Pearson

13.5: Expressing Solution Concentration

Key Concept Video **Solution Concentration: Molarity, Molality, Parts by Mass and Volume, Mole Fraction**

The amount of solute in a solution is an important property of the solution. A **dilute solution** contains small quantities of solute relative to the amount of solvent. A **concentrated solution** contains large quantities of solute relative to the amount of solvent. Common ways of reporting solution concentration include molarity, molality, parts by mass, parts by volume, mole fraction, and mole percent, as summarized in Table 13.5. We have seen two of these units before: molarity in Section 8.2 and mole fraction in Section 10.7. In this section of the chapter, we review the terms we have already covered and introduce the new ones.

Table 13.5 **Solution Concentration Terms**

Unit	Definition	Units
molarity (M)	$\frac{\text{amount solute (in mol)}}{\text{volume solution (in L)}}$	$\frac{\text{mol}}{\text{L}}$
molality (m)	$\frac{\text{amount solute (in mol)}}{\text{mass solvent (in kg)}}$	$\frac{\text{mol}}{\text{kg}}$
mole fraction (χ)	$\frac{\text{amount solute (in mol)}}{\text{total amount of solute and solvent (in mol)}}$	None
mole percent (mol %)	$\frac{\text{amount solute (in mol)}}{\text{total amount of solute and solvent (in mol)}} \times 100\%$	%
parts by mass	$\frac{\text{mass solute}}{\text{mass solution}} \times$ multiplication factor	
percent by mass (%)	multiplication factor = 100	%
parts per million by mass (ppm)	multiplication factor = 10^6	ppm
parts per billion by mass (ppb)	multiplication factor = 10^9	ppb
parts by volume (%, ppm, ppb)	$\frac{\text{volume solute}}{\text{volume solution}} \times$ multiplication factor*	

*Multiplication factors for parts by volume are identical to those for parts by mass.

Molarity

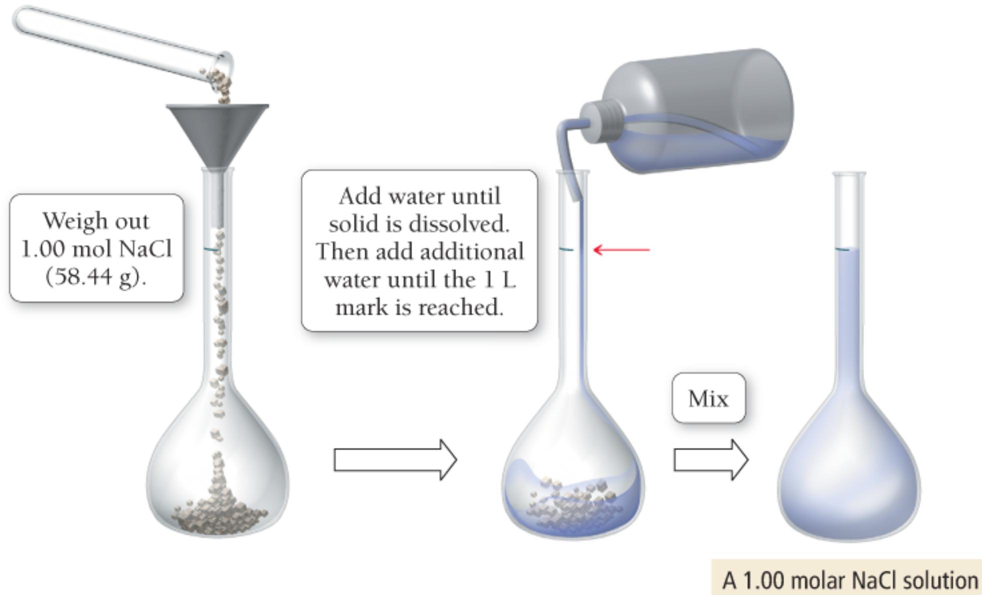
The **molarity (M)** of a solution is the amount of solute (in moles) divided by the volume of solution (in liters):

$$\text{molarity (M)} = \frac{\text{amount solute (in mol)}}{\text{volume solution (in L)}}$$

Note that molarity is moles of solute per liter of *solution*, not per liter of solvent. To make a solution of a specified molarity, we usually put the solute into a flask and then add water (or another solvent) to the desired volume of solution, as shown in Figure 13.12. Molarity is a convenient unit to use when making, diluting, and transferring solutions because it specifies the amount of solute per unit of solution.

