13.8 CONCENTRATION: MOLARITY

The **molarity** *of a solution, abbreviated* M, *is a ratio giving the number of moles of solute per liter of solution.*

$$\text{Molarity (M)} = \frac{\text{moles of solute}}{\text{liters of solution}}$$

A solution containing 1 mole of KBr in 1 L of solution has a molarity of 1 and is said to be a 1-M (1 *molar*) solution.

When a solution is to be used for a chemical reaction, concentration is almost always expressed in units of molarity. A major reason for this is the fact that the amount of solute is expressed in moles, a most convenient unit for dealing with stoichiometry in chemical reactions. Because chemical reactions occur between molecules and atoms, a unit that counts particles, as the mole does, is desirable.

To find the molarity of a solution we need to know the number of moles of solute present and the solution volume in liters and then take the ratio of the two quantities. An alternative to knowing the number of moles of solute is knowledge about the grams of solute present and the solute's molar mass.

Example 13.8

Determine the molarities of the following solutions.

(a) 1.45 moles of KCl dissolved in enough water to give 875 mL of solution

(b) 57.2 g of NH_4Br dissolved in enough water to give 2.15 L of solution

$\mathcal{M} = 97.9$

a) $M = n/V\,(L)$

b) $M = \frac{n}{V} = \frac{m/\mathcal{M}}{V}$

Solution

(a) The number of moles of solute is given in the problem statement.

$$\text{Moles of solute} = 1.45 \text{ moles KCl}$$

The volume of the solution is also given in the problem statement, but not in the right units. Molarity requires liters for volume units. Making the unit change gives

$$875 \cancel{\text{mL}} \times \frac{10^{-3}\text{ L}}{1 \cancel{\text{mL}}} = 0.875 \text{ L} \quad \text{(calculator and correct answer)}$$

The molarity of the solution is obtained by substituting the known quantities into the equation

$$\text{Molarity} = \frac{\text{moles of solute}}{\text{L of solution}}$$

which gives

$$\text{M} = \frac{1.45 \text{ moles KCl}}{0.875 \text{ L solution}} = 1.6571428 \frac{\text{moles KCl}}{\text{L solution}} \quad \text{(calculator answer)}$$

$$= 1.66 \frac{\text{moles KCl}}{\text{L solution}} \quad \text{(correct answer)}$$

Note that the units of molarity are always moles per liter.

(b) This time the volume of solution is given in the right units, liters.

$$\text{Volume of solution} = 2.15 \text{ L}$$

The moles of solute must be calculated from the grams of solute (given) and the solute's formula mass, which is 97.9 amu (calculated from a table of atomic masses).

$$57.2 \cancel{\text{g NH}_4\text{Br}} \times \frac{1 \text{ mole NH}_4\text{Br}}{97.9 \cancel{\text{g NH}_4\text{Br}}} = 0.58426966 \text{ mole NH}_4\text{Br} \quad \text{(calculator answer)}$$

$$= 0.584 \text{ mole NH}_4\text{Br} \quad \text{(correct answer)}$$

Substituting the known quantities into the defining equation for molarity gives

$$\text{M} = \frac{0.584 \text{ mole NH}_4\text{Br}}{2.15 \text{ L solution}} = 0.2716279 \frac{\text{mole NH}_4\text{Br}}{\text{L solution}} \quad \text{(calculator answer)}$$

$$= 0.272 \frac{\text{mole NH}_4\text{Br}}{\text{L solution}} \quad \text{(correct answer)}$$

Practice Exercise 13.8

What is the molarity of a solution prepared by dissolving 25.0 g of NaOH in enough water to give 2.50 L of solution?

Ans. 0.250 M NaOH

As the previous example indicates, when you perform a molarity calculation the chemical formula of the solute is always needed. You cannot calculate moles of solute without knowing the chemical formula of the solute. In contrast, when you perform percent concentration calculations (or parts per million or billion)—Sections 13.6 and 13.7—the chemical formula of the solute is not used in the calculation.

