1. CONCENTRATION UNITS

A solution is a homogeneous mixture of two or more chemical substances. If we have a solution made from a solid and a liquid, we say that the **solid is dissolved in the liquid** and we call the solid the **solute** and the liquid the **solvent**. Initially, we will consider only solutions of a solid in water. If a solution has a small amount of solute in a large amount of solvent, we say that the solution is **dilute** (*or* that we have a **dilute solution**). If a solution has a large amount of solute for a certain amount of solvent, we say that the solution is **concentrated** (*or* that we have a **concentrated solution**). We see that the terms dilute and concentrated are not precise and are merely used to give a rough indication of the amount of solute for a given amount of solvent. The amount of solute in a given amount of solvent (or solution) is called the **concentration** of the solution. In this course, we will consider two ways of expressing concentration - ***mass percent*** and ***molarity***. We will consider molarity here and mass percent later.

Molarity

The molarity of a solution (or, more precisely, of a solute in a solution) is the number of moles of the solute in 1 litre of the solution.

$$\text{molarity} = \frac{\text{moles (solute)}}{\text{litres (solution)}} \qquad M = \frac{n}{V(\text{L})} \qquad \text{N.B.: } n = \frac{\text{mass (g)}}{\text{MM}}$$

(MM = molar mass ≡ MW or FW)

The equation can also be used to find *n* (the number of moles of solute) if *M* (the molarity) and *V* (the volume in litres) are known, and *V* if *n* and *M* are known.

$$n = MV \qquad V = \frac{n}{M}$$

(a) Calculate the molarity of a solution of 0.25 mole of NaOH in 5.0 L of solution.

Solution: $\text{molarity} = \frac{0.25\ \text{mole}}{5.0\ \text{L}} = 0.050\ M$

(b) Calculate the molarity of a solution of 4.8 mole of HCl in 600 mL of solution. (N.B.: Convert volume to litres) (*Ans*. 8.0 *M*)

(c) Calculate the molarity of a solution of 3.6 g of NaOH in 300 mL of solution.

Solution: 300 mL = 0.300 L MM of NaOH = 40.0 g/mole

$$\text{moles NaOH} = \frac{3.6\ \text{g}}{40.0\ \text{g/mole}} = 0.090\ \text{mole}$$

$$\text{molarity} = \frac{0.090\ \text{mole}}{0.300\ \text{L}} = 0.30\ M$$

(d) Calculate the molarity of a solution of 1.25 g of Na_2CO_3 in 75.0 mL of solution. (*Ans*. 0.157 *M*)

(e) Calculate the number of moles of citric acid in 250 mL of a 0.400 *M* solution of citric acid. (*Ans*. 0.100 mole)

(f) Calculate the volume (in mL) of a 0.355 *M* NaOH solution which would contain 0.200 mole of NaOH. (*Ans*. 563 mL)

(g) Calculate the mass of Na_2CO_3 that must be used to make 700 mL of a 0.136 *M* Na_2CO_3 solution.

Solution: MM of Na_2CO_3 = (23.0x2)+12.0+(16.0x3) = 106

$$M = \frac{n}{V} \qquad n = MV = 0.136 \text{ mol/L} \times 0.700 \text{ L} = 0.0952 \text{ mol}$$

mass of Na_2CO_3 = 0.0952 mol x 106 g/mol = 10.1 g

(h) What mass of NaOH is needed to make 200 mL of a 0.300 *M* NaOH solution? (*Ans*. 2.40 g)

(i) What volume (in mL) of 0.200 *M* NaOH can be made from 1.20 g of NaOH?

