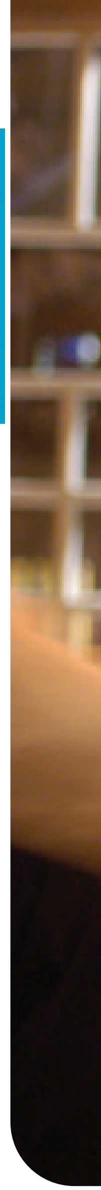
chapter 2

# Chemical Reactions



## In this chapter

Molecules Making Magic (Demonstration)

Web Activity: States of Matter and Changes in Matter

Chemical reactions are not just something that scientists study in a laboratory. Chemical changes or reactions are an essential part of nature—past, present, and future. For example, lightning initiates many chemical reactions in the atmosphere including the formation of nitrogen compounds that provide nutrients to plants on Earth. Plants carry out many chemical reactions, the most important of which is photosynthesis. Animals eat plants and use the chemical reactions of metabolism to survive and grow. Eventually plants and animals die, and their decomposition is another set of chemical reactions. The cycle of life is a cycle of chemical reactions.

Although you can learn some things about chemicals by observing their physical properties, laboratory work involving chemical reactions reveals a great deal more about the compounds. You can make inferences about chemicals based on the changes that occur in chemical reactions. By studying chemical reactions, you can construct generalizations and laws and, eventually, infer the theoretical structure of the compounds involved.

Initially, theories of the structure of matter attempt to explain the known chemical properties of a substance. The validity of a theory is determined by its ability to both explain and predict changes in matter. How and why do chemicals react? What compounds will form as a result of a reaction? How do we explain the different properties of compounds? Chemical combination represents not only the compounds we know, but also the processes or chemical reactions by which we know them.

## STARTING Points

**Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.**

1. List the kinds of evidence that indicate the occurrence of a chemical reaction.
2. Provide a theoretical explanation as to *how* and *why* chemical reactions occur.
3. Describe how an understanding of chemical reaction types can be used to predict the products of a chemical reaction.
4. Describe the process for balancing a chemical reaction equation.
5. The chemical amount of a substance is measured in moles. What is a mole?
6. List some perspectives on a science–technology–society (STS) issue.

Career Connection: Forensic Laboratory Analyst

**Figure 1**
What burns, when a server sets a dish of saganaki aflame?

## Exploration — *Molecules Making Magic (Demonstration)*

Have you ever wondered how magicians set fire to $100 bills without apparently damaging the paper? Or how a server can flambé a dish of food without burning it to a crisp (**Figure 1**)? Here is a teacher demonstration that might help you answer the puzzle of "how do they do that?"

**Materials**: eye protection, lab apron, protective gloves, a 13 × 100 mm test tube with stopper, a small beaker, propan-2-ol (rubbing alcohol), water, table salt, tongs, paper, scissors, safety lighter or match

**Propan-2-ol is highly flammable. Ensure that containers of the alcohol are sealed and stored far from any open flame.**

- Add a few crystals of table salt to a small test tube.
- Add propan-2-ol to nearly half-fill the test tube.
- Add water to nearly fill the test tube.
- Stopper the test tube and invert it several times to dissolve the components.
- Remove the stopper and pour the contents into a small beaker.
- Cut and insert a strip of paper into the alcohol solution.
- Use tongs to remove the paper.
- Remove the beaker of solution from the work area.
- Use the matches or lighter to light the wet paper.
- Repeat.
- Dispose of any excess solution in a waste container.

# 2.1 Science and Technology in Society

**Figure 1**
Many familiar materials, such as plastics, metals, ceramics, and soap, are products of both science and technology.

The science of chemistry goes hand-in-hand with the technology of chemistry: the skills, processes, and equipment required to make useful products, such as water-resistant adhesives, or to perform useful tasks, such as water purification. Chemists make use of many technologies, from test tubes to computers. Chemists may or may not thoroughly understand a particular chemical technology. For example, the technologies of glass-making and soap-making existed long before scientists could explain these processes. We now use thousands of metals, plastics, ceramics, and composite materials developed by chemical engineers and technologists (**Figure 1**). However, chemists do not have a complete understanding of superconductors, ceramics, chrome-plating, and some metallurgical processes. Sometimes technology leads science—as in glass-making and soap-making—and sometimes science leads technology. Overall, science and technology complement one another.

