Chapter 9

Chemical Formula and Mole Concept

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(1776 - 1856)

We know that compounds are formed when two or more elements react together. Compounds are formed by the combination of a fixed number of atoms of different elements.We use sugar, salt, water, baking soda etc. in our daily lives and these are all compounds. We have already leant a little bit about how formulae of compounds are written. Now, we will understand chemical formulae of compounds in more detail.

9.1 Formulae of covalent compounds

In a previous chapter, we saw many compounds such as carbon dioxide, water, ammonia etc. that show covalent bonding. In carbon dioxide, two-two electrons each of a carbon atom are shared equally with two-two electrons of two oxygen atoms (fig.1a).

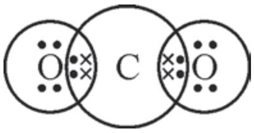


Fig. 1 (a)

Suppose we add another oxygen atom to a molecule of carbon dioxide, then the additional atom will share its electrons with which atom of the molecule?There are two possibilities.

First, it can share its electrons with the carbon atom and second it can share its electrons with one of the oxygen atoms. The additional oxygen atom cannot share its electrons with the carbon atom because all the electrons on the carbon atom are already being shared with two oxygen atoms and it has already attained inert gas configuration (fig.1 b). If we consider sharing of additional electrons with the oxygen atom of carbon dioxide (fig.1 c), then too it is not possible because then the number of electrons on the new oxygen atom will become eight but that on the first oxygen atom will become 10. That is, the number of electrons in the outermost shell of the oxygen atom will become more than 8.

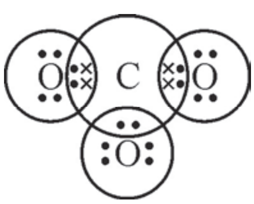


Fig. 1 (b)

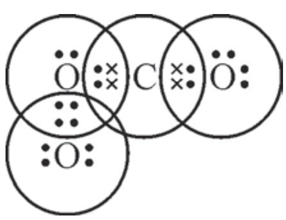


Fig. 1 (c)

Since, sharing of electron with an additional oxygen atom is not possible, therefore the compound CO_3 is not formed. A stable compound can be formed only between one carbon and two oxygen atoms and its formula is CO_2. Similarly, we can write the chemical formulae of other compounds if we know the symbols for different elements and their valencies.

9.2 Molecular weights of covalent compounds

We know that atoms of an element or of different elements combine together to form molecules. We can calculate the molecular weight of a molecule from the atomic weights of the elements present it. The molecular weight of a compound is the sum of the atomic weights of its constituent elements. For example, one atom of oxygen combines with two atoms of hydrogen to form a molecule of water. If we know the atomic weights of hydrogen and oxygen, we can calculate the molecular weight of water. Since the atomic weight of hydrogen is 1 u and that of oxygen is 16 u, therefore the molecular weight of water = $(2 \times 1) + 16 = 18$ u

Come, let us calculate the molecular weights of some more compounds –

The chemical formula of sulphur dioxide is SO_2. The atomic weight of sulphur is 32 u. Then,

The molecular weight of sulphur dioxide = $32 + (2 \times 16)$

= 64 u

Similarly, molecular weight of nitrogen = 2×14

= 28 u

Unit Formulae of ionic compounds and formula unit mass

Sodium chloride does not have a molecular formula because ionic solids do not have discrete molecules.The constituent particles of sodium chloride are sodium ions and chloride ions arranged in a three-dimensional structure. So the unit formula of sodium chloride is NaCl or Na^+Cl^-. Other ionic compounds also have similar unit formulae and these are used to calculate their weights. Since we are using unit formulae for weight calculation therefore it is called unit formula mass of ionic compounds. For example, the atomic weight of chlorine is 35.5 u and that of sodium is 23 u so the unit formula mass of sodium chloride is 35.5 + 23 = 58.5 u

Questions

1. If the atomic weight of carbon is 12 u then what will be the molecular weight of carbon dioxide?
2. If the atomic weight of nitrogen is 14 u then what is the molecular weight of ammonia?
3. Calculate the molecular weight of hydrogen.
4. Calculate the formula unit mass of the following ionic compounds:

   Na_2O, $MgCl_2$, $CaCl_2$, CaO

9.3 Polyatomic ions

We know that the solutions of ionic compounds in water conduct electricity. In activity-1 of chemical bonding chapter we saw that the solution of sodium chloride in water conducts electricity and that it ionizes to give sodium ions (Na^+) and chloride ions (Cl^-). If we repeat the same activity with a solution of sodium nitrate in water, it too conducts electricity. On this basis we can say that sodium nitrate is an ionic compound. It has Na^+ ions similar to NaCl. This implies that along with Na^+ions, the solution should also have negatively charged ions. This ion is NO_3^- where the nitrogen and three oxygen atoms have a sum negative charge. Such groups or clusters of atoms that carry a fixed charge are known as polyatomic ions.

$$NaNO_3 \longrightarrow Na^+ + NO_3^-$$

Other ionic compounds also dissolve in water to give positively and negatively charged ions. For example –

$$NH_4Cl \longrightarrow NH_4^+ + Cl^-$$
$$Na_2SO_4 \longrightarrow 2Na^+ + SO_4^{2-}$$
$$Ca(OH)_2 \longrightarrow Ca^{2+} + 2OH^-$$
$$Na_2CO_3 \longrightarrow 2Na^+ + CO_3^{2-}$$

NH_4^+, SO_4^{2-}, $OH^+$and CO_3^{2-} formed in the reactions given above are all examples of polyatomic ions.

The charges found on ions is also their valency. Table – 1 gives the valency of some ions:

Table 1 : Valencies of ions

Monovalent	Divalent	Polyvalent
Na^+, Ag^+, NH_4^+	Cu^{2+}, Zn^{2+}, Fe^{2+}, Mg^{2+}	Al^{3+}
Br^- (bromide) I^- (iodide) HCO_3^-(hydrogencarbonate) OH^-(hydroxide)	S^{2-} (sulphide) CO_3^{2-} (carbonate)	PO_4^{3-} (phosphate)

Radicals

Charged atoms and clusters of charged atoms are also known as radicals. Radicals are of two types, positive radicals and negative radicals.

Usually, the cations obtained from bases are known as basic radicals. For example,

$$NaOH \longrightarrow Na^{+} + OH^{-}$$

$$NH_4OH \longrightarrow NH_4^{+} + OH^{-}$$

$$Ca(OH)_2 \longrightarrow Ca^{2+} + 2OH^{-}$$

In the examples shown above, Na^+, NH_4^+(ammonium) and Ca^{2+} are basic radicals.

Usually, the anions obtained from acids are known as acidic radicals. For example –

$$HCl \longrightarrow H^{+} + Cl^{-}$$

$$HNO_3 \longrightarrow H^{+} + NO_3^{-}$$

$$H_2SO_4 \longrightarrow 2H^{+} + SO_4^{--}$$

In the examples given above, Cl^- (chloride), NO_3^- (nitrate), and SO_4^{2+} (sulfate) are acidic radicals.

9.3.1 Chemical formulae of compounds having polyatomic ions

Now we will use a special criss-cross method to write the chemical formulae using the charge present on ions (or the valence of ions). The given steps are followed while writing the chemical formulae:

Example – ammonium carbonate

1. First of all, we write down the names of the constituent ions keeping the symbol/formulae of the positive ion on the left side and the negatively charged ion on the right side.

NH_4 CO_3

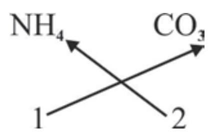
2. The valencies of the constituent ions are written below them.

Symbol/ Formulae	NH_4	CO_3
Valencies	1	2

3. The valencies of the ions are criss-crossed to determine their ratio in the compound.

Symbol/ Formulae

Valencies



This means that ammonium carbonate will have 2 ammonium ions and 1 carbonate ion.

4. The polyatomic ion is enclosed in a bracket and then the number that indicates the ratio is written as subscript. In case the number of polyatomic ion is one, the bracket is not required and 1 is also not written.

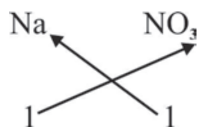
$(NH_4)_2CO_3$

Therefore, the formula of ammonium carbonate is $(NH_4)_2CO_3$.

