Module-16: Formula Mass and the Mole

EMPIRICAL FORMULA

- The empirical formula gives the smallest whole number ratio of various elements present in a compound.
- For example, caffeine's molecular formula is $C_8H_{10}N_4O_2$ and its empirical formula is $C_4H_5N_2O$.
- We should be aware of the fact that there are many compounds which have identical molecular and empirical formula. For the organic compound pyridine, the molecular formula and the empirical formula are the same, namely, C_5H_5N.

Example: 1 A sample of a compound is decomposed in the laboratory and produces 165 g carbon, 27.8 g hydrogen, and 220.2 g oxygen. Calculate the empirical formula of the compound.

First, we have to calculate the moles of each element from the given masses.

$$\boxed{165.0\,g\,C \times \frac{1\,mol\,C}{12.01\,g\,C} = 13.7\,mol\,C} \qquad \boxed{27.8\,g\,H \times \frac{1\,mol\,H}{1.008\,g\,H} = 27.6\,mol\,H}$$

$$\boxed{220.2\,g\,O \times \frac{1\,mol\,O}{16.00\,g\,O} = 13.7\,mol\,O}$$

From the moles of the elements obtained from the previous step, the ratios of these elements are $C_{13.7}H_{27.6}O_{13.7}$. Next, we have to divide all the subscripts by the smallest subscript, in this case the smallest subscript is 13.7.

$$\boxed{C_{\frac{13.7}{13.7}}\;H_{\frac{27.6}{13.7}}\;O_{\frac{13.7}{13.7}}}$$

The ratio we get, $\mathbf{CH_2O}$, after the division is the empirical formula of the substance.

Example: 2 A compound has an empirical formula of CH and a molar mass of 78.11 g/mol. Find its molecular formula.

The molecular formula can be calculated from the empirical formula using the relationship

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

Where, n is the multiplying factor and it can be determined from the molar mass and the empirical formula mass.

$$n = \frac{molar\, mass}{empirical\, formula\, molar\, mass}$$

The empirical formula mass of CH,

$$= (1 \times molar\, mass\, of\, C) + (1 \times molar\, mass\, of\, H)$$

$$\begin{aligned} &= (1 \times 12.01\, g/mol) + (1 \times 1.008\, g/mol) \\ &= 13.018\, g \end{aligned}$$

The molar mass (given) and empirical formula mass are known, and n is,

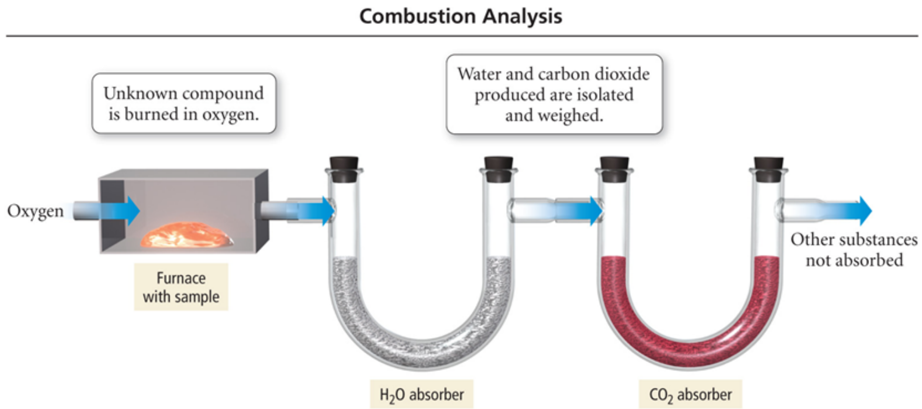
$$n = \frac{78.11}{13.018} = 6$$

Since we know n, we can find the molecular formula,

$$= (CH) \times 6$$ **or simply** $$C_6H_6$$

- Traditionally the empirical formulas of compounds containing carbon and hydrogen are found by combustion analysis.
- During the combustion analysis the substance that is to be analyzed is burned (combustion) in the presence of oxygen, the elements carbon and hydrogen are converted to carbon dioxide and water respectively.

- From the masses of CO_2 and H_2O, the moles of carbon and hydrogen present in the compound under investigation are determined.



Example: 3 Upon combustion, a 0.8009 sample of an organic compound containing only carbon, hydrogen and oxygen produced 1.6004 g CO_2 and 0.6551 g H_2O. Find the empirical formula of the element.

