SECTION 3.1

Writing Chemical Equations

Key Terms

chemical reaction
reactant
product
chemical equation
skeleton equation
balanced chemical equation
coefficient

chemical reaction a process in which substances interact, causing different substances with different properties to form

reactant a starting substance in a chemical reaction

product a substance that is formed in a chemical reaction

chemical equation a condensed statement that expresses chemical change using symbols and chemical names or formulas

You probably have no trouble understanding the message in **Figure 3.1**. Over time, you have learned the shortened words and abbreviations that are used to keep text messages brief, yet still express the intended information. In Unit 1, you learned how chemists use chemical formulas to convey a large amount of information about chemical compounds using a few simple characters—much like text messaging.

Chemists also need to convey information about what happens to chemicals and how they change when they interact in a chemical reaction. A **chemical reaction** is a process in which substances interact to form one or more different substances. In this section, you will learn two ways to represent chemical reactions.

Figure 3.1 Text messages use widely recognized abbreviations to convey information in a small amount of space. Similarly, chemists use symbols to communicate information about chemical processes.

Describing Chemical Reactions

When you see a rusty car or bridge, such as the bridge in **Figure 3.2**, you know that the rust is not a material that was originally used to build the structure. The iron in the steel has reacted with oxygen, causing rust to form. Rust is a substance with chemical and physical properties that are very different from those of iron. In every chemical reaction, the **reactants**, or starting substances, interact and form different substances, called the **products**. In this example, iron and oxygen are the reactants, and rust is the product of the reaction.

Suppose that you wanted to describe a chemical reaction, such as the burning of charcoal, C(s), or the bubbling that occurs when acetic acid, $CH_3COOH(aq)$, in vinegar reacts with sodium hydrogen carbonate, $NaHCO_3(s)$, in baking soda. You could write a sentence that described the reactants and products. You could also give some details about the reaction process. However, this is a long and tedious way to share the information. A **chemical equation** is a condensed statement that expresses chemical change using symbols and chemical names or formulas. A chemical equation can be a word equation, a skeleton equation, or a balanced chemical equation. In this section, you will learn how to write three forms of a chemical equation: a word equation, a skeleton equation, and a balanced chemical equation.

Figure 3.2 The rust that has formed on this bridge is the product of a chemical reaction in which iron and oxygen are the reactants.

Writing Word Equations

In a word equation, the reactants and products are identified by their names only. For example, a word equation for one of the reactions involved in the formation of rust is shown below.

$$\text{iron} + \text{oxygen} \rightarrow \text{iron(III) oxide}$$

reactants **product**

This equation can be read as follows: iron and oxygen react to form iron(III) oxide. The reactants are on the left side of an arrow, and the products are on the right side. The arrow shows the direction of the chemical change that is taking place. The arrow stands for *yields* or *reacts to produce*. If there are two or more substances on either side of the arrow, a plus sign is placed between their names. **Table 3.1** lists symbols commonly used in word equations and other chemical equations.

Note that some reactions are reversible, which means that the products can be changed back into the reactants. To illustrate this, a special type of arrow symbol is used, as shown in **Table 3.1**. For example, the chlorine-bleaching process that removes colour during the manufacturing of white paper involves a reversible chemical reaction. In this reaction, aqueous solutions of hypochlorous acid, $HOCl(aq)$, and hydrochloric acid react to form chlorine gas and liquid water. These products, chlorine gas and liquid water can, in turn, react to form the original products. Here is the word equation for this reaction:

$$\text{hypochlorous acid} + \text{hydrochloric acid} \rightleftharpoons \text{chlorine} + \text{water}$$

Table 3.1 Symbols Used in Chemical Equations

Symbol	Purpose
$+$	Indicates that two or more reactants or products are involved
$\rightarrow$	Shows the direction of the chemical change that is taking place
$\rightleftharpoons$	Indicates a reversible reaction

skeleton equation a chemical equation in which the reactants and products in a chemical reaction are represented by their chemical formulas; their relative quantities are not included

Writing Skeleton Equations

A **skeleton equation** is a chemical equation in which chemical formulas are used to represent the substances that are involved in a chemical reaction. The relative quantities of the substances, however, are not included.

