Appendix C
Molarity

C.1 MOLARITY AND THE MOLE

The molar mass is the mass of a mole of a pure substance while the *molarity*, **M**, is the number of moles of a pure substance contained in a liter of a *solution*.

$$\text{molarity} = \frac{\text{moles}}{\text{liter}} = \frac{n}{V}$$

One liter of a solution that contains 0.1 moles of sugar ($C_{12}H_{22}O_{11}$) is 0.1 M, or the solution is 0.1 molar in sugar. It can also be represented as: $[C_{12}H_{22}O_{11}]$ = 0.1 M, which is read as "the molar concentration of sugar is 0.1 molar."

C.2 MOLARITY AS A CONVERSION FACTOR

Molarity is used to convert between moles of substance and liters of solution.

Example 1

How many moles of NaCl are in 325 mL of 0.25 M NaCl solution?

Solution:

We first convert mL to L, and then apply molarity as a conversion factor.

$$325\text{ mL} \times \frac{1\text{ L}}{10^3\text{ mL}} \times \frac{0.25\text{ moles NaCl}}{1\text{ L}} = 0.081\text{ mol NaCl}$$

Example 2

How many mL of 5.0 M HCl contains 0.15 moles of HCl?

Solution:

Our known quantities are moles of HCl and molarity. We start with moles and apply molarity as a conversion factor. The final step is to convert liters to milliliters.

$$0.15\text{ mol HCl} \times \frac{1\text{ L}}{5.0\text{ mol HCl}} \times \frac{10^3\text{ mL}}{\text{L}} = 30\text{ mL}$$

Comment:

Note that our definition of molarity is turned upside down, and we were careful to write the units L and moles HCl in the numerator and denominator. Do not use M as the units of the conversion factor.

C.3 CONCENTRATIONS OF IONS

When ionic compounds dissolve, individual solvated ions are formed. (Recall that there are no molecules in ionic compounds.) When we refer to a 0.1 M NaCl solution, we mean that the solution has 0.1 moles of NaCl units in every liter. We can also determine the concentrations of the individual ions from the chemical formula. As discussed in Appendix A, the chemical formula relates moles of compound to moles of each element in the compound. In one mole of Na_2SO_4 there are two moles of Na^{1+} ions and one mole of SO_4^{2-} ions.

Example 3

a) **What is the concentrations of Na^{1+} ion and b) the total concentration of all ions in 0.25 M NaCl?**

Solution:

Part a), knowing the molarity of the compound and the formula, we can easily see that for every mole of NaCl, there is one mole of Na^{1+}.

$$\frac{\textbf{0.25 mol NaCl}}{\textbf{1 L}} \times \frac{\textbf{1 mol Na}^{1+}}{\textbf{1 mol NaCl}} = \frac{\textbf{0.25 mol Na}^{1+}}{\textbf{1 L}} = \textbf{0.25 M Na}^{1+}$$

Part b), for every mole of NaCl, there is one mole of Na^{1+} ions and one mole of Cl^{1-} ions, which adds up to two moles total of ions. Again, start with the concentration of the compound and find the concentration of ions.

$$\frac{\textbf{0.25 mol NaCl}}{\textbf{1 L}} \times \frac{\textbf{2 mol ions}}{\textbf{1 mol NaCl}} = \frac{\textbf{0.50 mol ions}}{\textbf{1 L}} = \textbf{0.50 M ions}$$

Comment:

In each step, we have used the moles of ions per mole of compound as a conversion factor much like we did in Examples 11-13 in Appendix A. Notice that this conversion gets us directly to the molarity of the ions (moles of ions per liter).

Example 4

a) **What is the concentration of chloride ions in a 0.1 M $CaCl_2$?**

b) **What is the total concentration of ions in a 0.1 M solution of $CaCl_2$?**

Solution:

As in Example 3, we start with the solution concentration and apply a conversion factor that converts moles of compound to moles of individual ions. In $CaCl_2$, the chemical formula tells us that there are two moles of Cl^{1-} in every mole of compound, and three moles of total ions (1 mole Ca^{2+}, 2 moles Cl^{1-}) in every mole of compound.

$$\frac{\textbf{0.1 mol CaCl}_2}{\textbf{1 L}} \times \frac{\textbf{2 mol Cl}^{1-}}{\textbf{1 mol CaCl}_2} = \frac{\textbf{0.2 mol Cl}^{1-}}{\textbf{1 L}} = \textbf{0.2 M Cl}^{1-}$$

$$\frac{\textbf{0.1 mol CaCl}_2}{\textbf{1 L}} \times \frac{\textbf{3 mol ions}}{\textbf{1 mol CaCl}_2} = \frac{\textbf{0.3 mol ions}}{\textbf{1 L}} = \textbf{0.3 M ions}$$

Comment:

We have taken some care to write down the units in detail for each conversion, but once you understand chemical formulas and the fact that ionic compounds dissolve to form individual ions, you will be able to do these calculations in your head!

