# Empirical Formula

1.
An organic compound is known to contain the elements carbon, nitrogen, hydrogen and oxygen. Combustion of a 3.400g sample of this compound yields 5.003g of carbon dioxide and 2.447g of water. A further 5.608g sample of the compound is treated to convert all the nitrogen to ammonia. The resulting ammonia is dissolved in 20.00mL of 6.250 mol $L^{-1}$ hydrochloric acid. The excess hydrochloric acid was titrated with 1.896 mol $L^{-1}$ sodium hydroxide solution. Equivalence was achieved by adding 36.05mL of the sodium hydroxide solution.

a) Determine the percentage by mass of each of the four elements in the organic compound.
b) What is the empirical formula of the compound?

2.
A sample of 4.121 g of a chlorofluorocarbon (a compound containing carbon, fluorine and chlorine only) was analysed as follows:

All the carbon in the sample was converted into carbon dioxide gas, and all its chlorine was converted into hydrochloric acid. The carbon dioxide weighed 1.320 g, and the hydrochloric acid formed required 85.70 mL of 1.050 mol $L^{-1}$ ammonia solution for complete neutralisation.

Another sample of the same gaseous compound of mass 3.721 g occupied 0.6068 L at S.T.P.

(a) Determine the empirical formula of the compound.
(b) Determine the molecular formula of the compound.
(c) Name and draw a possible structure of the compound.

3.
An organic compound containing only carbon, hydrogen and oxygen is analysed by combusting a 2.323g sample in excess oxygen. All the carbon in the compound is converted to carbon dioxide, and all the hydrogen it contains is converted to water.

(a) Given that the mass of carbon dioxide produced is 5.281 g and the mass of water is 2.162 g, calculate the empirical formula of the compound.
(b) When a 1.503 g sample of the compound is vaporised in the absence of air, the vapour occupies 579.7 mL at S.T.P. From this data, calculate the molecular formula of the compound.
c) Further analysis shows the presence of a – CHO group. From this information, draw the structural formula of the compound

4.
A chlorofluorocarbon (a compound containing only chlorine, fluorine and carbon) is analysed by preparing two identical samples of the compound of mass 2.320 g. The first sample is burnt in excess oxygen gas to convert all the carbon it contains into carbon dioxide. The second sample of the compound is chemically treated to convert all the chlorine it contains into hydrochloric acid.

(a) Given that the mass of carbon dioxide produced is 0.9267 g and the hydrochloric acid produced requires 17.20 mL of 3.062 mol $L^{-1}$ ammonia solution for complete neutralisation; calculate the empirical formula of the chlorofluorocarbon.

(b) When a 1.503 g sample of the compound is vaporised in the absence of air, the vapour occupies 152.8 mL at S.T.P. From this data, calculate the molecular formula of the compound.

(c) Draw a full structural formula for the possible isomer(s) of the chlorofluorocarbon.

5.
An organic compound containing only carbon, hydrogen and oxygen is analysed by combusting a 3.605 g sample in excess oxygen. All the carbon in the compound is converted to carbon dioxide, and all the hydrogen it contains is converted to water.

(a) Given that the mass of carbon dioxide produced is 8.802 g and the mass of water is 3.603 g, calculate the empirical formula of the compound.
(b) When a 1.234 g sample of the compound is vaporised in the absence of air, the vapour occupies 441.8 mL at $22.0C^0$ and 95.0 kPa. From this data, calculate the molecular formula of the compound.
(c) Further analysis shows the compound is an aldehyde. From this information, draw the structural formula of the compound.

6.
An analytical chemist is required to determine the percentage by mass of methanol in a sample of methylated spirits (a mixture of ethanol and methanol). The chemist takes a 20.0g sample of the methylated spirits, adds concentrated sulfuric acid and reacts the resulting liquid with excess pure ethanoic acid. After the resulting esterification reaction is complete, the chemist removes any residual ethanoic acid, dries the remaining liquid and finds it to be a mixture of methyl ethanoate and ethyl ethanoate. The mass of ethyl ethanoate was found to be 35.76g. Assume that complete recovery of both organic compounds was achieved.

(a) Determine the percentage by mass of methanol in the sample of methylated spirits.

(b) Determine the mass of water produced during the complete esterification of the 20.0 g sample of methylated spirits.

7.

