CHAPTER 10
CHEMICAL CALCULATIONS AND CHEMICAL EQUATIONS

A lthough Chapter 9 was full of questions that began with, "*How much…?*" we are not done with such questions yet. In Chapter 9, our questions focused on chemical formulas. For example, we answered such questions as, "*How much* of the element vanadium can be obtained from 2.3 metric tons of the compound V_2O_5?" The chemical formula V_2O_5 told us that there are two moles of vanadium, V, in each mole of V_2O_5. We used this molar ratio to convert from moles of V_2O_5 to moles of vanadium.

In this chapter, we encounter questions that focus instead on chemical reactions. These questions ask us to convert from amount of one substance in a given chemical reaction to amount of another substance participating in the same reaction. For example, a business manager, budgeting for the production of silicon-based computer chips, wants to know *how much* silicon can be produced from 16 kg of carbon and 32 kg of silica, SiO_2, in the reaction

$$SiO_2(s) + 2C(s) \xrightarrow{2000\,°C} Si(l) + 2CO(g)$$
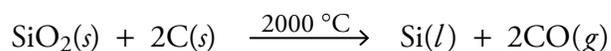
A safety engineer in a uranium processing plant, wants to know *how much* water needs to be added to 25 pounds of uranium hexafluoride to maximize the synthesis of UO_2F_2 by the reaction

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$$
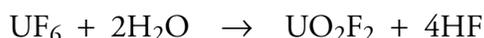
A chemistry student working in the lab might be asked to calculate *how much* 1-bromo-2-methylpropane, C_4H_9Br, could be made from 6.034 g of 2-methyl-2-propanol, C_4H_9OH, in the reaction

$$3C_4H_9OH + PBr_3 \rightarrow 3C_4H_9Br + H_3PO_3$$
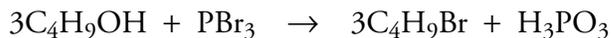
In these calculations, we will be generating conversion factors from the coefficients in the balanced chemical equation.

How much product can be made from the given reactants?

Review Skills

The presentation of information in this chapter assumes that you can already perform the tasks listed below. You can test your readiness to proceed by answering the Review Questions at the end of the chapter. This might also be a good time to read the Chapter Objectives, which precede the Review Questions.

- Balance chemical equations. (Section 4.1.)
- Write or identify the definitions of *solution*, *solute*, and *solvent*. (Section 4.2)
- Given a description of a solution, identify the solute and solvent. (Section 4.2)
- Describe water solutions in terms of the nature of the particles in solution and the attractions between them. (Sections 4.2 and 5.1)
- Given formulas for two ionic compounds, predict whether a precipitate will form when water solutions of the two are mixed, and write the complete equation that describes the reaction. (Section 4.2)
- Convert between names of chemical substances and their chemical formulas. (Section 5.3)
- Given the names or formulas for a monoprotic or polyprotic acid and an ionic compound containing hydroxide, carbonate, or hydrogen carbonate ions, write the complete balanced

equation for the neutralization reaction that takes place between them. (See Section 5.6)
- Make general unit conversions. (Sections 8.1 and 8.5)
- Report answers to calculations using the correct number of significant figures. (Section 8.2)
- Find the atomic mass for elements, the molecular mass for molecular compounds, and the formula mass for ionic compounds. (See Sections 9.2 and 9.3)
- Use the atomic mass for elements, the molecular mass for molecular compounds, and the formula mass for ionic compounds to convert between mass and moles of substance. (Sections 9.2 and 9.3)

10.1 Equation Stoichiometry

Chapter 9 asked you to pretend to be an industrial chemist at a company that makes phosphoric acid, H_3PO_4. The three-step "furnace method" for producing this compound is summarized by these three equations:

$$2Ca_3(PO_4)_2 + 6SiO_2 + 10C \rightarrow 4P + 10CO + 6CaSiO_3$$

$$4P(s) + 5O_2(g) \rightarrow P_4O_{10}(s)$$

$$P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$$
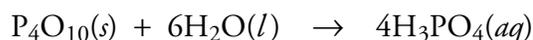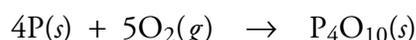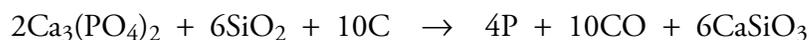
Following the strategy demonstrated in Example 9.6, we calculated the maximum mass of tetraphosphorus decoxide, P_4O_{10}, that can be made from 1.09×10^4 kilograms of phosphorus in the second of these three reactions. The answer is 2.50×10^4 kg P_4O_{10}. We used the following steps:

$$\boxed{1.09 \times 10^4 \text{ kg P}} \Rightarrow \boxed{\text{g P}} \Rightarrow \boxed{\text{mol P}} \Rightarrow \boxed{\text{mol } P_4O_{10}} \Rightarrow \boxed{\text{g } P_4O_{10}} \Rightarrow \boxed{\text{kg } P_4O_{10}}$$

$$? \text{ kg } P_4O_{10} = 1.09 \times 10^4 \text{ kg P} \left(\frac{10^3 \text{ g}}{1 \text{ kg}} \right) \left(\frac{1 \text{ mol P}}{30.9738 \text{ g P}} \right) \left(\frac{1 \text{ mol } P_4O_{10}}{4 \text{ mol P}} \right) \left(\frac{283.889 \text{ g } P_4O_{10}}{1 \text{ mol } P_4O_{10}} \right) \left(\frac{1 \text{ kg}}{10^3 \text{ g}} \right)$$

$$= 2.50 \times 10^4 \text{ kg } P_4O_{10}$$

The ratio of moles of P_4O_{10} to moles of P (which came from the subscripts in the chemical formula, P_4O_{10}) provided the key conversion factor that allowed us to convert from units of phosphorus to units of tetraphosphorus decoxide.

Now let's assume that you have been transferred to the division responsible for the final stage of the process, the step in which tetraphosphorus decoxide is converted into phosphoric acid in the third reaction in the list displayed above. Your first assignment there is to calculate the mass of water in kilograms that would be necessary to react with 2.50×10^4 kg P_4O_{10}. The steps for this conversion are very similar to those in Example 9.6:

$$\boxed{2.50 \times 10^4 \text{ kg } P_4O_{10}} \Rightarrow \boxed{\text{g } P_4O_{10}} \Rightarrow \boxed{\text{mol } P_4O_{10}} \Rightarrow \boxed{\text{mol } H_2O} \Rightarrow \boxed{\text{g } H_2O} \Rightarrow \boxed{\text{kg } H_2O}$$
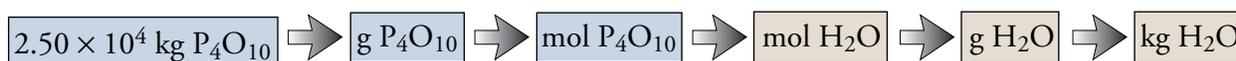
As part of our calculation, we convert from moles of one substance (P_4O_{10}) to moles of another (H_2O), so we need a conversion factor that relates the numbers of particles of these substances. The coefficients in the balanced chemical equation provide us with information that we can use to build this conversion factor. They tell us that six molecules of H_2O are needed to react with one molecule of P_4O_{10} in order to produce four molecules of phosphoric acid:

$$P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$$
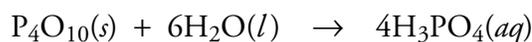
Thus the ratio of amount of H_2O to amount of P_4O_{10} is

$$\left(\frac{6 \text{ molecules } H_2O}{1 \text{ molecule } P_4O_{10}} \right)$$

We found in Chapter 9 that it is convenient to describe numbers of molecules in terms of moles. If the reaction requires six molecules of water for each molecule of P_4O_{10}, it would require six dozen H_2O molecules for each dozen P_4O_{10} molecules, or six moles of H_2O for each mole of P_4O_{10} (Table 10.1).

$$\left(\frac{6 \text{ dozen } H_2O}{1 \text{ dozen } P_4O_{10}} \right) \quad \text{or} \quad \left(\frac{6 \text{ mol } H_2O}{1 \text{ mol } P_4O_{10}} \right)$$

Table 10.1
Information Derived from the Coefficients in the Balanced Equation for the Reaction That Produces   OBJECTIVE 2
Phosphoric Acid

$P_4O_{10}(s)$	+	$6H_2O(l)$	$\rightarrow$	$4H_3PO_4(aq)$
1 molecule P_4O_{10}		6 molecules H_2O		4 molecules H_3PO_4
1 dozen P_4O_{10} molecules		6 dozen H_2O molecules		4 dozen H_3PO_4 molecules
6.022×10^{23} molecules P_4O_{10}		$6(6.022 \times 10^{23})$ molecules H_2O		$4(6.022 \times 10^{23})$ molecules H_3PO_4
1 mole P_4O_{10}		6 moles H_2O		4 moles H_3PO_4

Example 10.1 shows how the coefficients in a balanced chemical equation provide a number of conversion factors that allow us to convert from moles of any reactant or product to moles of any other reactant or product.

EXAMPLE 10.1 - Equation Stoichiometry

OBJECTIVE 2

Write three different conversion factors that relate moles of one reactant or product in the reaction below to moles of another reactant or product in this reaction.

$$P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$$
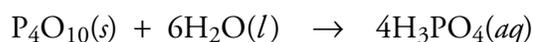
Solution

Any combination of two coefficients from the equation leads to a conversion factor.

$$\left(\frac{1 \text{ mol } P_4O_{10}}{6 \text{ mol } H_2O} \right) \qquad \left(\frac{1 \text{ mol } P_4O_{10}}{4 \text{ mol } H_3PO_4} \right) \qquad \left(\frac{6 \text{ mol } H_2O}{4 \text{ mol } H_3PO_4} \right)$$

OBJECTIVE 3
OBJECTIVE 4

Let's return to our conversion of 2.50×10^4 kg P_4O_{10} to kilograms of water. Like so many chemistry calculations, this problem can be worked using the unit analysis thought process and format. We start by identifying the unit that we want to arrive at (kg H_2O) and a known value that can be used to start the unit analysis setup (2.50×10^4 kg P_4O_{10}). We have already decided that we will convert from amount of P_4O_{10} to amount of H_2O using the molar ratio derived from the balanced equation, but before we can convert from moles of P_4O_{10} to moles of H_2O, we need to convert from mass of P_4O_{10} to number of moles of P_4O_{10}.

mass P_4O_{10} ➡ mol P_4O_{10} ➡ mol H_2O ➡ mass H_2O

15	
P	**8**
30.9738	**O**
	15.9994

1
H
1.00794
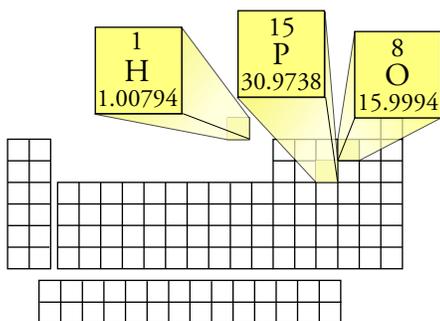
P_4O_{10} is a molecular compound, and we discovered in Section 9.3 that we can convert from mass of a molecular substance to moles using its molar mass, which comes from its molecular mass. Because we are starting with a mass measured in kilograms, our equation also needs a conversion factor for converting kilograms to grams. We can convert from moles of H_2O to grams of H_2O using the molar mass of water (which we determine from the molecular mass of H_2O). We then convert from grams to kilograms to complete the calculation.

$$? \text{ kg } H_2O = 2.50 \times 10^4 \text{ kg } P_4O_{10} \left(\frac{10^3 \text{ g}}{1 \text{ kg}} \right) \left(\frac{1 \text{ mol } P_4O_{10}}{283.889 \text{ g } P_4O_{10}} \right) \left(\frac{6 \text{ mol } H_2O}{1 \text{ mol } P_4O_{10}} \right) \left(\frac{18.0153 \text{ g } H_2O}{1 \text{ mol } H_2O} \right) \left(\frac{1 \text{ kg}}{10^3 \text{ g}} \right)$$

$$= 9.52 \times 10^3 \text{ kg } H_2O$$

There is a shortcut for this calculation. We can collapse all five of the conversion factors above into one. The reaction equation tells us that there are six moles of H_2O for each mole of P_4O_{10}. The molecular masses of these substances tell us that each mole of H_2O weighs 18.0153 g, and each mole of P_4O_{10} weighs 283.889 g. Thus the mass ratio of H_2O to P_4O_{10} is six times 18.0153 g to one times 283.889 g.

OBJECTIVE 4

$$\left(\frac{6 \times 18.0153 \text{ g } H_2O}{1 \times 283.889 \text{ g } P_4O_{10}} \right)$$

We can describe this mass ratio using any mass units we want.

$$\left(\frac{6 \times 18.0153 \text{ g } H_2O}{1 \times 283.889 \text{ g } P_4O_{10}} \right)$$

or

$$\left(\frac{6 \times 18.0153 \text{ kg } H_2O}{1 \times 283.889 \text{ kg } P_4O_{10}} \right)$$

or

$$\left(\frac{6 \times 18.0153 \text{ lb } H_2O}{1 \times 283.889 \text{ lb } P_4O_{10}} \right)$$

Thus our setup for this example can be simplified to the following.

$$? \text{ kg } H_2O = 2.50 \times 10^4 \text{ kg } P_4O_{10} \left(\frac{6 \times 18.0153 \text{ kg } H_2O}{1 \times 283.889 \text{ kg } P_4O_{10}} \right)$$

OBJECTIVE 4

$$= 9.52 \times 10^3 \text{ kg } H_2O$$

Calculations like this are called **equation stoichiometry** problems, or just stoichiometry problems. Stoichiometry, from the Greek words for "measure" and "element," refers to the quantitative relationships between substances. Calculations such as those in Chapter 9, in which we convert between an amount of compound and an amount of element in the compound, are one kind of stoichiometry problem, but the term is rarely used in that context. Instead, it is usually reserved for calculations such as the one above, which deal with the conversion of the amount of one substance in a chemical reaction into the amount of a different substance in the reaction.

The following is a sample study sheet for equation stoichiometry problems.

Sample Study Sheet 10.1

Basic Equation Stoichiometry– Converting Mass of One Substance in a Reaction to Mass of Another

OBJECTIVE 3
OBJECTIVE 4

TIP-OFF   The calculation calls for you to convert from an amount of one substance in a given chemical reaction to the corresponding amount of another substance participating in the same reaction.

GENERAL STEPS   Use a unit analysis format. Set it up around a mole-to-mole conversion in which the coefficients from a balanced equation are used to generate a mole ratio. (See Figure 10.1 for a summary.) The general steps are

STEP 1 If you are not given it, write and balance the chemical equation for the reaction.

STEP 2 Start your unit analysis in the usual way.

You want to calculate amount of substance 2, so you set that unknown equal to the given amount of substance 1. (In this section, the given units will be mass of an element or compound, but as you will see later in this chapter and in Chapter 13, the given units might instead be the volume of a solution or the volume of a gas.)

STEP 3 If you are given a unit of mass other than grams for substance 1, convert from the unit that you are given to grams. This may require one or more conversion factors.

STEP 4 Convert from grams of substance 1 to moles of substance 1, using the substance's molar mass.

STEP 5 Convert from moles of substance 1 to moles of substance 2 using their coefficients from the balanced equation to create a molar ratio to use as a conversion factor.

STEP 6 Convert from moles of substance 2 to grams of substance 2, using the substance's molar mass.

STEP 7 If necessary, convert from grams of substance 2 to the desired unit for substance 2. This may require one or more conversion factors.

STEP 8 Calculate your answer and report it with the correct significant figures (in scientific notation, if necessary) and with the correct unit.

The general form of the unit analysis setup follows.

$$? \text{ (unit) 2} = \text{(given) (unit) 1} \left(\frac{\text{--- g}}{\text{--- (unit)}} \right) \left(\frac{1 \text{ mol 1}}{\text{--- g 1}} \right) \left(\frac{\text{(coefficient 2) mol 2}}{\text{(coefficient 1) mol 1}} \right) \left(\frac{\text{--- g 2}}{1 \text{ mol 2}} \right) \left(\frac{\text{--- (unit)}}{\text{--- g}} \right)$$

Molar mass of substance 2

One or more conversion factors convert the given unit to grams.

