7.1 Chemical Reactions and Chemical Equations

Chemical changes lead to the formation of substances that help grow our food, make our lives more productive, and cure our heartburn.

A **chemical change** or **chemical reaction** is a process in which one or more pure substances are converted into one or more different pure substances. Chemical changes lead to the formation of substances that help grow our food, make our lives more productive, cure our heartburn, and much, much more. For example, nitric acid, HNO_3, which is used to make fertilizers and explosives, is formed in the chemical reaction of the gases ammonia, NH_3, and oxygen, O_2. Silicon dioxide, SiO_2, reacts with carbon, C, at high temperature to yield silicon, Si—which can be used to make computers—and carbon monoxide, CO. An antacid tablet might contain calcium carbonate, $CaCO_3$, which combines with the hydrochloric acid in your stomach to yield calcium chloride, $CaCl_2$, water, and carbon dioxide. The chemical equations for these three chemical reactions are below.

$$NH_3(g) + 2O_2(g) \rightarrow HNO_3(aq) + H_2O(l)$$

$$SiO_2(s) + 2C(s) \xrightarrow{2000\ ^\circ C} Si(l) + 2CO(g)$$

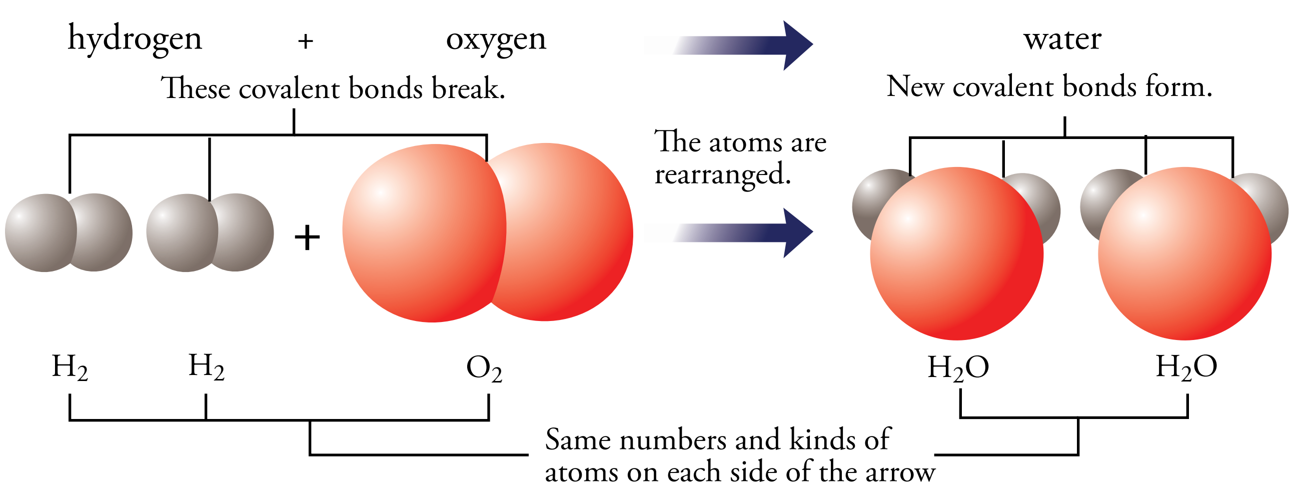
$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$$

Once you know how to read these chemical equations, they will tell you many details about the reactions that take place.

Interpreting a Chemical Equation

In chemical reactions, atoms are rearranged and regrouped through the breaking and making of chemical bonds. For example, when hydrogen gas, $H_2(g)$, is burned in the presence of gaseous oxygen, $O_2(g)$, a new substance, liquid water, $H_2O(l)$, forms. The covalent bonds within the H_2 molecules and O_2 molecules break, and new covalent bonds form between oxygen atoms and hydrogen atoms (Figure 7.1).

Figure 7.1
The Formation of Water from Hydrogen and Oxygen



A chemical equation is a shorthand description of a chemical reaction. The following equation describes the burning of hydrogen gas to form liquid water.

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$$

Objective 2

Chemical equations give the following information about chemical reactions.