A group of Year 12 chemistry students decided to prepare some sodium palmitate soap ($C_{15}H_{31}COO^-Na^+$) in the laboratory by the reaction between pure tripalmitin oil and sodium hydroxide. The reaction is:

$$
\begin{array}{lcccccc}
H_2COOCC_{15}H_{31} & & & & & & CH_2OH \\
\;\;| & & & & & & \;\;| \\
H\text{-}COOCC_{15}H_{31} & + & 3NaOH & \rightarrow & 3C_{15}H_{31}COO^-Na^+ & + & CHOH \\
\;\;| & & & & & & \;\;| \\
H_2COOCC_{15}H_{31} & & & & & & CH_2OH
\end{array}
$$

Tripalmitin + sodium hydroxide → sodium palmitate + glycerol

The students weighed out 42.0 g of the tripalmitin oil.

(a) Calculate:

(i) The mass of sodium hydroxide needed to react with the tripalmitin oil.

(ii) The number of moles of glycerol which are produced as a by-product of this reaction.

(b) The soap which was prepared was then dissolved in excess "hard" water [assumed to contain only $Ca^{2+}$ (aq) ions and $HCO_3^-$ (aq) ions]. This process produced a grey insoluble deposit of calcium palmitate. What mass of calcium palmitate is formed by dissolving 10.0 g of? sodium palmitate soap in excess "hard' water?

Answer

1. The sample is 3.400g

Find n(C) = 5.003/44.01 = 0.1137 mol with a 1:1 ratio C = 1.3655g
Find n(H) = 2.447/18.016 = 0.1358 mol with a 1:2 ratio H = 0.2716 H = 0.2738g
From the 5.608g sample, find N
$NH_3 + HCl \rightarrow NH_4Cl$
No of moles of HCl is VC = 0.02 x 6.250 = 0.1250
No of moles of NaOH is VC = 0.3605 x 1.896 = 0.0684
No of moles of N in sample is 0.1250 - 0.0684 = 0.7937

**<u>% of each C = 40.16% H = 8.05% N = 14.15% O = 37.64%</u>**

| C | H | N | O |
|---|---|---|---|
| 40.16/12.01 | 8.05/1.008 | 14.15/14.01 | 37.64/16 |
| 3.3439 | 7.9861 | 1.01 | 2.3525 |
| 3.3439/1.01 | 7.9861/1.01 | 1.01/1.01 | 2.3525/1.01 |
| 3.3439 | 7.9865 | 1 | 2.352 |
| 3 | 8 | 1 | 2 |

**<u>Formula = $C_3H_8NO_2$</u>**

2. (a) m ($CO_2$) = 1.320 g

n ($CO_2$) = m/M = 1.320 g /44.01 g $mol^{-1}$ = 0.02999 mol

n(C) = 2.999 x $10^{-2}$ mol m(C) = nM = (2.999 x $10^{-2}$ mol) (12.01 g $mol^{-1}$) = 0.3602 g

Reaction: $H^+$ (aq) + $NH_3$ (aq) □ $NH_4^+$ (aq) (neutralisation)

n ($NH_3$) = c.V = (1.050 mol $L^{-1}$) (0.0857 L) = 0.08999 mol

n (Cl) = n ($H^+$) = n ($NH_3$) = 8.999 x $10^{-2}$ mol

m (Cl) = n.M = (8.999 x $10^{-2}$ mol) (35.45 g $mol^{-1}$) = 3.190 g
m (F) = sample mass - [m(C) + m (Cl)] = 4.121 g - [0.3602 g + 3.190 g] = 0.57008 g
Hence, n (F) = m/M = 0.5708 g /19.00 g $mol^{-1}$ = 0.0300 mol.
Hence: n(C) = 0.02999 mol
n (Cl) = 0.08999 mol (Divide each mole number by 0.0300 n (F) = 0.0300 mol
to find simplest ratio.)

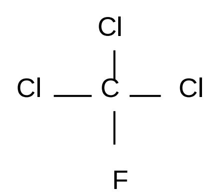
<u>Ans (a): E.F. = $CFCl_3$</u>

(b) m (compound) = 3.721 g
V (compound) = 0.6068 L at STP

n (compound) = V / 22.4 L $mol^{-1}$ = 0.6068 L / 22.4 L $mol^{-1}$ = 0.02709 mol.