Science, technology, and society (**STS**) are interrelated in complex ways (**Figure 2**). In this chapter and throughout this book, the nature of science, technology, and STS interrelationships will be introduced gradually, so that you can prepare for decision making about STS issues in the 21st century.

You can acquire specialized knowledge, skills, and attitudes for understanding STS issues by studying science. For example, a discussion of global warming becomes an informed debate when you have specific scientific knowledge about the topic; scientific skills to acquire and test new knowledge; and scientific attitudes and values to guide your thinking and your actions. You also need an understanding of the nature of science and of scientific knowledge.

**DID YOU KNOW ?**

**Imagination in Science**

"We especially need imagination in science. It is not all mathematics, nor all logic, but it is somewhat beauty and poetry."

–Maria Mitchell, American astronomer (1818–1889)

Scientists have indicated that, at present, both the observations and the interpretations of global warming are inadequate for fully understanding the present phenomenon and for accurately predicting the situation in the future. However, scientists will always state qualifications such as these, even 100 years from now, no matter how much more evidence is available. In a science course, you learn that scientific knowledge is never completely certain or absolute. When scientists testify in courts of law, present reports to parliamentary committees, or publish scientific papers, they tend to avoid authoritarian, exact statements. Instead, they state their results with some degree of uncertainty. In studying science, you learn to look for evidence, to evaluate experiments, and to attach a degree of certainty to scientific statements. You learn to expect and to accept uncertainty, but to search for increasingly greater certainty. This is the nature of scientific inquiry.

Chemicals and chemical processes represent both a benefit and a risk for our planet and its inhabitants. Chemistry has enabled people to produce more food, to dwell more comfortably in homes insulated with fibreglass and polystyrene, and to live longer, thanks to

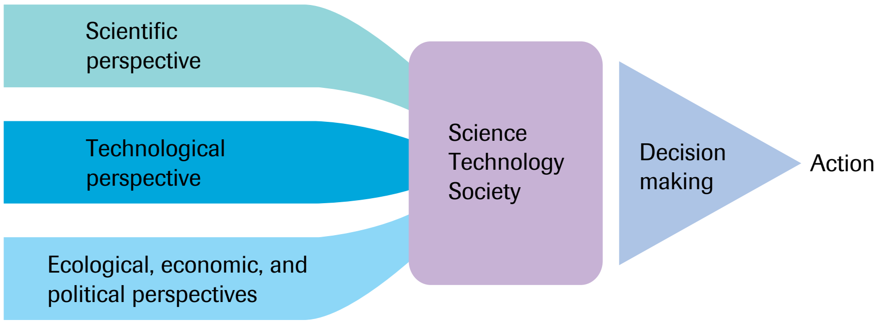



**Figure 2**
Many issues in society involve science and technology. Both the problems and the solutions involve complex interrelationships among these three categories. An example of an STS issue is the problem of climate change.

clean water supplies, more varied diets, and modern drugs. While enjoying these benefits, we also consciously and unconsciously assume certain risks. For example, when chemical wastes are dumped or oil spills into the environment, the effects can be disastrous. Assessing benefits and risks is a part of evaluating advances in science and technology.

The world increasingly depends on science and technology. Our society's affluence has led to countless technological applications of metal, paper, plastic, glass, wood, and other materials. Thousands of new scientific discoveries and technological advances are made each year. As our society embraces more and more sophisticated technology, we tend to seek technological "fixes" for problems, such as chemotherapy in treating cancer, and the use of fertilizers in agriculture. However, a strictly technological approach to problem solving overlooks the multidimensional nature of the problems confronting us.