Molar mass of substance 1

One or more conversion factors convert grams to the given unit.
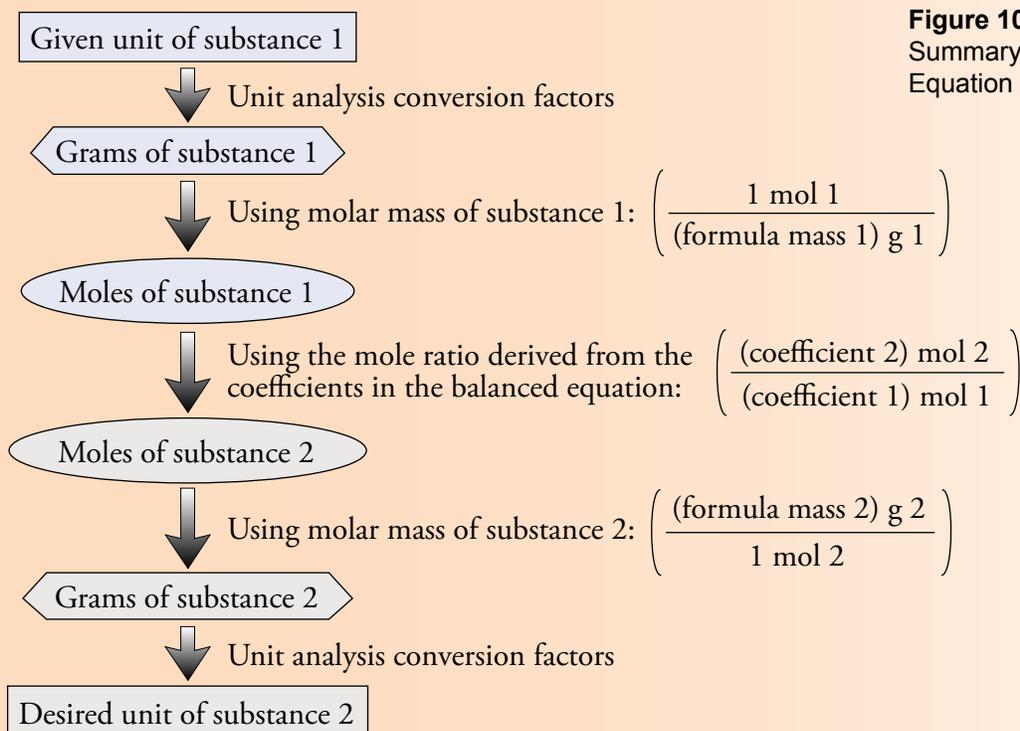
Figure 10.1
Summary of Steps for Mass-Mass Equation Stoichiometry Problems.

Given unit of substance 1

↓ Unit analysis conversion factors

Grams of substance 1

↓ Using molar mass of substance 1: $\left(\dfrac{1 \text{ mol } 1}{(\text{formula mass } 1) \text{ g } 1} \right)$

Moles of substance 1

↓ Using the mole ratio derived from the coefficients in the balanced equation: $\left(\dfrac{(\text{coefficient } 2) \text{ mol } 2}{(\text{coefficient } 1) \text{ mol } 1} \right)$

OBJECTIVE 4

Moles of substance 2

↓ Using molar mass of substance 2: $\left(\dfrac{(\text{formula mass } 2) \text{ g } 2}{1 \text{ mol } 2} \right)$

Grams of substance 2

↓ Unit analysis conversion factors

Desired unit of substance 2

SHORTCUT STEPS - If the mass unit desired for substance 2 is the same mass unit given for substance 1, the general steps described above can be condensed into a shortcut. (See Figure 10.2 for a summary.)

OBJECTIVE 4

STEP 1 If you are not given it, write and balance the chemical equation for the reaction.

STEP 2 Start your unit analysis set-up in the usual way.

STEP 3 Convert directly from the mass unit of substance 1 that you have been given to the same mass unit of substance 2, using a conversion factor having the following general form.

$$? \text{ (unit) } 2 = \text{(given) (unit) } 1 \left(\frac{(\text{coefficient } 2) (\text{formula mass } 2) (\text{any mass unit}) \text{ substance } 2}{(\text{coefficient } 1) (\text{formula mass } 1) (\text{same mass unit}) \text{ substance } 1} \right)$$

STEP 4 Calculate your answer and report it with the correct significant figures, in scientific notation if necessary, and with the correct unit.

EXAMPLE See Example 10.2.

Figure 10.2
Shortcut for Mass-Mass Equation Stoichiometry Problems.

Given mass of substance 1

↓ Using $\left(\dfrac{(\text{coefficient } 2) (\text{formula mass } 2) (\text{any mass unit}) \text{ substance } 2}{(\text{coefficient } 1) (\text{formula mass } 1) (\text{same mass unit}) \text{ substance } 1} \right)$

Same mass unit of substance 2
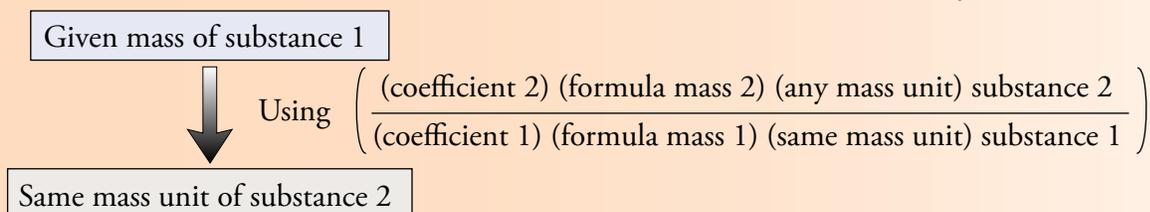
EXAMPLE 10.2 - Equation Stoichiometry

Aluminum sulfate is used in water purification as a coagulant that removes phosphate and bacteria and as a pH conditioner. It acts as a coagulant by reacting with hydroxide to form aluminum hydroxide, which precipitates from the solution and drags impurities down with it as it settles.

a. Write a complete, balanced equation for the reaction of water solutions of aluminum sulfate and sodium hydroxide to form solid aluminum hydroxide and aqueous sodium sulfate.

b. Write six different conversion factors that relate moles of one reactant or product to moles of another reactant or product.

c. If 0.655 Mg of $Al_2(SO_4)_3$ are added to water in a treatment plant, what is the maximum mass of $Al(OH)_3$ that can form?

Solution

a. The balanced equation is:

$$Al_2(SO_4)_3(aq) + 6NaOH(aq) \rightarrow 2Al(OH)_3(s) + 3Na_2SO_4(aq)$$
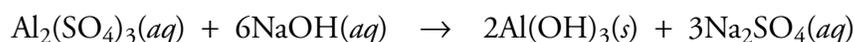
b. The stoichiometric relationships in the reaction lead to the following conversion factors.

$$\left(\frac{1 \text{ mol } Al_2(SO_4)_3}{6 \text{ mol NaOH}} \right) \quad \left(\frac{1 \text{ mol } Al_2(SO_4)_3}{2 \text{ mol } Al(OH)_3} \right) \quad \left(\frac{1 \text{ mol } Al_2(SO_4)_3}{3 \text{ mol } Na_2SO_4} \right)$$

$$\left(\frac{6 \text{ mol NaOH}}{2 \text{ mol } Al(OH)_3} \right) \quad \left(\frac{6 \text{ mol NaOH}}{3 \text{ mol } Na_2SO_4} \right) \quad \left(\frac{2 \text{ mol } Al(OH)_3}{3 \text{ mol } Na_2SO_4} \right)$$

c. We are asked to calculate the mass of $Al(OH)_3$, but we are not told what units to calculate. To choose an appropriate unit, keep the following criteria in mind.

■ Choose a metric unit unless there is a good reason to do otherwise. For this problem, that could be grams, kilograms, milligrams, megagrams, etc.

■ Choose a unit that corresponds to the size of the expected value. In this problem, for example, we expect the mass of $Al(OH)_3$ that forms from the large mass of 0.655 Mg of $Al_2(SO_4)_3$ to be large itself, so we might choose to calculate kilograms or megagrams instead of grams or milligrams.

■ Choose a unit that keeps the calculation as easy as possible. This usually means picking a unit that is mentioned in the problem. In this example, megagrams are mentioned, so we will calculate megagrams.

We are asked to convert from amount of one compound in a reaction to amount of another compound in the reaction: an equation stoichiometry problem. Note that the setup below follows the general steps described in Sample Study Sheet 10.1 and Figure 10.1.

1	13	16	8
H	Al	S	O
1.00794	26.9815	32.066	15.9994

$$? \text{ Mg Al(OH)}_3 = 0.655 \text{ Mg Al}_2\text{(SO}_4\text{)}_3 \left(\frac{10^6 \text{ g}}{1 \text{ Mg}} \right) \left(\frac{1 \text{ mol Al}_2\text{(SO}_4\text{)}_3}{342.154 \text{ g Al}_2\text{(SO}_4\text{)}_3} \right)$$

$$\left(\frac{2 \text{ mol Al(OH)}_3}{1 \text{ mol Al}_2\text{(SO}_4\text{)}_3} \right) \left(\frac{78.0035 \text{ g Al(OH)}_3}{1 \text{ mol Al(OH)}_3} \right) \left(\frac{1 \text{ Mg}}{10^6 \text{ g}} \right)$$

$$= \textbf{0.299 Mg Al(OH)}_3$$

The setup for the shortcut is:

$$? \text{ Mg Al(OH)}_3 = 0.655 \text{ Mg Al}_2\text{(SO}_4\text{)}_3 \left(\frac{2 \times 78.0035 \text{ Mg Al(OH)}_3}{1 \times 342.154 \text{ Mg Al}_2\text{(SO}_4\text{)}_3} \right)$$

$$= \textbf{0.299 Mg Al(OH)}_3$$

Note that this setup follows the steps described in Sample Study Sheet 10.1 and Figure 10.2.

EXERCISE 10.1 - Equation Stoichiometry

Tetrachloroethene, C_2Cl_4, often called perchloroethylene (perc), is a colorless liquid used in dry cleaning. It can be formed in several steps from the reaction of dichloroethane, chlorine gas, and oxygen gas. The equation for the net reaction is:

$$8C_2H_4Cl_2(l) + 6Cl_2(g) + 7O_2(g) \rightarrow 4C_2HCl_3(l) + 4C_2Cl_4(l) + 14H_2O(l)$$
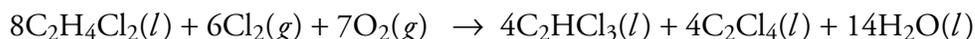
a. Fifteen different conversion factors for relating moles of one reactant or product to moles of another reactant or product can be derived from this equation. Write five of them.

b. How many grams of water form when 362.47 grams of tetrachloroethene, C_2Cl_4, are made in the reaction above?

c. What is the maximum mass of perchloroethylene, C_2Cl_4, that can be formed from 23.75 kilograms of dichloroethane, $C_2H_4Cl_2$?

Because substances are often found in mixtures, equation stoichiometry problems often include conversions between masses of pure substances and masses of mixtures containing the pure substances, using percentages as conversion factors. See calculations like these at the textbook's Web site.

10.2 Real-World Applications of Equation Stoichiometry

Let's return to the reaction of solid tetraphosphorus decoxide and water.

$$P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$$
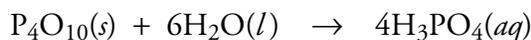
Imagine that it is your job to design an industrial procedure for running this reaction. Whenever such a procedure is developed, some general questions must be answered, including the following:

- *How much of each reactant should be added to the reaction vessel?* This might be determined by the amount of product that you want to make or by the amount of one of the reactants that you have available.

- *What level of purity is desired for the final product?* If the product is mixed with other substances (such as excess reactants), how will this purity be achieved?

To understand some of the issues relating to these questions, let's take a closer look at the reaction of P_4O_{10} and H_2O, keeping in mind that we want to react 2.50×10^4 kg P_4O_{10} per day. What if you used a shovel to transfer solid P_4O_{10} into a large container, and then added water with a garden hose? Could you expect both of these reactants to react completely? When the reaction is finished, would the only substance in the container be phosphoric acid?

To achieve the complete reaction of both reactants, the coefficients in the balanced equation show us that we would need to add exactly six times as many water molecules as P_4O_{10} molecules. With the precision expected from using a shovel and a hose to add the reactants, this seems unlikely. In fact, it is virtually impossible. The only way we could ever achieve the complete reaction of both reactants is by controlling the addition of reactants with a precision of plus or minus one molecule, and that is impossible (or at least highly improbable). No matter how careful we are to add the reactants in the correct ratio, we will always end up with at least a slight excess of one component compared to the other.

For some chemical reactions, chemists want to mix reactants in amounts that are as close as possible to the ratio that would lead to the complete reaction of each. This ratio is sometimes called the stoichiometric ratio. For example, in the production of phosphoric acid, the balanced equation shows that six moles of H_2O react with each mole of P_4O_{10}, so for efficiency's sake, or to avoid leaving an excess of one of the reactants contaminating the product, we might want to add a molar ratio of P_4O_{10} to H_2O as close to the 1:6 stoichiometric ratio as possible.

$$P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$$
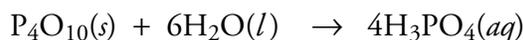
OBJECTIVE 5

Sometimes the chemist deliberately uses a limited amount of one reactant and excessive amounts of others. There are many practical reasons for such a decision. For example, an excess of one or more of the reactants will increase the likelihood that the other reactant or reactants will be used up. Thus, if one reactant is more expensive than the others, adding an excess of the less expensive reactants will ensure the greatest conversion possible of the one that is costly. For our reaction that produces phosphoric acid, water is much less expensive than P_4O_{10}, so it makes sense to add water in excess.

Sometimes one product is more important than others are, and the amounts of reactants are chosen to optimize its production. For example, the following reactions are part of the process that extracts pure silicon from silicon dioxide, SiO_2, for use in the semiconductor industry.

OBJECTIVE 5

$$SiO_2(s) + 2C(s) \rightarrow Si(l) + 2CO(g)$$

$$Si(s) + 3HCl(g) \rightarrow SiCl_3H(g) + H_2(g)$$

$$SiCl_3H(g) + H_2(g) \rightarrow Si(s) + 3HCl(g)$$
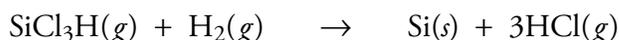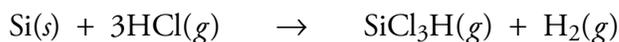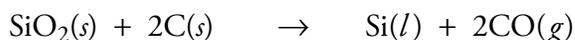
The ultimate goal of these reactions is to convert the silicon in SiO_2 to pure silicon, and the most efficient way to do this is to add an excess of carbon in the first reaction, an excess of HCl in the second reaction, and an excess of hydrogen gas in the last reaction.

Any component added in excess will remain when the reaction is complete. If one reactant is more dangerous to handle than others are, chemists would rather not have that reactant remaining at the reaction's end. For example, phosphorus, P, is highly reactive and dangerous to handle. Thus, in the reaction between P and O_2 to form P_4O_{10}, chemists would add the much safer oxygen in excess. When the reaction stops, the phosphorus is likely to be gone, leaving a product mixture that is mostly P_4O_{10} and oxygen.

OBJECTIVE 5

$$4P(s) + 5O_2(g) \text{ (with excess)} \rightarrow P_4O_{10}(s) + \text{excess } O_2(g)$$
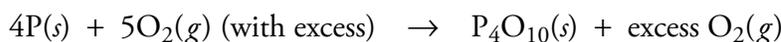
Another consideration is that when a reaction ends, some of the reactant that was added in excess is likely to be mixed in with the product. Chemists would prefer that the substance in excess be a substance that is easy to separate from the primary product. For example, if we add excess carbon in the following reaction, some of it will remain after the silica has reacted.

OBJECTIVE 5

$$SiO_2(s) + 2C(s) \text{ (with excess)} \rightarrow Si(l) + 2CO(g) + \text{excess } C(s)$$
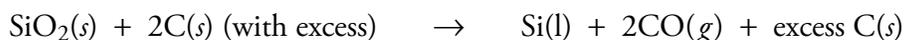
This excess carbon can be removed by converting it to carbon monoxide gas or carbon dioxide gas, which is easily separated from the silicon product.

Limiting Reactants

The reactant that runs out first in a chemical reaction limits the amount of product that can form. This reactant is called the **limiting reactant**. For example, say we add an excess of water to the reaction that forms phosphoric acid from water and P_4O_{10}:

$$P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$$
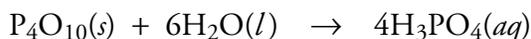
The amount of H_3PO_4 that can be formed will be determined by the amount of P_4O_{10}. Therefore, the P_4O_{10} will be the limiting reactant. When the P_4O_{10} is gone, the reaction stops, leaving an excess of water with the product.

A simple analogy might help to clarify the idea of the limiting reactant. To build a bicycle, you need one frame and two wheels (and a few other components that we will ignore). The following equation describes the production of bicycles from these two components.

1 frame + 2 wheels → 1 bicycle

Let's use this formula for bicycles to do a calculation very similar to the calculations

we will do for chemical reactions. Assume that you are making bicycles to earn money for college. If your storeroom contains seven frames and twelve wheels, what is the maximum number of bicycles you can make? To decide how many bicycles you can make, you need to determine which of your components will run out first. You can do this by first determining the maximum number of bicycles each component can make. Whichever component makes the fewer bicycles must run out first and limit the amount of product that can be made. From the formula for producing a bicycle, you obtain the necessary conversion factors:

$$\left(\frac{1 \text{ bicycle}}{1 \text{ frame}} \right) \quad \text{and} \quad \left(\frac{1 \text{ bicycle}}{2 \text{ wheels}} \right)$$

$$? \text{ bicycles} = 7 \cancel{\text{ frames}} \left(\frac{1 \text{ bicycle}}{1 \cancel{\text{ frame}}} \right) = 7 \text{ bicycles}$$

$$? \text{ bicycles} = 12 \cancel{\text{ wheels}} \left(\frac{1 \text{ bicycle}}{2 \cancel{\text{ wheels}}} \right) = 6 \text{ bicycles}$$

You have enough frames for seven bicycles but enough wheels for only six. The wheels will run out first. Even if you had 7000 frames, you could only make six bicycles with your twelve wheels. Therefore, the wheels are limiting, and the frames are in excess (Figure 10.3).

