Example 4.1 Stoichiometry

During photosynthesis, plants convert carbon dioxide and water into glucose ($C_6H_{12}O_6$) according to the reaction:

$$6\,CO_2(g) + 6\,H_2O(l) \xrightarrow{\text{sunlight}} 6\,O_2(g) + C_6H_{12}O_6(aq)$$

Suppose that a particular plant consumes 37.8 g of CO_2 in one week. Assuming that there is more than enough water present to react with all of the CO_2, what mass of glucose (in grams) can the plant synthesize from the CO_2?

Sort

The problem provides the mass of carbon dioxide and asks you to find the mass of glucose that can be produced.

Given: 37.8 g CO_2

Find: g $C_6H_{12}O_6$

Strategize

The conceptual plan follows the general pattern of mass A → amount A (in moles) → amount B (in moles) → mass B. From the chemical equation, deduce the relationship between moles of carbon dioxide and moles of glucose. Use the molar masses to convert between grams and moles.

Conceptual Plan

$$\text{g } CO_2 \xrightarrow{\frac{1\text{ mol } CO_2}{44.01\text{ g } CO_2}} \text{mol } CO_2 \xrightarrow{\frac{1\text{ mol } C_6H_{12}O_6}{6\text{ mol } CO_2}} \text{mol } C_6H_{12}O_6 \xrightarrow{\frac{180.2\text{ g } C_6H_{12}O_6}{1\text{ mol } C_6H_{12}O_6}} \text{g } C_6H_{12}O_6$$

Relationships Used

molar mass CO_2 = 44.01 g/mol

6 mol CO_2 : 1 mol $C_6H_{12}O_6$

molar mass $C_6H_{12}O_6$ = 180.2 g/mol

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Example 4.1 Stoichiometry

Continued

Solve

Follow the conceptual plan to solve the problem. Begin with g CO2 and use the conversion factors to arrive at g $C_6H_{12}O_6$.

Solution

$$37.8\ \text{g}\ \cancel{CO_2} \times \frac{1\ \cancel{\text{mol}\ CO}}{44.01\ \text{g}\ \cancel{CO_2}} \times \frac{1\ \cancel{\text{mol}\ C_6H_{12}O_6}}{6\ \cancel{\text{mol}\ CO_2}} \times \frac{180.2\ \text{g}\ C_6H_{12}O_6}{1\ \cancel{\text{mol}\ C_6H_{12}O_6}} = 25.8\ \text{g}\ C_6H_{12}O_6$$

Check

The units of the answer are correct. The magnitude of the answer (25.8 g) is less than the initial mass of CO_2 (37.8 g). This is reasonable because each carbon in CO_2 has two oxygen atoms associated with it, while in $C_6H_{12}O_6$ each carbon has only one oxygen atom associated with it and two hydrogen atoms, which are much lighter than oxygen. Therefore, the mass of glucose produced should be less than the mass of carbon dioxide for this reaction.

For Practice 4.1

Magnesium hydroxide, the active ingredient in milk of magnesia, neutralizes stomach acid, primarily HCl, according to the reaction:

$$Mg(OH)_2(aq) + 2\ HCl(aq) \longrightarrow 2\ H_2O(l) + MgCl_2(aq)$$

What mass of HCl, in grams, is neutralized by a dose of milk of magnesia containing 3.26 g $Mg(OH)_2$?

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Example 4.2 Stoichiometry

Sulfuric acid (H_2SO_4) is a component of acid rain that forms when SO_2, a pollutant, reacts with oxygen and water according to the simplified reaction:

$$2\,SO_2(g) + O_2(g) + 2\,H_2O(l) \longrightarrow 2\,H_2SO_4(aq)$$

The generation of the electricity used by a medium-sized home produces about 25 kg of SO_2 per year. Assuming that there is more than enough O_2 and H_2O, what mass of H_2SO_4, in kg, can form from this much SO_2?

Sort

The problem gives the mass of sulfur dioxide and asks you to find the mass of sulfuric acid.

Given: 5 kg SO_2

Find: kg H_2SO_4

Strategize

The conceptual plan follows the standard format of mass → amount (in moles) → amount (in moles) → mass. Since the original quantity of SO_2 is given in kilograms, you must first convert to grams. You can deduce the relationship between moles of sulfur dioxide and moles of sulfuric acid from the chemical equation. Since the final quantity is requested in kilograms, convert to kilograms at the end.

Conceptual Plan

$$\text{kg } SO_2 \xrightarrow{\frac{1000\text{ g}}{1\text{ kg}}} \text{g } SO_2 \xrightarrow{\frac{1\text{ mol } SO_2}{64.07\text{ g } SO_2}} \text{mol } SO_2 \xrightarrow{\frac{2\text{ mol } H_2SO_4}{2\text{ mol } SO_2}}$$

$$\text{mol } H_2SO_4 \xrightarrow{\frac{98.09\text{ g } H_2SO_4}{1\text{ mol } H_2SO_4}} \text{g } H_2SO_4 \xrightarrow{\frac{1\text{ kg}}{1000\text{ g}}} \text{kg } H_2SO_4$$

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Example 4.2 Stoichiometry

Continued

Relationships Used

1 kg = 1000 g

molar mass SO_2 = 64.07 g/mol

2 mol SO_2 : 2 mol H_2SO_4

molar mass H_2SO_4 = 98.09 g/mol

Solve

Follow the conceptual plan to solve the problem. Begin with the given amount of SO2 in kilograms and use the conversion factors to arrive at kg H_2SO_4.

Solution

$$25\ \cancel{\text{kg}}\ \cancel{SO_2} \times \frac{1000\ \cancel{\text{g}}}{1\ \cancel{\text{kg}}} \times \frac{1\ \cancel{\text{mol}\ SO_2}}{64.07\ \cancel{\text{g}\ SO_2}} \times \frac{2\ \cancel{\text{mol}\ H_2SO_4}}{2\ \cancel{\text{mol}\ SO_2}} \times \frac{98.09\ \cancel{\text{g}}\ H_2SO_4}{1\ \cancel{\text{mol}\ H_2SO_4}} \times \frac{1\ \text{kg}}{1000\ \cancel{\text{g}}} = 38\ \text{kg}\ H_2SO_4$$

Check

The units of the final answer are correct. The magnitude of the final answer (38 kg H_2SO_4) is larger than the amount of SO_2 given (25 kg). This is reasonable because in the reaction each SO_2 molecule “gains weight” by reacting with O_2 and H_2O.