Let us understand this through a few more examples:

- Sodium nitrate

  Symbol/ Formulae

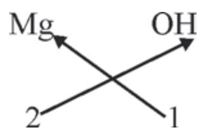


  Valencies

  So, formula is $NaNO_3$

- Magnesium hydroxide

  Symbol/ Formulae

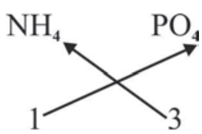


  Valencies

  So, formula is $Mg(OH)_2$

- Ammonium phosphate

  Symbol/ Formulae

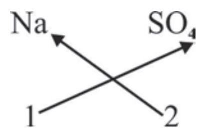


  Valencies

  So, formula is $(NH_4)_3PO_4$

- Sodium sulphate

  Symbol/ Formulae



  Valencies

  So, formula is Na_2SO_4

- Calcium sulphate

  Symbol/ Formulae Ca SO_4

  Valencies 2 2

  So, formula is $CaSO_4$

When the charge on both ions in the compound is same, the formula is simplified. Therefore, here $Ca_2\ (SO_4)_2$ is simplified to $CaSO_4$

- Aluminum sulphate

  Symbol/ Formulae Al SO_4

  Valencies 3 2

  So, formula is $Al_2(SO_4)_3$

Questions

1. Complete the table–

Name of compound	radicals present		No. of charges		Formula of compound
	Positive	Nagative	Positive	Nagative	
Ammonium nitrate			1		
Sodium carbonate				2	Na_2CO_3
Ammonium hydroxide				1	
Magnesium carbonate			2		$MgCO_3$
Iron phosphate	Fe^{++}				

2. Use the criss-cross method to write down the formulae of the following ionic compounds – ammonium chloride, calcium hydroxide, magnesium sulphate, ammonium sulphate, calcium phosphate

9.4 Mole concept

What is mole? Mole is a number. Come, let us read about why it is useful and how it came about. The story of the mole starts with some chemical reactions. In 1799, it was discovered that elements react with each other only in fixed ratios. At first, this fixed ratio was recognized as ratio of weights. Then the scientist Gay-Lussac studied the chemical reactions of different gases. He saw that at a given temperature and pressure, the gases reacted with each other in simple ratios of their volumes from which he derived the law of combining volumes. Dalton in his atomic theory had already described that elements react with each other in definite ratios by weight. But Dalton could not explain the reason behind Gay-Lussac's law. Many other scientists worked on Gay-Lussac's law and finally Berzelius was able to give a simple explanation. According to Berzelius, equal volumes of gases under identical conditions of temperature and pressure have the same number of atoms. This means that the number of particles in 1 litre of hydrogen gas is the same as the number of particles in 1 litre of chlorine gas. When 1 L hydrogen gas reacts with 1 L of chlorine gasthen hydrogen chloride is formed. Berzelius said that 1 litre of both the gases reacted completely with each other because the number of particles in both were same. Around the same time, relative atomic weights of different elements were also being calculated and were being used to calculate molecular weights. This made it possible to calculate the density and weights of gases. When the weights of atoms or molecules of gases were taken at a fixed temperature and pressure, it was found they all had the same volume. For example –

(i) At 0^oC and 1 atmospheric pressure (1 atm), the volume of 2 g of hydrogen was 22.4 L.

(ii) At 0^oC and 1 atmospheric pressure, the volume of 36.5 g of hydrogen chloride was 22.4 L

(iii) At standard temperature and pressure, the volume of 18 g of steam was also 22.4 L.

(iv) Similarly, if the weights of several gases equal to their molecular weight in grams are taken, they are found to occupy 22.414 L at 0 °C and 1 atm.

After many calculations, it was found that 22.4 L of any gas at standard pressure and temperature contains the same number of particles which is equal to 6.022×10^{23}. This was as per Berzelius's statement. $6.022 \text{ X } 10^{23}$is also known as Avogadro's number and represented by N_0.

If we repeat these calculations for solids or liquids, we can say that the number of particles in gram atomic or molecular weight of any substance is also 6.022×10^{23}. (Here, the atomic and molecular weights of substances are taken in grams).

In 1896, Wilhelm Ostwald proposed the term mole for Avogadro's number. Mole is the Latin word for heap or pile. Finally, in 1967 a standard definition was proposed for mole and it was recognized as the simplest way of describing extremely large numbers of atoms and molecules.