The moles of solute present in a known volume of solution is an easily calculated quantity if the molarity of the solution is known. In doing such a calculation, molarity serves as a conversion factor relating liters of solution to moles of solute.

Volume of solution (liters) $\xleftrightarrow{\text{molarity}}$ Moles of solute

Example 13.9

Citric acid, $C_6H_8O_7$, is the substance that gives lemon juice and other citrus fruit juices a sour taste. How many grams of citric acid are present in 125 mL of a 0.400 M citric acid solution? $\mathcal{M} = 192$

$n = VM = m/\mathcal{M} \Rightarrow m = VM\mathcal{M}$

Solution

The given quantity is 125 mL of solution, and the desired quantity is grams of $C_6H_8O_7$.

$$125 \text{ mL solution} = ?\ \text{g } C_6H_8O_7$$

The pathway to be used in solving this problem is

$$\text{mL solution} \longrightarrow \text{L solution} \longrightarrow \text{moles } C_6H_8O_7 \longrightarrow \text{g } C_6H_8O_7$$

The given molarity (0.400 M) will serve as the conversion factor for the second unit change; the molecular mass of citric acid (which must be calculated as it is not given) is used in accomplishing the third unit charge.

The dimensional analysis setup from this pathway is

$$125 \text{ mL solution} \times \frac{10^{-3} \text{ L solution}}{1 \text{ mL solution}} \times \frac{0.400 \text{ mole } C_6H_8O_7}{1 \text{ L solution}} \times \frac{192 \text{ g } C_6H_8O_7}{1 \text{ mole } C_6H_8O_7}$$

Canceling units and doing the arithmetic gives

$$\frac{125 \times 10^{-3} \times 0.400 \times 192}{1 \times 1 \times 1} \text{ g } C_6H_8O_7 = 9.6 \text{ g } C_6H_8O_7 \quad \text{(calculator answer)}$$

$$= 9.60 \text{ g } C_6H_8O_7 \quad \text{(correct answer)}$$

Practice Example 13.9

How many grams of ascorbic acid (vitamin C), $C_6H_8O_6$, are present in 125 mL of a 0.400-M vitamin C solution?

Ans. 8.80 g $C_6H_8O_6$

Example 13.10

The chemical formula for sucrose (table sugar) is $C_{12}H_{22}O_{11}$. How many liters of 2.00 M aqueous sucrose solution can be prepared from 25.0 g of sucrose? $\mathcal{M} = 342$

$n = VM = m/\mathcal{M} \Rightarrow V = \frac{m}{M\mathcal{M}}$

Solution

The given quantity is 25.0 g of $C_{12}H_{22}O_{11}$, and the desired quantity is liters of solution.

$$25.0 \text{ g } C_{12}H_{22}O_{11} = ?\ \text{L } C_{12}H_{22}O_{11} \text{ solution}$$

The pathway to be used in solving this problem will involve the following steps.

$$\text{g } C_{12}H_{22}O_{11} \longrightarrow \text{moles } C_{12}H_{22}O_{11} \longrightarrow \text{L } C_{12}H_{22}O_{11} \text{ solution}$$

The first unit conversion will be accomplished by using the molar mass of $C_{12}H_{22}O_{11}$ (which must be calculated since it is not given) as a conversion factor. The second unit conversion involves the use of the given molarity as a conversion factor.

$$25.0 \text{ g } C_{12}H_{22}O_{11} \times \frac{1 \text{ mole } C_{12}H_{22}O_{11}}{342 \text{ g } C_{12}H_{22}O_{11}} \times \frac{1 \text{ L } C_{12}H_{22}O_{11} \text{ solution}}{2.00 \text{ moles } C_{12}H_{22}O_{11}}$$

Canceling units and doing the arithmetic gives

$$\frac{25.0 \times 1 \times 1}{342 \times 2.00} \text{ L } C_{12}H_{22}O_{11} \text{ solution} = 0.036549707 \text{ L } C_{12}H_{22}O_{11} \text{ solution} \quad \text{(calculator answer)}$$

$$= 0.365 \text{ L } C_{12}H_{22}O_{11} \text{ solution} \quad \text{(correct answer)}$$

Practice Exercise 13.10

How many liters of 0.100 M aqueous sodium hydroxide (NaOH) solution can be prepared from 10.0 g of sodium hydroxide?

