Answer (b):

mass of A → number of moles of A

↑

subscripts in formula

↓

mass of B → number of moles of B

$$\text{number of moles of Al} = 10.0\,\cancel{\text{g Al}}\left(\frac{1\text{ mol Al}}{27.0\,\cancel{\text{g Al}}}\right) = 0.37\text{ mol Al}$$

$$\text{number of moles of O} = 8.9\,\cancel{\text{g O}}\left(\frac{1\text{ mol O}}{16.00\,\cancel{\text{g O}}}\right) = 0.556\text{ mol O}$$

We can calculate number of moles of O/number of moles of Al = 0.556 mol_O/0.370 mol_Al = 1.50 $\text{mol}_\text{O}/\text{mol}_\text{Al}$. This yields the empirical formula ($Al_{1.0}O_{1.5}$). But all subscripts must be whole numbers, so we multiply the subscripts in the empirical formula subscripts by 2 to give the correct empirical formula Al_2O_3, ($Al_{1.0}O_{1.5}$)(2).

Problem Set 3

3.1 Determine the empirical and molecular formulas of the following substances:

a. hydrogen peroxide; 5.94% H, 94.06% O; MM = 34.01 g mol^{-1}
b. disilane; 9.73% H, 90.27% Si; MM = 62.23 g mol^{-1}
c. benzoyl peroxide; 69.42% C, 4.16% H, 26.42% O; MM = 242.22 g mol^{-1}
d. phosphorus sulfide; 27.87% P, 72.13% S; MM = 444.58 g mol^{-1}
e. disulfiram (Antabuse); 40.50% C, 6.80% H, 9.45% N, 43.25% S; MM = 296.54 g mol^{-1}
f. alumina; 52.91% Al, 47.08% O; MM = 101.96 g mol^{-1}

3.2 Determine the percent composition of the following compounds:

a. BF_3
b. KCN
c. $BaSO_4$
d. $Ni(CO)_4$
e. $(NH_4)_2Cr_2O_7$

IV. Reaction Stoichiometry and Balanced Equations

The coefficients in a ***balanced*** chemical equation can be used to write conversion factors. For example, the general equation, $xA + yB \rightarrow zC$, yields the following equivalence statement:

$$x \text{ mol of } A = y \text{ mol of } B = z \text{ mol of } C$$

The general route for calculating the amounts of materials that react or are produced by the reaction described by this equation is:

mass of A ←(AM, MM, or FM)→ number of moles of A ←(coefficients in equation)→ number of moles of B ←(AM, MM, or FM)→ mass of B

Example 1: Ammonia is prepared by the Haber process, which combines nitrogen and hydrogen gases in a reaction described by the equation:

$$N_2(g) + 3\ H_2(g) \rightarrow 2\ NH_3(g)$$

What mass of hydrogen is necessary to completely react 50.0 g N_2?
Answer:

$$\text{g } N_2 \rightarrow \begin{array}{c}\text{number of}\\ \text{moles of } N_2\end{array} \rightarrow \begin{array}{c}\text{number of}\\ \text{moles of } H_2\end{array} \rightarrow \text{g } H_2$$

$$\begin{array}{c}\text{mass}\\ \text{of } H_2\end{array} = 50.0\ \cancel{\text{g}N_2}\left(\frac{\cancel{1\text{mol}N_2}}{28.02\cancel{\text{g}N_2}}\right)\left(\frac{3\cancel{\text{mol}H_2}}{\cancel{1\text{mol}N_2}}\right)\left(\frac{2.02\,\text{g}\,H_2}{\cancel{1\text{mol}H_2}}\right) = 10.8\,\text{g}\,H_2$$

Example 2: Given 35.0 g N_2 and 35.0 g H_2 reacting according to the equation in Example 1, which material will react completely, and which will be present in excess? How much NH_3 will be formed?