Figure 10.3
Limiting
Component

The wheels run out first, limiting the number of bicycles to six.

The frames are in excess.
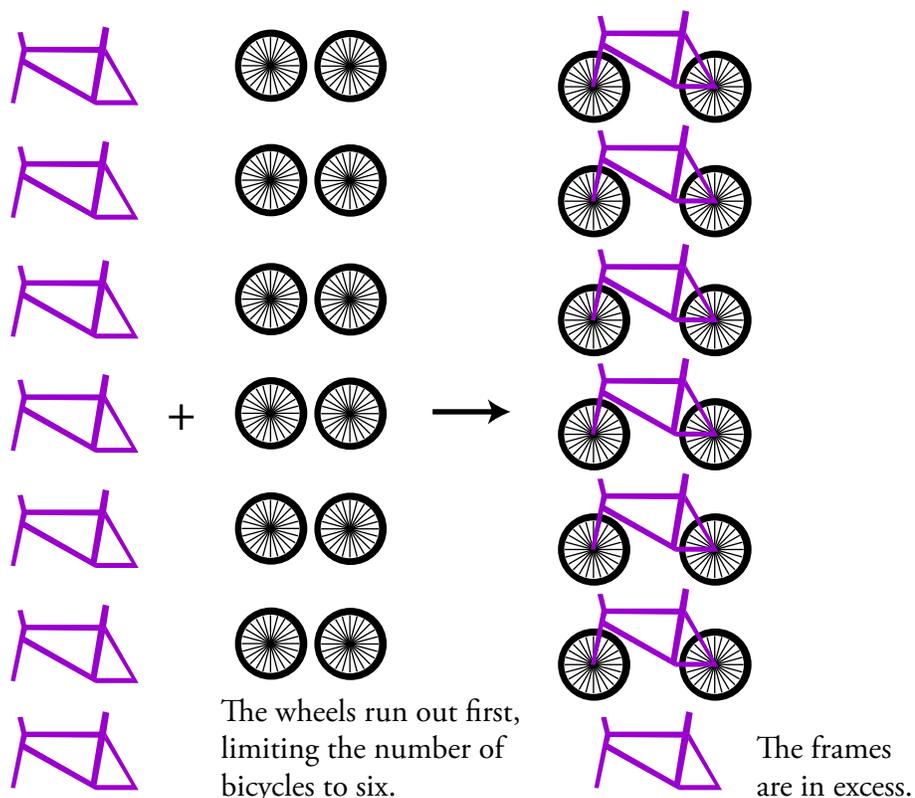
Now let's apply what we have learned from the bicycle example to a calculation that deals with a chemical reaction. Electronic grade (EG) silicon used in the electronics industry is a purified form of metallurgical grade silicon, which is made from the reaction of silica, SiO_2, with carbon in the form of coke at 2000 °C. (Silica is found in nature as quartz or quartz sand.)

$$SiO_2(s) \ + \ 2C(s) \ \xrightarrow{2000\ °C} \ Si(l) \ + \ 2CO(g)$$
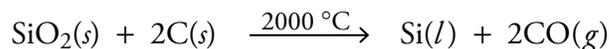
If 1000 moles of carbon are heated with 550 moles of silica, what is the maximum number of moles of metallurgical grade silicon, Si, that can be formed? This example is similar to the bicycle example. We need two times as many wheels as frames to build bicycles, and to get a complete reaction of silicon dioxide and carbon, we need two atoms (or moles of atoms) of carbon for every formula unit (or mole of formula units) of silicon dioxide.

$$1 \text{ frame } + \ 2 \text{ wheels } \ \rightarrow \ \ 1 \text{ bicycle}$$

$$SiO_2(s) \ + \ 2C(s) \ \ \rightarrow \ \ Si(l) \ + \ 2CO(g)$$
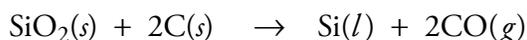
In the reaction between carbon and silicon dioxide, we can assume that one of the reactants is in excess and the other is limiting, but we do not yet know which is which. With the bicycle example, we discovered which component was limiting (and also the maximum number of bicycles that can be made) by calculating the maximum number of bicycles we could make from each component. The component that could make the fewer bicycles was limiting and that number of bicycles was the maximum number of bicycles that could be made.

For our reaction between carbon and silicon dioxide, we can determine which reactant is the limiting reactant by first calculating the maximum amount of silicon that can be formed from the given amount of each reactant. The reactant that forms the least product will run out first and limit the amount of product that can form. The coefficients in the balanced equation provide us with conversion factors to convert from moles of reactants to moles of products.

$$? \text{ mol Si} = 1000 \ \cancel{\text{mol C}} \left(\frac{1 \text{ mol Si}}{2 \ \cancel{\text{mol C}}} \right) = \textbf{500 mol Si}$$

$$? \text{ mol Si} = 550 \ \cancel{\text{mol SiO}_2} \left(\frac{1 \text{ mol Si}}{1 \ \cancel{\text{mol SiO}_2}} \right) = 550 \text{ mol Si}$$

The carbon will be used up after 500 moles of silicon have been formed. The silicon dioxide would not be used up until 550 moles of silicon were formed. Because the carbon produces the least silicon, it runs out first and limits the amount of product that can form. Therefore, the carbon is the limiting reactant, and the maximum amount of product that can form is 500 moles Si.

Now let's work a problem that is similar but deals with masses of reactants and products rather than moles. If 16.491 g of carbon are heated with 32.654 g of silica, what is the maximum mass of metallurgical grade silicon, Si, that can be formed?

For this calculation, we follow a procedure that is very similar to the procedure we would follow to calculate the moles of silicon that can be made from the reaction of 1000 moles of carbon and 550 moles of SiO_2. We calculate the amount of silicon that can be made from 16.491 g C and also from 32.654 g SiO_2. Whichever forms the least product is the limiting reactant and therefore determines the maximum amount of product that can form. These two calculations are equation stoichiometry problems, so we will use the procedure described in Sample Study Sheet 10.1.

$$? \text{ g Si} = 16.491 \text{ g C} \left(\frac{1 \text{ mol C}}{12.011 \text{ g C}} \right) \left(\frac{1 \text{ mol Si}}{2 \text{ mol C}} \right) \left(\frac{28.0855 \text{ g Si}}{1 \text{ mol Si}} \right)$$

$$\text{or} \quad ? \text{ g Si} = 16.491 \text{ g C} \left(\frac{1 \times 28.0855 \text{ g Si}}{2 \times 12.011 \text{ g C}} \right) = 19.281 \text{ g Si}$$

OBJECTIVE 6

$$? \text{ g Si} = 32.654 \text{ g SiO}_2 \left(\frac{1 \text{ mol SiO}_2}{60.0843 \text{ g SiO}_2} \right) \left(\frac{1 \text{ mol Si}}{1 \text{ mol SiO}_2} \right) \left(\frac{28.0855 \text{ g Si}}{1 \text{ mol Si}} \right)$$

$$\text{or} \quad ? \text{ g Si} = 32.654 \text{ g SiO}_2 \left(\frac{1 \times 28.0855 \text{ g Si}}{1 \times 60.0843 \text{ g SiO}_2} \right) = 15.264 \text{ g Si}$$

The SiO_2 will be used up after 15.264 g of silicon have been formed. The carbon would not be used up until 19.281 g of silicon were formed. Because the SiO_2 produces the least silicon, it runs out first and limits the amount of product that can form. Therefore, the silicon dioxide is the limiting reactant, and the maximum amount of product that can form is 15.264 g Si.

The following is a sample study sheet that summarizes the procedure for working limiting reactant problems.

Sample Study Sheet 10.2

Limiting Reactant Problems

OBJECTIVE 6

TIP-OFF   Given two or more amounts of reactants in a chemical reaction, you are asked to calculate the maximum amount of product that they can form.

GENERAL STEPS   Follow these steps.

■   Do separate calculations of the maximum amount of product that can form from each reactant. (These calculations are equation stoichiometry problems, so you can use the procedure described on Sample Study Sheet 10.1 for each calculation.)

■   The smallest of the values calculated in the step above is your answer. It is the maximum amount of product that can be formed from the given amounts of reactants.

EXAMPLE   See Example 10.3.

EXAMPLE 10.3 - Limiting Reactant

Titanium carbide, TiC, is the hardest of the known metal carbides. It can be made by heating titanium(IV) oxide, TiO_2, with carbon black to 2200 °C. (Carbon black is a powdery form of carbon that is produced when vaporized heavy oil is burned with 50% of the air required for complete combustion.)

$$TiO_2 + 3C \rightarrow TiC + 2CO$$
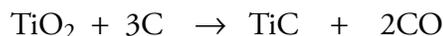
a. What is the maximum mass of titanium carbide, TiC, that can be formed from the reaction of 985 kg of titanium(IV) oxide, TiO_2, with 500 kg of carbon, C?   **OBJECTIVE 6**

b. Why do you think the reactant in excess was chosen to be in excess?   **OBJECTIVE 7**

Solution

a. Because we are given amounts of two reactants and asked to calculate an amount of product, we recognize this as a limiting reactant problem. Thus we first calculate the amount of product that can form from each reactant. The reactant that forms the least product is the limiting reactant and determines the maximum amount of product that can form from the given amounts of reactants.

$$? \text{ kg TiC} = 985 \text{ kg TiO}_2 \left(\frac{1 \times 59.878 \text{ kg TiC}}{1 \times 79.866 \text{ kg TiO}_2} \right) = \textbf{738 kg TiC}$$

$$? \text{ kg TiC} = 500 \text{ kg C} \left(\frac{1 \times 59.878 \text{ kg TiC}}{3 \times 12.011 \text{ kg C}} \right) = 831 \text{ kg TiC}$$

The limiting reactant is TiO_2 because it results in the least amount of product.

b. We are not surprised that the carbon is provided in excess. We expect it to be less expensive than titanium dioxide, and the excess carbon can be easily separated from the solid product by burning to form gaseous CO or CO_2.

EXERCISE 10.2 - Limiting Reactant

The uranium(IV) oxide, UO_2, used as fuel in nuclear power plants has a higher percentage of the fissionable isotope uranium-235 than is present in the UO_2 found in nature. To make fuel grade UO_2, chemists first convert uranium oxides to uranium hexafluoride, UF_6, whose concentration of uranium-235 can be increased by a process called gas diffusion. The enriched UF_6 is then converted back to UO_2 in a series of reactions, beginning with

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$$
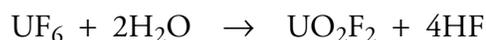
a. How many megagrams of UO_2F_2 can be formed from the reaction of 24.543 Mg UF_6 with 8.0 Mg of water?   **OBJECTIVE 6**

b. Why do you think the reactant in excess was chosen to be in excess?   **OBJECTIVE 7**

Percent Yield

In Examples 10.2 and 10.3, we determined the *maximum* amount of product that could be formed from the given amounts of reactants. This is the amount of product that could be obtained if 100% of the limiting reactant were converted to product and if this product could be isolated from the other components in the product mixture without any loss. This calculated maximum yield is called the **theoretical yield**. Often, somewhat less than 100% of the limiting reactant is converted to product, and somewhat less than the total amount of product is isolated from the mixture, so the **actual yield** of the reaction, the amount of product that one actually obtains, is less than the theoretical yield. The actual yield is sometimes called the experimental yield. The efficiency of a reaction can be evaluated by calculating the **percent yield**, the ratio of the actual yield to the theoretical yield expressed as a percentage.

$$\text{Percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

OBJECTIVE 8   There are many reasons why the actual yield in a reaction might be less than the theoretical yield. One key reason is that many chemical reactions are significantly reversible. As soon as some products are formed, they begin to convert back to reactants, which then react again to reform products.

$$\text{reactants} \rightleftharpoons \text{products}$$
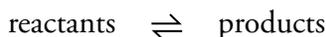
For example, we found in Chapter 5 that the reaction between a weak acid and water is reversible:

$$\underset{\text{acetic acid}}{HC_2H_3O_2(aq)} + \underset{\text{water}}{H_2O(l)} \rightleftharpoons \underset{\text{hydronium ion}}{H_3O^+(aq)} + \underset{\text{acetate}}{C_2H_3O_2^-(aq)}$$
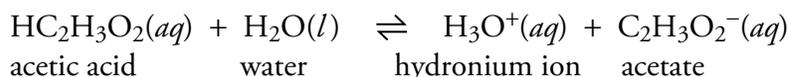
When an $HC_2H_3O_2$ molecule collides with an H_2O molecule, an H^+ ion is transferred to the water molecule to form an H_3O^+ ion and a $C_2H_3O_2^-$ ion. However, when an H_3O^+ ion and a $C_2H_3O_2^-$ ion collide, an H+ ion can be transferred back again to reform $HC_2H_3O_2$ and H_2O. Therefore, the reaction never goes to completion; there are always both reactants and products in the final mixture.

OBJECTIVE 8   A reaction's yield is also affected by the occurrence of side reactions. This is particularly common in reactions of organic (carbon-based) compounds. Side reactions are reactions occurring in the reaction mixture that form products other than the desired product. For example, in one reaction, butane, $CH_3CH_2CH_2CH_3$, reacts with chlorine gas in the presence of light to form 2-chlorobutane and hydrogen chloride:
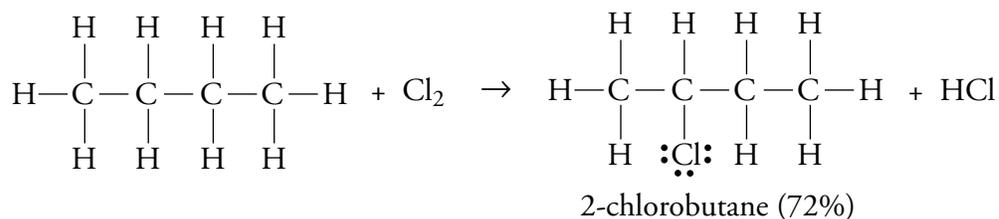
2-chlorobutane (72%)

However, this reaction does not lead to 100% yield of 2-chlorobutane because of an alternative reaction in which the butane and chlorine react to form 1-chlorobutane instead of 2-chlorobutane.
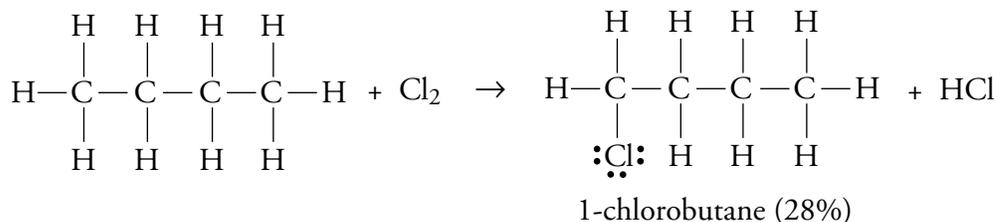
1-chlorobutane (28%)

Under normal conditions, the result of mixing butane with chlorine gas will be a mixture that is about 72% 2-chlorobutane and 28% 1-chlorobutane.

Another factor that affects the actual yield is a reaction's rate. Sometimes a reaction is so slow that it has not reached the maximum yield by the time the product is isolated. Finally, as we saw above, even if 100% of the limiting reactant proceeds to products, usually the product still needs to be separated from the other components in the product mixture (excess reactants, products of side reactions, and other impurities). This separation process generally leads to some loss of product.

OBJECTIVE 8

OBJECTIVE 8

Example 10.4 shows how percent yield calculations can be combined with equation stoichiometry problems.