For Practice 4.2

Another component of acid rain is nitric acid, which forms when NO_2, also a pollutant, reacts with oxygen and water according to the simplified equation:

$$4\ NO_2(g) + O_2(g) + 2\ H_2O(l) \longrightarrow 4\ HNO_3(aq)$$

The generation of the electricity used by a medium-sized home produces about 16 kg of NO_2 per year. Assuming that there is adequate O_2 and H_2O, what mass of HNO_3, in kg, can form from this amount of NO_2 pollutant?

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Example 4.3 Limiting Reactant and Theoretical Yield

Ammonia, NH_3, can be synthesized by the reaction:

$$2\,NO(g) + 5\,H_2(g) \longrightarrow 2\,NH_3(g) + 2\,H_2O(g)$$

Starting with 86.3 g NO and 25.6 g H_2, find the theoretical yield of ammonia in grams.

Sort

You are given the mass of each reactant in grams and asked to find the theoretical yield of a product.

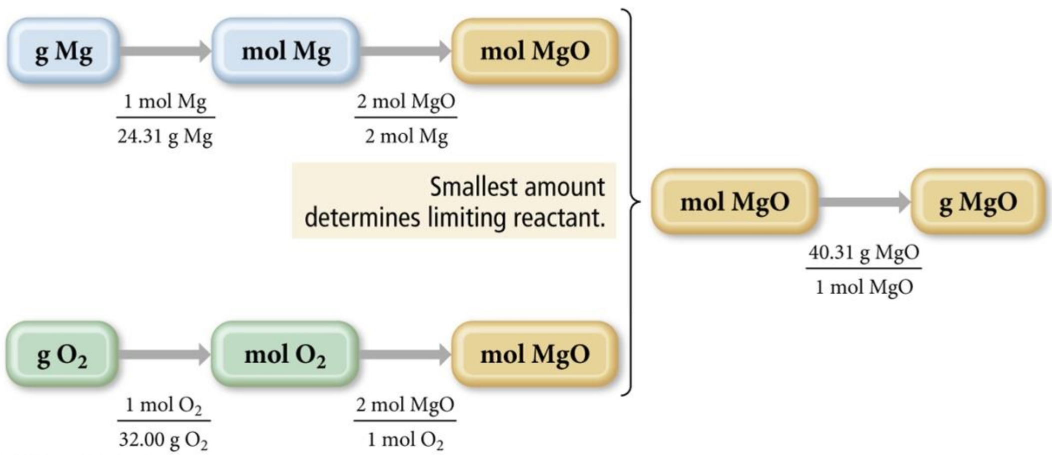
Given: 86.3 g NO, 25.6 g H_2

Find: theoretical yield of $NH_3(g)$

Strategize

Determine which reactant makes the least amount of product by converting from grams of each reactant to moles of the reactant to moles of the product. Use molar masses to convert between grams and moles and use the stoichiometric relationships (from the chemical equation) to convert between moles of reactant and moles of product. Remember that the reactant that makes *the least amount of product* is the limiting reactant. Convert the number of moles of product obtained using the limiting reactant to grams of product.

Conceptual Plan



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Example 4.3 Limiting Reactant and Theoretical Yield

Continued

Relationships Used

molar mass NO = 30.01 g/mol
molar mass H_2 = 2.02 g/mol
2 mol NO : 2 mol NH_3 (from chemical equation)
5 mol H_2 : 2 mol NH_3 (from chemical equation)
molar mass NH_3 = 17.03 g/mol

Solve

Beginning with the given mass of each reactant, calculate the amount of product that can be made in moles. Convert the amount of product made by the limiting reactant to grams—this is the theoretical yield.

Solution

$$\boxed{86.3\ \cancel{\text{g NO}}} \times \frac{1\ \cancel{\text{mol NO}}}{30.01\ \cancel{\text{g NO}}} \times \frac{2\ \text{mol NH}_3}{2\ \cancel{\text{mol NO}}} = \boxed{2.8\underline{7}57\ \text{mol NH}_3}$$

Limiting reactant

Least amount of product

$$25.6\ \cancel{\text{g H}_2} \times \frac{1\ \cancel{\text{mol H}_2}}{2.02\ \cancel{\text{g H}_2}} \times \frac{2\ \text{mol NH}_3}{5\ \cancel{\text{mol H}_2}} = 5.0\underline{6}93\ \text{mol NH}_3$$

$$2.8\underline{7}57\ \cancel{\text{mol NH}_3} \times \frac{17.03\ \text{g NH}_3}{\cancel{\text{mol NH}_3}} = 49.0\ \text{g NH}_3$$

Since NO makes the least amount of product, it is the limiting reactant, and the theoretical yield of ammonia is 49.0 g.

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Example 4.3 Limiting Reactant and Theoretical Yield

Continued

Check

The units of the answer (g NH_3) are correct. The magnitude (49.0 g) seems reasonable given that 86.3 g NO is the limiting reactant. NO contains one oxygen atom per nitrogen atom and NH_3 contains three hydrogen atoms per nitrogen atom. Since three hydrogen atoms have less mass than one oxygen atom, it is reasonable that the mass of NH_3 obtained is less than the mass of NO.

For Practice 4.3

Ammonia can also be synthesized by the reaction:

$$3\,H_2(g) + N_2(g) \longrightarrow 2\,NH_3(g)$$

What is the theoretical yield of ammonia, in kg, that we can synthesize from 5.22 kg of H_2 and 31.5 kg of N_2?

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Example 4.4 Limiting Reactant and Theoretical Yield

We can obtain titanium metal from its oxide according to the following balanced equation:

$$TiO_2(s) + 2\,C(s) \longrightarrow Ti(s) + 2\,CO(g)$$

When 28.6 kg of C reacts with 88.2 kg of TiO_2, 42.8 kg of Ti is produced. Find the limiting reactant, theoretical yield (in kg), and percent yield.