Answer:

$$\begin{array}{c}\text{mass of } H_2 \text{ needed to}\\ \text{completely react 35.0 g } N_2\end{array} = 35.0\ \cancel{\text{g}N_2}\left(\frac{\cancel{1\text{mol}N_2}}{28.02\cancel{\text{g}N_2}}\right)\left(\frac{3\cancel{\text{mol}H_2}}{\cancel{1\text{mol}N_2}}\right)\left(\frac{2.02\,\text{g}\,H_2}{1\cancel{\text{mol}H_2}}\right) = 7.57\,\text{g}\,H_2$$

Thus, there is an excess of H_2 (35.0 g H_2 available) and N_2 is the limiting reactant. The amount of NH_3 formed is dictated by the amount of N_2, the amount of the limiting reactant.

$$\begin{array}{c}\text{mass of}\\ NH_3 \text{ formed}\end{array} = 35.0\ \cancel{\text{g}N_2}\left(\frac{\cancel{1\text{mol}N_2}}{28.02\cancel{\text{g}N_2}}\right)\left(\frac{2\cancel{\text{mol}NH_3}}{\cancel{1\text{mol}N_2}}\right)\left(\frac{17.03\,\text{g}\,NH_3}{1\cancel{\text{mol}NH_3}}\right) = 42.5\,\text{g}\,NH_3$$

Problem Set 4

4.1 For each of the following balanced equations, calculate the mass of the second reactant needed to completely react with 100 g of the first reactant.

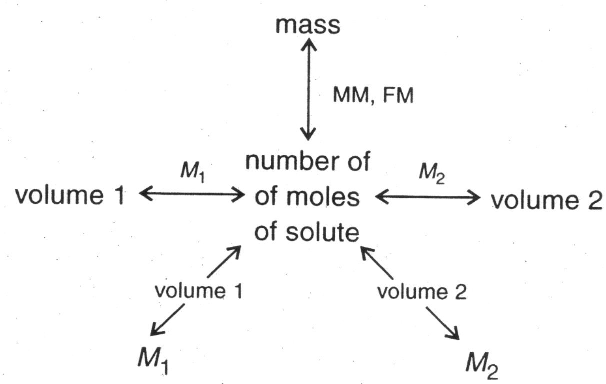
- **a.** $2\ K(s) + 2\ H_2O(g) \rightarrow 2\ KOH(aq) + H_2(g)$
- **b.** $2\ Al(s) + 3\ F_2(g) \rightarrow 2\ AlF_3(s)$
- **c.** $4\ NH_3(g) + 5\ O_2(g) \rightarrow 4\ NO(g) + 6\ H_2O(g)$
- **d.** $Fe_2O_3(s) + 3\ C(s) \rightarrow 2\ Fe(l) + 3\ CO(g)$
- **e.** $CaC_2(s) + 2\ H_2O(l) \rightarrow Ca(OH)_2(s) + C_2H_2(g)$
- **f.** $SiO_2(s) + 4\ HF(g) \rightarrow SiF_4(g) + 2\ H_2O(l)$
- **g.** $2\ C_4H_{10}(g) + 13\ O_2(g) \rightarrow 8\ CO_2(g) + 10\ H_2O(g)$
- **h.** $BaCl_2(aq) + Na_2SO_4(aq) \rightarrow 2\ NaCl(aq) + BaSO_4(s)$

4.2 Given 100.0 g of each reactant in the reactions described by the preceding equations, which reactant is the limiting reactant, and what mass of the first product listed will be formed?

V. Solution Concentrations and Volumes

Solutions are an important part of chemistry, and we need to perform a variety of calculations when dealing with solutions. For example, we may need to calculate the volume of a solution, in order to obtain the number of moles of solute necessary for a reaction. Or we may need to prepare a specific volume of solution containing a certain number of moles of solute. Or perhaps we need to calculate the change in concentration accompanying a change in the volume of a solution. The relationships necessary to solve problems of this sort are all related to **molarity *(M)***, which is the number of moles of solute per liter of solution.

A general route for converting among the various units associated with solutions is shown below:



Example 1: What volume of 0.050M NaCl solution contains 15 g of NaCl?