C.4 MAKING SOLUTIONS

One of the most common tasks in the chemistry laboratory is making solutions of desired concentrations. In this section, we will explore how to make solutions starting with a solid solute.

Example 5

How many grams of Na_2CO_3 (M_m = 105.99 g/mol) are required to make 0.500 L of a 0.10 M Na_2CO_3 solution?

Solution:

We have a target volume and molarity for our solution, and so we can calculate the necessary moles of Na_2CO_3. We can then use the molar mass to calculate the necessary grams of Na_2CO_3.

$$\textbf{0.500 L} \times \frac{\textbf{0.10 mol}}{\textbf{1 L}} \times \frac{\textbf{106 g}}{\textbf{1 mol}} = \textbf{5.3 g}$$

Example 6

What is the molar concentration of a 2.5 L of solution that contains 254 g of Na_2CO_3?

Solution:

In this problem, we have a known mass of solid and a molar mass, enough information to calculate moles of Na_2CO_3. We can then use the relationship between moles and volume to calculate molarity.

$$254\ \text{g} \times \frac{1\ \text{mol}}{106\ \text{g}} = 2.40\ \text{mol}$$

$$\text{concentration} = \frac{2.40\ \text{mol}}{2.5\ \text{L}} = 0.96\ \text{M}$$

Comment:

Note that Examples 5 and 6 start from opposite ends of the same type of calculation. In each case, we have enough information to calculate moles of Na_2CO_3. In Example 5, we had a target volume and molarity; in Example 6, we had a mass and a molar mass. Determining the amount of solute that is needed to make a desired solution or the concentration of a particular solution by knowing how it was made are two types of calculations that are performed routinely in the chemistry laboratory.

C.5 DILUTION OF SOLUTIONS

In the previous section, solution concentrations were related to the mass of the solute. That type of calculation is appropriate when the solutes come from a chemical supply house in solid form. Some compounds are supplied as concentrated solutions. HCl is a good example. Most HCl in the laboratory is purchased as 'concentrated hydrochloric acid', which is often called a "stock solution". The dilution of stock solutions to give new solutions of desired concentrations is another very common laboratory procedure. The quantitative aspects will be detailed here.

When calculating molarity and volume of diluted solutions, we can take a shortcut if we are simply diluting with pure solvent. (Be careful, this shortcut does not work for experiments where you dilute with another solution, see Example 9, or for reaction stoichiometry, see Appendix D.) The shortcut is based on the idea that in diluting a concentrated solution with pure solvent, you are not changing the number of moles of solute. The molarity changes of course, because the volume changes. Since the number of moles of solute in the concentrated stock solution (n_c) equals the number of moles of solute in the diluted solution (n_d), we can write that $n_c = n_d$.

Rearranging the relationship M = n/V, we find that n = MV, so:

$$M_cV_c = M_dV_d$$

The only restriction on the units of the volumes is that they must be the same.

Example 7

What is the concentration of the solution prepared by diluting 25 mL of 12 M HCl to 1.0 L with pure water?

Solution:

The volume of the concentrated solution (before dilution) is 25 mL, and its concentration is 12.0 M solution. The volume of the diluted solution is 1.0 L, but its concentration is unknown. Remember that the volumes must have the same units. Using our shortcut, we write:

$$(12\ \text{M})\ (25\ \text{mL}) = M_d\ (1000\ \text{mL})$$

$$M_d = 0.30\ \text{M}$$

Comment:

Notice that, upon rearranging the equation to solve for M_d, the mL units cancel out. Whether we use 25 and 1000 mL or 0.025 and 1.0 L for the two volumes, the results are the same. Also, we write the final result as 0.30 M. We could have written it out the long way, 0.30 moles/liter.

Example 8

An experiment requires 250. mL of 0.25 M KCl. How many mL of a 1.5 M stock solution of KCl must be used to prepare this solution?

Solution:

We are given the volume and molarity of a dilute solution and are asked for the volume of a stock (concentrated) solution of known molarity.

$$(1.5\ \text{M})\ V_c = (0.25\ \text{M})\ (250.\ \text{mL}) \quad \text{or} \quad V_c = 42\ \text{mL}$$

Comment:

We need to dilute 42 mL of the concentrated solution to 250. mL to give the desired solution.

Example 9

15 mL of a 12 M solution of HCl was diluted with 100. mL of a 0.50 M solution of HCl. What is the concentration of the resulting solution? Assume that the volumes are additive.