Sort

You are given the mass of each reactant and the mass of product formed. You are asked to find the limiting reactant, theoretical yield, and percent yield.

Given: 28.6 kg C, 88.2 kg TiO_2, 42.8 kg Ti produced

Find: limiting reactant, theoretical yield, % yield

Strategize

Determine which of the reactants makes the least amount of product by converting from kilograms of each reactant to moles of product. Convert between grams and moles using molar mass. Convert between moles of reactant and moles of product using the stoichiometric relationships derived from the chemical equation. Remember that the reactant that makes the *least amount of product* is the limiting reactant.

Determine the theoretical yield (in kilograms) by converting the number of moles of product obtained with the limiting reactant to kilograms of product.

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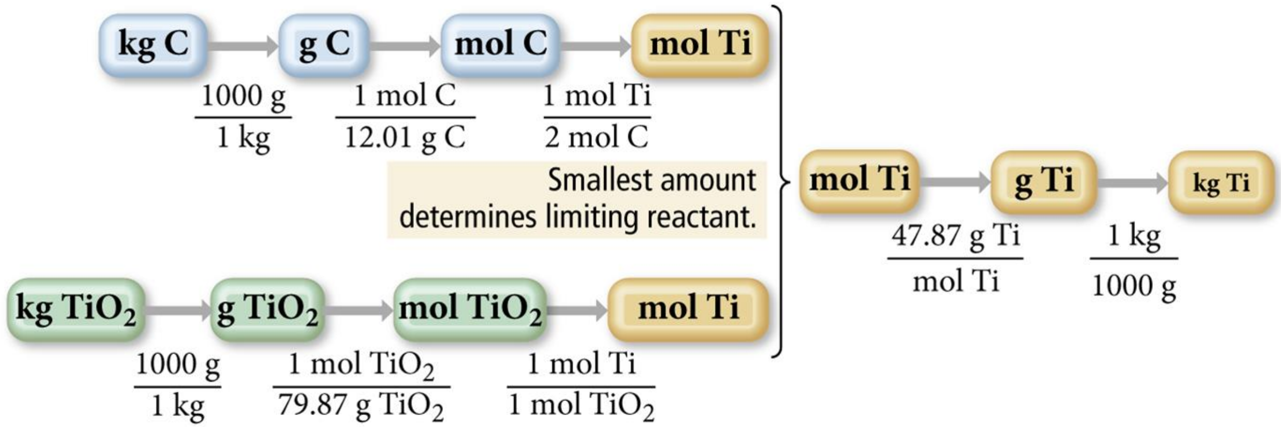
Example 4.4 Limiting Reactant and Theoretical Yield

Continued

Conceptual Plan



Relationships Used

1000 g = 1 kg

molar mass of C = 12.01 g/mol

molar mass of TiO_2 = 79.87 g/mol

1 mol TiO_2 : 1 mol Ti

2 mol C : 1 mol Ti

molar mass of Ti = 47.87 g/mol

Solve

Beginning with the actual amount of each reactant, calculate the amount of product that can be made in moles. Convert the amount of product made by the limiting reactant to kilograms—this is the theoretical yield.

Calculate the percent yield by dividing the actual yield (42.8 kg Ti) by the theoretical yield.

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Example 4.4 Limiting Reactant and Theoretical Yield

Continued

Solution

$$\mathbf{28.6\ \cancel{kg\ C}} \times \frac{1000\ \cancel{g}}{1\ \cancel{kg}} \times \frac{1\ \cancel{mol\ C}}{12.01\ \cancel{g\ C}} \times \frac{1\ mol\ Ti}{2\ \cancel{mol\ C}} = \mathbf{1.1\underline{9}07 \times 10^3\ mol\ Ti}$$

Limiting reactant

Least amount of product

$$\boxed{\mathbf{88.2\ \cancel{kg\ TiO_2}}} \times \frac{1000\ \cancel{g}}{1\ \cancel{kg}} \times \frac{1\ \cancel{mol\ TiO_2}}{79.87\ \cancel{g\ TiO_2}} \times \frac{1\ mol\ Ti}{1\ \cancel{mol\ TiO_2}} = \boxed{\mathbf{1.1\underline{0}43 \times 10^3\ mol\ Ti}}$$

$$\mathbf{1.10\underline{4}3 \times 10^3\ \cancel{mol\ Ti}} \times \frac{47.87\ \cancel{g\ Ti}}{1\ \cancel{mol\ Ti}} \times \frac{1\ kg}{1000\ \cancel{g}} = \mathbf{52.9\ kg\ Ti}$$

Since TiO_2 makes the least amount of product, it is the limiting reactant, and 52.9 kg Ti is the theoretical yield.

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\% = \frac{42.8\ \text{kg}}{52.9\ \text{kg}} \times 100\% = 80.9\%$$

Check

The theoretical yield has the correct units (kg Ti) and has a reasonable magnitude compared to the mass of TiO_2. Since Ti has a lower molar mass than TiO_2, the amount of Ti made from TiO_2 should have a lower mass. The percent yield is reasonable (under 100% as it should be).

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Example 4.4 Limiting Reactant and Theoretical Yield

Continued

For Practice 4.4

Mining companies use this reaction to obtain iron from iron ore:

$$Fe_2O_3(s) + 3\,CO(g) \longrightarrow 2\,Fe(s) + 3\,CO_2(g)$$

The reaction of 167 g Fe_2O_3 with 85.8 g CO produces 72.3 g Fe. Determine the limiting reactant, theoretical yield, and percent yield.

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Example 4.5 Calculating Solution Concentration

What is the molarity of a solution containing 25.5 g KBr dissolved in enough water to make 1.75 L of solution?

Sort

You are given the mass of KBr and the volume of a solution and asked to find its molarity.

Given: 25.5 g KBr, 1.75 L of solution

Find: molarity (M)

Strategize

When formulating the conceptual plan, think about the definition of molarity, the amount of solute *in moles* per liter of solution.

You are given the mass of KBr, so first use the molar mass of KBr to convert from g KBr to mol KBr.