Deciding how to use science and technology to benefit society is extremely complex. Most STS issues can be discussed from many different points of view, or **perspectives**. Even pure scientific research is complicated by economic and social perspectives. For example, should governments increase funding for scientific research when money is needed for social assistance programs? Environmental problems, such as discharge from pulp mills and air pollution, are controversial issues. For rational discussion and acceptable action on STS issues, a variety of perspectives must be taken into account. For example, five of many possible STS perspectives on air pollution are listed below:

- A **scientific perspective** leads to researching and explaining natural phenomena. Research into sources of air pollution and its effects involves a scientific perspective.
- A **technological perspective** is concerned with the development and use of machines, instruments, and processes that have a social purpose. The use of instruments to measure air pollution and the development of processes to prevent air pollution reflect a technological approach to the issue.
- An **ecological perspective** considers relationships between living organisms and the environment. Concern about the effect of a smelter's sulfur dioxide emissions on plants and animals, including humans, reflects an ecological perspective.
- An **economic perspective** focuses on the production, distribution, and consumption of wealth. The financial costs of preventing air pollution and the cost of repairing damage caused by pollution reflect an economic perspective.
- A **political perspective** involves governments, vote-getting actions or arguments based on an ideology. Debate over proposed legislation to control air pollution involves a political perspective.

**DID YOU KNOW ?**

**Technological Fixes**

Often our first thought when change is required is to ask for a technology to be invented and/or used to solve the problem. Some examples of technological fixes for societal problems (which themselves may create problems) are

- escalators and elevators
- cars and airplanes
- radios and televisions
- the Internet and cellphones
- pesticides and fertilizers
- gasoline and plastics

**Learning Tip**

A mnemonic that may be used to recall these five STS perspectives is STEEP.

## Section 2.1 Questions

1. Identify four or more current STS issues.
2. Classify each of the following statements about aluminium as representing a scientific, technological, ecological, economic, or political perspective:
   (a) Recycled aluminium costs less than one-tenth as much as aluminium produced from ore.
   (b) Aluminium ore mines in South America have destroyed the natural habitat of plants and animals.
   (c) Aluminium is refined in Canada using electricity from hydro-electric dams.
   (d) In Quebec, aluminium is refined using hydro-electric power that some politicians in Newfoundland have claimed belongs to their constituents.
   (e) In 1886, American chemist Charles Hall discovered through research that aluminium can be produced by using electricity to decompose aluminium oxide dissolved in molten cryolite.
3. Instead of changing their lifestyles, many people look to technology to solve problems caused by the use of technology! Suggest one technological fix and one lifestyle change that would help to solve each of the following problems:
   (a) Aluminium ore used to produce aluminium cans will be in short supply soon.
   (b) Aluminium cans are not magnetic and are, therefore, difficult to separate from the rest of the garbage.
   (c) People throw garbage into bins for recyclable aluminium cans.
4. Aluminium is used extensively for making beverage cans. List some benefits and risks of this practice. Are there any alternatives that might have equal or better benefits and fewer risks? Be prepared to argue your case.

www.science.nelson.com GO

# 2.2 Changes in Matter


**Figure 1**
**(a)** Hydrogen is liquified at –253 °C.
$H_2(g) \rightarrow H_2(l)$
**(b)** Hydrogen is burning—as it does during the space shuttle launch and in hydrogen-fueled automobiles.
$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$
**(c)** Hydrogen is undergoing nuclear fusion on the Sun and is being converted into helium.
$H(g) + H(g) \rightarrow He(g)$

The explanation of natural events is one of the aims in science. Careful observation, leading to the formation of a concept or theory, and followed by testing and evaluating the ideas involved, defines the basic process scientists use to increase understanding of the changes going on in the world around us. A useful way to begin is to classify the types of changes that occur in matter. Changes in matter can be explained at three levels according to size. Modern scientists study and discuss matter at a *macroscopic* (naked eye observable) level, or at a *microscopic* (too small to see without a microscope) level, or at a *molecular* (smallest entities of a substance) level. To understand their observations at a molecular level, chemists usually start by basing their explanations on the atomic theory proposed by John Dalton in 1803.

## Types of Changes in Matter

Chemists often describe changes in matter as a physical change, chemical change, or nuclear change (**Figure 1**), depending on whether they believe that a change has occurred in the molecules, electrons, or nuclei of the substance being changed. The quantity of energy associated with every change in matter can also help classify the type of change.