- Chemical equations show the formulas for the substances that take part in the reaction. The formulas on the left side of the arrow represent the **reactants**, the substances that change in the reaction. The formulas on the right side of the arrow represent the **products**, the substances that are formed in the reaction. If there are more than one reactant or more than one product, they are separated by plus signs. The arrow separating the reactants from the products can be read as "goes to" or "yields" or "produces."

Objective 3

- The physical states of the reactants and products are provided in the equation. A (g) following a formula tells us the substance is a gas. Solids are described with (s). Liquids are described with (l). When a substance is dissolved in water, it is described with (aq) for *aqueous*, which means "mixed with water."

- The relative numbers of particles of each reactant and product are indicated by numbers placed in front of the formulas. These numbers are called **coefficients**. An equation containing correct coefficients is called a balanced equation. For example, the 2's in front of H_2 and H_2O in the equation we saw above are coefficients. If a formula in a balanced equation has no stated coefficient, its coefficient is understood to be 1, as is the case for oxygen in the equation above (Figure 7.2).

Objective 2

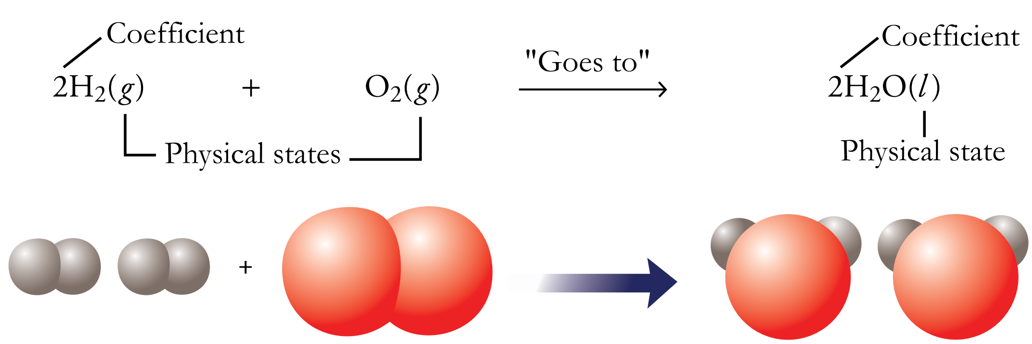


Figure 7.2
The Chemical Equation for the Formation of Water from Hydrogen and Oxygen

- If special conditions are necessary for a reaction to take place, they are often specified above the arrow. Some examples of special conditions are electric current, high temperature, high pressure, and light.

The burning of hydrogen gas must be started with a small flame or a spark, but that is not considered a special condition. There is no need to indicate it above the arrow in the equation for the creation of water from hydrogen and oxygen. However, the conversion of water back to hydrogen and oxygen does require a special condition—specifically, exposure to an electric current:

A special condition

$$2H_2O(l) \xrightarrow{\text{Electric current}} 2H_2(g) + O_2(g)$$

To indicate that a chemical reaction requires the *continuous* addition of heat in order to proceed, we place an upper case Greek delta, Δ, above the arrow in the equation. For example, the conversion of potassium chlorate (a fertilizer and food additive) to potassium chloride and oxygen requires the continuous addition of heat:

This indicates the continuous addition of heat.

$$2KClO_3(s) \xrightarrow{\Delta} 2KCl(s) + 3O_2(g)$$

Balancing Chemical Equations

In chemical reactions, atoms are neither created nor destroyed; they merely change partners. Thus the number of atoms of an element in the reaction's products is equal to the number of atoms of that element in the original reactants. The coefficients we often place in front of one or more of the formulas in a chemical equation reflect this fact. They are used whenever necessary to balance the number of atoms of a particular element on either side of the arrow.

For an example, let's return to the reaction of hydrogen gas and oxygen gas to form liquid water. The equation for the reaction between $H_2(g)$ and $O_2(g)$ to form $H_2O(l)$ shows there are two atoms of oxygen in the diatomic O_2 molecule to the left of the arrow, so there should also be two atoms of oxygen in the product to the right of the arrow. Because each water molecule, H_2O, contains only one oxygen atom, two water molecules must form for each oxygen molecule that reacts. The coefficient 2 in front of the $H_2O(l)$ makes this clear. But two water molecules contain four hydrogen atoms, which means that two hydrogen molecules must be present on the reactant side of the equation for the numbers of H atoms to balance (Figure 7.2 on the previous page).