Then use the number of moles of KBr and liters of solution to find the molarity.

Conceptual Plan

g KBr → **mol KBr**

$$\frac{1 \text{ mol}}{119.00 \text{ g}}$$

mol KBr, L solution → **Molarity**

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

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Example 4.5 Calculating Solution Concentration

Continued

Relationships Used

molar mass of KBr = 119.00 g/mol

Solve

Follow the conceptual plan. Begin with g KBr and convert to mol KBr; then use mol KBr and L solution to calculate molarity.

Solution

$$25.5\ \cancel{\text{g KBr}} \times \frac{1\ \text{mol KBr}}{119.00\ \cancel{\text{g KBr}}} = 0.21\underline{4}29\ \text{mol KBr}$$

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

$$= \frac{0.21\underline{4}29\ \text{mol KBr}}{1.75\ \text{L solution}}$$

$$= 0.122\ \text{M}$$

Check

The units of the answer (M) are correct. The magnitude is reasonable since common solutions range in concentration from 0 to about 18 M. Concentrations significantly above 18 M are suspect and should be double-checked.

For Practice 4.5

Calculate the molarity of a solution made by adding 45.4 g of $NaNO_3$ to a flask and dissolving it with water to create a total volume of 2.50 L.

For More Practice 4.5

What mass of KBr (in grams) do you need to make 250.0 mL of a 1.50 M KBr solution?

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Example 4.6 Using Molarity in Calculations

How many liters of a 0.125 M NaOH solution contain 0.255 mol of NaOH?

Sort

You are given the concentration of a NaOH solution. You are asked to find the volume of the solution that contains a given amount (in moles) of NaOH.

Given: 0.125 M NaOH solution, 0.255 mol NaOH

Find: volume of NaOH solution (in L)

Strategize

The conceptual plan begins with mol NaOH and shows the conversion to L of solution using molarity as a conversion factor.

Conceptual Plan

$$\text{mol NaOH} \xrightarrow[\frac{0.125\ \text{mol NaOH}}{}]{} \text{L solution}$$

Relationships Used

$$0.125\ \text{M NaOH} = \frac{0.125\ \text{mol NaOH}}{1\ \text{L solution}}$$

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Example 4.6 Using Molarity in Calculations

Continued

Solve

Follow the conceptual plan. Begin with mol NaOH and convert to L solution.

Solution

$$0.255\ \cancel{\text{mol NaOH}} \times \frac{1\ \text{L solution}}{0.125\ \cancel{\text{mol NaOH}}} = 2.04\ \text{L solution}$$

Check

The units of the answer (L) are correct. The magnitude is reasonable because the solution contains 0.125 mol per liter. Therefore, roughly 2 L contains the given amount of moles (0.255 mol).

For Practice 4.6

How many grams of sucrose ($C_{12}H_{22}O_{11}$) are in 1.55 L of 0.758 M sucrose solution?

For More Practice 4.6

How many mL of a 0.155 M KCl solution contain 2.55 g KCl?

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Example 4.7 Solution Dilution

To what volume should you dilute 0.200 L of a 15.0 M NaOH solution to obtain a 3.00 M NaOH solution?

Sort

You are given the initial volume, initial concentration, and final concentration of a solution. You need to determine the final volume.

Given: $V_1 = 0.200$ L
$M_1 = 15.0$ M
$M_2 = 3.00$ M

Find: V_2

Strategize

Equation 4.1 relates the initial and final volumes and concentrations for solution dilution problems. You are asked to find V_2. The other quantities (V_1, M_1, and M_2) are all given in the problem.

Conceptual Plan

$$\boldsymbol{V_1, M_1, M_2} \xrightarrow[M_1V_1 = M_2V_2]{} \boldsymbol{V_2}$$

Relationships Used

$M_1V_1 = M_2V_2$

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Example 4.7 Solution Dilution

Continued

Solve

Begin with the solution dilution equation and solve it for V_2.

Substitute in the required quantities and calculate V_2.

Make the solution by diluting 0.200 L of the stock solution to a total volume of 1.00 L (V_2). The resulting solution will have a concentration of 3.00 M.

Solution

$$M_1V_1 = M_2V_2$$

$$V_2 = \frac{M_1V_1}{M_2}$$

$$= \frac{15.0\ \cancel{\text{mol/L}} \times 0.200\ \text{L}}{3.00\ \cancel{\text{mol/L}}}$$

$$= 1.00\ \text{L}$$

Check

The final units (L) are correct. The magnitude of the answer is reasonable because the solution is diluted from 15.0 M to 3.00 M, a factor of five. Therefore, the volume should increase by a factor of five.

For Practice 4.7

To what volume (in mL) should you dilute 100.0 mL of a 5.00 M $CaCl_2$ solution to obtain a 0.750 M $CaCl_2$ solution?

For More Practice 4.7

What volume of a 6.00 M NaNO3 solution should you use to make 0.525 L of a 1.20 M NaNO3 solution?

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Example 4.8 Solution Stoichiometry

What volume (in L) of 0.150 M KCl solution will completely react with 0.150 L of a 0.175 M $Pb(NO_3)_2$ solution according to the following balanced chemical equation?

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

Sort

You are given the volume and concentration of a $Pb(NO_3)_2$ solution. You are asked to find the volume of KCl solution (of a given concentration) required to react with it.