**Physical changes** are any changes where the fundamental entities remain unchanged at a molecular level, such as the phase changes of evaporation and melting. There is no change in the chemical formula of the substance involved (**Figure 1(a)**). Dissolving a chemical is usually classified as a physical change. Other examples include changes in physical structure that change only the shape and appearance. Physical changes in matter usually involve relatively small amounts of energy change.

A **chemical change** involves some kind of change in the chemical bonds within the fundamental entities (between atoms and/or ions) of a substance, and is represented by a change in the chemical formula (**Figure 1(b)**). At least one new substance is formed, with physical and chemical properties different from those of the original matter. Normally, chemical changes involve larger energy changes than physical changes.

**Nuclear changes** (changes within the nucleus) create entirely new atomic entities (**Figure 1(c)**). These entities are represented by formulas that show new atomic symbols, different from those of the original matter. Nuclear changes involve extremely large changes in energy, which allow them to be identified. In 1896, Henri Becquerel noticed the continuous production of energy from a piece of rock that showed no other changes at all. His observation led to the discovery of radioactivity—a nuclear change.

Physical, chemical, and nuclear changes can be described both empirically and theoretically. **Table 1** provides these descriptions, along with an example of each. In this course, we will focus our attention almost entirely on chemical change. We can use classification systems, such as Table 1, to help us to organize our knowledge.

**WWW WEB Activity**

### *Case Study—States of Matter and Changes in Matter*

Watch the movie about properties of matter and physical changes.

(a) What properties of solids, liquids, and gases make them different from one another?

(b) What kinds of physical changes are not mentioned in the movie?

(c) What are some clues that a chemical reaction has taken place?

www.science.nelson.com GO

**Table 1** Physical, Chemical, and Nuclear Change

| Change | Empirical description | Theoretical description |
|---|---|---|
| physical | • state or energy change<br>• solid ⇄ liquid ⇄ gas<br>• no new substance<br>• small energy change | • $H_2(g) \rightarrow H_2(l)$ + energy<br>• $H_2O(s) \rightleftarrows H_2O(l) \rightleftarrows H_2O(g)$<br>• no new atoms/ions/molecules<br>• intermolecular forces broken and made |
| chemical | • colour, odour, state, and/or energy change<br>• new substance formed<br>• new permanent properties<br>• medium energy change | • $2\,H_2(g) + O_2(g) \rightarrow 2\,H_2O(g)$ + energy<br>• old (reactants) → new (products)<br>• atoms/ions/electrons rearranged<br>• chemical bonds broken and made |
| nuclear | • often radiation emitted<br>• new elements formed<br>• enormous energy change | • ${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He$ + energy<br>• new atoms formed<br>• nuclear bonds broken and made |

**EXTENSION**

**Nuclear Change**

There are two types of nuclear change. Read about both and then run the fission and fusion animations.

www.science.nelson.com GO

## The Kinetic Molecular Theory

Scientists observed gas pressure, diffusion, and chemical reactions, and eventually explained their observations using the concept of molecular motion. The idea of molecular motion led to the kinetic molecular theory, which has become a cornerstone of modern science.

The central idea of the **kinetic molecular theory** is that the smallest entities of a substance are in continuous motion. These entities may be atoms, ions, or molecules. As they move about, the entities collide with each other and with objects in their path (**Figure 2**).

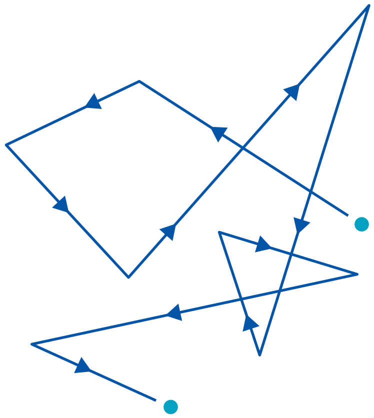


**Figure 2**
Observation of microscopic particles, such as pollen grains or specks of smoke, shows a continuous, random motion. This movement is known as Brownian motion, named for Scottish scientist Robert Brown, who first described it. Scientists' interpretations of this evidence led to the creation of the kinetic molecular theory.