Solution: $\text{moles NaOH} = \frac{1.20 \text{ g}}{40.0 \text{ g/mol}} = 0.0300 \text{ mole}$

$$M = \frac{n}{V} \qquad V = \frac{n}{M} = \frac{0.0300 \text{ mol}}{0.200 \text{ mol/L}} = 0.150 \text{ L} = 150 \text{ mL}$$

(j) What volume (in mL) of 0.440 *M* KBr can be made from 3.40 g of KBr? (*Ans*. 64.9 mL)

(k) Calculate the volume (in mL) of a 0.500 *M* Na_2CO_3 solution that contains 0.625 g of Na_2CO_3. (*Ans*. 11.8 mL)

2. SOLUTION STOICHIOMETRY

For all chemical reactions, the balanced chemical equation gives the mole ratios of reactants and products. If we are dealing with pure chemicals, the molar mass allows us to convert the mass of a reactant or product into moles. However, when we are reacting solutions we have to convert the volume of the solution into moles of the solute. This can only be done if the molarity of the solution is known. As we have seen above, the number of moles of the solute (reactant or product), *n*, is given by $n = MV$. In reactions such as acid-base reactions, adding a solution of one reactant to a solution of the other reactant until an **indicator** shows that just enough of the first reactant has been added to react completely with the second reactant is called a **titration**. The concentration of a solution whose concentration is not known can be determined by titration with a solution of known concentration. A certain volume of one solution is measured accurately with a pipet into a flask and a few drops of a suitable indicator is added. The other solution is added slowly from a buret until a colour change is seen, and the volume added from the buret is recorded.

(a) The reaction of NaOH with HCl is given by the equation shown below.

$$NaOH + HCl \rightarrow NaCl + H_2O$$

A 25.00 mL sample of 0.2442 *M* HCl required 19.26 mL of a NaOH solution. Calculate the molarity of the NaOH solution.

Solution:

$$M_{NaOH} = \frac{n_{NaOH}}{V_{NaOH}}$$

volume of NaOH solution = 19.26 mL; V_{NaOH} = 0.01926 L
From the equation, $n_{NaOH} = n_{HCl}$
$n_{NaOH} = n_{HCl} = M_{HCl}V_{HCl}$ = 0.2442 mol/L x 0.02500 L
= 0.006105 mol

$$M_{NaOH} = \frac{0.006105 \text{ mol}}{0.01926 \text{ L}} = 0.3170\ M$$

(b) NaOH reacts with H_2SO_4 as follows: $2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$
Calculate the molarity of a H_2SO_4 solution if 32.48 mL of 0.1268 *M* NaOH were required to titrate 25.00 mL of the H_2SO_4 solution. (*Ans*. 0.08237 *M*)

We can also **predict** the volume of a solution of one reactant that is required to react completely with a certain volume of another reactant if the molarities of both solutions are known.

(c) Calculate the volume (in mL) of 0.3500 *M* NaOH required to titrate 20.00 mL of 0.2500 *M* H_2SO_4.
The reaction is $2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$

Solution: moles H_2SO_4 = 0.2500 mol/L x 0.02000 L = 0.005000 mol

$$\text{moles NaOH} = 0.005000 \text{ mol } H_2SO_4 \times \frac{2 \text{ mol NaOH}}{1 \text{ mol } H_2SO_4} = 0.01000 \text{ mol}$$

$$V_{NaOH} = \frac{0.01000 \text{ mol}}{0.3500 \text{ mol/L}} = 0.02857 \text{ L} = 28.57 \text{ mL}$$

(d) Calculate the volume (in mL) of 0.1065 *M* $Sr(OH)_2$ required to titrate 25.00 mL of 0.2465 *M* H_3PO_4. (*Ans*. 86.80 mL). The reaction is given below.

$$3Sr(OH)_2 + 2H_3PO_4 \rightarrow Sr_3(PO_4)_2 + 6H_2O$$

For reactions involving pure substances reacting with substances in solution, the mass of the pure substance must be converted into moles.