Figure 13.12 Preparing a Solution of Known Concentration

To make a 1-M NaCl solution, we add 1 mol of the solid to a flask and dilute with water to make 1 L of solution.



Molarity depends on volume, and because volume varies with temperature, molarity also varies with temperature. For example, a 1-M aqueous solution at room temperature is slightly less than 1 M at an elevated temperature because the volume of the solution is greater at the elevated temperature.

Molality

A concentration unit that is independent of temperature is **molality (m)**, the amount of solute (in moles) divided by the mass of solvent (in kilograms):

$$\text{molality } (m) = \frac{\text{amount solute (in mol)}}{\text{mass solvent (in kg)}}$$

> Molality is abbreviated with a lowercase italic *m*, while molarity is abbreviated with a capital M.

Notice that we define molality with respect to kilograms *solvent*, not kilograms solution. Molality is particularly useful when we need to compare concentrations over a range of different temperatures.

Conceptual Connection 13.5 Molality

Interactive

Parts by Mass and Parts by Volume

It is often convenient to report a concentration as a ratio of masses. A **parts by mass** concentration is the ratio of the mass of the solute to the mass of the solution, all multiplied by a multiplication factor:

$$\frac{\text{mass solute}}{\text{mass solution}} \times \text{multiplication factor}$$

The particular parts by mass unit we use, which determines the size of the multiplication factor, depends on the concentration of the solution. For example, for **percent by mass** the multiplication factor is 100:

$$\text{percent by mass} = \frac{\text{mass solute}}{\text{mass solution}} \times 100$$

Percent means *per hundred*; a solution with a concentration of 14% by mass contains 14 g of solute per 100 g of solution.

For more dilute solutions, we can use **parts per million (ppm)**, which has a multiplication factor of 10^6, or **parts per billion (ppb)**, which has a multiplication factor of 10^9:

$$\text{ppm} = \frac{\text{mass solute}}{\text{mass solution}} \times 10^6$$
$$\text{ppb} = \frac{\text{mass solute}}{\text{mass solution}} \times 10^9$$

A solution with a concentration of 15 ppm by mass, for example, contains 15 g of solute per 10^6 g of solution.

> For dilute aqueous solutions near room temperature, the units of ppm are equivalent to milligrams solute/per liter of solution. This is because the density of a dilute aqueous solution near room temperature is 1.0 g/mL, so that 1 L has a mass of 1000 g.

Sometimes, we report concentrations as a ratio of volumes, especially for solutions in which both the solute and solvent are liquids. A **parts by volume** concentration is usually the ratio of the volume of the solute to the volume of the solution, all multiplied by a multiplication factor:

$$\frac{\text{volume solute}}{\text{volume solution}} \times \text{multiplication factor}$$

The multiplication factors are identical to those just described for parts by mass concentrations. For example, a 22% ethanol solution by volume contains 22 mL of ethanol for every 100 mL of solution.

