SECTION 3

Concentration of Solutions

OBJECTIVES

- Given the mass of solute and volume of solvent, calculate the concentration of a solution.
- Given the concentration of a solution, determine the amount of solute in a given amount of solution.
- Given the concentration of a solution, determine the amount of solution that contains a given amount of solute.

The **concentration** *of a solution is a measure of the amount of solute in a given amount of solvent or solution.* Some medications are solutions of drugs—a one-teaspoon dose at the correct concentration might cure the patient, while the same dose in the wrong concentration might kill the patient.

In this section, we introduce two different ways of expressing the concentrations of solutions: molarity and molality.

Sometimes, solutions are referred to as "dilute" or "concentrated," but these are not very definite terms. "Dilute" just means that there is a relatively small amount of solute in a solvent. "Concentrated," on the other hand, means that there is a relatively large amount of solute in a solvent. Note that these terms are unrelated to the degree to which a solution is saturated. A saturated solution of a substance that is not very soluble might be very dilute.

Molarity

Molarity *is the number of moles of solute in one liter of solution.* To relate the molarity of a solution to the mass of solute present, you must know the molar mass of the solute. For example, a "one molar" solution of sodium hydroxide, NaOH, contains one mole of NaOH in every liter of solution. The symbol for molarity is M, and the concentration of a one molar solution of sodium hydroxide is written as 1 M NaOH.

One mole of NaOH has a mass of 40.0 g. If this quantity of NaOH is dissolved in enough water to make exactly 1.00 L of solution, the solution is a 1 M solution. If 20.0 g of NaOH, which is 0.500 mol, is dissolved in enough water to make 1.00 L of solution, a 0.500 M NaOH solution is produced. This relationship between molarity, moles, and volume may be expressed in the following ways.

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

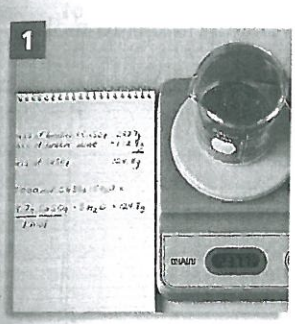
$$= \frac{0.500 \text{ mol NaOH}}{1.00 \text{ L}}$$

$$= 0.500 \text{ M NaOH}$$

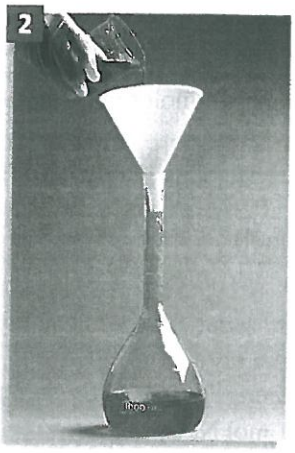
If twice the molar mass of NaOH, 80.0 g, is dissolved in enough water to make 1 L of solution, a 2 M solution is produced. The molarity of any solution can be calculated by dividing the number of moles of solute by the number of liters of solution.

Note that a 1 M solution is *not* made by adding 1 mol of solute to 1 L of *solvent*. In such a case, the final total volume of the solution might not be 1 L. Instead, 1 mol of solute is first dissolved in less than 1 L of solvent. Then, the resulting solution is carefully diluted with more solvent to bring the *total volume* to 1 L, as shown in **Figure 17.** The following sample problem will show you how molarity is often used.

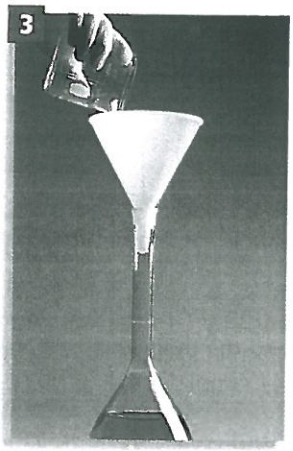
FIGURE 17 The preparation of a 0.5000 M solution of $CuSO_4 \cdot 5H_2O$ starts with calculating the mass of solute needed.