Ans. 2.50 L solution

Molarity and mass percent are probably the two most commonly used concentration units. The need to convert from one to the other often arises. Such a conversion can easily be done provided the density of the solution is known. Figure 13.4 shows schematically the steps involved in converting one of these concentration units to the other.

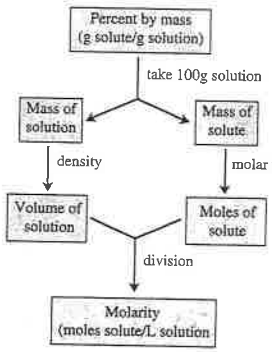


FIGURE 13.4 A "road-map" diagram showing the steps involved in converting from percent by mass to molarity or vice versa. (For the reverse process, reverse the direction of the arrows in the diagram.)

$M = \frac{n_A}{V_{sol'n}}$; $d = \frac{m_{sol'n}}{V_{sol'n}}$

$wt\% = \frac{m_A}{m_{sol'n}} \times 100$

⇒ Assume $m_{sol'n} = 100$
so $wt\% = m_A$

$\therefore M = \left(\frac{m_A/\mathcal{M}}{100 g\ sol'n}\right)(d)\left(\frac{1000 mL}{L}\right)$

Example 13.11

The skin irritation that accompanies insect bites is often caused by formic acid (H_2CO_2). A 40.00 percent by mass aqueous solution of formic acid has a density of 1.098 g/mL. What is the molarity of this solution? $\mathcal{M} = 46.03$

Solution

Calculate the moles of solute and liters of solution present in a sample of this solution. Since solution concentration is independent of sample size, any size sample can be the basis for the calculation. To simplify the math take a 100.0-g sample of solution.

STEP 1 *Moles of solute.* The given quantity is 100.0 g of solution, and the desired quantity is moles of H_2CO_2.

$$100.0 \text{ g solution} = ? \text{ moles } H_2CO_2$$

The pathway to be used in solving this problem is

$$\text{g solution} \longrightarrow \text{g solute} \longrightarrow \text{moles solute}$$

The known mass percent concentration will be the basis for the conversion factor that takes us from grams of solution to grams of solute.

$$100.0 \text{ g solution} \times \frac{40.00 \text{ g } H_2CO_2}{100 \text{ g solution}} \times \frac{1 \text{ mole } H_2CO_2}{46.03 \text{ g } H_2CO_2}$$

$$= 0.86899847 \text{ mole } H_2CO_2 \quad \text{(calculator answer)}$$
$$= 0.8690 \text{ mole } H_2CO_2 \quad \text{(correct answer)}$$

STEP 2 *Liters of solution.* The density of the solution is used as a conversion factor in obtaining the volume of solution. The pathway for the calculation is

$$\text{g solution} \longrightarrow \text{mL solution} \longrightarrow \text{L solution}$$

The set up is

$$100.0 \text{ g solution} \times \frac{1 \text{ mL solution}}{1.098 \text{ g solution}} \times \frac{10^{-3} \text{ L solution}}{1 \text{ mL solution}}$$

$$= 0.091074681 \text{ L solution} \quad \text{(calculator answer)}$$
$$= 0.09107 \text{ L solution} \quad \text{(correct answer)}$$

STEP 3 *Molarity.* With both moles of solute and liters of solution known, the molarity is obtained by substitution into the defining equation for molarity:

$$M = \frac{\text{moles } H_2CO_2}{\text{L solution}} = \frac{0.8690 \text{ mole } H_2CO_2}{0.09107 \text{ L solution}}$$
$$= \frac{9.5421104 \text{ moles } H_2CO_2}{\text{L solution}} \quad \text{(calculator answer)}$$
$$= \frac{9.542 \text{ moles } H_2CO_2}{\text{L solution}} \quad \text{(correct answer)}$$

Practice Exercise 13.11

A 15.00 percent by mass aqueous solution of silver nitrate ($AgNO_3$) has a density of 1.141 g/mL. What is the molarity of this solution?

