

- (v) How many moles are there in 25 g of H_2SO_4 ?
(a) 0.765 moles (b) 0.51 moles
(c) 0.255 moles (d) 0.4 moles
- (vi) A necklace has 6g of diamonds in it. What are the number of carbon atoms in it?
(a) 6.02×10^{23} (b) 12.04×10^{23}
(c) 1.003×10^{23} (d) 3.01×10^{23}
- (vii) What is the mass of Al in 204g of aluminium oxide, Al_2O_3 .
(a) 26g (b) 27g (c) 54g (d) 108g
- (viii) Which one of the following compounds will have the highest percentage of the mass of nitrogen?
(a) $\text{CO}(\text{NH}_2)_2$ (b) N_2H_4 (c) NH_3 (d) NH_2OH
- (ix) When one mole of each of the following compounds is reacted with oxygen, which will produce the maximum amount of CO_2 ?
(a) Carbon (b) Diamond
(c) Ethane (C_2H_6) (d) Methane (CH_4)
- (x) What mass of 95% CaCO_3 will be required to neutralize 50 cm^3 of 0.5M HCl solution?
(a) 9.5g (b) 1.25g (c) 1.32g (d) 1.45g

2. Questions for Short Answers

- Write down the chemical formula of barium nitride.
- Find out the molecular formula of a compound whose empirical formula is CH_2O and its molar mass is 180.
- How many molecules are present in 1.5 g H_2O ?
- What is the difference between a mole and Avogadro's number?
- Write down the chemical equation of the following reaction.

Copper + Sulphuric acid \rightarrow Coppersulphate + Sulphur dioxide + Water

3. Constructed Response Questions

- Different compounds will never have the same molecular formula but they can have the same empirical formula. Explain
- Write down the chemical formulas of the following compounds.
Calcium phosphate, Aluminium nitride, Sodium acetate, Ammonium carbonate and Bismuth sulphate.
- Why does Avogadro's number have an immense importance in chemistry?
- When 8.657g of a compound were converted into elements, it gave 5.217g of carbon, 0.962g of hydrogen and 2.478g of oxygen. Calculate the percentage of each element present in this compound.

- v. How can you calculate the masses of the products formed in a reversible reaction?

4. Descriptive Questions

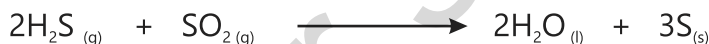
- i. Which conditions must be fulfilled before writing a chemical equation for a reaction?
- ii. Explain the concepts of Avogadro's number and mole.
- iii. How many grams of CO_2 will be produced when we react 10 g of CH_4 with excess of O_2 according to the following equation?



- iv. How many moles of coal are needed to produce 10 moles of CO according to the following equation?



- v. How much SO_2 is needed in grams to produce 10 moles of sulphur?



- vi. How much ammonia is needed in grams to produce 1 kg of urea fertilizer?



- vii. Calculate the number of atoms in the following.

(a) 3g of H_2 (b) 3.4 moles of N_2 (c) 10g of $\text{C}_6\text{H}_{12}\text{O}_6$.

5. Investigative Questions

- i. It is generally believed that drinking eight glasses of water every day is required to keep oneself hydrated especially in the summer. If a glass occupies 400 cm^3 of water on the average, how many moles of water are needed for a single adult?
- ii. The chemical formula for sand is SiO_2 but the sand does not exist in the form of discrete molecules like H_2O . How has its formula been determined keeping in view its structure?