EXAMPLE 10.4 - Percent Yield

OBJECTIVE 9

Phosphorus tribromide, PBr_3, can be used to add bromine atoms to alcohol molecules such as 2-methyl-1-propanol. In a student experiment, 5.393 g of 1-bromo-2-methylpropane form when an excess of PBr_3 reacts with 6.034 g of 2-methyl-1-propanol. What is the percent yield?

$$3CH_3CH(CH_3)CH_2OH + PBr_3 \rightarrow 3CH_3CH(CH_3)CH_2Br + H_3PO_3$$
2-methyl-1-propanol   1-bromo-2-methylpropane
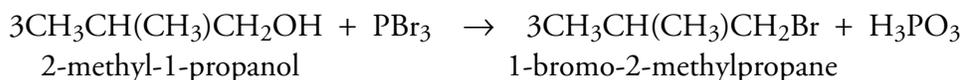
Solution

The percent yield is the actual yield divided by the theoretical yield times 100. The actual yield is the amount of product that the chemist is able to isolate after running a reaction. It is given to you in problems such as this one. Our actual yield is 5.393 g.

$$\text{Percent yield} = \frac{\text{Actual yield}}{\text{Theoretical yield}} \times 100\% = \frac{5.393 \text{ g } C_4H_9Br}{\text{Theoretical yield}} \times 100\%$$

We need to calculate the theoretical (or maximum) yield we would get if the 2-methyl-1-propanol, C_4H_9OH, which is the limiting reactant, were converted completely to 1-bromo-2-methylpropane, C_4H_9Br, and if the student was able to isolate the product with 100% efficiency.

$$? \text{ g } CH_3CH(CH_3)CH_2Br = 6.034 \text{ g } CH_3CH(CH_3)CH_2OH \left(\frac{3 \times 137.01 \text{ g } CH_3CH(CH_3)CH_2Br}{3 \times 74.123 \text{ g } CH_3CH(CH_3)CH_2OH} \right)$$

$$= 11.15 \text{ g } CH_3CH(CH_3)CH_2Br$$

The theoretical yield, 11.15 g C_4H_9Br, can be divided into the given actual yield, 5.393 g, to calculate the percent yield.

$$\text{Percent yield} = \frac{\text{Actual yield}}{\text{Theoretical yield}} \times 100\% = \frac{5.393 \text{ g } C_4H_9Br}{11.15 \text{ g } C_4H_9Br} \times 100\% = \textbf{48.37\% yield}$$

EXERCISE 10.3 - Percent Yield

The raw material used as a source of chromium and chromium compounds is a chromium iron ore called chromite. For example, sodium chromate, Na_2CrO_4, is made by roasting chromite with sodium carbonate, Na_2CO_3. (Roasting means heating in the presence of air or oxygen.) A simplified version of the net reaction is:

$$4FeCr_2O_4 \ + \ 8Na_2CO_3 \ + \ 7O_2 \quad \rightarrow \quad 8Na_2CrO_4 \ + \ 2Fe_2O_3 \ + \ 8CO_2$$
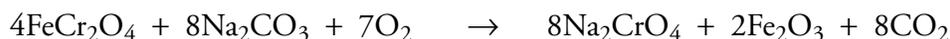
What is the percent yield if 1.2 kg of Na_2CrO_4 are produced from ore that contains 1.0 kg of $FeCr_2O_4$?

SPECIAL TOPIC 10.1   Big Problems Require Bold Solutions— Global Warming and Limiting Reactants

There is general agreement in the scientific community that the average temperature of the earth is increasing and that this global warming is potentially a major problem. The increase in temperature is expected to cause more frequent and intense heat waves, ecological disruptions that could lead certain types of forests to disappear and some species to become extinct, a decline in agricultural production that could result in hunger and famine, an expansion of deserts, and a rise in sea level.

The global system that regulates the earth's temperature is very complex, but many scientists believe the increase in temperature is caused by an increase of certain gases in the atmosphere that trap energy that would otherwise escape into space. These gases, called greenhouse gases, include carbon dioxide, methane, nitrous oxide, chlorofluorocarbons (CFCs), and the ozone in the lower atmosphere.

Because carbon dioxide plays a major role in global warming, many of the proposed solutions to the problem are aimed at reducing the levels of carbon dioxide in the atmosphere. One suggestion is to try altering the chemistry of the earth's oceans such that they will absorb more CO_2 from the air.

Huge amounts of carbon dioxide from the air are constantly dissolving in the ocean, and at the same time, carbon dioxide is leaving the ocean and returning to the air. The ocean takes about 100 billion tons of carbon dioxide out of the atmosphere per year, and ultimately returns 98 billion tons of it. The remaining 2 billion tons end up as organic deposits on the sea floor. If the rate of escape from the ocean to the air could be slowed, the net shift of CO_2 from the air to the ocean would increase, and the levels of CO_2 in the air would fall. The goal is to find some way to increase the use of CO_2 in the ocean before it can escape.

Phytoplankton, the microorganisms that form the base of the food web in the ocean, take CO_2 from the air and convert it into more complex organic compounds. When the phytoplankton die, they fall to the sea floor, and the carbon they contain becomes trapped in the sediment. If the rate of growth and reproduction of these organisms could be increased, more carbon dioxide would be used by them before it could escape from the ocean into the air. The late John Martin of the Moss Landing Marine Laboratories in California suggested a way of making this happen.

It has been known since the 1980s that large stretches of the world's ocean surface receive plenty of sunlight and possess an abundance of the major nutrients and yet contain fairly low levels of phytoplankton. One possible explanation for this low level of growth was that the level of some trace nutrient in the water was low. This nutrient would be acting as a limiting reactant in chemical changes necessary for the growth and reproduction of organisms.

Dr. Martin hypothesized that the limiting factor was iron. Iron is necessary for a number of crucial functions of phytoplankton, including the production of chlorophyll. He suggested that an increase in the iron concentration of the ocean would stimulate phytoplankton growth, and that more carbon dioxide would be drawn from the atmosphere to fuel that growth. In a 1988 seminar at Woods Hole Oceanographic Institution, Dr. Martin ventured a bold statement: "Give me a tankerload of iron, and I'll give you an ice age."

The first tests done in the laboratory had positive

results, but the conditions in the laboratory could not fully duplicate the conditions in the ocean. Dr. Martin's next bold suggestion was to do a large scale test in the ocean itself. Due to the difficulty of controlling conditions in the real world, ocean tests on the scale he suggested had never been done.

Sadly, Dr. Martin did not live long enough to see the results of the ocean experiments that have now been done. Two of these experiments were conducted in the Pacific Ocean about 300 miles south and 800 miles west of the Galapagos Islands. In October of 1993, about 450 kg of iron(II) sulfate was spread over about 64 square kilometers of ocean, and the chemistry and biology of the area were monitored for nine days. The rate of phytoplankton growth increased significantly, and the levels of CO_2 in the water decreased. These results confirmed Dr. Martin's main hypothesis, that iron was a limiting factor in the growth and reproduction of phytoplankton. Unfortunately, the CO_2 concentration leveled off after only one day at about 10% of the expected drop. A second test in 1995 led to 20 times the normal abundance of phytoplankton and a significant drop in CO_2 levels in the ocean, but as soon as the iron was gone, the levels returned to normal.

Because the decrease in CO_2 in the water was less than expected and because the increase in phytoplankton growth requires a constant addition of iron, it seems unlikely now that fertilizing the oceans with iron is going to solve the problem of global warming. This is disappointing, but it should not surprise us that a problem this big cannot be reversed by a single solution. The fact that fertilizing the oceans with iron did stimulate the phytoplankton growth to a marked degree encourages others to seek similarly bold solutions without being discouraged by the magnitude of the task.

Phytoplankton blooms in the southern Persian Gulf.

10.3 Molarity and Equation Stoichiometry

The general steps we have been following in setting up equation stoichiometry calculations can be summarized as follows.

Measurable property 1 ⟹ moles 1 ⟹ moles 2 ⟹ Measurable property 2
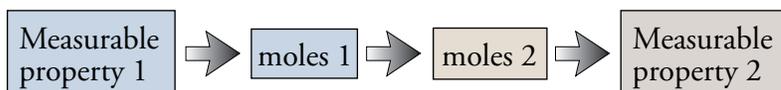
For pure liquids and solids, as we have seen, the most convenient measurable property is mass. It is very easy to measure the mass of a pure solid or liquid, and we can convert between that and the number of particles it represents using the molar mass as a conversion factor.

mass 1 ⟹ moles 1 ⟹ moles 2 ⟹ mass 2

Although these steps describe many important calculations, their usefulness is

limited by the fact that many reactions are run in the gas phase or in solution, where the determination of a reactant's mass or product's mass is more difficult. Equation stoichiometry involving gases is described in Chapter 13. This section shows how we can do equation stoichiometry problems for reactions run in solution.

Reactions in Solution and Molarity

To see why many reactions are run in solution and why we need a new component for our equation stoichiometry problems, let's assume that we want to make silver phosphate, Ag_3PO_4, a substance used in photographic emulsions and to produce pharmaceuticals. It is made by reacting silver nitrate, $AgNO_3$, and sodium phosphate, Na_3PO_4. Both of these substances are solids at room temperature. If the solids are mixed, no reaction takes place.

$$AgNO_3(s) + Na_3PO_4(s) \quad \text{No reaction}$$

In the solid form, the Ag^+ ions are still tightly bound to the NO_3^- ions, and the PO_4^{3-} ions are still linked to the Na^+ ions, so the Ag^+ ions and PO_4^{3-} ions are not able to move together and form silver phosphate.

For the reaction between $AgNO_3$ and Na_3PO_4 to proceed, the two reactants must first be dissolved in water. In solution, the Ag^+ ions are separate from the NO_3^- ions, and the PO_4^{3-} ions are separate from the Na^+ ions. All of these ions move freely throughout the liquid. This allows the Ag^+ and PO_4^{3-} ions to find each other in solution and combine to precipitate from the solution as Ag_3PO_4.

These two substances, silver nitrate and sodium phosphate, will not react in solid form (top). They must first be dissolved in water (bottom).

$$3AgNO_3(aq) + Na_3PO_4(aq) \quad \rightarrow \quad Ag_3PO_4(s) + 3NaNO_3(aq)$$
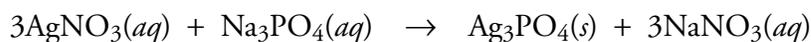
When two solutions are mixed to start a reaction, it is more convenient to measure their volumes than their masses. Therefore, in equation stoichiometry problems for such reactions, it is common for the chemist to want to convert back and forth between volume of solution and moles of the reacting substance in the solution. For example, you might be asked to calculate the volume of an $AgNO_3$ solution that must be added to 25.00 mL of a solution of Na_3PO_4 to precipitate all of the phosphate as Ag_3PO_4. Because we want to convert from amount of one substance in a given chemical reaction to amount of another substance participating in the same reaction, we recognize this as an equation stoichiometry problem. Thus we know that in the center of our conversion, we will convert from moles of Na_3PO_4 to moles of $AgNO_3$. The steps in our calculation will be

mL Na_3PO_4 soln $\Rightarrow$ mol Na_3PO_4 $\Rightarrow$ mol $AgNO_3$ $\Rightarrow$ mL $AgNO_3$ soln

The general steps for similar calculations will be

volume 1 solution $\Rightarrow$ mol 1 $\Rightarrow$ mol 2 $\Rightarrow$ volume 2 solution

Therefore, we need conversion factors that convert back and forth between volumes of solutions and moles of solute in those solutions. **Molarity** (abbreviated M), which is defined as moles of solute per liter of solution, provides such conversion factors.

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

For example, you might be told that a solution is 0.500 M Na_3PO_4. (You read this as "0.500 molar Na_3PO_4" or "0.500 molar sodium phosphate.") This means that there are 0.500 moles of Ag_3PO_4 in one liter of this solution. Because 1 liter is 10^3 milliliters, two useful conversion factors can be derived from the molarity of Ag_3PO_4:

$$0.500 \text{ M } Ag_3PO_4 \text{ means } \frac{0.500 \text{ mol } Ag_3PO_4}{1 \text{ L } Ag_3PO_4 \text{ solution}} \text{ or } \frac{0.500 \text{ mol } Ag_3PO_4}{10^3 \text{ mL } Ag_3PO_4 \text{ solution}}$$

Example 10.5 shows how to use unit analysis to determine the molarity of a solution.

EXAMPLE 10.5 - Calculating a Solution's Molarity

OBJECTIVE 10

A solution was made by dissolving 8.20 g of sodium phosphate in water and then diluting the mixture with water to achieve a total volume of 100.0 mL. What is the solution's molarity?

Solution

Because the answer we want, molarity, is a ratio of two units (moles of solute—in this case, Na_3PO_4—per liter of solution), we start our unit analysis setup with a ratio of two units. Because we want amount of Na_3PO_4 on the top when we are done, we start with 8.20 g Na_3PO_4 on the top. Because we want volume of solution on the bottom when we are done, we start with 100.0 mL of solution on the bottom. To convert mass of Na_3PO_4 to moles of Na_3PO_4, we use the molar mass of Na_3PO_4. We finish our conversion with a conversion factor that converts milliliters to liters.

Molarity expressed with more specific units

Given amount of solute

Converts mass to moles

Converts the given volume unit into the desired volume unit

$$? \text{ M } Na_3PO_4 = \frac{? \text{ mol } Na_3PO_4}{1 \text{ L } Na_3PO_4 \text{ soln}} = \frac{8.20 \text{ g } Na_3PO_4}{100 \text{ mL } Na_3PO_4 \text{ soln}} \left(\frac{1 \text{ mol } Na_3PO_4}{163.9408 \text{ g } Na_3PO_4} \right) \left(\frac{10^3 \text{ mL}}{1 \text{ L}} \right)$$

Given amount of solution

$$= \frac{0.500 \text{ mol } Na_3PO_4}{1 \text{ L } Na_3PO_4 \text{ soln}} = 0.500 \text{ M } Na_3PO_4$$

## EXERCISE 10.4 - Calculating a Solution's Molarity

OBJECTIVE 10

A silver perchlorate solution was made by dissolving 29.993 g of pure $AgClO_4$ in water and then diluting the mixture with additional water to achieve a total volume of 50.00 mL. What is the solution's molarity?

Equation Stoichiometry and Reactions in Solution

Conversion factors constructed from molarities can be used in stoichiometric calculations in very much the same way conversion factors from molar mass are used. When a substance is pure, its molar mass can be used to convert back and forth between the measurable property of mass and moles. When a substance is in solution, its molarity can be used to convert between the measurable property of volume of solution and moles of solute.

$$\boxed{\text{Measurable property}} \rightleftharpoons \boxed{\text{Moles}}$$

$$\boxed{\text{Mass}} \rightleftharpoons \boxed{\text{Moles of pure substance}}$$

$$\boxed{\text{Volume of solution}} \rightleftharpoons \boxed{\text{Moles of solute}}$$
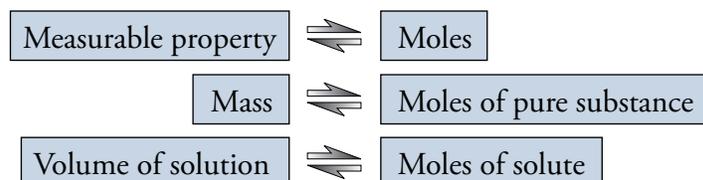
To see how molarity can be used in equation stoichiometry problems, let's take a look at the thought process for calculating the number of milliliters of 1.00 M $AgNO_3$ necessary to precipitate the phosphate from 25.00 mL of 0.500 M Na_3PO_4. The problem asks us to convert from amount of one substance in a chemical reaction to amount of another substance in the reaction, so we know it is an equation stoichiometry problem. The core of our setup will be the conversion factor for changing moles of sodium phosphate to moles of silver nitrate. To construct it, we need to know the molar ratio of $AgNO_3$ to Na_3PO_4, which comes from the balanced equation for the reaction.

$$3AgNO_3(aq) + Na_3PO_4(aq) \rightarrow Ag_3PO_4(s) + 3NaNO_3(aq)$$
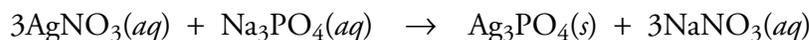
The balanced equation tells us that three formula units of $AgNO_3$ are required for each formula unit of Na_3PO_4, or three moles of $AgNO_3$ for each mole of Na_3PO_4.

Our general steps will be

$$\boxed{\text{mL } Na_3PO_4 \text{ soln}} \Rightarrow \boxed{\text{mol } Na_3PO_4} \Rightarrow \boxed{\text{mol } AgNO_3} \Rightarrow \boxed{\text{mL } AgNO_3 \text{ soln}}$$

We start our unit analysis setup in the usual way, setting what we want to know (the milliliters of silver nitrate solution) equal to one of the values we are given. Because we want a single unit in our final answer, we set milliliters of $AgNO_3$ solution equal to the only given value that has a single unit: 25.00 mL Na_3PO_4 solution. (1.00 M $AgNO_3$ and 0.500 M Na_3PO_4 may look like they have single units, but remember that molarity is actually a ratio of two units: moles and liters.)

$$? \text{ mL } AgNO_3 \text{ soln} = 25.00 \text{ mL } Na_3PO_4 \text{ soln} \left(\frac{}{} \right)$$

We need to convert from volume of Na_3PO_4 solution to moles of Na_3PO_4. The molarity of sodium phosphate provides two possible conversion factors for this conversion.