Start by calculating the mass of $CuSO_4 \cdot 5H_2O$ needed. Making a liter of this solution requires 0.5000 mol of solute. Convert the moles to mass by multiplying by the molar mass of $CuSO_4 \cdot 5H_2O$. This mass is calculated to be 124.8 g.

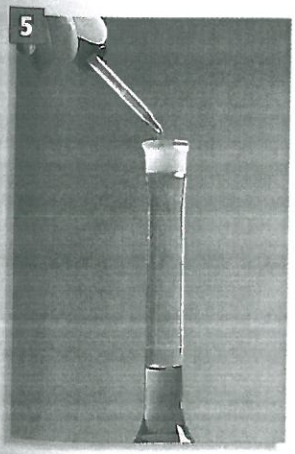


Add some solvent to the solute to dissolve it, and then pour it into a 1.0 L volumetric flask.

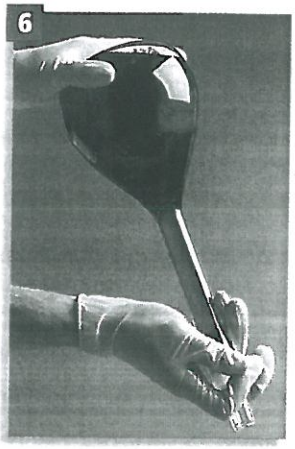


Rinse the weighing beaker with more solvent to remove all the solute, and pour the rinse into the flask. Add water until the volume of the solution nears the neck of the flask.

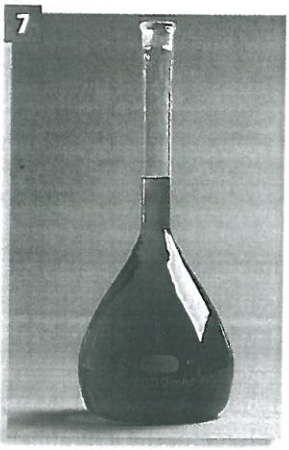
Put the stopper in the flask, and swirl the solution thoroughly.



Carefully fill the flask to the 1.0 L mark with water.



Restopper the flask, and invert it at least 10 times to ensure complete mixing.



The resulting solution has 0.5000 mol of solute dissolved in 1.000 L of solution, which is a 0.5000 M concentration.

SAMPLE PROBLEM A

For more help, go to the Math Tutor at the end of this chapter.

You have 3.50 L of solution that contains 90.0 g of sodium chloride, NaCl. What is the molarity of that solution?

SOLUTION

1 *ANALYZE*

Given: solute mass = 90.0 g NaCl
solution volume = 3.50 L

Unknown: molarity of NaCl solution

2 *PLAN*

Molarity is the number of moles of solute per liter of solution. The solute is described in the problem by mass, not the amount in moles. You need one conversion (grams to moles of solute) using the inverted molar mass of NaCl to arrive at your answer.

$$\text{grams of solute} \longrightarrow \text{number of moles of solute} \longrightarrow \text{molarity}$$

$$\text{g NaCl} \times \frac{1 \text{ mol NaCl}}{\text{g NaCl}} = \text{mol NaCl}$$

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

3 *COMPUTE*

You will need the molar mass of NaCl.
NaCl = 58.44 g/mol

$$90.0 \text{ g } \cancel{\text{NaCl}} \times \frac{1 \text{ mol NaCl}}{58.44 \text{ g } \cancel{\text{NaCl}}} = 1.54 \text{ mol NaCl}$$

$$\frac{1.54 \text{ mol NaCl}}{3.50 \text{ L of solution}} = 0.440 \text{ M NaCl}$$

4 *EVALUATE*

Because each factor involved is limited to three significant digits, the answer should have three significant digits, which it does. The units cancel correctly to give the desired moles of solute per liter of solution, which is molarity.

SAMPLE PROBLEM B

For more help, go to the Math Tutor at the end of this chapter.