Ans. 1.007 M

Molar concentrations do not give information about the amount of *solvent* present. All that is known is that enough solvent is present to give a specific volume of *solution*. The amount of solvent present in a solution of a known molarity can be calculated if the density of the solution is known. Without the density it cannot be calculated.

Sample 13.12

Large amounts of sulfuric acid (H_2SO_4) are used in the production of phosphate fertilizers. A 2.324 M H_2SO_4 solution has a density of 1.142 g/mL. How many grams of solvent (water) are present in 25.0 mL of this solution? $\mathcal{M} = 98.1$

Solution

To find the grams of solvent present we must first find the grams of solute (H_2SO_4) and the grams of solution. The grams of solvent present is then obtained by calculating the difference.

$$\text{g solvent} = \text{g solution} - \text{g solute}$$

STEP 1 *Grams of solution.* The volume of solution is given. Density, used as a conversion factor, will enable us to convert this volume to grams of solution.

$$25.0 \text{ mL solution} \times \frac{1.142 \text{ g solution}}{1 \text{ mL solution}} = 28.55 \text{ g solution} \quad \text{(calculator answer)}$$
$$= 28.6 \text{ g solution} \quad \text{(correct answer)}$$

STEP 2 *Grams of solute.* We will use the molarity of the solution as a conversion factor in obtaining the grams of solute. The setup for this calculation is similar to that in Example 13.9.

$n_A = (VM)_A = m_A/\mathcal{M}$
⇒ $m_A = n_A \mathcal{M}$
$d = \frac{m_{sol'n}}{V_{sol'n}}$ ⇒
$m_{sol'n} = dV_{sol'n}$
$\therefore m_{H_2O} = m_{sol'n} - m_A$

$$25.0\ \text{mL solution} \times \frac{10^{-3}\ \text{L solution}}{1\ \text{mL solution}} \times \frac{2.324\ \text{moles}\ H_2SO_4}{1\ \text{L solution}} \times \frac{98.1\ \text{g}\ H_2SO_4}{1\ \text{mole}\ H_2SO_4}$$

$= 5.69961\ \text{g}\ H_2SO_4$ (calculator answer)
$= 5.70\ \text{g}\ H_2SO_4$ (correct answer)

STEP 3 *Grams of solvent.* The grams of solvent will be the difference in mass between the grams of solution and the grams of solute.

28.6 g solution − 5.70 g solute = 22.9 g solvent (calculator and correct answer)

● Practice Exercise 13.12

A 0.750-M acetic acid ($HC_2H_3O_2$) solution has a density of 1.01 g/mL. How many grams of solvent are present in 125 mL of this solution?

Ans. 12$\bar{0}$ g solvent

13.10 DILUTION

A common problem encountered when working with solutions in the laboratory is that of diluting a solution of known concentration (usually called a stock solution) to a lower concentration. **Dilution** *is the process in which more solvent is added to a solution in order to lower its concentration.* Dilution always lowers the concentration of a solution. The same amount of solute is present, but it is now distributed in a larger amount of solvent (the original solvent plus the added solvent).

Since laboratory solutions are almost always liquids, dilution is normally a volumetric procedure. Most often, a solution of a specific molarity must be prepared by adding a predetermined volume of solvent to a specific volume of stock solution.