0.500 M Na_3PO_4 means

$$\left(\frac{0.500 \text{ mol } Na_3PO_4}{1 \text{ L } Na_3PO_4 \text{ soln}} \right) \quad \text{or} \quad \left(\frac{0.500 \text{ mol } Na_3PO_4}{10^3 \text{ mL } Na_3PO_4 \text{ soln}} \right)$$

These two conversion factors provide two ways to convert from milliliters of Na_3PO_4 solution to moles of Na_3PO_4.

$$? \text{ mL AgNO}_3 \text{ soln} = 25.00 \text{ mL Na}_3\text{PO}_4 \text{ soln} \left(\frac{1 \text{ L}}{10^3 \text{ mL}} \right) \left(\frac{0.500 \text{ mol Na}_3\text{PO}_4}{1 \text{ L Na}_3\text{PO}_4 \text{ soln}} \right)$$

$$? \text{ mL AgNO}_3 \text{ soln} = 25.00 \text{ mL Na}_3\text{PO}_4 \text{ soln} \left(\frac{0.500 \text{ mol Na}_3\text{PO}_4}{10^3 \text{ mL Na}_3\text{PO}_4 \text{ soln}} \right)$$

The second setup requires one less conversion factor than the first setup, so we will use it. We can now use the molar ratio to convert from moles of Na_3PO_4 to moles of $AgNO_3$.

$$? \text{ mL AgNO}_3 \text{ soln} = 25.00 \text{ mL Na}_3\text{PO}_4 \text{ soln} \left(\frac{0.500 \text{ mol Na}_3\text{PO}_4}{10^3 \text{ mL Na}_3\text{PO}_4 \text{ soln}} \right) \left(\frac{3 \text{ mol AgNO}_3}{1 \text{ mol Na}_3\text{PO}_4} \right)$$

We complete the problem by using the molarity of $AgNO_3$ to convert from moles of $AgNO_3$ to volume of $AgNO_3$ solution. The value 1.00 M $AgNO_3$ provides us with two possible conversion factors. Like any conversion factors, they can be used in the form you see here or inverted.

$$\left(\frac{1.00 \text{ mol AgNO}_3}{1 \text{ L AgNO}_3 \text{ soln}} \right) \quad \text{or} \quad \left(\frac{1.00 \text{ mol AgNO}_3}{10^3 \text{ mL AgNO}_3 \text{ soln}} \right)$$

The two possible setups for the problem are below.

Coefficients from balanced equation convert moles of one substance into moles of another substance.

$$? \text{ mL AgNO}_3 \text{ soln} =$$

$$25.00 \text{ mL Na}_3\text{PO}_4 \text{ soln} \left(\frac{0.500 \text{ mol Na}_3\text{PO}_4}{10^3 \text{ mL Na}_3\text{PO}_4 \text{ soln}} \right) \left(\frac{3 \text{ mol AgNO}_3}{1 \text{ mol Na}_3\text{PO}_4} \right) \left(\frac{10^3 \text{ mL AgNO}_3 \text{ soln}}{1.00 \text{ mol AgNO}_3} \right)$$

$$= 37.5 \text{ mL AgNO}_3 \text{ soln}$$

Molarity as a conversion factor converts milliliters into moles.

Molarity as a conversion factor converts moles into milliliters.

or

Coefficients from balanced equation convert moles of one substance into moles of another substance.

Converts given unit into liters.

Converts liters into desired unit.

$$? \text{ mL AgNO}_3 \text{ soln}$$

$$= 25.00 \text{ mL Na}_3\text{PO}_4 \text{ soln} \left(\frac{1 \text{ L}}{10^3 \text{ mL}} \right) \left(\frac{0.500 \text{ mol Na}_3\text{PO}_4}{1 \text{ L Na}_3\text{PO}_4 \text{ soln}} \right) \left(\frac{3 \text{ mol AgNO}_3}{1 \text{ mol Na}_3\text{PO}_4} \right) \left(\frac{1 \text{ L AgNO}_3 \text{ soln}}{1.00 \text{ mol AgNO}_3} \right) \left(\frac{10^3 \text{ mL}}{1 \text{ L}} \right)$$

$$= 37.5 \text{ mL AgNO}_3 \text{ soln}$$

Molarity as a conversion factor converts liters into moles.

Molarity as a conversion factor converts moles into liters.

Example 10.6 shows a very similar example.

EXAMPLE 10.6 - Molarity and Equation Stoichiometry

How many milliliters of 2.00 M sodium hydroxide are necessary to neutralize 25.00 mL of 1.50 M phosphoric acid?

Solution

Because we are asked to convert from the amount of one substance in a chemical reaction to amount of another substance in the reaction, we recognize the problem as an equation stoichiometry problem. Our general steps are

$$\boxed{\text{mL } H_3PO_4 \text{ soln}} \Rightarrow \boxed{\text{mol } H_3PO_4} \Rightarrow \boxed{\text{mol NaOH}} \Rightarrow \boxed{\text{mL NaOH soln}}$$

The molarity of phosphoric acid provides the conversion factor that converts from volume of H_3PO_4 solution to moles of H_3PO_4, and the molarity of sodium hydroxide provides the conversion factor that converts from moles of NaOH to volume of NaOH solution. The conversion from moles of H_3PO_4 to moles of NaOH is made with the molar ratio that comes from the coefficients in the balanced equation for the reaction.

$$3NaOH(aq) + H_3PO_4(aq) \rightarrow Na_3PO_4(aq) + 3H_2O(l)$$
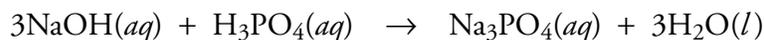
The two possible setups for the problem are below.

$$? \text{ mL NaOH soln} =$$

$$25.00 \text{ mL } H_3PO_4 \text{ soln} \left(\frac{1.50 \text{ mol } H_3PO_4}{10^3 \text{ mL } H_3PO_4 \text{ soln}} \right) \left(\frac{3 \text{ mol NaOH}}{1 \text{ mol } H_3PO_4} \right) \left(\frac{10^3 \text{ mL NaOH soln}}{2.00 \text{ mol NaOH}} \right)$$

or

$$? \text{ mL NaOH soln} =$$

$$25.00 \text{ mL } H_3PO_4 \text{ soln} \left(\frac{1 \text{ L}}{10^3 \text{ mL}} \right) \left(\frac{1.50 \text{ mol } H_3PO_4}{1 \text{ L } H_3PO_4 \text{ soln}} \right) \left(\frac{3 \text{ mol NaOH}}{1 \text{ mol } H_3PO_4} \right) \left(\frac{1 \text{ L NaOH soln}}{2.00 \text{ mol NaOH}} \right) \left(\frac{10^3 \text{ mL}}{1 \text{ L}} \right)$$

$$= \textbf{56.3 mL NaOH soln}$$

Molar mass conversions and molarity conversions can be combined to solve equation stoichiometry problems, as we see in Example 10.7.

EXAMPLE 10.7 - Molarity and Equation Stoichiometry

What volume of 6.00 M HCl is necessary to neutralize and dissolve 31.564 g of solid aluminum hydroxide?

Solution

Our steps for this equation stoichiometry problem are

$$\boxed{\text{mass Al(OH)}_3} \Rightarrow \boxed{\text{mol Al(OH)}_3} \Rightarrow \boxed{\text{mol HCl}} \Rightarrow \boxed{\text{mL HCl soln}}$$

The unit analysis setup is built around a mole to mole conversion factor

created from the coefficients in the balanced equation. The reaction is a neutralization reaction, so you can use the skills you developed in Chapter 5 to write the balanced equation.

$$3HCl(aq) + Al(OH)_3(s) \rightarrow 3H_2O(l) + AlCl_3(aq)$$
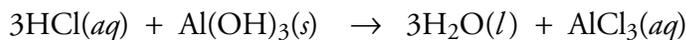
We use molar mass to convert mass of $Al(OH)_3$ to moles of $Al(OH)_3$, and we use molarity to convert moles of HCl to volume of HCl solution.

? mL HCl soln =

$$31.564 \text{ g Al(OH)}_3 \left(\frac{1 \text{ mol Al(OH)}_3}{78.0036 \text{ g Al(OH)}_3} \right)\left(\frac{3 \text{ mol HCl}}{1 \text{ mol Al(OH)}_3} \right)\left(\frac{10^3 \text{ mL HCl soln}}{6.00 \text{ mol HCl}} \right)$$

= 202 mL HCl soln

The following is a general study sheet for the types of equation stoichiometry problems that we have considered in this chapter.

TIP-OFF   You are asked to convert from amount of one substance in a chemical reaction to amount of another substance in the reaction.

GENERAL STEPS   Use the unit analysis format to make the following conversions. (Figure 10.4 summarizes these steps.)

1. If you are not given it, write and balance the chemical equation for the reaction.

2. Start your unit analysis in the usual way, setting the desired units of substance 2 equal to the given units of substance 1.

3. Convert from the units that you are given for substance 1 to moles of substance 1.

   ■ For pure solids and liquids, this means converting grams to moles using the molar mass of the substance. (It might be necessary to insert one or more additional conversion factors to convert from the given mass unit to grams.)

   ■ Molarity can be used to convert from volume of solution to moles of solute. (It might be necessary to insert one or more additional conversion factors to convert from the given volume unit to liters or milliliters.)

4. Convert from moles of substance 1 to moles of substance 2 using the coefficients from the balanced equation.

5. Convert from moles of substance 2 to the desired units for substance 2.

   ■ For pure solids and liquids, this means converting moles to mass using the molar mass of substance 2.

   ■ Molarity can be used to convert from moles of solute to volume of solution.

6. Calculate your answer and report it with the correct significant figures (in scientific notation, if necessary) and with the correct unit.

EXAMPLE   See Examples 10.6 and 10.7.

Sample Study Sheet 10.3

Equation Stoichiometry Problems

OBJECTIVE 13

Figure 10.4
General Steps for Equation Stoichiometry   OBJECTIVE 13

Start here when
mass of pure
substance is given.

| any mass unit 1 |

$$\left(\frac{\text{--- g}}{\text{--- (any mass unit)}} \right)$$

(grams 1)

$$\left(\frac{\text{1 mol 1}}{\text{(formula mass) g 1}} \right)$$

⟨ moles 1 ⟩

$$\frac{\text{(coef. 2) mol 2}}{\text{(coef. 1) mol 1}}$$

This is the core
of any equation
stoichiometry
problem.

$$\left(\frac{\text{(number from molarity) mol 1}}{\text{1 L (or } 10^3 \text{ mL) soln 1}} \right)$$

((L or mL) of solution 1)

$$\left(\frac{\text{--- (L or mL)}}{\text{--- (any volume unit)}} \right)$$

| any volume unit of solution 1 |
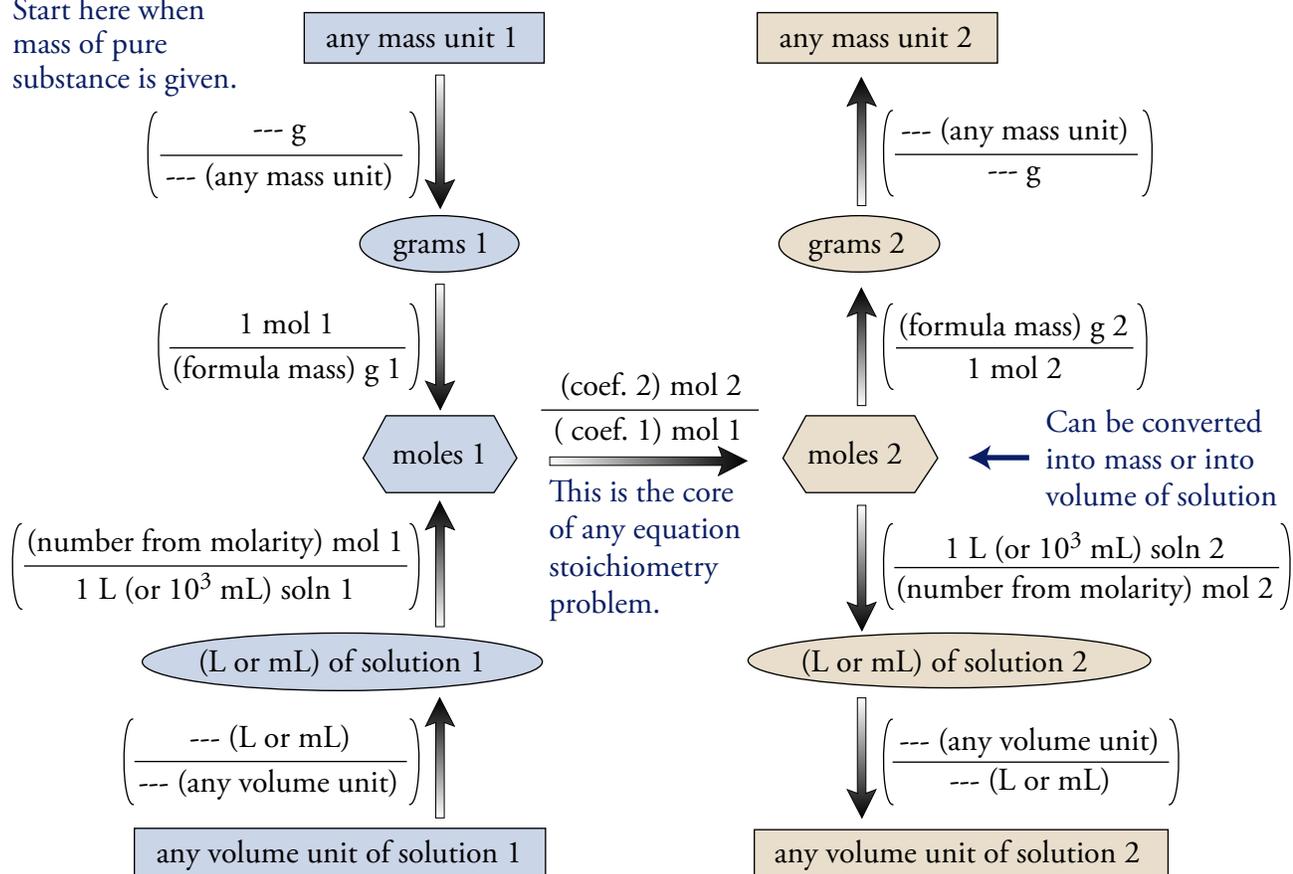
Start here when volume of solution is given.

| any mass unit 2 |

$$\left(\frac{\text{--- (any mass unit)}}{\text{--- g}} \right)$$

(grams 2)

$$\left(\frac{\text{(formula mass) g 2}}{\text{1 mol 2}} \right)$$

⟨ moles 2 ⟩

Can be converted
into mass or into
volume of solution

$$\left(\frac{\text{1 L (or } 10^3 \text{ mL) soln 2}}{\text{(number from molarity) mol 2}} \right)$$

((L or mL) of solution 2)

$$\left(\frac{\text{--- (any volume unit)}}{\text{--- (L or mL)}} \right)$$

| any volume unit of solution 2 |

EXERCISE 10.5 - Molarity and Equation Stoichiometry

OBJECTIVE 13

How many milliliters of 6.00 M HNO_3 are necessary to neutralize the carbonate in 75.0 mL of 0.250 M Na_2CO_3?

EXERCISE 10.6 - Molarity and Equation Stoichiometry

OBJECTIVE 13

What is the maximum number of grams of silver chloride that will precipitate from a solution made by mixing 25.00 mL of 0.050 M $MgCl_2$ with an excess of $AgNO_3$ solution?

You can see a description of a procedure called titration that can be used to determine the molarities of acidic and basic solutions at the textbook's Web site.

Equation stoichiometry   Calculations that make use of the quantitative relationships between the substances in a chemical reaction to convert the amount of one substance in the chemical reaction to the amount of a different substance in the reaction.

Limiting reactant   The reactant that runs out first and limits the amount of product that can form.

Theoretical yield   The calculated maximum amount of product that can form in a chemical reaction.

Actual yield   The amount of product that is actually obtained in a chemical reaction.

Percent yield   The actual yield divided by the theoretical yield times 100.

Molarity (abbreviated M)   Moles of solute per liter of solution.

> **You can test yourself on the glossary terms at the textbook's Web site.**

The goal of this chapter is to teach you to do the following.

1. Define all of the terms in the Chapter Glossary.

Section 10.1 Equation Stoichiometry

2. Given a balanced chemical equation (or enough information to write one), construct conversion factors that relate moles of any two reactants or products in the reaction.
3. Given a balanced chemical equation (or enough information to write one), convert from moles of one reactant or product to moles of any other reactant or product.
4. Given a balanced chemical equation (or enough information to write one), convert from mass of one reactant or product to mass of any other reactant or product.

Section 10.2 Real-World Applications and Equation Stoichiometry

5. Describe four reasons for adding an excess of one or more of the reactants in a chemical reaction.
6. Given the masses of two or more reactants, calculate the maximum mass of product that could form from the reaction between them.
7. Given a description of a specific chemical reaction, explain why a chemist might decide to add one of the reactants (rather than the others) in excess.
8. Describe four reasons why the actual yield in a chemical reaction is less than the theoretical yield.
9. Given an actual yield and a theoretical yield (or enough information to calculate a theoretical yield) for a chemical reaction, calculate the percent yield for the reaction.

Section 10.3 Molarity and Equation Stoichiometry

10. Given the mass of substance dissolved in a solution and the total volume of the solution, calculate the molarity of the solution.
11. Given the molarity of a substance, write a conversion factor that relates the moles of substance to liters of solution and a conversion factor that relates the moles of solute to milliliters of solution.

12. Use molarity to convert between moles of solute and volume of solution.
13. Convert between amount of one substance in a chemical reaction and amount of another substance in the reaction, when the amounts of the substances are described by either of the following:
    a. Mass of pure substance
    b. Volume of a solution that contains one of the substances along with the molarity of the solution

Review Questions

This chapter requires many of the same skills that were listed as review skills for Chapter 9. Thus you should make sure that you can do the Review Questions at the end of Chapter 9 before continuing with the questions that follow.