Because skeleton equations are written using chemical formulas, they convey more information than word equations do. Skeleton equations clearly show the number of atoms of each element in the reactants and products, while word equations do not. In addition, skeleton equations generally show the physical state of each substance by including one of the symbols shown in **Table 3.2** after each chemical formula. The word equation and skeleton equation for the formation of iron (III) oxide, commonly referred to as rust, are shown below. **Figure 3.3** shows powdered iron (III) oxide.

Word equation: iron + oxygen → iron(III) oxide

Skeleton equation: $Fe(s) + O_2(g) \rightarrow Fe_2O_3(s)$

Figure 3.3 Iron(III) oxide is an inorganic solid with the formula Fe_2O_3. In nature, this substance is the mineral hematite, which is a principal source of iron for the mining industry. Since prehistoric times, people around the world have used iron(III) oxide as a colouring agent (pigment) for painting. In this context, the substance is often called red ochre.

Table 3.2 Symbols Used in Chemical Equations for Physical State

Symbol	Purpose
(s)	Identifies a solid state
(ℓ)	Identifies a liquid state
(g)	Identifies a gaseous state
(aq)	Identifies an aqueous solution

In the case of the reversible reaction involving the chlorine-bleaching process, the reactants are in aqueous solution, and the products are a gas and liquid water. The word equation and skeleton equation for this reaction are given below.

Word equation:

hypochlorous acid + hydrochloric acid ⇌ chlorine + water

Skeleton equation:

$$HClO(aq) + HCl(aq) \rightleftharpoons Cl_2(g) + H_2O(\ell)$$

You can practise writing skeleton equations that represent chemical reactions by working through the Sample Problem and Practice Problems on the next page.

Sample Problem

Writing Skeleton Equations

Problem

When solid sodium carbonate is added to an aqueous solution of hydrochloric acid, liquid water, carbon dioxide gas, and an aqueous solution of sodium chloride are formed. What is the skeleton equation for this chemical reaction?

What Is Required?

A skeleton equation that represents the chemical reaction is required.

What Is Given?

You are given the reactants: solid sodium carbonate and an aqueous solution of hydrochloric acid.

You are given the products: liquid water, carbon dioxide gas, and an aqueous solution of sodium chloride.

Plan Your Strategy	Act on Your Strategy
Determine the chemical formula for each substance. Include the state.	Solid sodium carbonate: $Na_2CO_3(s)$ Aqueous solution of hydrochloric acid: $HCl(aq)$ Liquid water: $H_2O(\ell)$ Carbon dioxide gas: $CO_2(g)$ Aqueous solution of sodium chloride: $NaCl(aq)$
Write the skeleton equation. Use an arrow to show the direction of the chemical change that is taking place. Use a plus sign to separate two or more reactants or products.	$Na_2CO_3(s) + HCl(aq) \rightarrow H_2O(\ell) + CO_2(g) + NaCl(aq)$

Check Your Solution

The reactants are written on the left side of the arrow, and the products are written on the right side. The chemical formula for each substance is written correctly. The physical state of each reactant and product is shown.

Practice Problems

Write a skeleton equation for each chemical reaction. Indicate the state of each reactant and product in the skeleton equation. Remember that the following seven elements are diatomic: hydrogen, $H_2(g)$; nitrogen, $N_2(g)$; oxygen, $O_2(g)$; fluorine, $F_2(g)$; chlorine, $Cl_2(g)$; bromine, $Br_2(\ell)$; and iodine, $I_2(s)$.

1. Gaseous hydrogen and oxygen react to form gaseous water.
2. Solid sodium metal reacts with liquid water to form an aqueous solution of sodium hydroxide and hydrogen gas.
3. Solid potassium chlorate breaks down to form solid potassium chloride and oxygen gas.
4. Solid copper reacts with oxygen gas to form solid copper(II) oxide.
5. When aqueous solutions of silver nitrate and sodium chloride are combined, the reaction produces an aqueous solution of sodium nitrate and a precipitate of silver chloride.
6. The complete combustion of propane gas, $C_3H_8(g)$, in the presence of oxygen gas forms gaseous water and carbon dioxide.
7. Sulfur trioxide gas reacts with liquid water to form an aqueous solution of sulfuric acid.
8. Solid ammonium chloride is formed when hydrogen chloride gas reacts with gaseous ammonia.
9. Solid aluminum and gaseous fluorine form when solid aluminum fluoride breaks down.
10. Liquid mercury reacts with oxygen gas to form solid mercury(II) oxide.