With molar concentration units, a very simple mathematical relationship exists between the volumes and molarities of the diluted and stock solutions. This relationship is derived from the fact that the same amount of solute is present in both solutions; only solvent is added in a dilution procedure.

$$\text{Moles solute}_{\text{stock solution}} = \text{moles solute}_{\text{diluted solution}}$$

The number of moles of solute in both solutions is given by the expression

$$\text{Moles solute} = \text{molarity } (M) \times \text{liters of solution } (V)$$

(This equation is just a rearrangement of the defining equation for molarity to isolate moles of solute on the left side.) Substitution of this second expression into the first one gives the equation

$$M_s \times V_s = M_d \times V_d$$

In this equation M_s and V_s are the molarity and volume of the stock solution (the solution to be diluted) and M_d and V_d the molarity and volume of the solution resulting from the dilution. Because volume appears on both sides of the equation, any volume unit, not just liters, may be used as long as it is the same on both sides of the equation. Again, the validity of this equation is based on there being no change in the amount of solute present.

$n_1 = n_2 \Rightarrow$
$(MV)_1 = (MV)_2$
$M_2 = \frac{(MV)_1}{V_2}$

● *Example 13.16*

What is the molarity of the solution prepared by diluting 65 mL of 0.95 M sodium sulfate (Na_2SO_4) solution to a final volume of 135 mL?

Solution
Three of the four variables in the equation

$$M_s \times V_s = M_d \times V_d$$

are known.

$$M_s = 0.95\text{ M} \qquad M_d = ?\text{ M}$$
$$V_s = 65\text{ mL} \qquad V_d = 135\text{ mL}$$

Rearranging the equation to isolate M_d on the left side and substituting the known variables into it gives

$$M_d = M_s \times \frac{V_s}{V_d}$$
$$= 0.95\text{ M} \times \frac{65\text{ mL}}{135\text{ mL}} = 0.4574074\text{ M} \quad \text{(calculator answer)}$$
$$= 0.46\text{ M} \quad \text{(correct answer)}$$

Thus, the diluted solution's concentration is 0.46 M.

Practice Exercise 13.16

What is the molarity of the solution prepared by diluting 75 mL of 1.50 M silver nitrate ($AgNO_3$) solution to a final volume of 225 mL?

Ans. 0.50 M

Example 13.17

How much solvent must be added to 200.0 mL of a 1.25 M sodium chloride (NaCl) solution to decrease its concentration to 0.770 M?

Solution
The volume of solvent added is equal to the difference between the final and initial volumes. The initial volume is known. The final volume can be calculated using the equation

$$M_s \times V_s = M_d \times V_d$$

Once the final volume is known, the difference between the two volumes can be obtained.

Substituting the known quantities into the dilution equation, rearranged to isolate V_d on the left side, gives

$$V_d = V_s \times \frac{M_s}{M_d}$$
$$= 200.0\text{ mL} \times \frac{1.25\text{ M}}{0.770\text{ M}} = 324.67532\text{ mL} \quad \text{(calculator answer)}$$
$$= 325\text{ mL} \quad \text{(correct answer)}$$

The solvent added is

$$V_d - V_s = (325 - 200.0)\text{ mL} = 125\text{ mL} \quad \text{(calculator and correct answer)}$$

$n_1 = n_2 \Rightarrow$
$(MV)_1 = (MV)_2$
$V_2 = \frac{(MV)_1}{M_2}$
added $= V_2 - V_1$

$n_{TOT} = n_1 + n_2$
$V_{TOT} = V_1 + V_2$
$M = \left(\frac{n}{V}\right)_{TOT} = \frac{(MV)_1 + (MV)_2}{V_1 + V_2}$

Practice Exercise 13.17

How much solvent must be added to 50.0 mL of 2.20 M potassium chloride (KCl) solution to decrease its concentration to 0.0113 M?

Ans. 9680 mL

When two "like" solutions—that is, solutions that contain the same solute and the same solvent—of differing known molarities and volumes are mixed together, the molarity of the newly formed solution can be calculated by the same principles that apply in a simple dilution problem.

Again, the key concept involves the amount of solute present; it is constant. The sum of the amounts of solute present in the individual solutions prior to mixing is the same as the total amount of solute present in the solution after mixing. No solute is lost or gained in the mixing process. Thus, we can write

$$\text{Moles solute}_{\text{first solution}} + \text{moles solute}_{\text{second solution}} = \text{moles solute}_{\text{combined solution}}$$

Substituting the expression (M × V) for moles solute in this equation gives

$$(M_1 \times V_1) + (M_2 \times V_2) = M_3 \times V_3$$

where the subscripts 1 and 2 denote the solutions to be mixed and the subscript 3 is the solution resulting from the mixing. Again, this expression is valid only when the solutions that are mixed are "like" solutions.