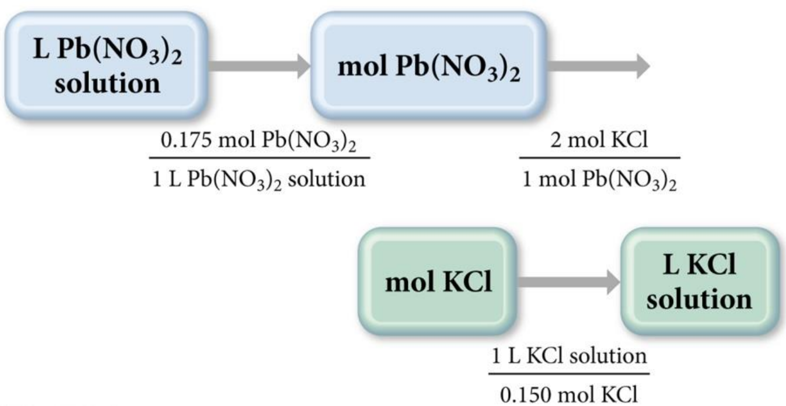
Given: 0.150 L of $Pb(NO_3)_2$ solution, 0.175 M $Pb(NO_3)_2$ solution, 0.150 M KCl solution

Find: volume KCl solution (in L)

Strategize

The conceptual plan has the form: volume A → amount A (in moles) → amount B (in moles) → volume B. Use the molar concentrations of the KCl and $Pb(NO_3)_2$ solutions as conversion factors between the number of moles of reactants in these solutions and their volumes. Use the stoichiometric coefficients from the balanced equation to convert between number of moles of $Pb(NO_3)_2$ and number of moles of KCl.

Conceptual Plan



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Example 4.8 Solution Stoichiometry

Continued

Relationships Used

$$\text{M Pb(NO}_3)_2 = \frac{0.175 \text{ mol Pb(NO}_3)_2}{1 \text{ L Pb(NO}_3)_2 \text{ solution}}$$

$$2 \text{ mol KCl} : 1 \text{ mol Pb(NO}_3)_2$$

$$\text{M KCl} = \frac{0.150 \text{ mol KCl}}{1 \text{ L KCl solution}}$$

Solve

Begin with L $Pb(NO_3)_2$ solution and follow the conceptual plan to arrive at L KCl solution.

Solution

$$0.150\ \cancel{\text{L Pb(NO}_3)_2 \text{ solution}} \times \frac{0.175\ \cancel{\text{mol Pb(NO}_3)_2}}{1\ \cancel{\text{L Pb(NO}_3)_2 \text{ solution}}} \times \frac{2\ \cancel{\text{mol KCl}}}{1\ \cancel{\text{mol Pb(NO}_3)_2}} \times \frac{1 \text{ L KCl solution}}{0.150\ \cancel{\text{mol KCl}}} = 0.350 \text{ L KCl solution}$$

Check

The final units (L KCl solution) are correct. The magnitude (0.350 L) is reasonable because the reaction stoichiometry requires 2 mol of KCl per mole of $Pb(NO_3)_2$. Since the concentrations of the two solutions are not very different (0.150 M compared to 0.175 M), the volume of KCl required is roughly two times the 0.150 L of $Pb(NO_3)_2$ given in the problem.

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Example 4.8 Solution Stoichiometry

Continued

For Practice 4.8

What volume (in mL) of a 0.150 M HNO_3 solution will completely react with 35.7 mL of a 0.108 M Na_2CO_3 solution according to the following balanced chemical equation?

$$Na_2CO_3(aq) + 2\,HNO_3(aq) \longrightarrow 2\,NaNO_3(aq) + CO_2(g) + H_2O(l)$$

For More Practice 4.8

In the previous reaction, what mass (in grams) of carbon dioxide forms?

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Example 4.9 Predicting Whether an Ionic Compound Is Soluble

Predict whether each compound is soluble or insoluble.

a. $PbCl_2$ **b.** $CuCl_2$ **c.** $Ca(NO_3)_2$ **d.** $BaSO_4$

Solution

a. Insoluble. Compounds containing Cl^- are normally soluble, but Pb^{2+} is an exception.
b. Soluble. Compounds containing Cl^- are normally soluble and Cu^{2+} is not an exception.
c. Soluble. Compounds containing NO_3^- are always soluble.
d. Insoluble. Compounds containing SO_4^{2-} are normally soluble, but Ba^{2+} is an exception.

For Practice 4.9

Predict whether each compound is soluble or insoluble.

a. NiS **b.** $Mg_3(PO_4)_2$ **c.** Li_2CO_3 **d.** NH_4Cl

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Example 4.10 Writing Equations for Precipitation Reactions

Write an equation for the precipitation reaction that occurs (if any) when solutions of potassium carbonate and nickel(II) chloride are mixed.

Procedure For…

Writing Equations for Precipitation Reactions

Solution

Step 1 Write the formulas of the two compounds being mixed as reactants in a chemical equation.

$$K_2CO_3(aq) + NiCl_2(aq) \longrightarrow$$

Step 2 Below the equation, write the formulas of the products that could form from the reactants. Obtain these by combining the cation from each reactant with the anion from the other. Make sure to write correct formulas for these ionic compounds using the procedure demonstrated in Section 3.5.

$$K_2CO_3(aq) + NiCl_2(aq) \longrightarrow$$

Possible products

KCl $NiCO_3$

Step 3 Refer to the solubility rules to determine whether any of the possible products are insoluble.

KCl is soluble. (Compounds containing Cl^- are usually soluble and K^+ is not an exception.)

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Example 4.10 Writing Equations for Precipitation Reactions

Continued

$NiCO_3$ is insoluble. (Compounds containing CO_3^{2-} are usually insoluble and Ni^{2+} is not an exception.)

Step 4 If all of the possible products are soluble, there is no precipitate. Write "NO REACTION" after the arrow.

Since this example has an insoluble product, we proceed to the next step.

Step 5 If any of the possible products are insoluble, write their formulas as the products of the reaction, using (*s*) to indicate solid. Include an (*aq*) to indicate aqueous after any soluble products.

$$K_2CO_3(aq) + NiCl_2(aq) \longrightarrow NiCO_3(s) + KCl(aq)$$

Step 6 Balance the equation. Remember to adjust only coefficients, not subscripts.

$$K_2CO_3(aq) + NiCl_2(aq) \longrightarrow NiCO_3(s) + 2\,KCl(aq)$$

For Practice 4.10

Write an equation for the precipitation reaction that occurs (if any) when solutions of ammonium chloride and iron(III) nitrate mix.

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Example 4.11 Writing Equations for Precipitation Reactions

Write an equation for the precipitation reaction that occurs (if any) when solutions of sodium nitrate and lithium sulfate are mixed.