Activity 3.1 Keeping Track of Atoms

In a chemical reaction, matter is conserved. All the atoms in the reactant(s) are incorporated into the product(s). A different quantity of molecules may be formed, but the amount of each type of atom is conserved. In this activity, you will model the reaction of molecular hydrogen with molecular oxygen to form water.

Materials

- models of 8 hydrogen atoms
- models of 4 oxygen atoms
- 8 connectors

Procedure

1. Divide the models of atoms into two equal sets of four hydrogen atoms and two oxygen atoms. One set of atoms will represent the reactants. The other set will represent the products.
2. Using the set for the reactants, assemble two hydrogen molecules and one oxygen molecule to represent the reactants.
3. Using the set for the products, assemble as many water molecules as possible to represent the products.

Questions

1. **a.** How many models of atoms were left over after you assembled the reactants and the products?
   b. What do your results tell you about the conservation of atoms in the reaction of molecular hydrogen with molecular oxygen to form water?
2. **a.** How many models did you assemble to represent reactant molecules?
   b. How many models did you assemble to represent product molecules?
   c. When hydrogen and oxygen react, are molecules conserved? Explain.

Beyond Skeleton Equations

A skeleton equation is more useful than a word equation because it shows the formulas and states of the substances in a chemical reaction. However, it is still not a complete description of what happens in the reaction. Compare the reactants and products in **Figure 3.4**:

aluminum + bromine → aluminum bromide

$$Al(s) + Br_2(g) \rightarrow AlBr_3(s)$$

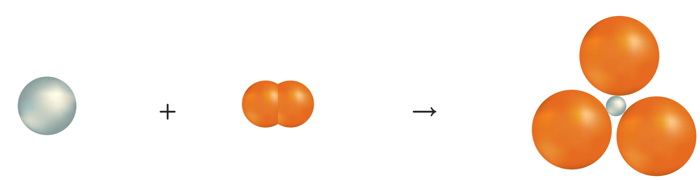


Figure 3.4 As this model shows, a skeleton equation is an incomplete representation of a reaction because it does not have an equal number of atoms of each element in both the reactants and the products.

***Compare** the number of atoms of each element shown on the reactant side and the product side of the chemical equation.*

From the models in **Figure 3.4**, you can see that the number of atoms of bromine on the reactant side is not equal to the number of atoms of bromine on the product side. While skeleton equations clearly show the substances that are involved in a reaction, they do not show the relative numbers of atoms, molecules, and ions.

Learning Check

1. Describe the connection between a chemical reaction and a skeleton equation.
2. According to **Table 3.1**, what symbol is used to represent the physical state of a substance that is dissolved in water?
3. In photosynthesis, plants produce glucose, $C_6H_{12}O_6(s)$, and oxygen from carbon dioxide and water.
   a. What information would be included in a skeleton equation representing this chemical reaction?
   b. What information would not be included?
4. Explain the meaning of the following symbol in a chemical equation:

$$\rightleftharpoons$$

5. The following skeleton equation was written to represent solid sodium metal reacting with liquid water to form an aqueous solution of sodium hydroxide and hydrogen gas.

$$Na(s) + H_2O(g) + Na(OH)_2(\ell) + H(g)$$

   a. Analyze the skeleton equation, and identify the errors in it.
   b. Write the skeleton equation in correct form.
6. Identify the reactants and products in each reaction, and write a skeleton equation for each reaction.
   a. Bubbles of hydrogen gas and oxygen gas form as water is broken down using an electric current.
   b. Liquid bromine and zinc chloride form as chlorine gas is bubbled through an aqueous solution of zinc bromide.

Writing Balanced Chemical Equations

To reflect the ratios of substances involved in a chemical reaction accurately, an equation must show an equal number of atoms of each element in both the reactants and the products. A **balanced chemical equation** is a statement that uses chemical formulas and coefficients to show the identities and ratios of the reactants and products in a chemical reaction. A **coefficient** is a positive number that is placed in front of a chemical formula to show the relative number of particles (atoms, ions, molecules, or formula units) of the substance that are involved in the reaction.