1 mole = 6.022×10^{23}(Avogadro's number N_0)

Mole concept gives us the number of particles in a definite amount of any substance. For example, 23 g of sodium has 6.022×10^{23} particles and 1 mole sodium atoms. If we have 46 g of sodium then it means that we have 2 moles of sodium atoms and 12.044×10^{23} particles.

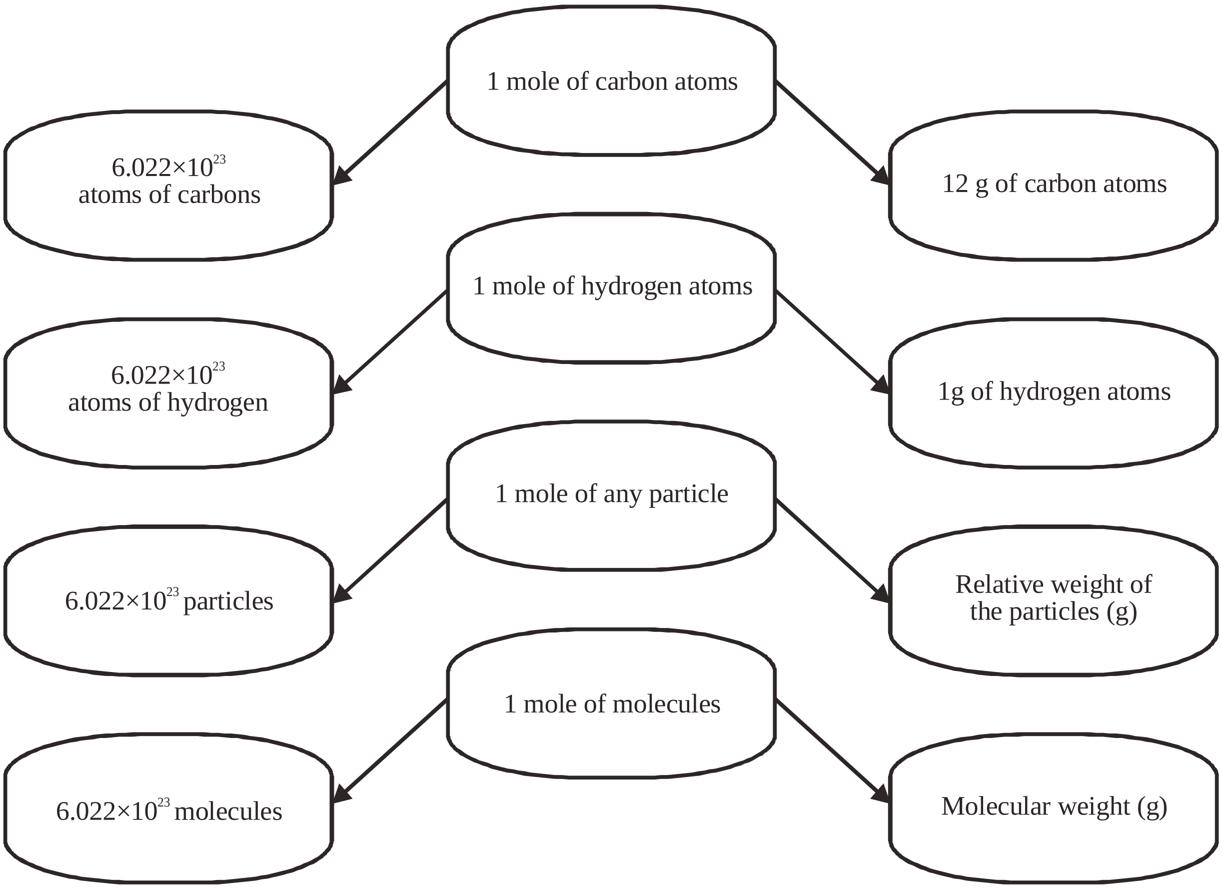


Fig. 3 : Relation between mole, Avogadro's number and weight

9.5 Representing weight of substances in Mole

We know that elements have atomic weight or gram atomic weight and molecules have molecular weight or gram molecular weight. On this basis, we can calculate the number of moles as follows:

For elements–

$$\text{Number of moles (n)} = \frac{\text{Mass given (m)}}{\text{Gram atomic weight (M)}}$$

For compounds or molecules–

$$\text{Number of moles (n)} = \frac{\text{Given mass (m)}}{\text{Gram molecular weight (M)}}$$

Showing number of particles in moles

The number of atoms/molecules/ions is related to moles as follows:

$$\text{Number of moles (n)} = \frac{\text{Number of particles (N)}}{\text{Avogadro's number } (N_0)}$$

Example-1

(a) 92 g sodium

Solution : Number of moles (n) = ?

Mass given (m) = 92 g

Gram atomic weight (M) = 23 g

Formula– $n = \frac{m}{M}$

$= \frac{92}{23}$

$=$ 4 moles

(b) 36 g water

Solution : Number of moles (n) = ?

Mass given (m) = 36 g

Gram molecular weight (M) = 18 g

Formula– $n = \frac{m}{M}$

$= \frac{36}{18}$

$=$ 2 moles

2. Find the number of moles:

(a) In 18.066×10^{23} Oxygen atoms

Solution : Number of moles (n) = ?

Number of particles (N) = 18.066×10^{23}

Avogadro's number (N_0) = 6.022×10^{23}

Formula– $$n = \frac{N}{N_0}$$

$$n = \frac{18.066 \times 10^{23}}{6.022 \times 10^{23}}$$

$$= 3 \text{ moles}$$

(b) 6.022×10^{23} oxygen molecules

Solution : Number of moles (n) = ?

Number of particles (N) = 6.022×10^{23}

Avogadro's number (N_0) = 6.022×10^{23}

Formula– $$n = \frac{N}{N_0}$$

$$n = \frac{6.022 \times 10^{23}}{6.022 \times 10^{23}}$$

$$= 1 \text{ mole}$$

3. Find the number of particles:

(a) In 10 g N_2 molecules

Solution : Number of particles (N) = ?

Mass given (m) = 10 gm.

Gram molecular weight (M) = 28 gm.

Formula– $N = n \times N_0$

$$n = \frac{m}{M}$$

$$N = \frac{m \times N_0}{M}$$

$$N = \frac{10 \times 6.022 \times 10^{23}}{28}$$

$$= 2.15 \times 10^{23}$$

(b) 2 moles of carbon atoms

Solution : Number of particles (N) = ?

	Number of moles (n)	=	2 moles
	Avogadro's number (N_0)	=	6.022×10^{23}
Formula–	N	=	$n \times N_0$
		=	$2 \times 6.022 \times 10^{23}$
		=	12.044×10^{23}

9.5.1 Let us understand mole concept

We know that the mass of 1 mole (6.022×10^{23}) particles of a substance is equal to its relative atomic or molecular or formula mass, given in grams. For gases, we can take volumes instead of weights. At 0^oC and 1 atmospheric pressure, one mole of any gas occupies 22.4 L of space.

This gives us another way of understanding and writing formulae and chemical equations. When we say that carbon dioxide is taking part in a reaction and depict it as CO_2 then are we saying that one molecule of CO_2 is involved?

We know that atoms and molecules are extremely minute particles and it is impossible to carry out a reaction where only atom or molecule of substances are taking part. This means that when we write CO_2 then it can also stand for 1 mole of CO_2 molecules. Let us see how this can prove useful.

The reaction of hydrogen and oxygen to form water can be written as:

$$2H_2 + O_2 \longrightarrow 2H_2O$$

In the given example, we can say that two molecules of hydrogen combine with one molecule of oxygen to form two molecules of water. But, can we have ½ molecule of oxygen as written below? What does it mean?

$$H_2 + \tfrac{1}{2}O_2 \longrightarrow H_2O$$

We can understand the above reaction using the mole concept. Here, one mole of hydrogen molecules combines with half mole of oxygen molecules to form one mole of water molecules. Therefore, when we write H_2 it can have two meanings:

- 1 molecule of hydrogen with relative molecular weight of 2 u.
- 1 mole of hydrogen molecules whose gram molecular weight is 2 grams.