You have 0.8 L of a 0.5 M HCl solution. How many moles of HCl does this solution contain?

SOLUTION

1 *ANALYZE*

Given: volume of solution = 0.8 L
concentration of solution = 0.5 M HCl

Unknown: moles of HCl in a given volume

2 *PLAN*

The molarity indicates the moles of solute that are in one liter of solution. Given the volume of the solution, the number of moles of solute can then be found.

$$\text{concentration (mol of HCl/L of solution)} \times \text{volume (L of solution)} = \text{mol of HCl}$$

3 COMPUTE

$$\frac{0.5 \text{ mol HCl}}{1.0 \text{ L of solution}} \times 0.8 \text{ L of solution} = 0.4 \text{ mol HCl}$$

4 EVALUATE The answer is correctly given to one significant digit. The units cancel correctly to give the desired unit, mol. There should be less than 0.5 mol HCl, because less than 1 L of solution was used.

SAMPLE PROBLEM C

For more help, go to the Math Tutor at the end of this chapter.

To produce 40.0 g of silver chromate, you will need at least 23.4 g of potassium chromate in solution as a reactant. All you have on hand is 5 L of a 6.0 M K_2CrO_4 solution. What volume of the solution is needed to give you the 23.4 g K_2CrO_4 needed for the reaction?

SOLUTION

1 ANALYZE

Given: volume of solution = 5 L
concentration of solution = 6.0 M K_2CrO_4
mass of solute = 23.4 g K_2CrO_4
mass of product = 40.0 g Ag_2CrO_4

Unknown: volume of K_2CrO_4 solution in L

2 PLAN The molarity indicates the moles of solute that are in 1 L of solution. Given the mass of solute needed, the amount in moles of solute can then be found. Use the molarity and the amount in moles of K_2CrO_4 to determine the volume of K_2CrO_4 that will provide 23.4 g.

grams of solute ⟶ moles solute
moles solute and molarity ⟶ liters of solution needed

3 COMPUTE To get the moles of solute, you'll need to calculate the molar mass of K_2CrO_4.

$$1 \text{ mol } K_2CrO_4 = 194.2 \text{ g } K_2CrO_4$$

$$23.4 \text{ g } \cancel{K_2CrO_4} \times \frac{1 \text{ mol } K_2CrO_4}{194.2 \text{ g } \cancel{K_2CrO_4}} = 0.120 \text{ mol } K_2CrO_4$$

$$6.0 \text{ M } K_2CrO_4 = \frac{0.120 \text{ mol } K_2CrO_4}{x \text{ L } K_2CrO_4 \text{ soln}}$$

$$x = 0.020 \text{ L } K_2CrO_4 \text{ soln}$$

4 EVALUATE The answer is correctly given to two significant digits. The units cancel correctly to give the desired unit, liters of solution.

PRACTICE

Answers in Appendix E

1. What is the molarity of a solution composed of 5.85 g of potassium iodide, KI, dissolved in enough water to make 0.125 L of solution?
2. How many moles of H_2SO_4 are present in 0.500 L of a 0.150 M H_2SO_4 solution?
3. What volume of 3.00 M NaCl is needed for a reaction that requires 146.3 g of NaCl?

extension
Go to **go.hrw.com** for more practice problems that ask you to calculate molarity.
Keyword: HC6SLNX

Molality

Molality *is the concentration of a solution expressed in moles of solute per kilogram of solvent.* A solution that contains 1 mol of solute, sodium hydroxide, NaOH, for example, dissolved in exactly 1 kg of solvent is a "one molal" solution. The symbol for molality is *m,* and the concentration of this solution is written as 1 *m* NaOH.