Procedure For…

Writing Equations for Precipitation Reactions

Solution

Step 1 Write the formulas of the two compounds being mixed as reactants in a chemical equation.

$$NaNO_3(aq) + Li_2SO_4(aq) \longrightarrow$$

Step 2 Below the equation, write the formulas of the products that could form from the reactants. Obtain these by combining the cation from each reactant with the anion from the other. Make sure to write correct formulas for these ionic compounds using the procedure demonstrated in Section 3.5.

$$NaNO_3(aq) + Li_2SO_4(aq) \longrightarrow$$

Possible products

$LiNO_3$ Na_2SO_4

Step 3 Refer to the solubility rules to determine whether any of the possible products are insoluble.

$LiNO_3$ is soluble. (Compounds containing NO^{2-} are soluble and Li^+ is not an exception.)

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Example 4.11 Writing Equations for Precipitation Reactions

Continued

Na_2SO_4 is soluble. (Compounds containing SO_4^{2-} are generally soluble and Na^+ is not an exception.)

Step 4 If all of the possible products are soluble, there is no precipitate. Write "NO REACTION" after the arrow.

Since this example has no insoluble product, there is no reaction.

$$NaNO_3(aq) + Li_2SO_4(aq) \longrightarrow \text{NO REACTION}$$

Step 5 If any of the possible products are insoluble, write their formulas as the products of the reaction, using (*s*) to indicate solid. Include an (*aq*) to indicate aqueous after any soluble products.

Step 6 Balance the equation. Remember to adjust only coefficients, not subscripts.

For Practice 4.11

Write an equation for the precipitation reaction that occurs (if any) when solutions of sodium hydroxide and copper(II) bromide mix.

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Example 4.12 Writing Complete Ionic and Net Ionic Equations

Write complete ionic and net ionic equations for each reaction.

a. $3\,SrCl_2(aq) + 2\,Li_3PO_4(aq) \longrightarrow Sr_3(PO_4)_2(s) + 6\,LiCl(aq)$

b. $HC_2H_3O_2(aq) + KOH(aq) \longrightarrow H_2O(l) + KC_2H_3O_2(aq)$

Solution

a. Write the complete ionic equation by separating aqueous ionic compounds into their constituent ions. The $Sr_3(PO_4)_2(s)$, precipitating as a solid, remains as one unit.

Write the net ionic equation by eliminating the spectator ions, those that do not change from one side of the reaction to the other.

Complete ionic equation:

$$3\,Sr^{2+}(aq) + 6\,Cl^-(aq) + 6\,Li^+(aq) + 2\,PO_4{}^{3-}(aq) \longrightarrow Sr_3(PO_4)_2(s) + 6\,Li^+(aq) + 6\,Cl^-(aq)$$

Net ionic equation:

$$3\,Sr^{2+}(aq) + 2\,PO_4{}^{3-}(aq) \longrightarrow Sr_3(PO_4)_2(s)$$

b. Write the complete ionic equation by separating aqueous ionic compounds into their constituent ions. Do not separate $HC_2H_3O_2(aq)$ because it is a weak electrolyte.

Write the net ionic equation by eliminating the spectator ions.

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Example 4.12 Writing Complete Ionic and Net Ionic Equations

Continued

Complete ionic equation:

$$HC_2H_3O_2(aq) + K^+(aq) + OH^-(aq) \longrightarrow H_2O(l) + K^+(aq) + C_2H_3O_2^-(aq)$$

Net ionic equation:

$$HC_2H_3O_2(aq) + OH^-(aq) \longrightarrow H_2O(l) + C_2H_3O_2^-(aq)$$

For Practice 4.12

Write the complete ionic equation and net ionic equation for the following reaction:

$$2\,HI(aq) + Ba(OH)_2(aq) \longrightarrow 2\,H_2O(l) + BaI_2(aq)$$

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Example 4.13 Writing Equations for Acid–Base Reactions Involving a Strong Acid

Write a molecular and net ionic equation for the reaction between aqueous HI and aqueous $Ba(OH)_2$.

Solution

First identify these substances as an acid and a base. Begin by writing the unbalanced equation in which the acid and the base combine to form water and a salt.

$$\underset{\text{acid}}{HI(aq)} + \underset{\text{base}}{Ba(OH)_2(aq)} \longrightarrow \underset{\text{water}}{H_2O(l)} + \underset{\text{salt}}{BaI_2(aq)}$$

Next, balance the equation; this is the molecular equation.

Molecular equation:

$$2\,HI(aq) + Ba(OH)_2(aq) \longrightarrow 2\,H_2O(l) + BaI_2(aq)$$

Write the net ionic equation by removing the spectator ions.

Net ionic equation:

$$2\,H^+(aq) + 2\,OH^-(aq) \longrightarrow 2\,H_2O(l)$$
$$\text{or simply } H^+(aq) + OH^-(aq) \longrightarrow H_2O(l)$$

For Practice 4.13

Write a molecular and a net ionic equation for the reaction that occurs between aqueous HBr and aqueous LiOH.

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Example 4.14 Writing Equations for Acid–Base Reactions Involving a Weak Acid

Write a molecular equation, ionic equation, and net ionic equation for the reaction between aqueous acetic acid ($HC_2H_3O_2$) and aqueous potassium hydroxide (KOH).

Solution

Begin by writing the molecular equation in which the acid and the base combine to form water and a salt. (The equation is already balanced.)

Molecular equation:

$$HC_2H_3O_2(aq) + KOH(aq) \longrightarrow H_2O(l) + KC_2H_3O_2(aq)$$

Write the complete ionic equation by separating aqueous ionic compounds into their constituent ions. Do not separate $HC_2H_3O_2(aq)$ because it is a weak acid (and a weak electrolyte).

Complete ionic equation:

$$HC_2H_3O_2(aq) + K^+(aq) + OH^-(aq) \longrightarrow H_2O(l) + K^+(aq) + C_2H_3O_2^-(aq)$$

Write the net ionic equation by eliminating the spectator ions.

Net ionic equation:

$$HC_2H_3O_2(aq) + OH^-(aq) \longrightarrow H_2O(l) + C_2H_3O_2^-(aq)$$

For Practice 4.14

Write the net ionic equation for the reaction between $HCHO_2$ (a weak acid) and NaOH.