The first step involves the conversion of grams CO_2 and H_2O into moles of carbon and hydrogen.

$$mol\ of\ C = 1.6004\, g\, CO_2 \times \frac{1\, mol\, CO_2}{44.01\, g\, CO_2} \times \frac{1\, mol\, C}{1\, mol\, CO_2} = 0.0364\, mol\, C$$

$$mol\ of\ H = 0.6551 g\, H_2O \times \frac{1\, mol\, H_2O}{18.01\, g\, H_2O} \times \frac{2\, mol\, H}{1\, mol\, H_2O} = 0.0727\, mol\, H$$

The masses of carbon, hydrogen and oxygen are calculated from the number of moles.

$$mass\ of\ C = 0.0364\, mol\ C \times \frac{12.01\, g\, C}{1\, mol\, C} = 0.4372\, g\, C$$

$$mass\ of\ H = 0.0727\, mol\ H \times \frac{1.008\, g\, H}{1\, mol\, H} = 0.0733\, g\, C$$

$$\begin{aligned} mass\ of\ O &= total\ mass - (mass\ of\ C + mass\ of\ H) \\ &= 0.8009\ g - (0.4372\, g\, C + 0.0727\ g\, H) \\ &= 0.2904\ g\, O \end{aligned}$$

We know the number of moles of carbon and hydrogen, but not that of oxygen. The number of moles of oxygen is calculated from the mass of oxygen from the previous step.

$$\boxed{moles\ of\ O = 0.2904\ g\,O \times \frac{1 mol\,O}{16.00\,g\,O} = 0.0182\,mol}$$

The ratios of the elements are: $C_{0.0364}\,H_{0.0727}\,O_{0.0182}$

We have to divide all the subscripts by the smallest subscript, in this case the smallest subscript is 0.0182.

$$\boxed{C_{\frac{0.0364}{0.0182}}\,H_{\frac{0.0727}{0.0182}}\,O_{\frac{0.0182}{0.0182}}}$$

Upon dividing we get the empirical formula of the compound.

$$\boxed{C_2H_4O_1}$$

MASS PERCENT

- Mass percent gives the percent mass of an element in a compound.

Example: 4 Calculate the mass percent of calcium in calcium phosphate $Ca_3(PO_4)_2$.

Molar mass of $Ca_3(PO_4)_2$ = 310.18 g/mol

Molar mass of calcium = 40.1 g/mol

Mass percent of calcium = $\dfrac{3 \times Molar\ mass\ of\ calcium}{Molar\ mass\ of\ Ca_3(PO_4)_2} \times 100$

$$= \frac{3 \times 40.1\ g/mol}{310.18\ g/mol} \times 100 = 38.8\ \%$$

Example: 5 Calculate the mass percent of sulfur in copper sulfate pentahydrate $CuSO_4.5H_2O$.

Molar mass of $CuSO_4.5H_2O$ = 249.69 g/mol

Molar mass of sulfur = 32.06 g/mol

Mass percent of sulfur = $\dfrac{Molar\ mass\ of\ sulfur}{Molar\ mass\ of\ CuSO_4.5H_2O} \times 100$

$$= \frac{32.06\ g/mol}{249.69\ g/mol} \times 100 = 12.84\%$$

Practice Problems

1. What is the atomic mass of the element M in the compound $M[P(C_6H_5)_3]_4$. The molar mass of the compound $M[P(C_6H_5)_3]_4$ is about 1244.4 g/mol.

(A) 195.2 g/mol (B) 306.1 g/mol (C) 982.11 g/mol (D) 97.6 g/mol

2. Identify the compound which has the lowest molar mass.

(A) $FeCl_2$ (B) $NiCl_2$ (C) NiS (D) FeF_3

3. Calculate the mass percent composition of lithium in Li_3PO_4.

(A) 26.75 % (B) 17.98 % (C) 30.72 % (D) 20.82 %

4. Consider the hydrated compound $CoSO_4.7H_2O$ which has the molar mass of 281.1 g/mol. What is the mass percent of oxygen in the compound and what is the mass percent of oxygen in the hydrated portion alone?

	Mass percent of oxygen in the hydrated compound	Mass percent of oxygen in the hydrated portion alone
(A)	22.8%	39.8
(B)	62.6%	39.8%
(C)	62.6%	44.8%
(D)	44.8%	22.8%

5. A metal chloride of the formula MCl_x has the molar mass of 349.01 g/mol. The mass percent of chlorine is 40.63% what is the atomic mass of the element M? Give the answer in three significant figures.

(A) 308 (B) 60 (C) 207 (D) 186

6. Cholesterol has the molecular formula of $C_{27}H_{46}O$, what is its empirical formula?

(A) $C_{27}H_{46}O$ (B) $C_{13.5}H_{23}O_{0.5}$ (C) $C_{27}H_{23}O$ (D) $C_{5.75}H_{11.5}O_{0.25}$

7. The empirical formula of a salt consisting of Sr^{2+} and NO_2^- ions is

(A) $SrNO_2$ (B) $Sr_2(NO_2)_3$ (C) Sr_2NO_2 (D) $Sr(NO_2)_2$

8. What is the empirical formula mass of glucose, $C_6H_{12}O_6$?

(A) 180.2 (B) 90.1 (C) 45 (D) 360.4

9. Determine the empirical formula for a compound that contains only C, H and O. The mass percent of carbon and oxygen are respectively 52.14% and 34.73%.

(A) $C_4H_{13}O_2$ (B) C_2H_6O (C) CH_4O_3 (D) CH_3O

10. Determine the molecular formula of a compound that has a molar mass of 183.2 g/mol and an empirical formula of $C_2H_5O_2$.

(A) $C_2H_5O_2$ (B) $C_6H_{15}O_6$ (C) $C_3H_7O_3$ (D) $C_4H_{10}O_4$