Figure 3.5 shows the balanced chemical equation for the reaction of aluminum and bromine. There are two aluminum atoms and six bromine atoms on each side of the equation. The whole numbers 2, 3, and 2 in front of the formulas are coefficients.

balanced chemical equation a statement that uses chemical formulas and coefficients to show the identities and ratios of the reactants and products in a chemical reaction

coefficient in a balanced chemical equation, a positive number that is placed in front of a formula to show the relative number of particles of the substance that are involved in the reaction

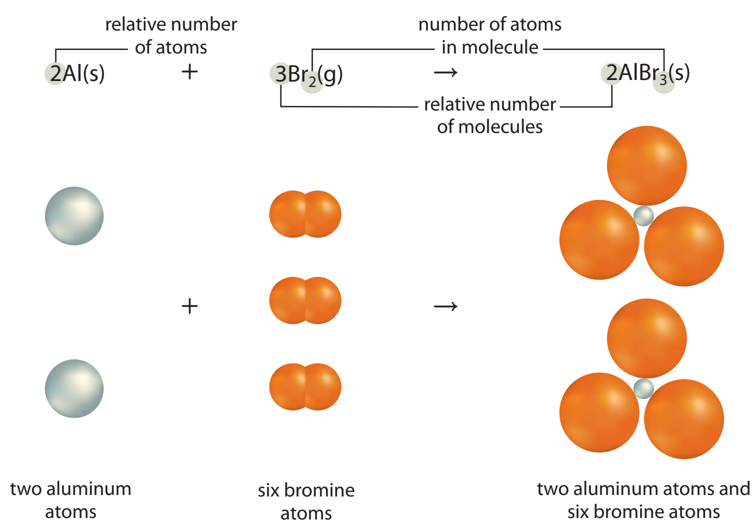


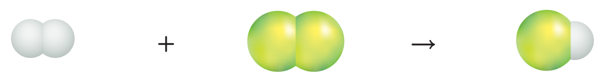
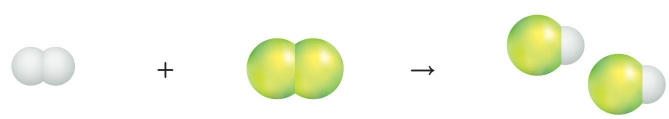
Figure 3.5 In a balanced chemical equation, each atom on the reactant side must have a corresponding atom of the same element on the product side.

***Explain** why six bromine atoms are shown on each side of the equation.*

How to Balance a Chemical Equation

Most chemical equations can be balanced by following the steps given in **Table 3.3**. As you gain more experience balancing chemical equations, you may discover patterns when balancing certain types of equations. These patterns will help you become more proficient and faster at balancing the equations. As you read each step in the table, closely examine how it applies to balancing the equation for the reaction of hydrogen and chlorine to form hydrogen chloride.

Table 3.3 Steps for Balancing Chemical Equations

Step	Process	Example
1	**Write the skeleton equation for the reaction.** Make sure that the chemical formulas correctly represent the substances. Use an arrow to separate the reactants from the products. Use a plus sign to separate multiple reactants and products. Show the physical state of each reactant and product.	$H_2(g)$ + $Cl_2(g)$ → $HCl(g)$  two hydrogen atoms; two chlorine atoms; one hydrogen atom and one chlorine atom
2	**Count the atoms of each element in the reactants. Identify any polyatomic ions that are present.** The reaction at the right does not involve any polyatomic ions. If the reactants and products in another reaction contain the same polyatomic ion, count it as a single item rather than counting each atom within it.	**$H_2(g) + Cl_2(g) \rightarrow$** Two atoms of hydrogen and two atoms of chlorine appear in the reactants. There are no polyatomic ions present.
3	**Count the atoms of each element in the products. Identify any polyatomic ions that are present.**	**$HCl(g)$** One atom of hydrogen and one atom of chlorine appear in the products. There are no polyatomic ions present.
4	**Add coefficients so that you have an equal number of atoms of each element on both sides of the equation. If different numbers of the same polyatomic ion are present on either side of the equation, add a coefficient to the compound that will cause the number of the ion to be equal on both sides.** Do *not* change a subscript in a chemical formula to balance an equation. This would change the formula to the formula for a different substance—a substance that is not involved in the reaction.	$H_2(g)$ 2 atoms H + $Cl_2(g)$ 2 atoms Cl → $2HCl(g)$ 2 atoms H + 2 atoms Cl  two hydrogen atoms; two chlorine atoms; two hydrogen atoms and two chlorine atoms
5	**Write the coefficients in their lowest possible ratio.**	**$H_2(g) + Cl_2(g) \rightarrow 2HCl(g)$** The ratio 1 hydrogen to 1 chlorine to 2 hydrogen chloride (1:1:2) is the lowest possible ratio because the coefficients cannot be reduced further and still be whole numbers.
6	**Check your work.** Make sure that the chemical formulas are written correctly. Then check that the number of atoms of each element is equal on both sides of the equation. You may want to examine each element in a polyatomic ion separately when checking your solution.	**$H_2(g) + Cl_2(g) \rightarrow 2HCl(g)$** There are two hydrogen atoms and two chlorine atoms on both sides of the equation.