(e) What volume of 2.00 *M* HCl is needed to react completely with 5.65 g of $Ca(OH)_2$? The reaction is

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O$$

Solution:

MM of $Ca(OH)_2$ = 40.1 + (2 x 16.0) + (2 x 1.0) = 74.1

$$\text{moles of } Ca(OH)_2 = 5.65 \text{ g} \times \frac{1 \text{ mol}}{74.1 \text{ g}} = 0.07625 \text{ mole}$$

$$\text{moles HCl} = 0.07625 \text{ mole } Ca(OH)_2 \times \frac{2 \text{ mol HCl}}{1 \text{ mol } Ca(OH)_2} = 0.1525 \text{ mole}$$

$$\text{mL HCl solution} = 0.1525 \text{ mol HCl} \times \frac{1000 \text{ mL HCl soln.}}{2.00 \text{ mole HCl}} = 76.3 \text{ mL}$$

(f) Calculate the molarity of a HCl solution if 18.25 mL of the solution were required to titrate 1.75 g of $Ca(OH)_2$. (*Ans*. 2.59 *M*)

(g) What mass of NaOH will react completely with 25.0 mL of 3.00 *M* H_2SO_4? The reaction is

$$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$$

(*Ans*. 6.00 g)

(h) A mass of 0.8186 g of "KHP" (potassium hydrogen phthalate; 204.2 g/mole) was dissolved in water and made up to 100.0 mL in a volumetric flask. 15.00 mL of the "KHP" solution required 24.85 mL of a $Sr(OH)_2$ solution. Calculate the molarity of the $Sr(OH)_2$ solution. The reaction is:

$$2KHP + Sr(OH)_2 \rightarrow Sr(KP)_2 + 2H_2O$$

((*Ans*. 0.01210 *M*)

3. DILUTION

Dilution is the process of adding solvent to a solution. Since this makes the *volume* of the solution larger but the *number of moles of solute* remains the same, the *concentration* of the solution decreases and the solution is said to have been *diluted*.

Consider a solution of molarity M_O (molarity of the original solution) and volume V_O litres. The number of moles of solute in this solution is given by $n_O = M_O V_O$. Suppose more solvent is added to the solution and the new volume is V_D (volume of the diluted solution). The molarity of the solution will decrease to a value M_D. Since no solute has been added, the number of moles of solute remains n_O. Therefore, for the diluted solution $n_O = M_D V_D = M_O V_O$.

In the equation $n = MV$, V must be in litres. However, in $M_D V_D = M_O V_O$, V_O and V_D can be in any units provided they are in the same units.

For dilute solutions, it can be assumed that the volume of a diluted solution is equal to the sum of the volume of the original solution and the volume of solvent added ($V_D = V_O + V_S$).

(a) Calculate the molarity of a solution made by adding 125 mL of water to 55 mL of a 2.00 *M* NaOH solution.

Solution:

$M_O = 2.00\ M$ $\quad V_O = 55$ mL

$M_D = ?$ $\quad V_D = (55 + 125)$ mL $= 180$ mL

$M_D V_D = M_O V_O$ $\quad M_D \times 180$ mL $= 2.00\ M \times 55$ mL

$$M_D = \frac{2.00 \times 55}{180} = 0.61\ M$$

(b) Calculate the molarity of a solution made by adding 545 mL of a 0.410 *M* HCl solution to 255 mL of water. (*Ans*. 0.279 *M*)

(c) Calculate the molarity of the solution produced when 250. mL of 0.963 *M* KOH is diluted to 750 mL. (*Ans*. 0.321 *M*)

(d) Calculate the molarity of a KOH solution if adding 35 mL of it to 65 mL of water produced 0.800 *M* KOH. (*Ans*. 2.30 *M*)

(e) Calculate the volume of a 3.50 *M* NaOH solution that must be added to 500 mL of water to produce 1.00 *M* NaOH. (*Ans*. 200 mL)

(f) Calculate the volume of water that must be added to 15 mL of 0.600 *M* HCl to make 0.100 *M* HCl. (*Ans*. 75 mL)

4. MASS PERCENT

$$\text{The mass percent of a solute in a solution} = \frac{\text{mass of solute}}{\text{mass of solution}} \times 100$$

The mass of the solution is, obviously, the mass of the solute(s) plus the mass of the solvent.

(a) What is the mass percent of NaCl in a solution of 4.50 g of NaCl in 35.0 g of water?

Solution:

$$\text{mass percent} = \frac{4.50\text{ g}}{(35.0 + 4.50)\text{ g}} \times 100 = 11.4\%$$

(b) What mass of NaOH is needed to make 250 g of 15.0% NaOH?