Example 13.18

What is the molarity of the solution obtained by mixing 50.0 mL of 2.25 M hydrochloric acid (HCl) solution with 160.0 mL of 1.25 M hydrochloric acid solution?

Solution
Five of the six variables in the equation

$$(M_1 \times V_1) + (M_2 \times V_2) = M_3 \times V_3$$

are known:

$$M_1 = 2.25\text{ M} \quad V_1 = 50.0\text{ mL}$$
$$M_2 = 1.25\text{ M} \quad V_2 = 160.0\text{ mL}$$
$$M_3 = ?\text{ M} \quad V_3 = 210.0\text{ mL}$$

Note that in the mixing process we consider the volumes of the solution to be additive; that is,

$$V_3 = V_1 + V_2$$

This is a valid assumption for "like" solutions.

Solving our equation for M_3 and then substituting the known quantities into it gives

$$M_3 = \frac{(M_1 \times V_1) + (M_2 \times V_2)}{V_3} = \frac{(2.25\text{ M} \times 50.0\text{ mL}) + (1.25\text{ M} \times 160.0\text{ mL})}{(210.0\text{ mL})}$$

$= 1.4904761$ M (calculator answer)
$= 1.49$ M (correct answer)

● Practice Exercise 13.18

What is the molarity of the solution obtained by mixing 50.0 mL of 1.25 M ammonium chloride (NH_4Cl) solution with 175 mL of 0.125 M ammonium chloride solution?

Ans. 0.375 M

In the solution of Example 13.18 the given liquid volumes were considered additive. In Section 13.6, when discussing volume percent, it was stressed that volumes were not additive. Why the difference? Volumes of different liquids (Sec. 13.6) are not additive; volumes of the same liquid (Example 13.18) are additive.

13.11 Molarity and Chemical Equations

Section 10.8 introduced a general problem-solving procedure for setting up problems that involve chemical equations. With this procedure, if information is given about one reactant or product in a chemical reaction (number of grams, moles, or particles), similar information can easily be obtained for any other reactant or product.

In Section 12.13 this procedure was refined to allow us to do mass-to-volume or volume-to-mass calculations for reactions when at least one reactant or product is a gas.

This section further refines our problem-solving procedure in order to deal efficiently with reactions that occur in aqueous solution. Of primary importance in this new area of problem solving will be *solution volume*. In most situations, solution volume is more conveniently determined than solution mass.

When solution concentrations are expressed in terms of molarity, a direct relationship exists between solution volume (in liters) and moles of solute present. The definition of molarity itself gives the relationship; molarity is the ratio of moles of solute to volume (in liters) of solution. Thus, molarity is the connection that links volume of solution to the other common problem-solving parameters, such as moles and grams. Figure 13.6 shows diagrammatically the place that volume of solution occupies, relative to other parameters, in the overall scheme of chemical-equation-based problem solving. This diagram is a simple modification of Figure 12.9; "volume of solution" boxes have replaced "particles" boxes. It is used in the same way as Figure 12.9 was.

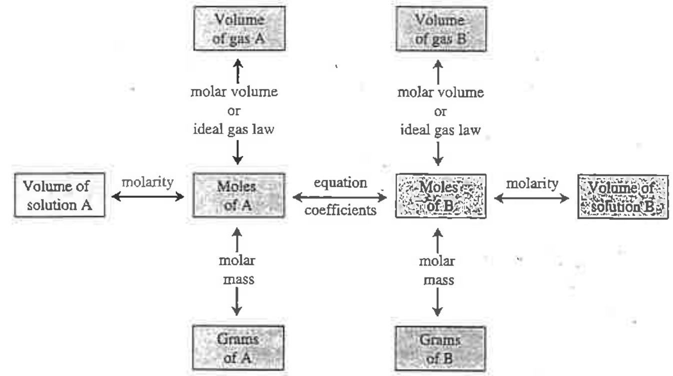


Figure 13.6 Conversion factor relationships needed to solve problems involving chemical reactions that occur in aqueous solution.