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Example 4.15 Acid–Base Titration

The titration of 10.00 mL of HCl solution of unknown concentration requires 12.54 mL of a 0.100 M NaOH solution to reach the equivalence point. What is the concentration of the unknown HCl solution in M?

Sort

You are given the volume and concentration of NaOH solution required to titrate a given volume of HCl solution. You are asked to find the concentration of the HCl solution.

Given: 12.54 mL of NaOH solution, 0.100 M NaOH solution, 10.00 mL of HCl solution

Find: concentration of HCl solution

Strategize

Since this problem involves an acid–base neutralization reaction between HCl and NaOH, start by writing the balanced equation, using the techniques covered earlier in this section.

The first part of the conceptual plan has the form volume A → moles A → moles B. The concentration of the NaOH solution is a conversion factor between moles and volume of NaOH. The balanced equation provides the relationship between number of moles of NaOH and number of moles of HCl.

In the second part of the conceptual plan, use the number of moles of HCl (from the first part) and the volume of HCl solution (given) to calculate the molarity of the HCl solution.

$$HCl(aq) + NaOH(aq) \longrightarrow H_2O(l) + NaCl(aq)$$

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Example 4.15 Acid–Base Titration

Continued

Conceptual Plan

$$\text{mL NaOH} \xrightarrow{\frac{1\ \text{L}}{1000\ \text{mL}}} \text{L NaOH} \xrightarrow{\frac{0.100\ \text{mol NaOH}}{\text{L NaOH}}}$$

$$\text{mol NaOH} \xrightarrow{\frac{1\ \text{mol HCl}}{1\ \text{mol NaOH}}} \text{mol HCl}$$

$$\text{mol HCl, L HCl solution} \xrightarrow{\text{M} = \frac{\text{mol}}{\text{L}}} \text{Molarity}$$

Relationships Used

$$1\ \text{L} = 1000\ \text{mL}$$

$$\text{M (NaOH)} = \frac{0.100\ \text{mol NaOH}}{\text{L NaOH}}$$

$$1\ \text{mol HCl} : 1\ \text{mol NaOH}$$

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

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Example 4.15 Acid–Base Titration

Continued

Solve

In the first part of the solution, determine the number of moles of HCl in the unknown solution.

In the second part of the solution, divide the number of moles of HCl by the volume of the HCl solution in L. 10.00 mL is equivalent to 0.01000 L.

Solution

$$12.54\ \cancel{\text{mL}}\ \cancel{\text{NaOH}} \times \frac{1\ \cancel{\text{L}}}{1000\ \cancel{\text{mL}}} \times \frac{0.100\ \cancel{\text{mol NaOH}}}{\cancel{\text{L}}\ \cancel{\text{NaOH}}} \times \frac{1\ \text{mol HCl}}{1\ \cancel{\text{mol NaOH}}} = 1.25 \times 10^{-3}\ \text{mol HCl}$$

$$\text{Molarity} = \frac{1.25 \times 10^{-3}\ \text{mol HCl}}{0.01000\ \text{L}} = 0.125\ \text{M HCl}$$

Check

The units of the answer (M HCl) are correct. The magnitude of the answer (0.125 M) is reasonable because it is similar to the molarity of the NaOH solution, as expected from the reaction stoichiometry (1 mol HCl reacts with 1 mol NaOH) and the similar volumes of NaOH and HCl.

For Practice 4.15

The titration of a 20.0-mL sample of an H_2SO_4 solution of unknown concentration requires 22.87 mL of a 0.158 M KOH solution to reach the equivalence point. What is the concentration of the unknown H_2SO_4 solution?

For More Practice 4.15

What volume (in mL) of 0.200 M NaOH do we need to titrate 35.00 mL of 0.140 M HBr to the equivalence point?

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Example 4.16 Writing Equations for Gas-Evolution Reactions

Write a molecular equation for the gas-evolution reaction that occurs when you mix aqueous nitric acid and aqueous sodium carbonate.

Begin by writing an unbalanced equation in which the cation of each reactant combines with the anion of the other.

$$HNO_3(aq) + Na_2CO_3(aq) \longrightarrow H_2CO_3(aq) + NaNO_3(aq)$$

You must then recognize that $H_2CO_3(aq)$ decomposes into $H_2O(l)$ and $CO_2(g)$ and write these products into the equation.

$$HNO_3(aq) + Na_2CO_3(aq) \longrightarrow H_2O(l) + CO_2(g) + NaNO_3(aq)$$

Finally, balance the equation.

$$2\,HNO_3(aq) + Na_2CO_3(aq) \longrightarrow H_2O(l) + CO_2(g) + 2\,NaNO_3(aq)$$

For Practice 4.16

Write a molecular equation for the gas-evolution reaction that occurs when you mix aqueous hydrobromic acid and aqueous potassium sulfite.

For More Practice 4.16

Write a net ionic equation for the reaction that occurs when you mix hydroiodic acid with calcium sulfide.

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Example 4.17 Assigning Oxidation States

Assign an oxidation state to each atom in each element, ion, or compound.

a. Cl_2 **b.** Na^+ **c.** KF **d.** CO_2 **e.** SO_4^{2-} **f.** K_2O_2

Solution

Since Cl_2 is a free element, the oxidation state of both Cl atoms is 0 (rule 1).

a. Cl_2

$\underset{0}{Cl}\underset{0}{Cl}$

Since Na^+ is a monoatomic ion, the oxidation state of the Na^+ ion is +1 (rule 2).

b. Na^+

$\underset{+1}{Na^+}$

The oxidation state of K is +1 (rule 4). The oxidation state of F is –1 (rule 5). Since this is a neutral compound, the sum of the oxidation states is 0.

c. KF

$\underset{+1}{K}\underset{-1}{F}$

sum: $+1 - 1 = 0$

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Example 4.17 Assigning Oxidation States

Continued

The oxidation state of oxygen is –2 (rule 5). The oxidation state of carbon must be deduced using rule 3, which says that the sum of the oxidation states of all the atoms must be 0.