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$$

Note that we do not change the subscripts in the formulas, because that would change the identities of the substances. For example, changing the formula on the right of the arrow in the equation above to H_2O_2 would balance the atoms without using coefficients, but the resulting equation would be incorrect.

$$H_2(g) + O_2(g) \rightarrow \cancel{H_2O_2}(l)$$

Water is H_2O, whereas H_2O_2 is hydrogen peroxide, a very different substance from water. (You add water to your hair to clean it; you add hydrogen peroxide to your hair to bleach it.)

The following sample study sheet shows a procedure that you can use to balance chemical equations. It is an approach that chemists often call balancing equations "by inspection." Examples 7.1 through 7.5, which follow the study sheet, will help to clarify the process.

Sample Study Sheet 7.1 Balancing Chemical Equations

OBJECTIVE 4

TIP-OFF You are asked to balance a chemical equation.

GENERAL STEPS

- Consider the first element listed in the first formula in the equation.

  If this element is mentioned in two or more formulas on the same side of the arrow, skip it until after the other elements are balanced. (*See Example 7.2.*)

  If this element is mentioned in one formula on each side of the arrow, balance it by placing coefficients in front of one or both of these formulas.

- Moving from left to right, repeat the process for each element.
- When you place a number in front of a formula that contains an element you tried to balance previously, recheck that element and put its atoms back in balance. (*See Examples 7.2 and 7.3.*)
- Continue this process until the number of atoms of each element is balanced.

The following strategies can be helpful for balancing certain equations.

STRATEGY 1 Often, an element can be balanced by using the subscript for this element on the left side of the arrow as the coefficient in front of the formula containing this element on the right side of the arrow, and vice versa (using the subscript of this element on the right side of the arrow as the coefficient in front of the formula containing this element on the left side). (*See Example 7.3.*)

STRATEGY 2 It is sometimes easiest, as a temporary measure, to balance the pure nonmetallic elements (H_2, O_2, N_2, F_2, Cl_2, Br_2, I_2, S_8, Se_8, and P_4) with a fractional coefficient ($\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, etc.). If you do use a fraction during the balancing process, you can eliminate it later by multiplying each coefficient in the equation by the fraction's denominator (which is usually the number 2). (*See Example 7.4.*)

STRATEGY 3 If polyatomic ions do not change in the reaction, and therefore appear in the same form on both sides of the chemical equation, they can be balanced as though they were single atoms. (*See Example 7.5.*)

STRATEGY 4 If you find an element difficult to balance, leave it for later.

EXAMPLES See Examples 7.1 to 7.5.

Example 7.1 - Balancing Equations

Objective 4

Balance the following equation so that it correctly describes the reaction for the formation of dinitrogen oxide (commonly called nitrous oxide), an anesthetic used in dentistry and surgery.

$$NH_3(g) + O_2(g) \rightarrow N_2O(g) + H_2O(l)$$

Solution

The following table shows that the atoms are not balanced yet.

Element	Left	Right
N	1	2
H	3	2
O	2	2

Nitrogen is the first element in the first formula. It is found in one formula on each side of the arrow, so we can try to balance it now. There are two nitrogen atoms on the right side of the equation and only one on the left; we bring them into balance by placing a 2 in front of NH_3.

$$\mathbf{2}NH_3(g) + O_2(g) \rightarrow N_2O(g) + H_2O(l)$$

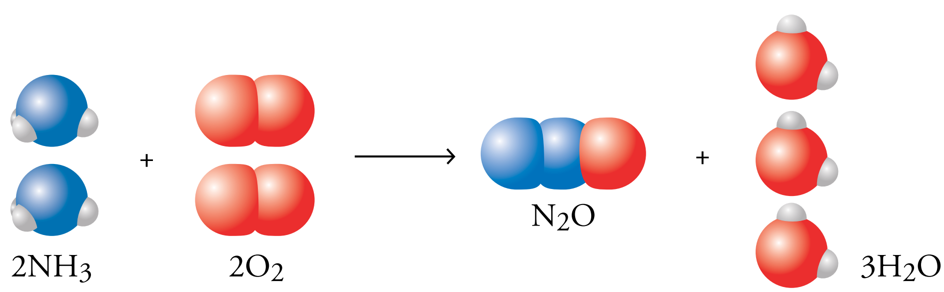
There are now six hydrogen atoms on the left side of the arrow (in the two NH_3 molecules) and only two H's on the right, so we balance the hydrogen atoms by placing a 3 in front of the H_2O. This gives six atoms of hydrogen on each side.