$n_{NaHCO_3} = 3n_{C_6H_8O_7}$

$(VM)_{NaHCO_3} = 3(VM)_{C_6H_8O_7}$

$V = \frac{3(VM)_{C_6H_8O_7}}{M}$

● *Example 13.19*

The fizz produced when an Alka-Seltzer tablet is dissolved in water is due to the reaction between sodium bicarbonate, $NaHCO_3$, and citric acid, $C_6H_8O_7$.

$$3\,NaHCO_3(aq) + C_6H_8O_7(aq) \longrightarrow 3\,CO_2\,(g) + 3\,H_2O(l) + Na_3C_6H_8O_7(aq)$$

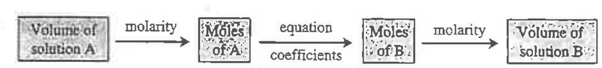
If this reaction were run in a laboratory, what volume, in liters, of 2.50 M $NaHCO_3$ solution is needed to react completely with 0.025 L of 3.50 M $C_6H_8O_7$ solution?

Solution

Step 1 The given quantity is 0.025 L of $C_6H_8O_7$ solution, and the desired quantity is liters of $NaHCO_3$ solution.

$$0.025\text{ L } C_6H_8O_7 = ?\text{ L } NaHCO_3$$

Step 2 This problem is a "volume of solution A" to "volume of solution B" problem. The pathway used in solving it, in terms of Figure 13.6, is



Step 3 The dimensional analysis setup for the calculation is

$$0.025\text{ L } C_6H_8O_7 \times \frac{3.50\text{ moles } C_6H_8O_7}{1\text{ L } C_6H_8O_7} \times \frac{3\text{ moles } NaHCO_3}{1\text{ mole } C_6H_8O_7} \times \frac{1\text{ L } NaHCO_3}{2.50\text{ moles } NaHCO_3}$$

Step 4 Combining all of the numerical factors gives

$$\frac{0.025 \times 3.50 \times 3 \times 1}{1 \times 1 \times 2.50}\text{ L } NaHCO_3 = 0.105\text{ L } NaHCO_3 \quad \text{(calculator answer)}$$

$$= 0.10\text{ L } NaHCO_3 \quad \text{(correct answer)}$$

Practice Exercise 13.19

What volume, in liters, of a 3.40 M potassium hydroxide (KOH) solution is needed to react completely with 0.100 L of a 6.72-M sulfuric acid (H_2SO_4) solution according to the following equation?

$$2\ KOH(aq) + H_2SO_4(aq) \longrightarrow K_2SO_4(aq) + 2\ H_2O(l)$$

Ans. 0.395 L KOH

Example 13.20

How many grams of lead(II) chloride can be produced from the reaction of 1.05 L of 0.470 M potassium chloride (KCl) solution with an excess of 4.00 M lead(II) nitrate [$(Pb(NO_3)_2$] solution according to the following equation. $\mathcal{M}$ 278

$$2\ KCl(aq) + Pb(NO_3)_2(aq) \longrightarrow PbCl_2(s) + 2\ KNO_3(aq)$$

Solution

STEP 1 The given quantity is 1.05 L of KCl solution, and the desired quantity is grams of $PbCl_2$.

$$1.05\ L\ KCl = ?\ g\ PbCl_2$$

STEP 2 This is a "volume of solution A" to "grams of B" problem. The pathway, in terms of Figure 13.6, is

Volume of solution A —molarity→ Moles of A —equation coefficients→ Moles of B —molar mass→ Grams of B

STEP 3 The dimensional analysis setup for the calculation is

$$1.05\ \text{L KCl} \times \frac{0.470\ \text{mole KCl}}{1\ \text{L KCl}} \times \frac{1\ \text{mole } PbCl_2}{2\ \text{mole KCl}} \times \frac{278\ \text{g } PbCl_2}{1\ \text{mole } PbCl_2}$$