We can use the parts by mass (or parts by volume) concentration of a solution as a conversion factor between mass (or volume) of the solute and mass (or volume) of the solution. For example, for a solution containing 3.5% sodium chloride by mass, we write the following conversion factor:

$$\frac{3.5\text{ g NaCl}}{100\text{ g solution}} \quad \text{converts} \quad \boxed{\text{g solution}} \longrightarrow \boxed{\text{g NaCl}}$$

This conversion factor converts from grams solution to grams NaCl. To convert the other way, we invert the conversion factor:

$$\frac{100\text{ g solution}}{3.5\text{ g NaCl}} \quad \text{converts} \quad \boxed{\text{g NaCl}} \longrightarrow \boxed{\text{g solution}}$$

Example 13.3 Using Parts by Mass in Calculations

What volume (in mL) of a soft drink that is 10.5% sucrose $(C_{12}H_{22}O_{11})$ by mass contains 78.5 g of sucrose? (The density of the solution is 1.04 g/mL.)

SORT You are given a mass of sucrose and the concentration and density of a sucrose solution, and you are asked to find the volume of solution containing the given mass.

GIVEN:

$$78.5\text{ g } C_{12}H_{22}O_{11}$$
$$10.5\%\ C_{12}H_{22}O_{11}\text{ by mass}$$
$$\text{density} = 1.04\text{ g/mL}$$

FIND: mL

STRATEGIZE Begin with the mass of sucrose in grams. Use the mass percent concentration of the solution (written as a ratio, as shown under relationships used) to find the number of grams of solution containing this quantity of sucrose. Then use the density of the solution to convert grams to milliliters of solution.

CONCEPTUAL PLAN

$$\text{g } C_{12}H_{22}O_{11} \xrightarrow[\frac{100\text{ g soln}}{10.5\text{ g } C_{12}H_{22}O_{11}}]{} \text{g soln} \xrightarrow[\frac{1\text{ mL}}{1.04\text{ g}}]{} \text{mL soln}$$

RELATIONSHIPS USED

$$\frac{10.5\text{ g } C_{12}H_{22}O_{11}}{100\text{ g soln}}\text{(percent by mass written as ratio)}$$

$$\frac{1\text{ mL}}{1.04\text{ g}}\text{(given density of the solution)}$$

SOLVE Begin with 78.5 g $C_{12}C_{22}C_{11}$ and multiply by the conversion factors to arrive at the volume of solution.

SOLUTION

$$78.5\text{ g } C_{12}H_{22}O_{11} \times \frac{100\text{ g soln}}{10.5\text{ g } C_{12}H_{22}O_{11}} \times \frac{1\text{ mL}}{1.04\text{ g}} = 719\text{ mL soln}$$

CHECK The units of the answer are correct. The magnitude seems correct because the solution is approximately 10% sucrose by mass. As the density of the solution is approximately 1 g/mL, the volume containing 78.5 g sucrose should be roughly 10 times larger, as calculated $(719 \approx 10 \times 78.5)$.

FOR PRACTICE 13.3 What mass of sucrose $\left(C_{12}H_{22}O_{11}\right)$, in g, is in 355 mL (12 fl oz) of a soft drink that is 11.5% sucrose by mass? (Assume a density of 1.04 g/mL.)

FOR MORE PRACTICE 13.3 A water sample contains the pollutant chlorobenzene with a concentration of 15 ppb (by mass). What volume of this water contains 5.00×10^2 mg of chlorobenzene? (Assume a density of 1.00 g/mL.)

Interactive Worked Example 13.3 **Using Parts by Mass in Calculations**

Mole Fraction and Mole Percent

For some applications, especially those in which the ratio of solute to solvent can vary widely, the most useful way to express concentration is the amount of solute (in moles) divided by the total amount of solute and solvent (in moles). This ratio is the **mole fraction** $\left(\chi_{\text{solute}}\right)$:

$$\chi_{\text{solute}} = \frac{\text{amount solute (in mol)}}{\text{total amount of solute and solvent (in mol)}} = \frac{n_{\text{solute}}}{n_{\text{solute}} + n_{\text{solvent}}}$$

> The mole fraction can also be defined for the solvent:
>
> $$\chi_{\text{solvent}} = \frac{n_{\text{solvent}}}{n_{\text{solute}} + n_{\text{solvent}}}$$

Also in common use is the **mole percent (mol %)**, which is the mole fraction × one hundred percent:

$$\text{mol \%} = \chi_{\text{solute}} \times 100\,\%$$

Example 13.4 Calculating Concentrations

You prepare a solution by dissolving 17.2 g of ethylene glycol $\left(C_2H_6O_2\right)$ in 0.500 kg of water.

