



11.2 Quantitative Units of Concentration

LEARNING OBJECTIVE

1. Learn to determine specific concentrations with several common units.\

Rather than qualitative terms ([Section 11.1 "Some Definitions"](#)), we need quantitative ways to express the amount of solute in a solution; that is, we need specific units of concentration. In this section, we will introduce several common and useful units of concentration.

Molarity (M) is defined as the number of moles of solute divided by the number of liters of solution:

$$\text{molarity} = \frac{\text{moles of solute}}{\text{liters of solution}}$$

which can be simplified as

$$M = \frac{\text{mol}}{\text{L}}, \text{ or mol/L}$$

As with any mathematical equation, if you know any two quantities, you can calculate the third, unknown, quantity.

For example, suppose you have 0.500 L of solution that has 0.24 mol of NaOH dissolved in it. The concentration of the solution can be calculated as follows:

$$\text{molarity} = \frac{0.24 \text{ mol NaOH}}{0.500 \text{ L}} = 0.48 \text{ M NaOH}$$

The concentration of the solution is 0.48 M, which is spoken as “zero point forty-eight molarity” or “zero point forty-eight molar.” If the quantity of the solute is given in mass units, you must convert mass units to mole units before using the definition of molarity to calculate concentration. For example, what is the molar concentration of a solution of 22.4 g of HCl dissolved in 1.56 L? First, convert the mass of solute to moles using the molar mass of HCl (36.5 g/mol):

$$22.4 \text{ g HCl} \times \frac{1 \text{ mol HCl}}{36.5 \text{ g HCl}} = 0.614 \text{ mol HCl}$$

Now we can use the definition of molarity to determine a concentration:

$$M = \frac{0.614 \text{ mol HCl}}{1.56 \text{ L}} = 0.394 \text{ M}$$

EXAMPLE 3

What is the molarity of a solution made when 32.7 g of NaOH are dissolved to make 445 mL of solution?

Solution

To use the definition of molarity, both quantities must be converted to the proper units. First, convert the volume units from milliliters to liters:

$$445 \cancel{\text{ mL}} \times \frac{1 \text{ L}}{1,000 \cancel{\text{ mL}}} = 0.445 \text{ L}$$

Now we convert the amount of solute to moles, using the molar mass of NaOH, which is 40.0 g/mol:

$$32.7 \cancel{\text{ g NaOH}} \times \frac{1 \text{ mol NaOH}}{40.0 \cancel{\text{ g NaOH}}} = 0.818 \text{ mol NaOH}$$

Now we can use the definition of molarity to determine the molar concentration:

$$M = \frac{0.818 \text{ mol NaOH}}{0.445 \text{ L}} = 1.84 \text{ M NaOH}$$

Test Yourself

What is the molarity of a solution made when 66.2 g of $\text{C}_6\text{H}_{12}\text{O}_6$ are dissolved to make 235 mL of solution?

Answer

1.57 M

The definition of molarity can be used to determine the amount of solute or the volume of solution, if the other information is given. Example 4 illustrates this situation.

EXAMPLE 4

How many moles of solute are present in 0.108 L of a 0.887 M NaCl solution?

Solution

We know the volume and the molarity; we can use the definition of molarity to mathematically solve for the amount in moles. Substituting the quantities into the definition of molarity:

$$0.887 \text{ M} = \frac{\text{mol NaCl}}{0.108 \text{ L}}$$

We multiply the 0.108 L over to the other side of the equation and multiply the units together; “molarity × liters” equals moles, according to the definition of molarity. So

$$\text{mol NaCl} = (0.887 \text{ M})(0.108 \text{ L}) = 0.0958 \text{ mol}$$

Test Yourself

How many moles of solute are present in 225 mL of a 1.44 M CaCl_2 solution?

Answer

$$0.324 \text{ mol}$$

If you need to determine volume, remember the rule that the unknown quantity must be by itself and in the numerator to determine the correct answer. Thus rearrangement of the definition of molarity is required.

EXAMPLE 5

What volume of a 2.33 M NaNO_3 solution is needed to obtain 0.222 mol of solute?

Solution

Using the definition of molarity, we have

$$2.33 \text{ M} = \frac{0.222 \text{ mol}}{\text{L}}$$

To solve for the number of liters, we bring the 2.33 M over to the right into the denominator, and the number of liters over to the left in the numerator. We now have

$$\text{L} = \frac{0.222 \text{ mol}}{2.33 \text{ M}}$$

Dividing, the volume is 0.0953 L = 95.3 mL.

Test Yourself

What volume of a 0.570 M K_2SO_4 solution is needed to obtain 0.872 mol of solute?

Answer

1.53 L

A similar unit of concentration is **molality** (m), which is defined as the number of moles of solute per kilogram of solvent, not per liter of solution:

$$\text{molality} = \frac{\text{moles solute}}{\text{kilograms solvent}}$$

Mathematical manipulation of molality is the same as with molarity.

Another way to specify an amount is **percentage composition by mass (or mass percentage, % m/m)**. It is defined as follows:

$$\% \text{ m/m} = \frac{\text{mass of solute}}{\text{mass of entire sample}} \times 100 \%$$

It is not uncommon to see this unit used on commercial products ([Figure 11.1 "Concentration in Commercial Applications"](#)).

EXAMPLE 6

What is the mass percentage of Fe in a piece of metal with 87.9 g of Fe in a 113 g sample?

Solution

Using the definition of mass percentage, we have

$$\% \text{ m/m} = \frac{87.9 \text{ g Fe}}{113 \text{ g sample}} \times 100 \% = 77.8 \% \text{ Fe}$$

Test Yourself

What is the mass percentage of H₂O₂ in a solution with 1.67 g of H₂O₂ in a 55.5 g sample?