1. Write balanced equations for the following reactions. You do not need to include the substances' states.
   a. Hydrofluoric acid reacts with silicon dioxide to form silicon tetrafluoride and water.
   b. Ammonia reacts with oxygen gas to form nitrogen monoxide and water.
   c. Water solutions of nickel(II) acetate and sodium phosphate react to form solid nickel(II) phosphate and aqueous sodium acetate.
   d. Phosphoric acid reacts with potassium hydroxide to form water and potassium phosphate.

2. Write complete equations, including states, for the precipitation reaction that takes place between the reactants in part (a) and the neutralization reaction that takes place in part (b).
   a. $Ca(NO_3)_2(aq) + Na_2CO_3(aq) \rightarrow$
   b. $HNO_3(aq) + Al(OH)_3(s) \rightarrow$

3. How many moles of phosphorous acid, H_3PO_3, are there in 68.785 g of phosphorous acid?

4. What is the mass in kilograms of 0.8459 mole of sodium sulfate?

Key Ideas

Complete the following statements by writing one of these words or phrases in each blank.

100%	remaining
actual	reversible
amount of product	runs out first
balanced chemical equation	separated
costly	side reactions
easy to separate	slow
excess	solute
less	solution
loss	stoichiometric
mass	stoichiometry
molar mass	two or more amounts
optimize	volume of solution
remain	volumes

5. If a calculation calls for you to convert from an amount of one substance in a given chemical reaction to the corresponding amount of another substance participating in the same reaction, it is an equation _____ problem.

6. The coefficients in a(n) _____ provide us with information that we can use to build conversion factors that convert from an amount of one substance in a given chemical reaction to the corresponding amount of another substance participating in the same reaction.

7. For some chemical reactions, chemists want to mix reactants in amounts that are as close as possible to the ratio that would lead to the complete reaction of each. This ratio is sometimes called the _____ ratio.

8. A(n) _____ of one or more of the reactants will increase the likelihood that the other reactant or reactants will be used up. Thus, if one reactant is more expensive than the others, adding an excess of the _____ expensive reactants will ensure the greatest conversion possible of the one that is

_____.

9. Sometimes one product is more important than others are, and the amounts of reactants are chosen to _____ its production.

10. Any component added in excess will _____ when the reaction is complete. If one reactant is more dangerous to handle than others are, chemists would rather not have that reactant _____ at the reaction's end.

11. Because some of the reactant that was added in excess is likely to be mixed with the product, chemists would prefer that the substance in excess be a substance that is _____ from the primary product.

12. The reactant that _____ in a chemical reaction limits the amount of product that can form. This reactant is called the limiting reactant.

13. The tip-off for limiting reactant problems is that you are given _____ of reactants in a chemical reaction, and you are asked to calculate the maximum _____ that they can form.

14. The theoretical yield is the maximum amount of product that could be formed from the given amounts of reactants. This is the amount of product that could be obtained if _____ of the limiting reactant were converted to product and if this product could be isolated from the other components in the product mixture without any _____. The efficiency of a reaction can be evaluated by calculating the percent yield, the ratio of the _____ yield to the theoretical yield expressed as a percentage.

15. There are many reasons why the actual yield in a reaction might be less than the theoretical yield. One key reason is that many chemical reactions are significantly

_____.

16. A reaction's yield is also affected by the occurrence of _____.

17. Another factor that affects the actual yield is a reaction's rate. Sometimes a reaction is so _____ that it has not reached the maximum yield by the time the product is isolated.

18. Even if 100% of the limiting reactant proceeds to products, usually the product still needs to be _____ from the other components in the product mixture (excess reactants, products of side reactions, and other impurities). This process generally leads to some loss of product.

19. When two solutions are mixed to start a reaction, it is more convenient to measure their _____ than their masses.

20. Molarity (abbreviated M) is defined as moles of _____ per liter of _____ _____.

21. Conversion factors constructed from molarities can be used in stoichiometric calculations in very much the same way conversion factors from _____ are used. When a substance is pure, its molar mass can be used to convert back and forth between the measurable property of _____ and moles. When a substance is in solution, its molarity can be used to convert between the measurable property of _____ and moles of solute.

Chapter Problems

Section 10.1 Equation Stoichiometry

Section 10.2 Real-World Applications of Equation Stoichiometry

OBJECTIVE 2
OBJECTIVE 3

22. Because the bond between fluorine atoms in F_2 is relatively weak while the bonds between fluorine atoms and atoms of other elements are relatively strong, it is difficult to make diatomic fluorine, F_2. One way it can be made is to run an electric current through liquid hydrogen fluoride, HF. This reaction yields hydrogen gas, H_2, and fluorine gas, F_2.

  a. Write a complete balanced equation, including states, for this reaction.
  b. Draw a picture of the reaction, using rough sketches of space-filling models in place of the coefficients and formulas in the equation. Fluorine atoms have a little more than twice the diameter of hydrogen atoms.
  c. Write a conversion factor that could be used to convert between moles of HF and moles of F_2.
  d. How many moles of F_2 form when one mole of HF reacts completely?
  e. How many moles of HF react to yield 3.452 moles of H_2?

OBJECTIVE 2
OBJECTIVE 3

23. Hydrogen gas is used for many purposes, including the hydrogenation of vegetable oils to make margarine. The most common industrial process for producing hydrogen is "steam reforming," in which methane gas, CH_4, from natural gas reacts with water vapor to form carbon monoxide gas and hydrogen gas.

  a. Write a complete balanced equation, including states, for this reaction.
  b. Draw a picture of the reaction, using rough sketches of space-filling models in place of the coefficients and formulas in the equation. Draw the carbon atoms a little larger than the oxygen atoms. Both carbon and oxygen atoms have over twice the diameter of hydrogen atoms.
  c. Write a conversion factor that could be used to convert between moles of methane and moles of hydrogen.
  d. How many moles of hydrogen form when 4 moles of methane react completely?
  e. How many moles of water vapor react to yield 174.82 moles of hydrogen?

24. The bond between nitrogen atoms in N_2 molecules is very strong, making N_2 very unreactive. Because of this, magnesium is one of the few metals that react with nitrogen gas directly. This reaction yields solid magnesium nitride.

   a. Write a complete balanced equation, without including states, for the reaction between magnesium and nitrogen to form magnesium nitride.

   b. Write a conversion factor that could be used to convert between moles of magnesium and moles of magnesium nitride.

   c. How many moles of magnesium nitride form when 1.0 mole of magnesium reacts completely?

   d. Write a conversion factor that could be used to convert between moles of nitrogen and moles of magnesium nitride.

   e. How many moles of nitrogen react to yield 3.452 moles of magnesium nitride?

25. Fluorine gas is an important chemical because it is used to add fluorine atoms to many different compounds. As mentioned in Problem 22, it is difficult to make, but the following two-step process produces fairly high yields of F_2.

$$2KMnO_4 + 2KF + 10HF + 3H_2O_2 \rightarrow 2K_2MnF_6 + 8H_2O + 3O_2$$

$$2K_2MnF_6 + 4SbF_5 \rightarrow 4KSbF_6 + 2MnF_3 + F_2$$
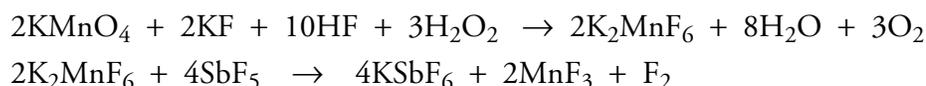
For the second of these two reactions:

   a. Write a conversion factor that could be used to convert between moles of antimony pentafluoride, SbF_5, and moles of fluorine, F_2.

   b. How many moles of F_2 form when 8 moles of SbF_5 react completely?

   c. What is the maximum number of moles of F_2 that could form in the combination of 2.00 moles of K_2MnF_6 and 5.00 moles of SbF_5?

   d. What is the maximum number of moles of F_2 that could form in the combination of 2 moles of K_2MnF_6 and 5000 moles of SbF_5?

   e. Write a conversion factor that could be used to convert between moles of manganese(III) fluoride, MnF_3, and moles of F_2.

   f. How many moles of F_2 form along with 0.802 mole of MnF_3?

26. For many years, it was thought that no reaction could produce sodium perbromate, but the discovery of a reaction producing the equally elusive xenon difluoride, XeF_2, led to the discovery of the following reaction that yields sodium perbromate.

$$NaBrO_3 + XeF_2 + H_2O \rightarrow NaBrO_4 + 2HF + Xe$$
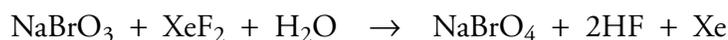
   a. Write a conversion factor that could be used to convert between moles of xenon difluoride, XeF_2, and moles of hydrogen fluoride, HF.

   b. How many moles of XeF_2 are necessary to form 16 moles of hydrogen fluoride?

   c. What is the maximum number of moles of $NaBrO_4$ that could form in the combination of 2 moles of $NaBrO_3$ and 3 moles of XeF_2?

   d. What is the maximum number of moles of $NaBrO_4$ that could form in the combination of 2 moles of $NaBrO_3$ and 3 million moles of XeF_2?

   e. Write a conversion factor that could be used to convert between moles of sodium perbromate, $NaBrO_4$, and moles of hydrogen fluoride, HF.

   f. How many moles of HF form along with 5.822 moles of sodium perbromate, $NaBrO_4$?

OBJECTIVE 2
OBJECTIVE 3

27. The thiocyanate polyatomic ion, SCN^-, is commonly called a pseudohalogen because it acts very much like halide ions. For example, we know that the pure halogens consist of diatomic molecules, such as Cl_2. Thiocyanate ions form similar molecules in the following reaction:

$$2NaSCN + 2H_2SO_4 + MnO_2 \rightarrow (SCN)_2 + 2H_2O + MnSO_4 + Na_2SO_4$$
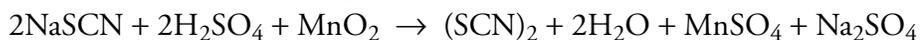
a. Write a conversion factor that could be used to convert between moles of NaSCN and moles of $(SCN)_2$.

b. How many moles of $(SCN)_2$ form when 0.50 moles of NaSCN react completely?

c. What is the maximum number of moles of $(SCN)_2$ that could form in the combination of 4 moles of NaSCN and 3 moles of MnO_2?

d. Write a conversion factor that could be used to convert between moles of sulfuric acid, H_2SO_4, and moles of manganese(II) sulfate, $MnSO_4$.

e. What is the minimum number of moles of H_2SO_4 that must react to form 1.7752 moles of manganese(II) sulfate?

OBJECTIVE 2
OBJECTIVE 3

28. In Chapter 3, you were told that halogen atoms generally form a single covalent bond, but there are many compounds in which halogen atoms form more than one bond. For example, bromine pentafluoride (used as an oxidizing agent in rocket propellants) has bromine atoms with five covalent bonds. Liquid bromine pentafluoride is the only product in the reaction of gaseous bromine monofluoride with fluorine gas.

a. Write a complete balanced equation, including states, for this reaction.

b. Write a conversion factor that could be used to convert between moles of fluorine and moles of bromine pentafluoride.

c. How many moles of bromine pentafluoride form when 6 moles of fluorine react completely?

d. What is the maximum number of moles of bromine pentafluoride that could form in the combination of 8 moles of bromine monofluoride with 12 moles of fluorine?

e. Write a conversion factor that could be used to convert between moles of bromine monofluoride and moles of bromine pentafluoride.

f. How many moles of bromine monofluoride must react to yield 0.78 mole of bromine pentafluoride?

OBJECTIVE 2
OBJECTIVE 3

29. Potassium chlorate, $KClO_3$, acts as an oxidizing agent in matches, explosives, flares, and fireworks. In the equation below, it is formed from the element chlorine and potassium hydroxide.

$$3Cl_2 + 6KOH \rightarrow KClO_3 + 5KCl + 3H_2O$$

a. Write a conversion factor that could be used to convert between moles of potassium hydroxide and moles of potassium chlorate.

b. How many moles of potassium chlorate form when 2 moles of potassium hydroxide react completely?

c. What is the maximum number of moles of $KClO_3$ that could form in the combination of 6.0 moles of Cl_2 with 9.0 moles of KOH?

d. Write a conversion factor that could be used to convert between moles of chlorine and moles of potassium chloride.

e. How many moles of chlorine react when 2.006 moles of potassium chloride form?

30. Potassium perchlorate, $KClO_4$, is a better oxidizing agent than the potassium chlorate, $KClO_3$, described in the previous problem. Potassium perchlorate, which is used in explosives, fireworks, flares, and solid rocket propellants, is made by carefully heating potassium chlorate to between 400 °C and 500 °C. The unbalanced equation for this reaction is

$$KClO_3 \rightarrow KClO_4 + KCl$$

  a. Balance this equation.
  b. Write a conversion factor that could be used to convert between moles of potassium chlorate and moles of potassium perchlorate.
  c. How many moles of potassium perchlorate form from the complete reaction of 12 moles of potassium chlorate?
  d. Write a conversion factor that could be used to convert between moles of potassium perchlorate and moles of potassium chloride.
  e. How many moles of potassium chloride form along with 11.875 moles of potassium perchlorate?

31. Aniline, $C_6H_5NH_2$, is used to make many different chemicals, including dyes, photographic chemicals, antioxidants, explosives, and herbicides. It can be formed from nitrobenzene, $C_6H_5NO_2$, in the following reaction with iron(II) chloride as a catalyst.

$$4C_6H_5NO_2 + 9Fe + 4H_2O \xrightarrow{FeCl_2} 4C_6H_5NH_2 + 3Fe_3O_4$$
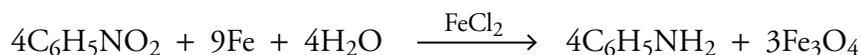
  a. Write a conversion factor that could be used to convert between moles of iron and moles of nitrobenzene.
  b. What is the minimum mass of iron that would be necessary to react completely with 810.5 g of nitrobenzene, $C_6H_5NO_2$?
  c. Write a conversion factor that could be used to convert between moles of aniline and moles of nitrobenzene.
  d. What is the maximum mass of aniline, $C_6H_5NH_2$, that can be formed from 810.5 g of nitrobenzene, $C_6H_5NO_2$, with excess iron and water?
  e. Write a conversion factor that could be used to convert between moles of Fe_3O_4 and moles of aniline.
  f. What is the mass of Fe_3O_4 formed with the amount of aniline, $C_6H_5NH_2$, calculated in part (d)?
  g. If 478.2 g of aniline, $C_6H_5NH_2$, are formed from the reaction of 810.5 g of nitrobenzene, $C_6H_5NO_2$, with excess iron and water, what is the percent yield?

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 4
OBJECTIVE 9

32. Tetraboron carbide, B_4C, is a very hard substance used for grinding purposes, ceramics, and armor plating. Because boron is an efficient absorber of neutrons, B_4C is also used as a protective material in nuclear reactors. The reaction that forms B_4C from boron(III) oxide, B_2O_3, is

$$2B_2O_3 + 7C \xrightarrow{\text{2400 °C}} B_4C + 6CO$$
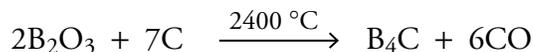
a. Write a conversion factor that could be used to convert between moles of carbon and moles of boron(III) oxide.
b. What is the minimum mass of carbon, in grams, necessary to react completely with 24.675 g of boron(III) oxide, B_2O_3?
c. Write a conversion factor that could be used to convert between moles of B_4C and moles of boron(III) oxide.
d. What is the maximum mass, in grams, of B_4C that can be formed from the reaction of 24.675 g of boron(III) oxide, B_2O_3 with an excess of carbon?
e. If 9.210 g of B_4C is isolated in the reaction of 24.675 g of boron(III) oxide, B_2O_3, with an excess of carbon, what is the percent yield?

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 4

33. Because of its red-orange color, sodium dichromate, $Na_2Cr_2O_7$, has been used in the manufacture of pigments. It can be made by reacting sodium chromate, Na_2CrO_4, with sulfuric acid. The products other than sodium dichromate are sodium sulfate and water.

a. Write a balanced equation for this reaction. (You do not need to write the states.)
b. How many kilograms of sodium chromate, Na_2CrO_4, are necessary to produce 84.72 kg of sodium dichromate, $Na_2Cr_2O_7$?
c. How many kilograms of sodium sulfate are formed with 84.72 kg of $Na_2Cr_2O_7$?

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 4
OBJECTIVE 9

34. Chromium(III) oxide, often called chromic oxide, has been used as a green paint pigment, as a catalyst in organic synthesis, as a polishing powder, and to make metallic chromium. One way to make chromium(III) oxide is by reacting sodium dichromate, $Na_2Cr_2O_7$, with ammonium chloride at 800 to 1000 °C to form chromium(III) oxide, sodium chloride, nitrogen, and water.

a. Write a balanced equation for this reaction. (You do not need to write the states.)
b. What is the minimum mass, in megagrams, of ammonium chloride necessary to react completely with 275 Mg of sodium dichromate, $Na_2Cr_2O_7$?
c. What is the maximum mass, in megagrams, of chromium(III) oxide that can be made from 275 Mg of sodium dichromate, $Na_2Cr_2O_7$, and excess ammonium chloride?
d. If 147 Mg of chromium(III) oxide is formed in the reaction of 275 Mg of sodium dichromate, $Na_2Cr_2O_7$, with excess ammonium chloride, what is the percent yield?