$$\mathbf{2}NH_3(g) + O_2(g) \rightarrow N_2O(g) + \mathbf{3}H_2O(l)$$

There are now two oxygen atoms on the left and four on the right (in one N_2O and three H_2O's), so we balance the oxygen atoms by placing a 2 in front of the O_2.

$$\mathbf{2}NH_3(g) + \mathbf{2}O_2(g) \rightarrow N_2O(g) + \mathbf{3}H_2O(l)$$

The following space-filling models show how you might visualize the relative number of particles participating in this reaction. You can see that the atoms regroup but are neither created nor destroyed.



The following table shows that the atoms are now balanced.

Element	Left	Right
N	2	2
H	6	6
O	4	4

Example 7.2 - Balancing Equations

Objective 4

Balance the following equation.

$$N_2H_4(l) + N_2O_4(l) \rightarrow N_2(g) + H_2O(l)$$

Solution

Nitrogen is the first element in the equation; however, because nitrogen is found in two formulas on the left side of the arrow, we will leave the balancing of the nitrogen atoms until later.

Balance the hydrogen atoms by placing a 2 in front of H_2O.

$$N_2H_4(l) + N_2O_4(l) \rightarrow N_2(g) + \mathbf{2}H_2O(l)$$

Balance the oxygen atoms by changing the 2 in front of H_2O to a 4.

$$N_2H_4(l) + N_2O_4(l) \rightarrow N_2(g) + \mathbf{4}H_2O(l)$$

Because we unbalanced the hydrogen atoms in the process of balancing the oxygen atoms, we need to go back and re-balance the hydrogen atoms by placing a 2 in front of the N_2H_4.

$$\mathbf{2}N_2H_4(l) + N_2O_4(l) \rightarrow N_2(g) + \mathbf{4}H_2O(l)$$

Finally, we balance the nitrogen atoms by placing a 3 in front of N_2.

$$\mathbf{2N_2H_4(l) + N_2O_4(l) \rightarrow 3N_2(g) + 4H_2O(l)}$$

The following table shows that the atoms are now balanced.

Element	Left	Right
N	6	6
H	8	8
O	4	4

Example 7.3 - Balancing Equations

Objective 4

Balance the following equation so that it correctly describes the reaction for the formation of tetraphosphorus trisulfide (used in the manufacture of matches).

$$P_4(s) + S_8(s) \rightarrow P_4S_3(s)$$

Solution

The phosphorus atoms appear to be balanced at this stage.

We can balance the sulfur atoms by using the subscript for the sulfur on the right (3) as the coefficient for S_8 on the left and using the subscript for the sulfur on the left (8) as the coefficient for the sulfur compound on the right. (Strategy 1)

$$P_4(s) + S_8(s) \rightarrow P_4S_3(s)$$

$$P_4(s) + 3S_8(s) \rightarrow 8P_4S_3(s)$$

We restore the balance of the phosphorus atoms by placing an 8 in front of P_4.

$$\mathbf{8P_4(s) + 3S_8(s) \rightarrow 8P_4S_3(s)}$$

Tetraphosphorus trisulfide is used to make matches.

Example 7.4 - Balancing Equations

Objective 4

Balance the following equation so that it correctly describes the reaction for the formation of aluminum oxide (used to manufacture glass).

$$Al(s) + O_2(g) \rightarrow Al_2O_3(s)$$

Solution

Balance the aluminum atoms by placing a 2 in front of the Al.