Hence, M (compound) = m/n = 3.721 g / 0.02709 mol = 137.4 g $mol^{-1}$
But EFM = 1(C) + 1(F) = 3(Cl) = 12.01 + 19.00 + 106.35 = 137.4
Clearly, the empirical formula mass is equal to the true formula mass.
<u>Ans (b): The molecular formula = E.F. = $CFCl_3$</u>

<u>Ans (c): The compound is trichlorofluoromethane:</u>




3. (a) m ($CO_2$) = 5.281 g

$n\ (CO_2)$ = m/M = 5.281 g / 44.01g $mol^{-1}$ = 0. 1200 mol.
n(C) = 0. 1200 mol.
m(C) = nM = (0. 1200 mol) (12.01 g $mol^{-1}$) = 1.4412 g.
$m\ (H_2O)$ = 2.162 g
$n\ (H_2O)$ = m/M = 2.162 g / 18.016 g $mol^{-1}$ = 0. 1200 mol.
n (H) = 2n $(H_2O)$ = 0.2400 mol.
m (H) = nM = (0.2400 mol) (1.008 g $mol^{-1}$) = 0.2419 g
m (O) = Sample mass - [m(C) + m (H)] = 2.323 g - 1.683 g = 0.6399 g.
Hence, <u>n(C) = 0. 1200 mol</u> and <u>n (H) = 0.2400 mol</u>
n (O) = m/M = 0.6399 g / 116.00 g $mol^{-1}$ = <u>0.0400 mol</u>.
Hence, E.F. = $C_3H_6O_1$

<u>Ans (a): Empirical formula = $C_3H_6O_1$</u>

(b) m (compound) = 1.503 g
V (compound) = 0.5797 L at STP
n (compound) = 0.5797 L / 22.4 L $mol^{-1}$= 0.02588 rnol.
M (compound) = m/M = 1.503 g 10.02588 mol = 58.08 g $mol^{-1}$
Now, EFM = 3(C) + 6(H) + 1(0) = 36.03 + 6.048 + 16.00 = 58.08.
Clearly, EFM = TFM
TF = EF = $C_3H_6O_1$

<u>Ans (b): The molecular formula is $C_3H_6O$</u>

(c) Subtract CHO from molecular formula and write as a functional group:
<u>Ans (c):</u> $C_2H_5CHO = CH_3CH_2CHO$

4. (a). $C_xCl_yF_z \rightarrow xCO_2(g) + yHCl(aq)$

2.320 g $\rightarrow$ 0.9267 g + n(HCl) = $n(NH_3)$ = c.V
$m(CO_2)$ = 0.9267 g
$\therefore n(CO_2)$ = m/M = 0.9267 g / 44.01 g $mol^{-1}$ = 0.02106 mol.
$\therefore$ n(C) = 0.02106 mol
$\therefore$ m(C) = nM = (0.02106 mol)(12.01 g $mol^{-1}$) = 0.2529 g
n(Cl) = n(HCl) = $n(NH_3)$ = cV = (3.062 mol $L^{-1}$)(0.0172 L) = 0.05267 mol.
$\therefore$ m(Cl) = nM = (0.05267 mol)(35.45 g $mol^{-1}$) = 1.867 g
Now, m(F) = Sample mass - [(m(C) + m(Cl)] = 2.320 g - 2.120 g = 0.200 g.
Hence, n(C) = 0.02106 mol = 2
n(Cl) = 0.05267 mol = 5
n(F) = m/M = 0.200 g / 19.00 g $mol^{-1}$ = 0.01053 mol = 1

<u>Ans (a): The empirical formula of the compound is $C_2FCl_5$.</u>

(b). m(compound) = 1.503 g n(compound) = (V L) / (22.4 L $mol^{-1}$) = 0.15428 L / 22.4 L $mol^{-1}$ = 6.821 x $10^{-3}$ mol.
Now, since n = m/M $\therefore$ M = m/n = 1.503 g / 6.821 x $10^{-3}$ mol
$\therefore$ T.F.M = 220.3 g $mol^{-1}$ Now, since EF = $C_2FCl_5$
$\therefore$ E.F.M. = 2(12.01) + 1(19.00) + 5(35.45) = 220.3 Hence, E.F.M. = T.F.M.
$\therefore$ T.F = E.F = $C_2FCl_5$

<u>Ans (b): The molecular formula of the compound is $C_2FCl_5$</u>
(c) There is only ONE structure for the compound so there is only one isomer.

5. (a) $n(CO_2)$ = 8.802/44.01 = 0.200 mol.