35. The tanning agent, $Cr(OH)SO_4$, is formed in the reaction of sodium dichromate $(Na_2Cr_2O_7)$, sulfur dioxide, and water. Tanning protects animal hides from bacterial attack, reduces swelling, and prevents the fibers from sticking together when the hides dry. This leads to a softer, more flexible leather.

$$Na_2Cr_2O_7 + 3SO_2 + H_2O \rightarrow 2Cr(OH)SO_4 + Na_2SO_4$$

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 4
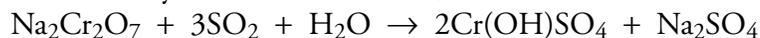
   a. How many kilograms of sodium dichromate, $Na_2Cr_2O_7$, are necessary to produce 2.50 kg of $Cr(OH)SO_4$?

   b. How many megagrams of sodium sulfate are formed with 2.50 Mg of $Cr(OH)SO_4$?

36. The mineral hausmannite, Mn_3O_4, which contains both manganese(II) and manganese(III) ions, is formed from heating manganese(IV) oxide to 890 °C.

$$3MnO_2(l) \xrightarrow{\text{800 °C}} Mn_3O_4(s) + O_2(g)$$

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 4
OBJECTIVE 9
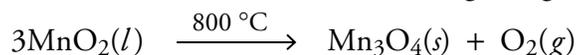
   a. What is the maximum mass, in megagrams, of Mn_3O_4 that can be formed from the decomposition of 31.85 Mg of manganese(IV) oxide, MnO_2?

   b. If 24.28 Mg of Mn_3O_4 is isolated in the decomposition reaction of 31.85 Mg of manganese(IV) oxide, MnO_2, what is the percent yield?

37. Describe four reasons for adding an excess of one or more of the reactants in a chemical reaction.

OBJECTIVE 5

38. Chromium(III) oxide can be made from the reaction of sodium dichromate and ammonium chloride. What is the maximum mass, in grams, of chromium(III) oxide that can be produced from the complete reaction of 123.5 g of sodium dichromate, $Na_2Cr_2O_7$, with 59.5 g of ammonium chloride? The other products are sodium chloride, nitrogen gas, and water.

OBJECTIVE 6

39. The equation for one process for making aluminum fluoride follows. What is the maximum mass, in grams, of aluminum fluoride, AlF_3, that can be produced from the complete reaction of 1.4×10^3 g of aluminum hydroxide, $Al(OH)_3$, with 1.0×10^3 g of H_2SiF_6?

$$2Al(OH)_3 + H_2SiF_6 \xrightarrow{\text{100 °C}} 2AlF_3 + SiO_2 + 4H_2O$$

OBJECTIVE 6
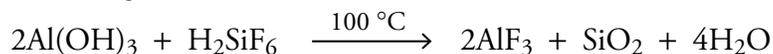
40. Tetraboron carbide, B_4C, which is used as a protective material in nuclear reactors, can be made from boric acid, H_3BO_3.

$$4H_3BO_3 + 7C \xrightarrow{\text{2400 °C}} B_4C + 6CO + 6H_2O$$

OBJECTIVE 6
OBJECTIVE 7
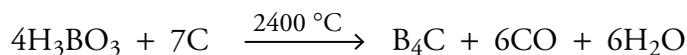
   a. What is the maximum mass, in kilograms, of B_4C formed in the reaction of 30.0 kg of carbon with 54.785 kg of H_3BO_3?

   b. Explain why one of the substances in part (a) is in excess and one is limiting.

41. Potassium permanganate, $KMnO_4$, a common oxidizing agent, is made from various ores that contain manganese(IV) oxide, MnO_2. The following equation shows the net reaction for one process that forms potassium permanganate.

$$2MnO_2 + 2KOH + O_2 \rightarrow 2KMnO_4 + H_2$$

OBJECTIVE 6
OBJECTIVE 7
OBJECTIVE 9
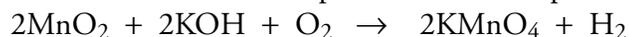
   a. What is the maximum mass, in kilograms, of $KMnO_4$ that can be made from the reaction of 835.6 g of MnO_2 with 585 g of KOH and excess oxygen gas?

   b. Explain why the oxygen gas is in excess.

   c. If 1.18 kg of $KMnO_4$ are isolated from the product mixture of the reaction of 835.6 g of MnO_2 with 585 g of KOH and excess oxygen gas, what is the percent yield?

OBJECTIVE 6
OBJECTIVE 7

42. Aniline, $C_6H_5NH_2$, which is used to make antioxidants, can be formed from nitrobenzene, $C_6H_5NO_2$, in the following reaction.

$$4C_6H_5NO_2 + 9Fe + 4H_2O \xrightarrow{\text{FeCl}_2} 4C_6H_5NH_2 + 3Fe_3O_4$$

    a. What is the maximum mass of aniline, $C_6H_5NH_2$, formed in the reaction of 810.5 g of nitrobenzene, $C_6H_5NO_2$, with 985.0 g of Fe and 250 g of H_2O?

    b. Explain why two of these substances are in excess and one is limiting.

OBJECTIVE 6
OBJECTIVE 7

43. Uranium is distributed in a form called yellow cake, which is made from uranium ore. In the second step of the reactions that form yellow cake from uranium ore, uranyl sulfate, UO_2SO_4, is converted to $(NH_4)_2U_2O_7$.

$$2UO_2SO_4 + 6NH_3 + 3H_2O \rightarrow (NH_4)_2U_2O_7 + 2(NH_4)_2SO_4$$
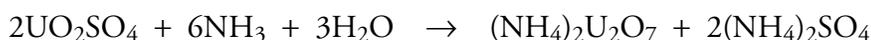
    a. What is the maximum mass, in kilograms, of $(NH_4)_2U_2O_7$ that can be formed from the reaction of 100 kg of water and 100 kg of ammonia with 481 kg of UO_2SO_4?

    b. Explain why two of these substances are in excess and one is limiting.

OBJECTIVE 6

44. Calcium carbide, CaC_2, is formed in the reaction between calcium oxide and carbon. The other product is carbon monoxide.

    a. Write a balanced equation for this reaction. (You do not need to write the states.)

    b. If you were designing the procedure for producing calcium carbide from calcium oxide and carbon, which of the reactants would you have as the limiting reactant? Why?

    c. Assuming 100% yield from the limiting reactant, what are the approximate amounts of CaO and carbon that you would combine to form 860.5 g of CaC_2?

OBJECTIVE 6

45. Calcium carbide, CaC_2, reacts with water to form acetylene, C_2H_2, and calcium hydroxide.

    a. Write a balanced equation for this reaction. (You do not need to write the states.)

    b. If you were designing the procedure for producing acetylene from calcium carbide and water, which of the reactants would you have as the limiting reactant? Why?

    c. Assuming 100% yield from the limiting reactant, what are the approximate amounts of CaC_2 and water that you would combine to form 127 g of C_2H_2?

OBJECTIVE 8

46. Give four reasons why the actual yield in a chemical reaction is less than the theoretical yield.

47. When determining the theoretical yield for a reaction, why must we first determine which reactant is the limiting reactant?

48. Does the reactant in excess affect the actual yield for a reaction? If it does, explain how.

49. Can the calculated percent yield ever be above 100%. If it can, explain how.

Section 10.3 Molarity and Equation Stoichiometry

50. What is the molarity of a solution made by dissolving 37.452 g of aluminum sulfate, $Al_2(SO_4)_3$, in water and diluting with water to 250.0 mL total?

OBJECTIVE 10

51. What is the molarity of a solution made by dissolving 18.476 g of potassium carbonate, K_2CO_3, in water and diluting with water to 100.0 mL total?

OBJECTIVE 10

52. The following equation represents the first step in the conversion of UO_3, found in uranium ore, into the uranium compounds called "yellow cake."

OBJECTIVE 11
OBJECTIVE 12
OBJECTIVE 13

$$UO_3 + H_2SO_4 \rightarrow UO_2SO_4 + H_2O$$

   a. How many milliliters of 18.0 M H_2SO_4 are necessary to react completely with 249.6 g of UO_3?

   b. What is the maximum mass, in grams, of UO_2SO_4 that forms from the complete reaction of 125 mL of 18.0 M H_2SO_4?

53. Most of the sodium chlorate, $NaClO_3$, produced in the United States is converted into chlorine dioxide, which is then used for bleaching wood pulp.

OBJECTIVE 11
OBJECTIVE 12
OBJECTIVE 13

$$NaClO_3(aq) + 2HCl(aq) \rightarrow ClO_2(g) + \tfrac{1}{2}Cl_2(g) + NaCl(aq) + H_2O(l)$$

   a. How many milliliters of 12.1 M HCl are necessary to react completely with 35.09 g of sodium chlorate, $NaClO_3$?

   b. What is the maximum mass, in grams, of ClO_2 that can be formed from the complete reaction of 65 mL of 12.1 M HCl?

54. When a water solution of sodium sulfite, Na_2SO_3, is added to a water solution of iron(II) chloride, $FeCl_2$, iron(II) sulfite, $FeSO_3$, precipitates from the solution.

OBJECTIVE 11
OBJECTIVE 12
OBJECTIVE 13

   a. Write a balanced equation for this reaction.

   b. What is the maximum mass of iron(II) sulfite that will precipitate from a solution prepared by adding an excess of a Na_2SO_3 solution to 25.00 mL of 1.009 M $FeCl_2$?

55. Consider the precipitation reaction that takes place when a water solution of aluminum nitrate, $Al(NO_3)_3$, is added to a water solution of potassium phosphate, K_3PO_4.

OBJECTIVE 11
OBJECTIVE 12
OBJECTIVE 13

   a. Write a balanced equation for this reaction.

   b. What is the maximum mass of aluminum phosphate that will precipitate from a solution prepared by adding an excess of an $Al(NO_3)_3$ solution to 50.00 mL of 1.525 M K_3PO_4?

56. Consider the neutralization reaction that takes place when nitric acid reacts with aqueous potassium hydroxide.

OBJECTIVE 11
OBJECTIVE 12
OBJECTIVE 13

   a. Write a conversion factor that relates moles of HNO_3 to moles of KOH for this reaction.

   b. What is the minimum volume of 1.50 M HNO_3 necessary to neutralize completely the hydroxide in 125.0 mL of 0.501 M KOH?

57. Consider the neutralization reaction that takes place when hydrochloric acid reacts with aqueous sodium hydroxide.

OBJECTIVE 11
OBJECTIVE 12
OBJECTIVE 13

   a. Write a conversion factor that relates moles of HCl to moles of NaOH for this reaction.

   b. What is the minimum volume of 6.00 M HCl necessary to neutralize completely the hydroxide in 750.0 mL of 0.107 M NaOH?

58. Consider the neutralization reaction that takes place when sulfuric acid reacts with aqueous sodium hydroxide.

   a. Write a conversion factor that relates moles of H_2SO_4 to moles of NaOH for this reaction.

   b. What is the minimum volume of 6.02 M H_2SO_4 necessary to neutralize completely the hydroxide in 47.5 mL of 2.5 M NaOH?

59. Consider the neutralization reaction that takes place when phosphoric acid reacts with aqueous potassium hydroxide.

   a. Write a conversion factor that relates moles of H_3PO_4 to moles of KOH for this reaction.

   b. What is the minimum volume of 2.02 M H_3PO_4 necessary to neutralize completely the hydroxide in 183 mL of 0.550 M KOH?

60. Consider the neutralization reaction that takes place when hydrochloric acid reacts with solid cobalt(II) hydroxide.

   a. Write a conversion factor that relates moles of HCl to moles of $Co(OH)_2$ for this reaction.

   b. What is the minimum volume of 6.14 M HCl necessary to react completely with 2.53 kg of solid cobalt(II) hydroxide, $Co(OH)_2$?

61. Consider the neutralization reaction that takes place when hydrochloric acid reacts with solid nickel(II) carbonate.

   a. Write a conversion factor that relates moles of HCl to moles of $NiCO_3$ for this reaction.

   b. What is the minimum volume of 6.0 M HCl necessary to react completely with 14.266 g of solid nickel(II) carbonate, $NiCO_3$?

62. Consider the neutralization reaction that takes place when nitric acid reacts with solid chromium(III) hydroxide.

   a. Write a conversion factor that relates moles of HNO_3 to moles of $Cr(OH)_3$ for this reaction.

   b. What is the minimum volume of 2.005 M HNO_3 necessary to react completely with 0.5187 kg of solid chromium(III) hydroxide, $Cr(OH)_3$?

63. Consider the neutralization reaction that takes place when nitric acid reacts with solid iron(II) carbonate.

   a. Write a conversion factor that relates moles of HNO_3 to moles of $FeCO_3$ for this reaction.

   b. What is the minimum volume of 2.00 M HNO_3 necessary to react completely with 1.06 kg of solid iron(II) carbonate, $FeCO_3$?

Additional Problems

64. Because nitrogen and phosphorus are both nonmetallic elements in group 15 on the periodic table, we expect them to react with other elements in similar ways. To some extent, they do, but there are also distinct differences in their chemical behavior. For example, nitrogen atoms form stable triple bonds to carbon atoms in substances such as hydrogen cyanide (often called hydrocyanic acid), HCN. Phosphorus atoms also form triple bonds to carbon atoms, in substances such as HCP, but those substances are much less stable. The compound HCP can be formed in the following reaction.

$$CH_4 + PH_3 \xrightarrow{\text{electric arc}} HCP + 3H_2$$
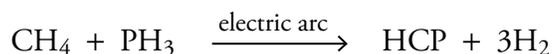
   a. Write a conversion factor that could be used to convert between moles of HCP and moles of H_2.
   b. How many moles of HCP form along with 9 moles of H_2?
   c. Write a conversion factor that could be used to convert between moles of methane, CH_4, and moles of hydrogen, H_2.
   d. How many moles of hydrogen gas form when 1.8834 moles of CH_4 react with an excess of PH_3?

65. Because carbon and silicon are both elements in group 14 on the periodic table, we expect them to react with other elements in similar ways. To some extent, they do, but in some cases, carbon and silicon compounds that seem to have analogous structures have very different chemical characteristics. For example, carbon tetrachloride, CCl_4, is very stable in the presence of water, but silicon tetrachloride, $SiCl_4$, reacts quickly with water. The unbalanced equation for this reaction is
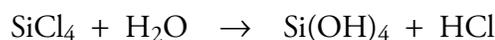
$$SiCl_4 + H_2O \rightarrow Si(OH)_4 + HCl$$

   a. Balance this equation.
   b. Write a conversion factor that could be used to convert between moles of $SiCl_4$ and moles of H_2O.
   c. How many moles of $SiCl_4$ react with 24 moles of water?
   d. Write a conversion factor that could be used to convert between moles of $Si(OH)_4$ and moles of water.
   e. How many moles of $Si(OH)_4$ form when 4.01 moles of H_2O react with an excess of $SiCl_4$?

66. Iodine pentafluoride is an incendiary agent, a substance that ignites combustible materials. This compound is usually made by passing fluorine gas over solid iodine, but it also forms when iodine monofluoride changes into the element iodine and iodine pentafluoride.
   a. Write a balanced equation, without including states, for the conversion of iodine monofluoride into iodine and iodine pentafluoride.
   b. How many moles of the element iodine form when 15 moles of iodine monofluoride react completely?
   c. How many moles of iodine pentafluoride form when 7.939 moles of iodine monofluoride react completely?

67. The first laboratory experiments to produce compounds containing noble gas atoms aroused great excitement, not because the compounds might be useful but because they demonstrated that the noble gases were not completely inert. Since that time, however, important uses have been found for a number of noble gas compounds. For example, xenon difluoride, XeF_2, is an excellent fluorinating agent (a substance that adds fluorine atoms to other substances). One reason it is preferred over certain other fluorinating agents is that the products of its fluorinating reactions are easily separated from the gaseous xenon. The following unbalanced equation represents one such reaction:

$$S_3O_9 + XeF_2 \rightarrow S_2O_6F_2 + Xe$$
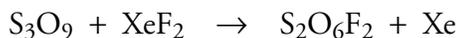
   a. Balance this equation.
   b. What is the minimum number of moles of XeF_2 necessary to react with 4 moles of S_3O_9?
   c. What is the maximum number of moles of $S_2O_6F_2$ that can form from the complete reaction of 4 moles of S_3O_9 and 7 moles of XeF_2?
   d. How many moles of xenon gas form from the complete reaction of 0.6765 mole of S_3O_9?

68. Xenon hexafluoride is a better fluorinating agent than the xenon difluoride described in the previous problem, but it must be carefully isolated from any moisture. This is because xenon hexafluoride reacts with water to form hydrogen fluoride (hydrogen monofluoride) and the dangerously explosive xenon trioxide.

   a. Write a balanced equation, without including states, for the reaction of xenon hexafluoride and water to form xenon trioxide and hydrogen fluoride.
   b. How many moles of hydrogen fluoride form when 0.50 mole of xenon hexafluoride reacts completely?
   c. What is the maximum number of moles of xenon trioxide that can form in the combination of 7 moles of xenon hexafluoride and 18 moles of water?