### How and Why Chemical Reactions Occur

Chemical changes are also called chemical reactions. To explain chemical reactions, we can expand the kinetic molecular theory to create a theory of chemical reactions. According to the kinetic molecular theory, the entities of a substance are in continuous, random motion. This motion inevitably results in collisions between the entities. If different substances are present, all the different entities will collide randomly with each other. If the collision has a certain orientation and sufficient energy, the components of the entities will rearrange to form new entities. The rearrangement of entities that occurs is the chemical reaction. This general view of a chemical reaction is known as the *collision–reaction theory* (**Figure 3**).

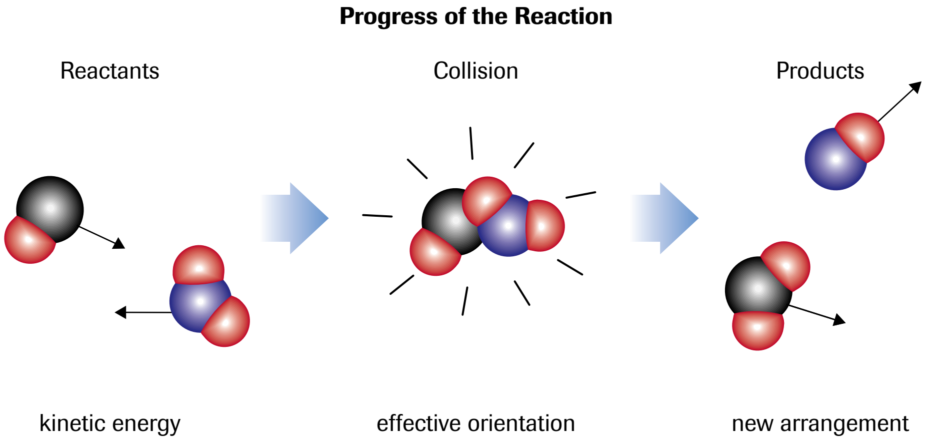



**Figure 3**
Collision–reaction theory explains that chemical entities must collide with the correct orientation to react.

**CAREER CONNECTION**

**Forensic Laboratory Analyst**

As vital members of an investigative team, forensic laboratory analysts examine and test physical evidence related to a criminal offence, and provide expert testimony. With their knowledge of biology and chemistry, they conduct experiments and tests on documents, firearms, and biological tissues.

Find out more about the personal characteristics of these valued law-enforcement scientists.

www.science.nelson.com GO

A theoretical explanation of why chemical reactions occur is partially covered in Chapter 1. Atoms often react in order to obtain a more stable electron arrangement (often an octet of electrons like the nearest noble gas). The how and why of chemical reactions can be summarized in a statement such as, "when chemical entities collide, they may exchange or share electrons to obtain a more favourable (stable) electron arrangement."

## Chemical Reactions

Recall that chemical reactions produce new substances. How do you know if an unfamiliar change is a chemical reaction? Certain characteristic evidence is associated with chemical reactions (**Table 2**).

**Table 2** Evidence of Chemical Reactions

| Evidence | Description and example |
| --- | --- |
| colour change | The final product(s) may have a different colour than the colour(s) of the starting material(s). For example, the solution changes from colourless to blue. |
| odour change | The final material(s) may have a different odour than the odour(s) of the starting material(s). For example, mixing solutions of sodium acetate and hydrochloric acid produces a mixture that smells like vinegar. |
| state change | The final material(s) may include a substance in a state that differs from the starting material(s). Most commonly, either a gas or a solid (precipitate) is produced. |
| energy change | When a chemical reaction occurs, energy in the form of heat, light, sound, or electricity is absorbed or released. For most chemical reactions, the energy absorbed or released is in the form of heat. A common example of an energy change is the combustion, or burning, of a fuel. If energy is absorbed, the reaction is *endothermic*. If energy is released, the reaction is *exothermic*. |

A **diagnostic test** is a short and specific laboratory procedure, with expected evidence and analysis, that is used as an empirical test for the presence of a substance. Diagnostic tests increase the certainty that a new substance has formed in a chemical reaction. Appendix C.4 describes diagnostic tests for chemicals such as hydrogen and oxygen. If the diagnostic test entails a single step for a specific chemical, you may find it convenient to summarize this test using the format, "If [procedure] and [evidence], then [analysis]." An example of a diagnostic test is shown in **Figure 4**.