$$2Al(s) + O_2(g) \rightarrow Al_2O_3(s)$$

There are three oxygen atoms on the right and two on the left. We can bring them into balance by placing $3/2$ in front of the O_2. Alternatively, we could place a 3 in front of the O_2 and a 2 in front of the Al_2O_3, but that would un-balance the aluminum atoms. By inserting only one coefficient, in front of the O_2, to balance the oxygen atoms, the aluminum atoms remain balanced. We arrive at $3/2$ by asking what number times the subscript 2 of the O_2 would give us three atoms of oxygen on the left side: $3/2$ times 2 is 3. (Strategy 2)

$$2Al(s) + \tfrac{3}{2}O_2(g) \rightarrow Al_2O_3(s)$$

It is a good habit to eliminate the fraction by multiplying all the coefficients by the denominator of the fraction, in this case 2. (Some instructors consider fractional coefficients to be incorrect, so check with your instructor to find out if you will be allowed to leave them in your final answer.)

$$\mathbf{4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)}$$

Example 7.5 - Balancing Equations

Objective 4

Zinc phosphate is used to galvanize nails.

Balance the following equation for the chemical reaction that forms zinc phosphate (used in dental cements and for making galvanized nails).

$$Zn(NO_3)_2(aq) + Na_3PO_4(aq) \rightarrow Zn_3(PO_4)_2(s) + NaNO_3(aq)$$

Solution

Balance the zinc atoms by placing a 3 in front of $Zn(NO_3)_2$.

$$3Zn(NO_3)_2(aq) + Na_3PO_4(aq) \rightarrow Zn_3(PO_4)_2(s) + NaNO_3(aq)$$

The nitrate ions, NO_3^-, emerge unchanged from the reaction, so we can balance them as though they were single atoms. There are six NO_3^- ions in three $Zn(NO_3)_2$. We therefore place a 6 in front of the $NaNO_3$ to balance the nitrates. (Strategy 3)

$$3Zn(NO_3)_2(aq) + Na_3PO_4(aq) \rightarrow Zn_3(PO_4)_2(s) + 6NaNO_3(aq)$$

Balance the sodium atoms by placing a 2 in front of the Na_3PO_4.

$$3Zn(NO_3)_2(aq) + 2Na_3PO_4(aq) \rightarrow Zn_3(PO_4)_2(s) + 6NaNO_3(aq)$$

The phosphate ions, PO_4^{3-}, do not change in the reaction, so we can balance them as though they were single atoms. There are two on each side, so the phosphate ions are balanced. (Strategy 3)

$$\mathbf{3Zn(NO_3)_2(aq) + 2Na_3PO_4(aq) \rightarrow Zn_3(PO_4)_2(s) + 6NaNO_3(aq)}$$

Exercise 7.1 - Balancing Equations

Objective 4

Balance the following chemical equations.

a. $P_4(s) + Cl_2(g) \rightarrow PCl_3(l)$
Phosphorus trichloride, PCl_3, is an intermediate for the production of pesticides and gasoline additives.

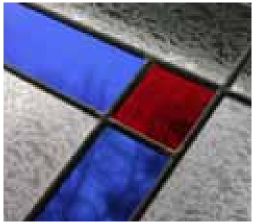
b. $PbO(s) + NH_3(g) \rightarrow Pb(s) + N_2(g) + H_2O(l)$
Lead, Pb, is used in storage batteries and as radiation shielding.

c. $P_4O_{10}(s) + H_2O(l) \rightarrow H_3PO_4(aq)$
Phosphoric acid, H_3PO_4, is used to make fertilizers and detergents.

d. $Mn(s) + CrCl_3(aq) \rightarrow MnCl_2(aq) + Cr(s)$
Manganese(II) chloride, $MnCl_2$, is used in pharmaceutical preparations.

e. $C_2H_2(g) + O_2(g) \rightarrow CO_2(g) + H_2O(l)$
Acetylene, C_2H_2, is used in welding torches.

f. $Co(NO_3)_2(aq) + Na_3PO_4(aq) \rightarrow Co_3(PO_4)_2(s) + NaNO_3(aq)$
Cobalt phosphate, $Co_3(PO_4)_2$, is used to color glass and as an additive to animal feed.



g. $CH_3NH_2(g) + O_2(g) \rightarrow CO_2(g) + H_2O(l) + N_2(g)$
Methylamine, CH_3NH_2, is a fuel additive.

h. $FeS(s) + O_2(g) + H_2O(l) \rightarrow Fe_2O_3(s) + H_2SO_4(aq)$
Iron(III) oxide, Fe_2O_3, is a paint pigment.

You can find a computer tutorial that will provide more practice balancing equations at the textbook's Web site.