$n(C) = n(CO_2) = 0.200$ mol.
$m(C) = nM = (0.200 \text{ mol})(12.01 \text{ g mol}^{-1}) = 2.402$ g.
$n(H_2O) = 3.603/18.016 = 0.200$ mol.
$n(H) = 2n(H_2O) = 0.400$ mol
$m(H) = nM = (0.400 \text{ mol})(1.008 \text{ g mol}^{-1}) = 0.4032$ g.
$m(O)$ = sample mass – $[m(C) + m(H)] = 0.800$ g.
$n(O) = m/M = 0.800 \text{ g}/16.00 \text{ g mol}^{-1} = 0.05$ mol.
Hence we have:
$n(C) = 0.200$ mol; $n(H) = 0.400$ mol; $n(O) = 0.05$ mol.
By dividing mole numbers by the smallest value i.e. 0.05, we obtain:

Ans (a): The empirical formula = $C_4 H_8 O_1$

(b) First convert the vapour from non-STP to STP condition.
Since $P_1V_1/T_1 = P_2V_2/T_2$, $V_2 = P_1V_1T_2/P_2T_1$.
Hence, V2 = (95.0 kPa)(0.4418 L)(273K)/(101.3 kPa)(295K) = 0.3834 L (at STP)
n(compound) = V(STP) / 22.41 L $\text{mol}^{-1}$ = 0.01711 mol.
M(compound) = m/n = 1.234 g / 0.01711 mol. = 72.1 g $\text{mol}^{-1}$
The EFM = 4(C) + 8(H) + 1(O) = 72.1

Ans (b): Clearly, the molecular formula = the empirical formula = $C_4 H_8 O_1$

Ans (c): $CH_3CH_2CH_2CHO$

6.(a) $xC_2H_5OH + yCH_3OH + zCH_3COOH \rightarrow CH_3COOC_2H_5 + H_3COOCH_3 + a\ H_2O$
$m(CH_3COOC_2H_5) = 35.76$ g.
$n(CH_3COOC_2H_5) = m/M = (35.76 \text{ g}) / (88.104 \text{ g mol}^{-1}) = 0.4059$ mol.
Since $n(CH_3COOC_2H_5) = n(C_2H_5OH) = 0.4059$ mol.
$m(C_2H_5OH) = n.M = (0.4059 \text{ mol})(46.068 \text{ g mol}^{-1}) = 18.70$ g.
Hence, the 20.0 g sample of spirits contains 18.70 g ethanol and (20.0 – 18.70) g = 1.30 g methanol. ∴ % methanol = (mass of methanol) / (mass of sample) x 100
= (1.30 g) / (20.0 g) x 100 = 6.50 %

Ans (a): The percentage by mass of methanol = 6.50 %

(b) Since $n(H_2O)_{TOTAL} = n(C_2H_5OH) + n(CH_3OH)\ n(C_2H_5OH) = 0.4059$ mol.
$n(CH_3OH) = m/M = (1.30 \text{ g}) / (32.042 \text{ g mol}^{-1}) = 0.04057$ mol.
$n(H_2O)_{TOTAL} = 0.4059 \text{ mol.} + 0.04057 \text{ mol.} = 0.4465$ mol.
Hence, $m(H_2O) = nM = (0.4465 \text{ mol})(18.016 \text{ g mol}^{-1}) = 8.04$ g.

Ans (b): The mass of water produced is 8.04 g.

7. (a)i n(tripalmitin) = m/M = (42.0 g)/(807.294 g) = 0.05203 mol.
n(NaOH) = 3n(tripalmitin) = 3(0.05203 mol) = 0.15608 mol.
m(NaOH) = n.M = (0.15608 mol)(39.998 g $mol^{-1}$) = 6.243 g.

Ans (a)i: The mass of sodium hydroxide needed is 6.24 g.

(a)ii n(glycerol) = n(tripalmitin) = 0.0520 mol

Ans (a)ii: The moles of glycerol produced is 0.0520 mol.

(b) n(sodium palmitate soap) = m/M = (10.0 g)/(278.398 g $mol^{-1}$) = 0.035920 mol.

Reaction is: $Ca^{2+}(aq) + 2C_{15}H_{31}COO^{-}(aq) \rightarrow (C_{15}H_{31}COO)_2Ca(s)$

n(calcium palmitate) = ½ n(palmitate) = ½ n(sodium palmitate) = 0.01796 mol.

m(calcium palmitate) = n.M = (0.01796 mol)(550.896 g $mol^{-1}$) = 9.894 g.

Ans (b): The mass of calcium palmitate is 9.89 g