Solution:

Note here that we are not diluting a stock solution with pure solvent as was done in Examples 7 and 8. We will not be able to use our shortcut because both the 12.0 M and the 0.50 M solutions contribute some moles of HCl to the final solution. Instead, we add up the total number of moles of HCl and divide by the total volume.

The first solution contributes:

$$15\ \text{mL} \times \frac{1\ \text{L}}{10^3\ \text{mL}} \times \frac{12.0\ \text{mol HCl}}{1\ \text{L}} = 0.18\ \text{mol HCl}$$

The second solution contributes:

$$100\ \text{mL} \times \frac{1\ \text{L}}{10^3\ \text{mL}} \times \frac{0.50\ \text{mol HCl}}{1\ \text{L}} = 0.050\ \text{mol HCl}$$

The total number of moles of HCl in the final solution is:

$$0.18 + 0.050 = 0.23\ \text{moles}$$

The total volume is: **15 mL + 100. mL = 115 mL = 0.115 L**

The concentration of the final solution is:

$$\frac{0.23\ \text{moles}}{0.115\ \text{L}} = 2.0\ \text{M}$$

Comment:

We found the total number of moles contributed by both initial solutions by first finding the number of moles of HCl in each solution separately and adding them together. Because we are not using the shortcut, volumes had to be in liters, and the appropriate conversions were applied. This problem also points out that a small volume of a more concentrated solution (the first one) often contains more of the solute than a larger volume of a less concentrated solution.

C.6 EXERCISES

1. What is the concentration of NaCl when 25.0 g of NaCl is dissolved in water to make 450. mL of solution?
2. How many mL of a 5.0 M solution of HCl contains 0.10 moles of HCl?
3. How many moles of K_2SO_4 are contained 100. mL of a 1.35 M solution?
4. What is the concentration of K^{1+} ions in 500. mL of a 0.125 M solution of K_2SO_4?
5. How many mL of a 0.10 M solution of NaCl contains 6.2×10^{-3} moles of NaCl?
6. How many grams of $CaCl_2$ are required to make 10.0 mL of 1.00 M $CaCl_2$ solution?
7. How many moles of Cl^{1-} ions are contained in 250. mL of a 0.552 M solution of $MgCl_2$?
8. How many mL of a 0.80 M solution of Na_2CO_3 contains 0.20 moles of Na^{1+} ions?
9. How many moles of Li_2CO_3 are contained in 25.0 mL of a 1.15 M solution?
10. An experiment calls for 1.00 L of a 0.150 M KCl solution. How many mL of a 4.00 M stock solution of KCl must be used to prepare this solution?
11. How many moles of Cl^{1-} ions are contained in 18.5 mL of a 1.28 M solution of NaCl?
12. What is the concentration of K^{1+} ions in 25.0 mL of a 1.00 M solution of KCl?
13. What is the concentration of NaCl when 5.75 g of NaCl is dissolved in water to make 1.86 L of solution?
14. How many grams of LiCl are required to make 125 mL of 0.100 M LiCl solution?
15. How many mL of a 1.25 M solution of KCl contains 2.35 g of KCl?
16. How many grams of LiCl are required to make 625 mL of 2.87 M LiCl solution?
17. 10.0 mL of a 3.25 M solution of HCl is diluted with 200 mL of a 0.100 M solution of HCl. What is the concentration of the resulting solution? Assume that the volumes are additive.
18. What is the concentration of the solution prepared by diluting 25 mL of a 0.50 M solution of HCl to 125 mL with pure water?
19. What is the concentration of the solution prepared by diluting 5.0 mL of a 6.25 M solution of HCl to 65 mL with pure water?
20. How many moles of Li^{1+} ions are contained in 0.500 L of a 2.25 M solution of Li_2CO_3?
21. An experiment calls for 125 mL of a 0.625 M HCl solution. How many mL of a 12.0 M stock solution of HCl must be used to prepare this solution?
22. 12.5 mL of a 12.0 M stock solution of HCl is diluted with 85.0 mL of a 0.200 M solution of HCl. What is the concentration of the resulting solution? Assume that the volumes are additive.

ANSWERS:

1. 0.950 M	**6.** 1.11 g	**11.** 0.0237 mol	**16.** 76.1 g	**21.** 6.51 mL
2. 20 mL	**7.** 0.276 mol	**12.** 1.00 M	**17.** 0.250 M	**22.** 1.71 M
3. 0.135 mol	**8.** 125 mL	**13.** 0.0528 M	**18.** 0.10 M	
4. 0.250 M	**9.** 0.0288 mol	**14.** 0.530 g	**19.** 0.48 M	
5. 62 mL	**10.** 37.5 mL	**15.** 25.2 mL	**20.** 2.25 mol	