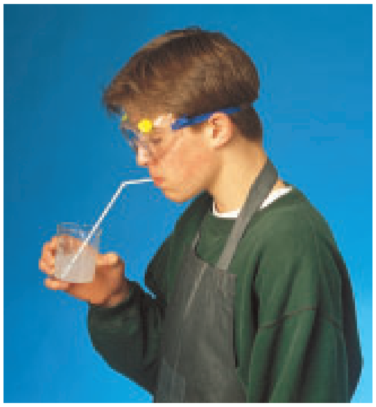


**Figure 4**
If an unidentified gas is bubbled through a limewater solution, and the mixture becomes cloudy, then the gas most likely contains carbon dioxide. The limewater diagnostic test provides evidence for carbon dioxide gas in the breath you exhale.

## Conservation of Mass in Chemical Changes

Experimenters have found that the total mass of matter present after a chemical change is always the same as the total mass present before the change, no matter how different the new substances appear. This finding, called the law of conservation of mass, was one of the compelling reasons why scientists accepted the atomic theory of matter. If a chemical change is thought of as a rearrangement of entities at the molecular level, then it is simple to argue that the mass must be constant. The individual entities do not change, except in the ways they are associated with each other.

## Communicating Chemical Reactions

A **balanced chemical equation** is one in which the total number of each kind of atom or ion in the reactants is equal to the total number of the same kind of atom or ion in the products.

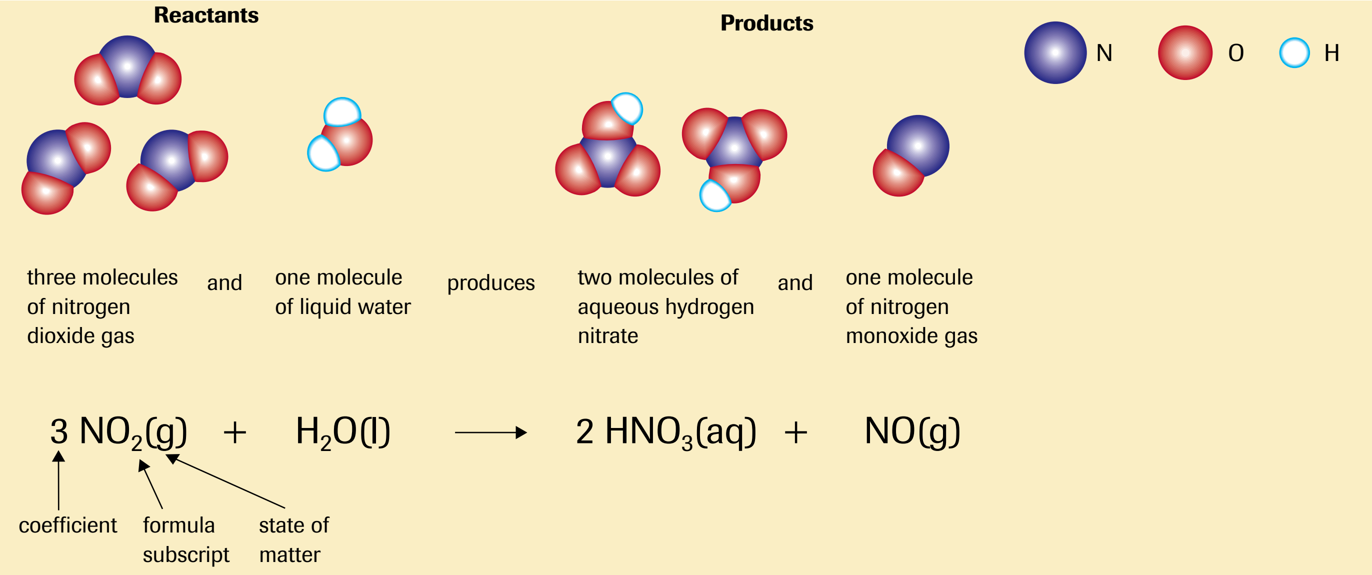



**Figure 5**
The balanced chemical equation and the molecular models for the reactants and products in the chemical reaction of nitrogen dioxide and water. Models such as these help us to visualize non-observable processes.