d. CO_2

(C ox state) + 2(O ox state) = 0

(C ox state) + 2(– 2) = 0

(C ox state) = +4

CO_2

$+4 -2$

sum: $+4 + 2(-2) = 0$

The oxidation state of oxygen is –2 (rule 5). You would ordinarily expect the oxidation state of S to be – 2 (rule 5). However, if that were the case, the sum of the oxidation states would not equal the charge of the ion. Since O is higher on the list than S, it takes priority and you calculate the oxidation state of sulfur by setting the *sum* of all of the oxidation states equal to – 2 (the charge of the ion).

e. SO_4^{2-}

(S ox state) + 4(O ox state) = – 2

(S ox state) + 4(– 2) = – 2

S ox state = +6

SO_4^{2-}

$+6 -2$

sum: $+6 + 4(-2) = -2$

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Example 4.17 Assigning Oxidation States

Continued

The oxidation state of potassium is +1 (rule 4). You would ordinarily expect the oxidation state of O to be –2 (rule 5), but rule 4 takes priority, you deduce the oxidation state of O by setting the sum of all of the oxidation states equal to 0.

f. K_2O_2

2(K ox state) + 2(O ox state) = 0

2(+1) + 2(O ox state) = 0

O ox state = –1

K_2O_2

+1 −1

sum: 2(+1)+2(−1) = 0

For Practice 4.17

Assign an oxidation state to each atom in each element, ion, or compound.

a. Cr **b.** Cr^{3+} **c.** CCl_4 **d.** $SrBr_2$ **e.** SO_3 **f.** NO_3^-

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Example 4.18 Using Oxidation States to Identify Oxidation and Reduction

Use oxidation states to identify the element that is oxidized and the element that is reduced in the following redox reaction:

$$Mg(s) + 2\,H_2O(l) \longrightarrow Mg(OH)_2(aq) + H_2(g)$$

Solution

Begin by assigning oxidation states to each atom in the reaction.

$$\begin{array}{lcccc} & C & + & 2\,S & \longrightarrow & CS_2 \\ \text{Oxidation states:} & 0 & & 0 & & +4\ -2 \end{array}$$

Reduction

Oxidation

Since Mg increased in oxidation state, it was oxidized. Since H decreased in oxidation state, it was reduced.

For Practice 4.18

Use oxidation states to identify the element that is oxidized and the element that is reduced in the following redox reaction:

$$Sn(s) + 4\,HNO_3(aq) \longrightarrow SnO_2(s) + 4\,NO_2(g) + 2\,H_2O(g)$$

For More Practice 4.18

Determine whether or not each reaction is a redox reaction. If the reaction is a redox reaction, identify which element is oxidized and which is reduced.

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Example 4.18 Using Oxidation States to Identify Oxidation and Reduction

Continued

a. $Hg_2(NO_3)_2(aq) + 2\,KBr(aq) \longrightarrow Hg_2Br_2(s) + 2\,KNO_3(aq)$
b. $4\,Al(s) + 3\,O_2(g) \longrightarrow 2\,Al_2O_3(s)$
c. $CaO(s) + CO_2(g) \longrightarrow CaCO_3(s)$

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Example 4.19 Identifying Redox Reactions, Oxidizing Agents, and Reducing Agents

Determine whether each reaction is an oxidation–reduction reaction. For each oxidation–reduction reaction, identify the oxidizing agent and the reducing agent.

a. $2\,Mg(s) + O_2(g) \longrightarrow 2\,MgO(s)$

b. $2\,HBr(aq) + Ca(OH)_2(aq) \longrightarrow 2\,H_2O(l) + CaBr_2(aq)$

c. $Zn(s) + Fe^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Fe(s)$

Solution

This is a redox reaction because magnesium increases in oxidation number (oxidation) and oxygen decreases in oxidation number (reduction)

a. $$\underset{0}{2\,Mg(s)} + \underset{0}{O_2(g)} \longrightarrow 2\,\underset{+2\;-2}{MgO(s)}$$

Reduction

Oxidation

Oxidizing agent: O_2
Reducing agent: Mg

This is not a redox reaction because none of the atoms undergo a change in oxidation number.

b. $$2\,\underset{+1-1}{HBr(aq)} + \underset{+2-2+1}{Ca(OH)_2(aq)} \rightarrow 2\,\underset{+1-2}{H_2O(l)} + \underset{+2-1}{CaBr_2(aq)}$$

This is a redox reaction because zinc increases in oxidation number (oxidation) and iron decreases in oxidation number (reduction).

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Example 4.19 Identifying Redox Reactions, Oxidizing Agents, and Reducing Agents

Continued

c. $$\underset{0}{Zn(s)} + \underset{+2}{Fe^{2+}(aq)} \longrightarrow \underset{+2}{Zn^{2+}(aq)} + \underset{0}{Fe(s)}$$

Reduction

Oxidation

Oxidizing agent: Fe^{2+}
Reducing agent: Zn

For Practice 4.19

Determine whether or not each reaction is a redox reaction. For each redox reaction, identify the oxidizing agent and the reducing agent.

a. $2\,Li(s) + Cl_2(g) \longrightarrow 2\,LiCl(s)$

b. $2\,Al(s) + 3\,Sn^{2+}(aq) \longrightarrow 2\,Al^{3+}(aq) + 3\,Sn(s)$

d. $Pb(NO_3)_2(aq) + 2\,LiCl(aq) \longrightarrow PbCl_2(s) + 2\,LiNO_3(aq)$

e. $C(s) + O_2(g) \longrightarrow CO_2(g)$

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Example 4.20 Writing Equations for Combustion Reactions

Write a balanced equation for the combustion of liquid methyl alcohol (CH_3OH).

Solution

Begin by writing an unbalanced equation showing the reaction of CH_3OH with O_2 to form CO_2 and H_2O.

$$CH_3OH(l) + O_2(g) \longrightarrow CO_2(g) + H_2O(g)$$

Balance the equation using the guidelines in Section 3.10.

$$2\,CH_3OH(l) + 3\,O_2(g) \longrightarrow 2\,CO_2(g) + 4\,H_2O(g)$$

For Practice 4.20

Write a balanced equation for the complete combustion of liquid C_2H_5SH.

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