Let us take another reaction –

$$H_2 + Cl_2 \longrightarrow 2HCl$$

We can describe the reaction in two ways-

- Two molecules of hydrogen chloride are formed when we react one molecule of hydrogen with one molecule of chlorine.

- When one mole of hydrogen molecules react with one mole of chlorine molecules, 2 moles of hydrogen chloride molecules are formed.

Questions

Explain the following reactions using the mole concept:

(a) $C + \frac{1}{2} O_2 \longrightarrow CO$

(b) $\frac{1}{2} Al_2O_3 + 3\ HCl \longrightarrow AlCl_3 + 1\frac{1}{2} H_2O$

Keywords

(molecular weight, empirical formula, unit formula mass, criss-cross method, mole, Avogadro number

What we have learnt

- The chemical formula of a compound is the symbolic representation of its composition.
- The molecular mass of a covalent compound can be calculated from the atomic mass of its constituent elements.
- Ions (cations and anions) are constituent particles of ionic compounds.
- The positive ions obtains from bases are called basic radicals and the negative ions obtained from acids are known as acidic radicals.
- Clusters of atoms carrying a fixed charge are known as polyatomic ions.
- In ionic compounds, the valency of each constituent ion is used to determine the chemical formula of the compound.
- The unit formula mass of ionic compounds is determined by using the weights of their constituent ions.
- The number of particles in one mole of any substance is called Avogadro's number. The value of Avogadro's number is 6.022×10^{23}.

International Mole Day

Every year, 23rd October is celebrated as international mole day. The day starts at 6:02 am and ends at 6:02 pm. The reason for choosing these timings is their similarity with Avogadro's number which is equal to 6.022×10^{23}.

Exercises

1. Choose the correct option–

   (i) The molecular weight of CH_3OH is–

   (a) 32 u (b) 29 u

   (c) 25 u (d) 20 u

   (ii) Basic radical is–

   (a) Positively charged ion (b) negatively charged ion

   (c) neutral atom (d) none of the above

   (iii) Ions that have a negative charge are–

   (a) Positively charged ion (b) Basic radicals

   (c) Acidic radicals (d) Neutral atoms

   (iv) The value of Avogadro's number is–

   (a) 6.022×10^{23} (b) 6.022×10^{22}

   (c) 6.022×10^{24} (d) 60.22×10^{23}

   (v) The volume of any gas at 0^oC and 1 atm pressure–

   (a) 11.2 litre (b) 22.4 litre

   (c) 100 litre (d) 33.8 litre

2. Fill in the blanks

   (i) Unit formula mass is used for .... compounds.

   (ii) The molecular weight of $C_{12}H_{22}O_{11}$ is ....

   (iii) The number of elements in PO_4^{3-} ....

   (iv) The number of atoms in one mole of carbon is ....

   (v) The mass of one mole of water is ....

3. How do we get acidic and basic radicals?

4. What are polyatomic ions? Give examples.

5. Connect the appropriate pairs:

	Column A		Column B
(i)	Number of atoms in one mole	(i)	14 gram
(ii)	Acidic radical	(ii)	Mg^{2+}
(iii)	Basic radical	(iii)	SO_4^{2-}
(iv)	The weight of one mole of nitrogen atoms	(iv)	2 mol
(v)	The number of moles in 88 g of CO_2	(v)	6.022×10^{23}

6. What is unit formula mass? Calculate the unit formula mass of $MgSO_4$.
7. If the formula of the carbonate of a metal is M_2CO_3 then what will be the formula of its nitrate.
8. If the formula of aluminium sulphate is $Al_2(SO_4)_3$ then what is the charge on Al ion and what is the formula of zinc sulphate?
9. The ion X has two positive charges on it. Write the formulae of the nitrate, sulphate and phosphate of X.
10. Calculate the molecular weights of the following:

    PCl_5, H_2O_2, S_8, HCl, NH_3
11. Calculate the masses of the following-

    5 moles of ammonia, 0.5 moles of water, 1.50 moles of Na^+ ions, 0.2 moles of oxygen atoms
12. Calculate the number of moles in the following:

    12 g of O_2, 22 g of CO_2
13. Determine the chemical formulae of the following using the crisscross method:

    Iron sulphate, Copper nitrate, Sodium sulphide, Magnesium hydrogencarbonate