Answer: mass NaCl → number of moles of NaCl → volume NaCl

$$\text{volume NaCl, L} = 15\,\cancel{\text{g NaCl}}\left(\frac{1\,\cancel{\text{mol NaCl}}}{58.4\,\cancel{\text{g NaCl}}}\right)\left(\frac{1\,\text{L}}{0.050\,\cancel{\text{mol NaCl}}}\right) = 5.1\,\text{L}$$

Example 2: How much HCl is required to prepare exactly 250 mL of a 0.150M solution?

Answer: M of HCl → number of moles of HCl → mass HCl

$$\text{mass HCl, g} = 250\,\cancel{\text{mL solution}}\left(\frac{0.150\,\cancel{\text{mol HCl}}}{\cancel{1\text{L solution}}}\right)\left(\frac{\cancel{1\text{L}}}{1000\,\cancel{\text{mL}}}\right)\left(\frac{36.5\,\text{g HCl}}{1\,\cancel{\text{mol HCl}}}\right) = 1.37\,\text{g HCl}$$

Note that the use of dimensional analysis in the preceding answer prevented an error of a factor of 10^3, by reminding us to change mL to L so that the units cancel properly.

Example 3: If 100.0 mL of a 0.100M solution of KCl is diluted to 250.0 mL, what is the new concentration of the solution?

Answer: The route shows that the common link between M_1 and M_2 is the number of moles of solute. Set up your calculation this way: M_1 → number of moles → M_2. Note that to get from M_1 to number of moles, we must ***multiply*** by volume, but to get from number of moles to M_2, we must ***divide*** by volume.

$$\text{new concentration of KCl} = \left(\frac{0.100\,\text{mol KCl}}{1\,\text{L}\,\cancel{\text{solution}_1}}\right)(100.0\,\cancel{\text{mL solution}_1})\left(\frac{1}{250.0\,\cancel{\text{mL}}\,\text{solution}_2}\right) = 0.0400M$$

Because the mL cancel, it is not necessary to convert mL to L in this case.

For chemical reactions in solution, the general route for calculations is:

$$\begin{array}{c}\text{volume of solution}\\\text{containing } A\end{array} \overset{M_A}{\longleftrightarrow} \begin{array}{c}\text{number of}\\\text{moles of } A\end{array} \overset{\text{coefficients in equation}}{\longleftrightarrow} \begin{array}{c}\text{number of}\\\text{moles of } B\end{array} \overset{M_B}{\longleftrightarrow} \begin{array}{c}\text{volume of solution}\\\text{containing } B\end{array}$$

$$\begin{array}{c}\uparrow\\\text{volume of solution}\\\text{containing } A\\\downarrow\\M_A\end{array} \qquad\qquad \begin{array}{c}\uparrow\\\text{volume of solution}\\\text{containing } B\\\downarrow\\M_B\end{array}$$

Example 4: For the reaction,

$$KOH(aq) + HCl(aq) \rightarrow KCl(aq) + H_2O(l)$$

what volume of $0.150M$ KOH is required to react completely with 50.00 ml of $0.300M$ HCl?

Answer: The route to follow is:

$$\begin{array}{c}\text{volume of}\\\text{HCl solution}\end{array} \rightarrow \begin{array}{c}\text{number of}\\\text{moles of HCl}\end{array} \rightarrow \begin{array}{c}\text{number of}\\\text{moles of KOH}\end{array} \rightarrow \begin{array}{c}\text{volume of}\\\text{KOH solution}\end{array}$$

$$\begin{array}{c}\text{volume of KOH}\\\text{solution, mL}\end{array} = 50.00\text{ mL HCl}\left(\frac{\cancel{1\text{L}}}{\cancel{1000\text{ mL}}}\right)\left(\frac{0.300\ \cancel{\text{mol HCl}}}{\cancel{1\text{L solution}}}\right)\left(\frac{1\ \cancel{\text{mol KOH}}}{1\ \cancel{\text{mol HCl}}}\right)\left(\frac{\cancel{1\text{L solution}}}{0.150\ \cancel{\text{mol KOH}}}\right)\left(\frac{\cancel{1000\text{ mL}}}{\cancel{1\text{L}}}\right) = 100.0\text{ ml}$$

Example 5: For the reaction

$$2\ NaOH(aq) + H_2SO_4(aq) \rightarrow Na_2SO_4(aq) + 2\ H_2O(l)$$

4.5 mL of $0.100MH_2SO_4$ is required to completely react with 10.0 mL of NaOH solution. What is the concentration of the NaOH solution?