The final volume of the solution is 515 mL. For this solution, calculate the concentration in each unit.

a. molarity
b. molality
c. percent by mass
d. mole fraction
e. mole percent

SOLUTION

a. To calculate molarity, first find the amount of ethylene glycol in moles from the mass and molar mass. Divide the amount in moles by the volume of the solution in liters.

$$\begin{aligned} \text{mol } C_2H_6O_2 &= 17.2 \text{ g } C_2H_6O_2 \times \frac{1 \text{ mol } C_2H_6O_2}{62.7 \text{ g } C_2H_6O_2} = 0.277^{-}1 \text{ mol } C_2H_6O_2 \\ \text{molarity (M)} &= \frac{\text{amount solute (in mol)}}{\text{volume solution (in L)}} \\ &= \frac{0.277^{-}1 \text{ mol } C_2H_6O_2}{0.515 \text{ L solution}} \\ &= 0.538 \text{ M} \end{aligned}$$

b. To calculate molality, use the amount of ethylene glycol in moles from (a), and divide by the mass of the water in kilograms.

$$\begin{aligned} \text{molarity } (m) &= \frac{\text{amount solute (in mol)}}{\text{mass solvent (in kg)}} \\ &= \frac{0.277^{-}1 \text{ mol } C_2H_6O_2}{0.500 \text{ L solution}} \\ &= 0.554\ m \end{aligned}$$

c. To calculate percent by mass, divide the mass of the solute by the sum of the masses of the solute and solvent and multiply the ratio by 100%.

$$\begin{aligned} \text{percent by mass} &= \frac{\text{mass solute}}{\text{mass solution}} \times 100\ \% \\ &= \frac{17.2 \text{ g}}{17.2 \text{ g} + 5.00 \times 10^2 \text{ g}} \times 100\ \% \\ &= 3.33\ \% \end{aligned}$$

d. To calculate mole fraction, first determine the amount of water in moles from the mass of water and its molar mass.
Divide the amount of ethylene glycol in moles from (a) by the total number of moles.

$$\text{mol } H_2O = 5.00 \times 10^2 \text{ g} H_2O \times \frac{1 \text{ mol } H_2O}{18.02 \text{ g } H_2O} = 27.75^{-} \text{ mol } H_2O$$

$$\begin{aligned} \chi_{\text{solute}} &= \frac{n_{\text{solute}}}{n_{\text{solute}} + n_{\text{solvent}}} \\ &= \frac{0.277^{-}1 \text{ mol}}{0.277^{-}1 \text{ mol} + 27.7^{-}5 \text{ mol}} \\ &= 9.89 \times 10^{-3} \end{aligned}$$

e. To calculate mole percent, multiply the mole fraction from (d) by 100%.

$$\begin{aligned} \text{mol } \% &= \chi_{\text{solute}} \times 100\ \% \\ &= 0.989\ \% \end{aligned}$$

FOR PRACTICE 13.4 You prepare a solution by dissolving 50.4 g sucrose $(C_{12}H_{22}O_{11})$ in 0.332 kg of water. The final volume of the solution is 355 mL. Calculate the concentration of the solution in each unit.

- **a.** molarity
- **b.** molality
- **c.** percent by mass
- **d.** mole fraction
- **e.** mole percent

Interactive Worked Example 13.4 **Calculating Concentrations**

Example 13.5 Converting between Concentration Units

What is the molarity of a 6.56% by mass glucose $(C_6H_{12}O_6)$ solution? (The density of the solution is 1.03 g/mL.)