STEP 4 The answer, obtained from combining all of the numerical factors, is

$$\frac{1.05 \times 0.470 \times 1 \times 278}{1 \times 2 \times 1}\ g\ PbCl_2 = 68.5965\ g\ PbCl_2 \quad \text{(calculator answer)}$$

$$= 68.6\ g\ PbCl_2 \quad \text{(correct answer)}$$

Note that the concentration of $Pb(NO_3)_2$ solution, given as 4.00 M in the problem statement, did not enter into the calculation. This is because the $Pb(NO_3)_2$ solution is present in excess; we know that we have enough of it. If a specific volume of $Pb(NO_3)_2$ solution had been given in the problem statement, we would have had to determine the limiting reactant ($Pb(NO_3)_2$ or KCl) as the first step in working the problem. The concept of a limiting reactant was discussed in Section 10.9.

$n_{PbCl_2} = \frac{1}{2} n_{KCl} = \frac{1}{2}(VM)_{KCl}$

$= (m/\mathcal{M})_{PbCl_2}$

$\therefore m = \frac{(VM)_{KCl}\mathcal{M}}{2}$

$n_{NO} = n_{HNO_3} = (VM)_{HNO_3}$

$= \left(\frac{PV}{RT}\right)_g$

$\therefore V_g = \frac{(VM)_{HNO_3} RT_g}{P_g}$

Practice Exercise 13.20

How many grams of $BaCrO_4$ can be produced from the reaction of 1.05 L of 0.470 M $BaCl_2$ solution with an excess of 2.00 M K_2CrO_4 solution according to the following equation?

$$BaCl_2(aq) + K_2CrO_4(aq) \longrightarrow BaCrO_4(s) + 2\ KCl(aq)$$

Ans. 125 g $BaCrO_4$

Example 13.21

What volume, in liters of nitric oxide gas, NO, measured at STP can be produced from 1.75 L of 0.550 M nitric acid, HNO_3, and an excess of 0.650 M hydrosulfuric acid, H_2S, according to the following reaction?

$$2\ HNO_3(aq) + 3\ H_2S(aq) \longrightarrow 2\ NO(g) + 3\ S(s) + 4\ H_2O(l)$$

Solution

STEP 1 The given quantity is 1.75 L of HNO_3 solution, and the desired quantity is liters of NO gas at STP.

$$1.75\ L\ HNO_3 = ?\ L\ NO\ \text{(at STP)}$$

STEP 2 This is a "volume of solution A" to "volume of gas B" problem. From Figure 13.6 the pathway for solving the problem is

Volume of solution A —molarity→ Moles of A —equation coefficients→ Moles of B —molar volume→ Volume of gas B

STEP 3 The dimensional analysis setup for the calculation is

$$1.75\ \text{L } HNO_3 \times \frac{0.550\ \text{mole } HNO_3}{1\ \text{L } HNO_3} \times \frac{2\ \text{moles NO}}{2\ \text{moles } HNO_3} \times \frac{22.4\ \text{L NO}}{1\ \text{mole NO}}$$

The last conversion factor is derived from the fact that 1 mole of any gas occupies 22.4 L at STP conditions (Sec. 12.10).

STEP 4 The result, obtained by combining all of the numerical factors, is

$$\frac{1.75 \times 0.550 \times 2 \times 22.4}{1 \times 2 \times 1}\ L\ NO = 21.56\ L\ NO \quad \text{(calculator answer)}$$

$$= 21.6\ L\ NO \quad \text{(correct answer)}$$

Practice Exercise 13.21

What volume, in liters, of H_2 gas measured at STP can be produced from 0.575 L of 1.22 M HBr solution and an excess of Zn according to the following equation?

$$2\ HBr(aq) + Zn(s) \longrightarrow ZnBr_2(aq) + H_2(g)$$

Ans. 7.86 L H_2