One mole of NaOH has a molar mass of 40.0 g, so 40.0 g of NaOH dissolved in 1 kg of water results in a one molal NaOH solution. If 20.0 g of NaOH, which is 0.500 mol of NaOH, is dissolved in exactly 1 kg of water, the concentration of the solution is 0.500 *m* NaOH.

$$\text{molality} = \frac{\text{moles solute}}{\text{mass of solvent (kg)}}$$

$$\frac{0.500 \text{ mol NaOH}}{1 \text{ kg } H_2O} = 0.500 \; m \text{ NaOH}$$

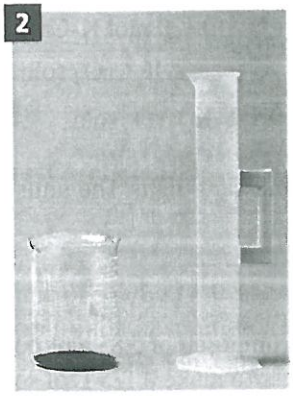
If 80.0 g of sodium hydroxide, which is 2 mol, is dissolved in 1 kg of water, a 2.00 *m* solution of NaOH is produced. The molality of any solution can be found by dividing the number of moles of solute by the mass in kilograms of the solvent in which it is dissolved. Note that if the amount of solvent is expressed in grams, the mass of solvent must be converted to kilograms by multiplying by the following conversion factor.

$$1 \text{ kg}/1000 \text{ g}$$

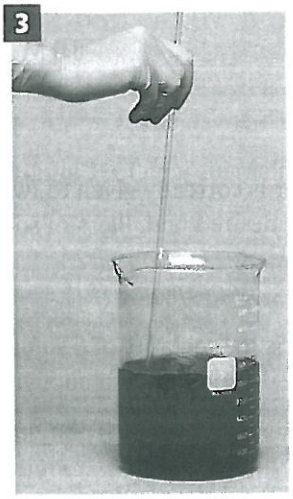
Figure 18 shows how a 0.5000 *m* solution of $CuSO_4 \cdot 5H_2O$ is prepared, in contrast with the 0.5000 M solution in **Figure 17.**

FIGURE 18 The preparation of a 0.5000 *m* solution of $CuSO_4 \cdot 5H_2O$ also starts with the calculation of the mass of solute needed.

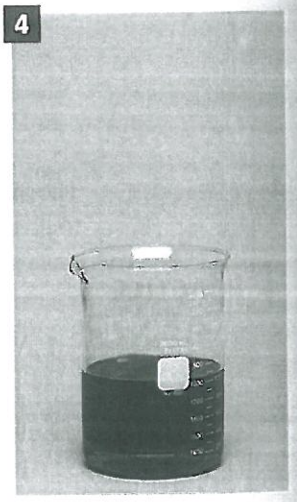
Calculate the mass of $CuSO_4 \cdot 5H_2O$ needed. Making this solution will require 0.5000 mol of $CuSO_4 \cdot 5H_2O$ per kilogram of solvent (1000 g). This mass is calculated to be 124.8 g.



Add 1.000 kg of solvent to the solute in the beaker. Because the solvent is water, 1.000 kg will equal 1000 mL.



Mix thoroughly.



The resulting solution has 0.5000 mol of solute dissolved in 1.000 kg of solvent.

Concentrations are expressed as molalities when studying properties of solutions related to vapor pressure and temperature changes. Molality is used because it does not change with changes in temperature. Below is a comparison of the equations for molarity and molality.

$$\text{molarity, M} = \frac{\text{amount of A (mol)}}{\text{volume of solution (L)}}$$

$$\text{molality, } m = \frac{\text{amount of A (mol)}}{\text{mass of solvent (kg)}}$$

SAMPLE PROBLEM D

A solution was prepared by dissolving 17.1 g of sucrose (table sugar, $C_{12}H_{22}O_{11}$) in 125 g of water. Find the molal concentration of this solution.