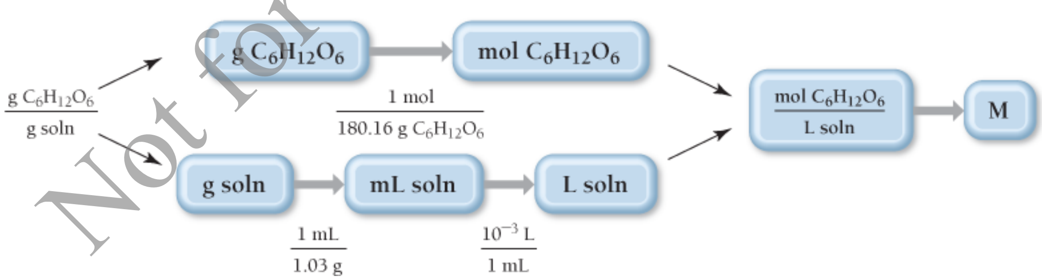
SORT You are given the concentration of a glucose solution in percent by mass and the density of the solution. Find the concentration of the solution in molarity.

GIVEN:
6.56 % $C_6H_{12}O_6$
density = 1.03 g/mL

FIND: M

STRATEGIZE Begin with the mass percent concentration of the solution written as a ratio, and separate the numerator from the denominator. Convert the numerator from g $C_6H_{12}O_6$ to mol $C_6H_{12}O_6$. Convert the denominator from g soln to mL of solution and then to L solution. Divide the numerator (now in mol) by the denominator (now in L) to obtain molarity.

CONCEPTUAL PLAN



RELATIONSHIPS USED

$$\frac{6.56 \text{ g } C_6H_{12}O_6}{100 \text{ g soln}} \text{(percent by mass written as ratio)}$$

$$\frac{1 \text{ mol}}{180.16 \text{ g } C_6H_{12}O_6} \text{(from molar mass of glucose)}$$

$$\frac{1 \text{ mL}}{1.03 \text{ g}} \text{(from given density of the solution)}$$

SOLVE Begin with the numerator $(6.56 \text{ g } C_6H_{12}O_6)$ and use the molar mass to convert to mol $C_6H_{12}O_6$.

Convert the denominator (100 g solution) into mL of solution (using the density) and then to L of solution.

Finally, divide mol $C_6H_{12}O_6$ by L solution to arrive at molarity.

Finally, divide mol $C_6H_{12}O_6$ by L solution to arrive at molarity.

SOLUTION

$$6.56\ \text{g}\ C_6H_{12}O_6 \times \frac{1\ \text{mol}\ C_6H_{12}O_6}{180.16\ \text{g}\ C_6H_{12}O_6} = 0.0364{}^{-}12\ \text{mol}\ C_6H_{12}O_6$$

$$100\ \ \text{g soln} \times \frac{1\ \text{mL}}{1.03\ \text{g}} \times \frac{10^{-3}\text{L}}{\text{mL}} = 0.0970{}^{-}87\ \text{L soln}$$

$$\frac{0.0364{}^{-}12\ \text{mol}\ C_6H_{12}O_6}{0.0970{}^{-}87\ \text{L soln}} = 0.375\ \text{M}\ C_6H_{12}O_6$$

CHECK The units of the answer are correct. The magnitude seems correct. Very high molarities (especially those above 25 M) should immediately appear suspect. One liter of water contains about 55 moles of water molecules, so molarities higher than 55 M are physically impossible.

FOR PRACTICE 13.5 What is the molarity of a 10.5% by mass glucose $(C_6H_{12}O_6)$ solution? (The density of the solution is 1.03 g/mL.)

FOR MORE PRACTICE 13.5 What is the molality of a 10.5% by mass glucose $(C_6H_{12}O_6)$ solution? (The density of the solution is 1.03 g/mL.)

Interactive Worked Example 13.5 **Converting between Concentration Units**