Tips for Balancing Equations

Balancing equations is an essential skill to master in your study of chemistry. The steps that are summarized in **Figure 3.6** will help you balance many equations throughout this course. If you are having trouble balancing a particularly difficult or complex equation, the following tips may be helpful:

- Try balancing the substance with the largest number of atoms, on either side of the equation, first. Balance hydrogen, oxygen, and any element that appears in more than two substances later.
- Balance polyatomic ions as single items, as mentioned in **Table 3.3**.
- If the addition of coefficients to balance one type of atom or polyatomic ion causes another atom or polyatomic ion to be unbalanced, then repeat steps 2 through 4 in **Table 3.3**.
- If you find yourself repeatedly adjusting the same two coefficients, double-check that the formulas are correct.
- An incorrect formula can prevent an equation from balancing. Keep in mind the seven diatomic elements: hydrogen, $H_2(g)$; nitrogen, $N_2(g)$; oxygen, $O_2(g)$; fluorine, $F_2(g)$; chlorine, $Cl_2(g)$; bromine, $Br_2(\ell)$; and iodine, $I_2(s)$.

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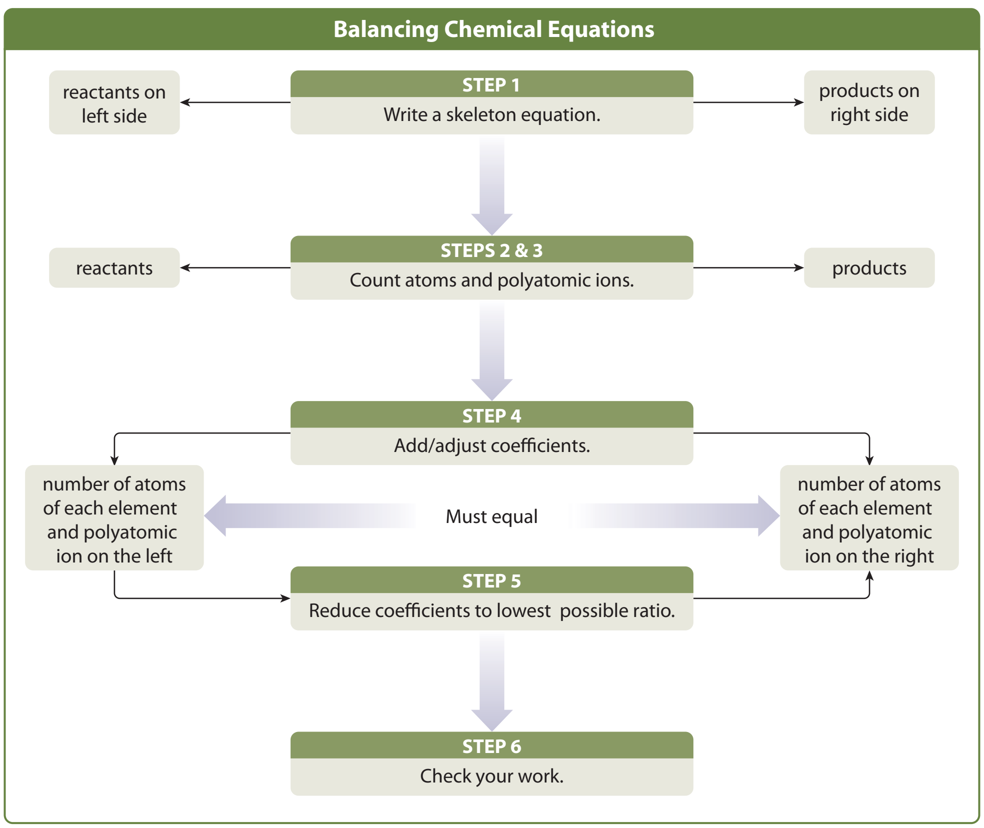