69. It is fairly easy to make the fluorides of xenon by combining xenon gas with fluorine gas. Unfortunately, the products of the reaction—XeF_2, XeF_4, and XeF_6—are difficult to separate. The percentage of XeF_2 can be raised by adding a large excess of xenon and removing the product mixture soon after the reaction has begun. The percentage of XeF_6 can be raised by running the reaction at 700 to 800 °C in the presence of a nickel catalyst with a large excess of fluorine. If XeF_4 is desired, a different reaction can be used. For example, XeF_4 can be made from the reaction of xenon gas with dioxygen difluoride. The reaction also produces oxygen gas.

   a. Write a balanced equation, including states, for the reaction of xenon gas and dioxygen difluoride gas to form xenon tetrafluoride gas and oxygen gas.
   b. How many moles of xenon tetrafluoride form from 7.50 moles of dioxygen difluoride?
   c. What is the maximum number of moles of xenon tetrafluoride gas that can form in the combination of 4.75 moles of xenon and 9.00 moles of dioxygen difluoride?

70. Hydriodic acid is produced industrially by the reaction of hydrazine, N_2H_4, with iodine, I_2. HI(aq) is used to make iodine salts such as AgI, which are used to seed clouds to promote rain. What is the minimum mass of iodine, I_2, necessary to react completely with 87.0 g of hydrazine, N_2H_4?

$$N_2H_4 \; + \; 2I_2 \;\; \rightarrow \;\; 4HI \; + \; N_2$$
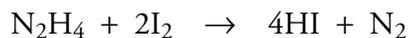
71. Calcium dihydrogen phosphate, which is used in the production of triple superphosphate fertilizers, can be formed from the reaction of apatite, $Ca_5(PO_4)_3F$, with phosphoric acid. How many grams of calcium dihydrogen phosphate can be formed from 6.78 g of $Ca_5(PO_4)_3F$?

$$2Ca_5(PO_4)_3F \; + \; 14H_3PO_4 \;\; \rightarrow \;\; 10Ca(H_2PO_4)_2 \; + \; 2HF$$
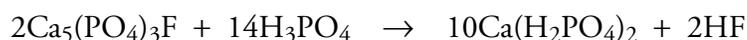
72. Because plants need nitrogen compounds, potassium compounds, and phosphorus compounds to grow, these are often added to the soil as fertilizers. Potassium sulfate, which is used to make fertilizers, is made industrially by reacting potassium chloride with sulfur dioxide gas, oxygen gas, and water. Hydrochloric acid is formed with the potassium sulfate.
  a. Write a balanced equation for this reaction. (You do not need to include states.)
  b. What is the maximum mass, in kilograms, of potassium sulfate that can be formed from 2.76×10^5 kg of potassium chloride with excess sulfur dioxide, oxygen, and water?
  c. If 2.94×10^5 kg of potassium sulfate is isolated from the reaction of 2.76×10^5 kg of potassium chloride, what is the percent yield?

73. Sodium hydrogen sulfate is used as a cleaning agent and as a flux (a substance that promotes the fusing of metals and prevents the formation of oxides). One of the ways in which sodium hydrogen sulfate is manufactured is by reacting sodium dichromate, $Na_2Cr_2O_7$, with sulfuric acid. This process also forms water and chromium(VI) oxide, CrO_3.
  a. Write a balanced equation for this reaction. (You do not need to include states.)
  b. How many kilograms of sodium dichromate, $Na_2Cr_2O_7$, are necessary to produce 130.4 kg of sodium hydrogen sulfate?
  c. How many kilograms of chromium(VI) oxide are formed when 130.4 kg of sodium hydrogen sulfate is made?
  d. What is the minimum volume of 18.0 M H_2SO_4 solution necessary to react with 874.0 kg of sodium dichromate?
  e. What is the maximum mass of sodium hydrogen sulfate, $NaHSO_4$, that can be formed from the reaction of 874.0 kg of sodium dichromate with 400.0 L of 18.0 M H_2SO_4?

74. The element phosphorus can be made by reacting carbon in the form of coke with calcium phosphate, $Ca_3(PO_4)_2$, which is found in phosphate rock.

$$Ca_3(PO_4)_2 + 5C \rightarrow 3CaO + 5CO + 2P$$
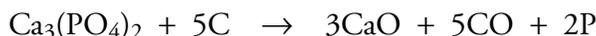
a. What is the minimum mass of carbon, C, necessary to react completely with 67.45 Mg of $Ca_3(PO_4)_2$?

b. What is the maximum mass of phosphorus produced from the reaction of 67.45 Mg of $Ca_3(PO_4)_2$ with an excess of carbon?

c. What mass of calcium oxide, CaO, is formed with the mass of phosphorus calculated in part (b)?

d. If 11.13 Mg of phosphorus is formed in the reaction of 67.45 Mg of $Ca_3(PO_4)_2$ with an excess of carbon, what is the percent yield?

75. When coal is burned, the sulfur it contains is converted into sulfur dioxide. This SO_2 is a serious pollutant, so it needs to be removed before it escapes from the stack of a coal fired plant. One way to remove the SO_2 is to add limestone, which contains calcium carbonate, $CaCO_3$, to the coal before it is burned. The heat of the burning coal converts the $CaCO_3$ to calcium oxide, CaO. The calcium oxide reacts with the sulfur dioxide in the following reaction:

$$2CaO + 2SO_2 + O_2 \rightarrow 2CaSO_4$$

The solid calcium sulfate does not escape from the stack as the gaseous sulfur dioxide would. What mass of calcium sulfate forms for each 1.00 Mg of SO_2 removed by this technique?

76. Thionyl chloride, $SOCl_2$, is a widely used source of chlorine in the formation of pesticides, pharmaceuticals, dyes, and pigments. It can be formed from disulfur dichloride in the following reaction.

$$2SO_2 + S_2Cl_2 + 3Cl_2 \rightarrow 4SOCl_2$$

If 1.140 kg of thionyl chloride is isolated from the reaction of 457.6 grams of disulfur dichloride, S_2Cl_2, with excess sulfur dioxide and chlorine gas, what is the percent yield?

77. Chromium(III) oxide, which can be converted into metallic chromium, is formed in the following reaction:

$$Na_2Cr_2O_7 + S \xrightarrow{\text{800-1000 °C}} Cr_2O_3 + Na_2SO_4$$
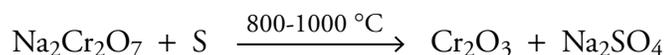
a. How many grams of chromium(III) oxide, Cr_2O_3, are formed in the reaction of 981 g of sodium dichromate, $Na_2Cr_2O_7$, with 330 g of sulfur, S?

b. Explain why one of these substances is in excess and one is limiting.

78. Sodium dichromate, $Na_2Cr_2O_7$, is converted to chromium(III) sulfate, which is used in the tanning of animal hides. Sodium dichromate can be made by reacting sodium chromate, Na_2CrO_4, with water and carbon dioxide.

$$2Na_2CrO_4 + H_2O + 2CO_2 \rightleftharpoons Na_2Cr_2O_7 + 2NaHCO_3$$
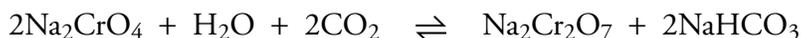
a. Show that the sodium chromate is the limiting reactant when 87.625 g of Na_2CrO_4 reacts with 10.008 g of water and excess carbon dioxide.

b. Explain why the carbon dioxide and water are in excess and sodium chromate is limiting.

79. What is the molarity of a solution made by dissolving 37.895 g of $CoCl_2$ in water and diluting with water to 250.0 mL total?

80. What is the molarity of a solution made by dissolving 100.065 g of $SnBr_2$ in water and diluting with water to 1.00 L total?

81. Sodium dichromate, $Na_2Cr_2O_7$, can be made by reacting sodium chromate, Na_2CrO_4, with sulfuric acid.

$$2Na_2CrO_4 + H_2SO_4 \rightarrow Na_2Cr_2O_7 + Na_2SO_4 + H_2O$$

a. What is the minimum volume of 18.0 M H_2SO_4 necessary to react completely with 15.345 kg of sodium chromate, Na_2CrO_4?

b. What is the maximum mass, in kilograms, of sodium dichromate that can be formed from the reaction of 203 L of 18.0 M H_2SO_4?

82. A precipitation reaction takes place when a water solution of sodium carbonate, Na_2CO_3, is added to a water solution of chromium(III) nitrate, $Cr(NO_3)_3$.

a. Write a balanced equation for this reaction.

b. What is the maximum mass of chromium(III) carbonate that will precipitate from a solution prepared by adding an excess of a Na_2CO_3 solution to 10.00 mL of 0.100 M $Cr(NO_3)_3$?

83. A precipitation reaction takes place when a water solution of potassium phosphate, K_3PO_4, is added to a water solution of cobalt(II) chloride, $CoCl_2$.

a. Write a balanced equation for this reaction.

b. What is the maximum mass of cobalt(II) phosphate that will precipitate from a solution prepared by adding an excess of a K_3PO_4 solution to 5.0 mL of 1.0 M $CoCl_2$?

84. Consider the neutralization reaction between nitric acid and aqueous barium hydroxide.

a. Write a conversion factor that shows the ratio of moles of nitric acid to moles of barium hydroxide.

b. What volume of 1.09 M nitric acid would be necessary to neutralize the hydroxide in 25.00 mL of 0.159 M barium hydroxide?

85. Consider the neutralization reaction between sulfuric acid and aqueous lithium hydroxide.

a. Write a conversion factor that shows the ratio of moles of sulfuric acid to moles of lithium hydroxide.

b. What volume of 0.505 M sulfuric acid would be necessary to neutralize the hydroxide in 25.00 mL of 2.87 M lithium hydroxide?

86. Consider the neutralization reaction between hydrochloric acid and solid zinc carbonate.

a. Write a conversion factor that shows the ratio of moles of hydrochloric acid to moles of zinc carbonate.

b. What volume of 0.500 M hydrochloric acid would be necessary to neutralize and dissolve 562 milligrams of solid zinc carbonate?

87. Consider the neutralization reaction between nitric acid and solid cadmium hydroxide.

a. Write a conversion factor that shows the ratio of moles of nitric acid to moles of cadmium hydroxide.

b. What volume of 3.00 M nitric acid would be necessary to neutralize and dissolve 2.56 kg of solid cadmium hydroxide?

Challenge Problems

88. A solution is made by adding 22.609 g of a solid that is 96.3% NaOH to a beaker of water. What volume of 2.00 M H_2SO_4 is necessary to neutralize the NaOH in this solution?

89. Potassium hydroxide can be purchased as a solid that is 88.0% KOH. What is the minimum mass of this solid necessary to neutralize all of the HCl in 25.00 mL of 3.50 M HCl?

90. Aluminum sulfate, often called alum, is used in paper making to increase the paper's stiffness and smoothness and to help keep the ink from running. It is made from the reaction of sulfuric acid with the aluminum oxide found in bauxite ore. The products are aluminum sulfate and water. Bauxite ore is 30% to 75% aluminum oxide.

    a. Write a balanced equation for this reaction. (You do not need to write the states.)

    b. What is the maximum mass, in kilograms, of aluminum sulfate that could be formed from 2.3×10^3 kilograms of bauxite ore that is 62% aluminum oxide?

91. The element phosphorus can be made by reacting carbon in the form of coke with $Ca_3(PO_4)_2$ found in phosphate ore. When 8.0 Mg of ore that is 68% $Ca_3(PO_4)_2$ is combined with an excess of carbon in the form of coke, what is the maximum mass, in megagrams, of phosphorus that can be formed?

$$Ca_3(PO_4)_2 + 5C \quad \rightarrow \quad 3CaO + 5CO + 2P$$
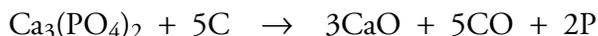
92. Sodium tripolyphosphate (or STPP), $Na_5P_3O_{10}$, is used in detergents. It is made by combining phosphoric acid with sodium carbonate at 300 to 500 °C. What is the minimum mass, in kilograms, of sodium carbonate that would be necessary to react with excess phosphoric acid to make enough STPP to produce 1.025×10^5 kg of a detergent that is 32% $Na_5P_3O_{10}$?

$$6H_3PO_4 + 5Na_2CO_3 \quad \rightarrow \quad 2Na_5P_3O_{10} + 9H_2O + 5CO_2$$

93. Hydrazine, N_2H_4, is a liquid with many industrial purposes, including the synthesis of herbicides and pharmaceuticals. It is made from urea in the following reaction at 100 °C.

$$NH_2CONH_2 + NaOCl + 2NaOH$$
$$\rightarrow \quad N_2H_4 + NaCl + Na_2CO_3 + H_2O$$
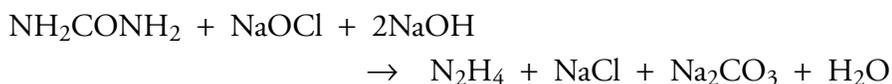
If the percent yield for the reaction is 90.6%, how many kilograms of hydrazine, N_2H_4, are formed from the reaction of 243.6 kg of urea, NH_2CONH_2, with excess sodium hypochlorite and sodium hydroxide?

94. Urea, NH_2CONH_2, is a common nitrogen source used in fertilizers. When urea is made industrially, its temperature must be carefully controlled because heat turns urea into biuret, $NH_2CONHCONH_2$, a compound that is harmful to plants. Consider a pure sample of urea that has a mass of 92.6 kg. If 0.5% of the urea in this sample decomposes to form biuret, what mass, in grams, of $NH_2CONHCONH_2$ will it contain?

$$2NH_2CONH_2 \rightarrow NH_2CONHCONH_2 + NH_3$$

95. Chilean niter deposits are mostly sodium nitrate, but they also contain 0.3% iodine in the form of calcium iodate, $Ca(IO_3)_2$. After the sodium nitrate in the niter is dissolved and recrystallized, the remaining solution contains 9 g/L sodium iodate, $NaIO_3(aq)$. The $NaIO_3$ is converted to iodine when it reacts with sulfur dioxide and water.

$$2NaIO_3 + 5SO_2 + 4H_2O \rightarrow Na_2SO_4 + 4H_2SO_4 + I_2$$
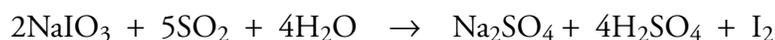
   a. How many liters of sodium iodate solution that contains 9 g of $NaIO_3$ per liter would be necessary to form 127.23 kg of iodine, I_2?
   b. What mass, in megagrams, of Chilean niter that is 0.3% I would be necessary to form the volume of sodium iodate solution you calculated in part (a)?

96. The white pigment titanium(IV) oxide (often called titanium dioxide), TiO_2, is made from rutile ore that is about 95% TiO_2. Before the TiO_2 can be used, it must be purified. The equation that follows represents the first step in this purification.

$$3TiO_2(s) + 4C(s) + 6Cl_2(g) \xrightarrow{900 \text{ °C}} 3TiCl_4(l) + 2CO(g) + 2CO_2(g)$$
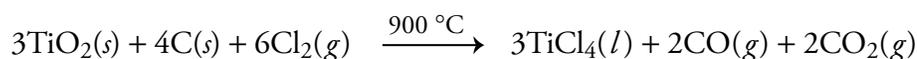
   a. How many pounds of $TiCl_4$ can be made from the reaction of 1.250×10^5 pounds of rutile ore that is 95% TiO_2 with 5.0×10^4 pounds of carbon?
   b. Explain why two of these substances are in excess and one is limiting.

97. The tanning agent $Cr(OH)SO_4$ is formed in the reaction of sodium dichromate, $Na_2Cr_2O_7$, sulfuric acid, and the sucrose in molasses:

$$8Na_2Cr_2O_7 + 24H_2SO_4 + C_{12}H_{22}O_{11}$$
$$\rightarrow 16Cr(OH)SO_4 + 8Na_2SO_4 + 12CO_2 + 22H_2O$$
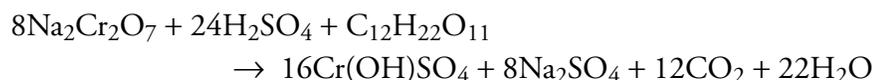
What is the maximum mass of $Cr(OH)SO_4$ formed from the reaction of 431.0 kg of sodium dichromate with 292 L of 18.0 M H_2SO_4 and 90.0 kg of $C_{12}H_{22}O_{11}$?

98. What is the maximum mass of calcium hydrogen phosphate, $CaHPO_4$, that can form from the mixture of 12.50 kg of a solution that contains 84.0% H_3PO_4, 25.00 kg of $Ca(NO_3)_2$, 25.00 L of 14.8 M NH_3, and an excess of CO_2 and H_2O?

$$3H_3PO_4 + 5Ca(NO_3)_2 + 10NH_3 + 2CO_2 + 2H_2O$$
$$\rightarrow 10NH_4NO_3 + 2CaCO_3 + 3CaHPO_4$$