Answer: The route to follow is:

$$\begin{array}{c}\text{volume of}\\H_2SO_4\text{ solution}\end{array} \rightarrow \begin{array}{c}\text{number of}\\\text{moles of }H_2SO_4\end{array} \rightarrow \begin{array}{c}\text{number of}\\\text{moles of NaOH}\end{array} \rightarrow M\text{ of NaOH solution}$$

$$\begin{array}{c}M\text{ of NaOH}\\\text{solution, }M\end{array} = \frac{\text{number of moles of NaOH}}{1\text{ L NaOH solution}} = \begin{array}{c}0.0045\ \cancel{\text{L}}\\\cancel{H_2SO_4}\\\cancel{\text{solution}}\end{array}\left(\frac{0.100\ \cancel{\text{mol }H_2SO_4}}{\cancel{1\text{L }H_2SO_4\text{ solution}}}\right)\left(\frac{2\text{ mol NaOH}}{1\ \cancel{\text{mol }H_2SO_4}}\right)\left(\frac{1}{0.0100\text{ L NaOH solution}}\right) = 0.090M$$

Note that dimensional analysis reminded us that 2 mol of NaOH rea with 1 mol of H_2SO_4.

Problem Set 5

5.1 Calculate the new concentration of the solution when:

a. 25.0 mL of 1.43*M* HCl is diluted to 500.0 mL.
b. 10.0 mL of 3.42*M* NaOH is diluted to 10.0 L.
c. 450.0 mL of 0.20*M* H_2SO_4 is evaporated to a volume of 90.0 mL.
d. 60.0 mL of 0.450*M* NaCl is diluted to 90.0 mL.

5.2 What volume of each of the following solutions contains 0.150 mol of the solute?

a. 0.0025*M* HCl
b. 1.25*M* $ZnSO_4$
c. 17.5*M* NH_4OH
d. 0.100*M* $CuCl_2$

5.3 What volume of 0.250*M* $Ba(OH)_2$ is required to completely react 100.0 mL of a 0.500*M* solution of the acid in each of the following reactions?

a. $Ba(OH)_2(aq) + 2\ HCl(aq) \rightarrow BaCl_2(aq) + 2\ H_2O(l)$
b. $Ba(OH)_2(aq) + H_2SO_4(aq) \rightarrow BaSO_4(aq) + 2\ H_2O(l)$
c. $Ba(OH)_2(aq) + H_3PO_4(aq) \rightarrow BaHPO_4(aq) + 2\ H_2O(l)$
d. $3\ Ba(OH)_2(aq) + 2\ H_3PO_4(aq) \rightarrow Ba_3(PO_4)_2(s) + 6\ H_2O(l)$

5.4 In each of the following acid–base reactions, 25.0 mL of an HCl solution (the acid) completely reacts 10.0 mL of a 0.100*M* solution of the second reactant (the base). Calculate the concentration of the HCl solution in each case.

a. $HCl(aq) + NH_4OH(aq) \rightarrow NH_4Cl(aq) + H_2O(l)$
b. $2\ HCl(aq) + Ca(OH)_2(aq) \rightarrow CaCl_2(aq) + 2\ H_2O(l)$
c. $4\ HCl(aq) + NaAl(OH)_4(aq) \rightarrow AlCl_3(aq) + 4\ H_2O(l) + NaCl(aq)$
d. $2\ HCl(aq) + Na_2C_2O_4(aq) \rightarrow 2\ NaCl(aq) + H_2C_2O_4(aq)$