Figure 3.6 The numbered steps in this flowchart show how to balance chemical equations. These steps correspond to the steps in **Table 3.3**.

Uses of Balanced Chemical Equations in Industry

Balanced chemical equations are used in the production of a vast array of products, including pharmaceuticals, fragrances, food additives and flavours, cleaning products, fuels, ceramics, and fertilizers. The chemical engineers who oversee industrial chemical processes make sure that the correct amounts of reactants are used. In Unit 3, you will learn how to use balanced chemical equations to calculate the quantities of reactants and products.

You can practise balancing equations that represent chemical reactions by working through the Sample Problem and Practice Problems on the next page.

Sample Problem

Balancing Chemical Equations

Problem

Write the balanced chemical equation for the reaction that occurs between aqueous solutions of silver nitrate and calcium chloride. Solid silver chloride and an aqueous solution of calcium nitrate are formed.

What Is Required?

A balanced chemical equation that represents the chemical reaction is required.

What Is Given?

You are given the reactants: aqueous silver nitrate and aqueous calcium chloride.
You are given the products: solid silver chloride and aqueous calcium nitrate.

Plan Your Strategy	Act on Your Strategy
Write a skeleton equation. Show the physical state of each reactant and product.	$AgNO_3(aq) + CaCl_2(aq) \rightarrow AgCl(s) + Ca(NO_3)_2(aq)$
Count the atoms or ions of each element in the reactants. Consider a polyatomic ion as a single unit if it appears in the reactants and the products.	Reactants: 1 Ag^+, 1 NO_3^-, 1 Ca^{2+}, 2 Cl^-
Count the atoms or ions of each element in the products.	Products: 1 Ag^+, 2 NO_3^-, 1 Ca^{2+}, 1 Cl^-
Insert the coefficient 2 in front of $AgNO_3$ to balance the nitrate ions.	$2AgNO_3(aq) + CaCl_2(aq) \rightarrow AgCl(s) + Ca(NO_3)_2(aq)$
Insert the coefficient 2 in front of AgCl to balance the silver and chloride ions.	$2AgNO_3(aq) + CaCl_2(aq) \rightarrow 2AgCl(s) + Ca(NO_3)_2(aq)$
Adjust the coefficients if necessary, so they are in the lowest possible ratio.	The ratio 2:1:2:1 cannot be reduced. It is the lowest possible ratio.
Check to make sure that the number of atoms of each element and the number of the same polyatomic ion are equal on both sides of the equation.	Reactants: 2 Ag^+, 2 NO_3^-, 1 Ca^{2+}, 2 Cl^- Products: 2 Ag^+, 2 NO_3^-, 1 Ca^{2+}, 2 Cl^-

Check Your Solution

The chemical formula for each substance is written correctly. The number of atoms of each element and the number of the same polyatomic ion are equal on both sides of the equation. The coefficients are written in the lowest possible ratio. The balanced chemical equation for this reaction is

$$2AgNO_3(aq) + CaCl_2(aq) \rightarrow 2AgCl(s) + Ca(NO_3)_2(aq)$$

Practice Problems

Write a balanced chemical equation for each reaction.