Answer

3.01%

Related concentration units are **parts per thousand (ppth)**, **parts per million (ppm)**, and **parts per billion (ppb)**. Parts per thousand is defined as follows:

$$\text{ppth} = \frac{\text{mass of solute}}{\text{mass of sample}} \times 1,000$$

There are similar definitions for parts per million and parts per billion:

$$\text{ppm} = \frac{\text{mass of solute}}{\text{mass of sample}} \times 1,000,000$$

and

$$\text{ppb} = \frac{\text{mass of solute}}{\text{mass of sample}} \times 1,000,000,000$$

Each unit is used for progressively lower and lower concentrations. The two masses must be expressed in the same unit of mass, so conversions may be necessary.

EXAMPLE 7

If there is 0.6 g of Pb present in 277 g of solution, what is the Pb concentration in parts per thousand?

Solution

Use the definition of parts per thousand to determine the concentration. Substituting

$$\frac{0.6 \text{ g Pb}}{277 \text{ g solution}} \times 1,000 = 2.17 \text{ ppth}$$

Test Yourself

If there is 0.551 mg of As in 348 g of solution, what is the As concentration in ppm?

Answer

1.58 ppm

As with molarity and molality, algebraic rearrangements may be necessary to answer certain questions.

EXAMPLE 8

The concentration of Cl^- ion in a sample of H_2O is 15.0 ppm. What mass of Cl^- ion is present in 240.0 mL of H_2O , which has a density of 1.00 g/mL?

Solution

First, use the density of H_2O to determine the mass of the sample:

$$240.0 \cancel{\text{ mL}} \times \frac{1.00 \text{ g}}{\cancel{\text{ mL}}} = 240.0 \text{ g}$$

Now we can use the definition of ppm:

$$15.0 \text{ ppm} = \frac{\text{mass solute}}{240.0 \text{ g solution}} \times 1,000,000$$

Rearranging to solve for the mass of solute,

$$\text{mass solute} = \frac{(15.0 \text{ ppm})(240.0 \text{ g solution})}{1,000,000} = 0.0036 \text{ g} = 3.6 \text{ mg}$$

Test Yourself

The concentration of Fe^{3+} ion in a sample of H_2O is 335.0 ppm. What mass of Fe^{3+} ion is present in 3,450 mL of H_2O , which has a density of 1.00 g/mL?

Answer

1.16 g

For ionic solutions, we need to differentiate between the concentration of the salt versus the concentration of each individual ion. Because the ions in ionic compounds go their own way when a compound is dissolved in a solution, the resulting concentration of the ion may be different from the concentration of the complete salt. For example, if 1 M NaCl were prepared, the solution could also be described as a solution of 1 M $\text{Na}^+(\text{aq})$ and 1 M $\text{Cl}^-(\text{aq})$ because there is one Na^+ ion and one Cl^- ion per formula unit of the salt. However, if the solution were 1 M CaCl_2 , there are two $\text{Cl}^-(\text{aq})$ ions for every formula unit dissolved, so the concentration of $\text{Cl}^-(\text{aq})$ would be 2 M, not 1 M.

In addition, the total ion concentration is the sum of the individual ion concentrations. Thus for the 1 M NaCl, the total ion concentration is 2 M; for the 1 M CaCl_2 , the total ion concentration is 3 M.

KEY TAKEAWAY

- Quantitative units of concentration include molarity, molality, mass percentage, parts per thousand, parts per million, and parts per billion.

EXERCISES

1. Differentiate between molarity and molality.
2. Differentiate between mass percentage and parts per thousand.

3. What is the molarity of a solution made by dissolving 13.4 g of NaNO_3 in 345 mL of solution?
4. What is the molarity of a solution made by dissolving 332 g of $\text{C}_6\text{H}_{12}\text{O}_6$ in 4.66 L of solution?
5. How many moles of MgCl_2 are present in 0.0331 L of a 2.55 M solution?
6. How many moles of NH_4Br are present in 88.9 mL of a 0.228 M solution?
7. What volume of 0.556 M NaCl is needed to obtain 0.882 mol of NaCl ?
8. What volume of 3.99 M H_2SO_4 is needed to obtain 4.61 mol of H_2SO_4 ?
9. What volume of 0.333 M $\text{Al}(\text{NO}_3)_3$ is needed to obtain 26.7 g of $\text{Al}(\text{NO}_3)_3$?
10. What volume of 1.772 M BaCl_2 is needed to obtain 123 g of BaCl_2 ?
11. What are the individual ion concentrations and the total ion concentration in 0.66 M $\text{Mg}(\text{NO}_3)_2$?
12. What are the individual ion concentrations and the total ion concentration in 1.04 M $\text{Al}_2(\text{SO}_4)_3$?
13. If the $\text{C}_2\text{H}_3\text{O}_2^-$ ion concentration in a solution is 0.554 M, what is the concentration of $\text{Ca}(\text{C}_2\text{H}_3\text{O}_2)_2$?
14. If the Cl^- ion concentration in a solution is 2.61 M, what is the concentration of FeCl_3 ?



ANSWERS

1. Molarity is moles per liter, whereas molality is moles per kilogram of solvent.
3. 0.457 M
5. 0.0844 mol
7. 1.59 L
9. 0.376 L
11. $\text{Mg}^{2+} = 0.66 \text{ M}$; $\text{NO}_3^- = 1.32 \text{ M}$; total: 1.98 M
13. 0.277 M