Solution: A 15.0% solution of NaOH has 15.0 g for 100 g of solution

$$\text{mass of NaOH needed} = 250\text{ g solution} \times \frac{15.0\text{ g NaOH}}{100\text{ g solution}}$$

= 37.5 g NaOH

(c) What volume of water is needed to dissolve 16.0 g of NaCl to make a 10.% NaCl solution?

Solution: Use 1.00 g/mL as the density of water
Let volume of water = ***x*** mL; mass of water = ***x*** g

$$\frac{16.0 \text{ g}}{(16.0 + \boldsymbol{x}) \text{ g}} \times 100 = 10.0 \qquad 1600 = 160 + 10\boldsymbol{x}$$

$10\boldsymbol{x} = 1600 - 160 = 1440$ $\qquad \boldsymbol{x} = 1440/10 = 144$
Volume of water = 144 mL

(d) What mass of a 25.0% NaOH solution can be made from 5.00 g of NaOH? (*Ans*. 20.0 g)

(e) What mass of NaCl must be dissolved in 74.0 mL of water to make a 22.0% solution? (*Ans*.20.9 g)

5. INTERCONVERSION OF MOLARITY AND MASS PERCENT

$$\text{Molarity} = \frac{\text{moles (of solute)}}{\text{volume (of solution in litres)}} \qquad \text{Mass Percent} = \frac{\text{mass of solute}}{\text{mass of solution}} \times 100$$

It is clear that mass and moles of solute can be interconverted using the molar mass (or FW) of the solute. Also, the mass and volume of the solution can be interconverted if the density of the **solution** is known.

(a) Calculate the molarity of muriatic acid (a 38% solution of HCl) whose density is 1.19 g/mL).

Solution: Consider a definite amount of the solution; 100 g or 1 L is convenient. We will do it both ways!

(1) Consider 100 g of solution; mass of HCl = 38 g

$$\text{moles of HCl} = 38 \text{ g} \times \frac{1 \text{ mole HCl}}{36.45 \text{ g HCl}} = 1.04 \text{ moles}$$

$$\text{volume of solution} = 100 \text{ g} \times \frac{1 \text{ mL}}{1.19 \text{ g}} \times \frac{1 \text{ L}}{1000 \text{ mL}} = 0.0840 \text{ L}$$

$$\text{molarity} = \frac{1.04 \text{ moles}}{0.0840 \text{ L}} = 12\ M$$

(2) Consider 1 L of solution; mass of solution = 1000 mL x 1.19 g/mL = 1190 g

$$\text{mass of HCl} = 1190 \text{ g solution} \times \frac{38 \text{ g HCl}}{100 \text{ g solution}} = 452.2 \text{ g}$$

$$\text{moles HCl} = 452.2 \text{ g} \times \frac{1 \text{ mole HCl}}{36.45 \text{ g HCl}} = 12; \text{ molarity} = 12 \text{ moles}/1 \text{ L} = 12\ M$$

(b) Calculate the molarity of a 16.6% solution of NaCl whose density is 1.23 g/mL. (*Ans*. 3.50 *M*)

(c) Calculate the molarity of a 13.00% NH_4Cl whose density is 1.037 g/mL. (*Ans*. 2.520 *M*)

(d) Calculate the mass percent of NaOH in a 7.576 *M* NaOH solution whose density is 1.265 g/mL. (*Ans*. 24.00%)

(e) Calculate the mass percent of $KHCO_3$ in a 2.017 *M* $KHCO_3$ solution whose density is 1.122 g/mL. (*Ans*. 18.00%)

(f) Calculate the density of a 20.00% KNO_3 solution which is 2.241 *M*. (*Ans*. 1.135 g/mL)

(g) Calculate the density of a 40.00% KBr solution which is 4.620 *M*. (*Ans*. 1.375 g/mL)

(h) Calculate the molar mass of **A** if 36.00% **A** is 2.312 *M* and has a density of 1.157 g/mL. (*Ans*. 180.2)

(i) Calculate the molar mass of **B** if 16.00% **B** is 2.112 *M* and has a density of 1.083 g/mL. (*Ans*. 82.04)