11. $NO(g) + O_2(g) \rightarrow NO_2(g)$

12. $Mg(s) + AlCl_3(aq) \rightarrow Al(s) + MgCl_2(aq)$

13. $NaOH(aq) + CuCl_2(aq) \rightarrow NaCl(aq) + Cu(OH)_2(s)$

14. $C_2H_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

15. $Cu(s) + AgNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + Ag(s)$

16. $Al(s) + MnO_2(s) \rightarrow Al_2O_3(s) + Mn(s)$

17. Propane, $C_3H_8(g)$, burns in the presence of oxygen gas to form carbon dioxide gas and water vapour.

18. Gaseous ammonia and oxygen react to form nitrogen dioxide gas and liquid water.

19. Aqueous solutions of potassium sulfide and cobalt(II) chloride react to form a solution of potassium chloride and a precipitate of cobalt(II) sulfide.

20. Carbon dioxide gas, liquid water, and an aqueous solution of sodium chloride form when hydrogen chloride gas is bubbled through a solution of sodium carbonate.

Section 3.1 REVIEW

Section Summary

- A chemical equation is a representation of a chemical reaction. An arrow separates the reactants from the products. Plus signs separate multiple reactants or products.
- A skeleton equation represents a chemical reaction by using chemical formulas for the reactants and products, and symbols for the physical states of these substances. A skeleton equation is an incomplete representation because it does not show that all the atoms in the reactants must appear in the same quantities in the products.
- A balanced chemical equation uses chemical formulas and coefficients to show the relative number of particles of each substance that is involved in a chemical reaction.
- A balanced chemical equation reflects the law of conservation of mass.
- A balanced equation shows the same number of atoms of each element in the reactants and the products.

Review Questions

1. K/U List three forms of a chemical equation that can be used to represent a chemical reaction.
2. T/I The only reactant in a chemical reaction is potassium chlorate, $KClO_3(s)$. Can this reaction have phosphoryl chloride, $POCl_3(\ell)$, as a product? Explain.
3. C Create a Venn diagram to compare and contrast a word equation and a balanced chemical equation.
4. C What symbols are used to differentiate liquid water from an aqueous solution when writing a chemical equation?
5. A A fume hood provides ventilation to protect people from toxic gases or dust released during a chemical reaction. Consider the reaction
$NaOCl(aq) + 2HCl(aq) \rightarrow Cl_2(g) + NaCl(aq) + H_2O(\ell)$
Identify the reactant or product that requires the use of a fume hood.
6. K/U Why is a skeleton equation considered to be an incomplete description of a reaction?
7. A Adding an effervescent (fizzy) tablet to a glass of water produces the result shown below. Based on this photograph, what symbol should be used in the skeleton equation for at least one of the products?

8. K/U Where are the coefficients placed when balancing a chemical equation?
9. C Make a flowchart to show the sequence of steps that are required to write a balanced chemical equation.
10. K/U Why can you not change a subscript to balance a chemical equation?
11. T/I Write a balanced chemical equation for each chemical reaction.
    - **a.** Solid potassium reacts with gaseous chlorine to form solid potassium chloride.
    - **b.** Aluminum foil is placed in an aqueous solution of copper(II) sulfate, producing solid copper metal and a solution of aluminum sulfate.
    - **c.** Nitrogen gas and hydrogen gas react to form gaseous ammonia.
    - **d.** An aqueous solution of calcium chloride reacts with fluorine gas to form an aqueous solution of calcium fluoride and chlorine gas.
12. T/I Barium hydroxide can react with phosphoric acid to form barium hydrogen phosphate and water:
$Ba(OH)_2(s) + H_3PO_4(aq) \rightarrow BaHPO_4(s) + H_2O(\ell)$
    - **a.** Identify the polyatomic ions in the reactants.
    - **b.** Can each polyatomic ion be treated as a unit when balancing the equation? Explain why or why not.
    - **c.** Write the balanced chemical equation.
13. T/I Sodium hydroxide and sulfuric acid react to form sodium sulfate and water. Does the following chemical equation correctly describe the reaction? If not, explain the error and write the correct chemical equation.
$4NaOH(aq) + 2H_2SO_4(aq) \rightarrow 2Na_2SO_4(aq) + 4H_2O(\ell)$
14. T/I Your friend has written the following balanced equation for the reaction in which aluminum and chlorine form aluminum(III) chloride:
$$Al(s) + Cl(g) \rightarrow AlCl(s)$$
Is this correct? If not, how would you suggest that your friend correct it?