SOLUTION

1 ANALYZE

Given: solute mass = 17.1 g $C_{12}H_{22}O_{11}$
solvent mass = 125 g H_2O

Unknown: molal concentration

2 PLAN

To find molality, you need moles of solute and kilograms of solvent. The given grams of sucrose must be converted to moles. The mass in grams of solvent must be converted to kilograms.

$$\text{mol } C_{12}H_{22}O_{11} = \frac{\text{g } C_{12}H_{22}O_{11}}{\text{molar mass } C_{12}H_{22}O_{11}}$$

$$\text{kg } H_2O = \text{g } H_2O \times \frac{1 \text{ kg}}{1000 \text{ g}}$$

$$\text{molality } C_{12}H_{22}O_{11} = \frac{\text{mol } C_{12}H_{22}O_{11}}{\text{kg } H_2O}$$

3 COMPUTE

Use the periodic table to compute the molar mass of $C_{12}H_{22}O_{11}$.
$C_{12}H_{22}O_{11} = 342.34$ g/mol

$$17.1 \text{ g } \cancel{C_{12}H_{22}O_{11}} \times \frac{1 \text{ mol } C_{12}H_{22}O_{11}}{342.34 \text{ g } \cancel{C_{12}H_{22}O_{11}}} = 0.0500 \text{ mol } C_{12}H_{22}O_{11}$$

$$\frac{125 \text{ g } H_2O}{1000 \text{ g/kg}} = 0.125 \text{ kg } H_2O$$

$$\frac{0.0500 \text{ mol } C_{12}H_{22}O_{11}}{0.125 \text{ kg } H_2O} = 0.400 \, m \, C_{12}H_{22}O_{11}$$

4 EVALUATE

The answer is correctly given to three significant digits. The unit mol solute/kg solvent is correct for molality.

SAMPLE PROBLEM E

A solution of iodine, I_2, in carbon tetrachloride, CCl_4, is used when iodine is needed for certain chemical tests. How much iodine must be added to prepare a 0.480 *m* solution of iodine in CCl_4 if 100.0 g of CCl_4 is used?

SOLUTION

1 *ANALYZE*

Given: molality of solution = 0.480 *m* I_2
mass of solvent = 100.0 g CCl_4

Unknown: mass of solute

2 *PLAN*

Your first step should be to convert the grams of solvent to kilograms. The molality gives you the moles of solute, which can be converted to the grams of solute using the molar mass of I_2.

3 *COMPUTE*

Use the periodic table to compute the molar mass of I_2.
$I_2 = 253.8$ g/mol

$$100.0 \text{ g } \cancel{CCl_4} \times \frac{1 \text{ kg}}{1000 \text{ g } \cancel{CCl_4}} = 0.100 \text{ kg } CCl_4$$

$$0.480 \ m = \frac{x \text{ mol } I_2}{0.1 \text{ kg } H_2O} \qquad x = 0.0480 \text{ mol } I_2$$

$$0.0480 \text{ } \cancel{\text{mol } I_2} \times \frac{253.8 \text{ g } I_2}{\cancel{\text{mol } I_2}} = 12.2 \text{ g } I_2$$

4 *EVALUATE*

The answer has three significant digits and the units for mass of I_2.

PRACTICE

Answers in Appendix E

1. What is the molality of acetone in a solution composed of 255 g of acetone, $(CH_3)_2CO$, dissolved in 200. g of water?
2. What quantity, in grams, of methanol, CH_3OH, is required to prepare a 0.244 *m* solution in 400. g of water?

extension
Go to **go.hrw.com** for more practice problems that ask you to calculate molality.
Keyword: HC6SLNX

SECTION REVIEW

1. What quantity represents the ratio of the number of moles of solute for a given volume of solution?
2. We dissolve 5.00 grams of sugar, $C_{12}H_{22}O_{11}$, in water to make 1.000 L of solution. What is the concentration of this solution expressed as a molarity?

Critical Thinking

3. **ANALYZING DATA** You evaporate all of the water from 100. mL of NaCl solution and obtain 11.3 grams of NaCl. What was the molarity of the NaCl solution?
4. **RELATING IDEAS** Suppose you know the molarity of a solution. What additional information would you need to calculate the molality of the solution?