**Figure 5** shows the balanced chemical equation and molecular models representing the reaction of nitrogen dioxide gas and water to produce nitric acid and nitrogen monoxide gas. By studying the molecular models, you can see there are three nitrogen atoms on the reactant side and three on the product side of the equation arrow. Likewise, there are seven oxygen atoms on both sides of the equation arrow, and two hydrogen atoms.

If more than one molecule is involved (for example, three molecules of nitrogen dioxide), then a number called a **coefficient** is placed in front of the chemical formula. In this example, *three* molecules of nitrogen dioxide and *one* molecule of water react to produce *two* molecules of nitric acid and *one* molecule of nitrogen monoxide. Coefficients are part of a balanced chemical equation and should not be confused with formula subscripts, which are part of the chemical formula for a substance.

A substance's state of matter is given in parentheses after the chemical formula. It is not part of the theoretical description given by the molecular models. Chemical formulas showing states of matter provide both a theoretical and an empirical description of a substance.

## SUMMARY Chemical Reaction Equations

- A chemical reaction is communicated by a balanced chemical equation in which the same number of each kind of atom or ion appears on the reactant and product sides of the equation.
- A *coefficient* in front of a chemical formula in a chemical equation communicates the number of molecules or formula units of a reactant or product that are involved in the reaction.
- Within formulas, a numerical subscript communicates the number of atoms or ions present in one molecule or formula unit of a substance.
- A state of matter in parentheses in a chemical equation communicates the physical state of the reactants and products at SATP.

### DID YOU KNOW ?

**Language**

Learning the language of chemistry is essential to communicating chemical knowledge.

"Language grows out of life, out of its needs and experiences.... Language and knowledge are indissolubly connected; they are interdependent. Good work in language presupposes and depends on a real knowledge of things."

—Annie Sullivan, American educator of persons who were visually and hearing impaired (1866–1936)

## Section 2.2 Questions

1. Provide two examples each of physical, chemical, and nuclear changes.
2. What different entities are rearranged during physical, chemical, and nuclear changes?
3. According to the collision–reaction theory, identify the requirements for a chemical reaction to take place.
4. What is the purpose of classification systems, such as those for types of changes by substances?
5. List four changes that can be used as evidence for chemical reactions.
6. Provide two examples from everyday life of each of the four types of changes listed in your answer to the previous question.
7. Use an "If [procedure] and [evidence], then [analysis]" format to write diagnostic tests for an acid and for hydrogen (see Appendix C.4).
8. Identify one scientific law that led John Dalton to create the theory that atoms are conserved in a chemical reaction.
9. Distinguish between a formula subscript, such as $H_2$, and a coefficient, such as 2 H. How are they similar and how are they different?
10. An investigation is conducted to observe and classify evidence of chemical changes. The substances are mixed and the evidence obtained is recorded in **Table 3**.
    (a) Match as many mixtures as possible to each of the four categories of evidence of chemical reactions (see **Table 2**, page 48).
    (b) Which mixture did not appear to have a chemical reaction? How certain are you about this interpretation?
    (c) In general terms, what additional laboratory work could be done to improve the certainty that a chemical reaction has occurred?

**Extension**

11. A common media mistake is to refer to the dissolving of a chemical in water or the reaction of a metal with a solution as melting. How would you explain to the media that their concept of melting is incorrect?
12. There is debate among chemists as to whether dissolving is a physical change or a chemical change. What does the existence of a debate tell you about classification systems?
13. Evidence-based reasoning is a mainstay of scientific work. There are a few terms that a scientifically literate person needs to know to read newspapers, magazines, and scientific reports (see Appendix B.4.) What do the following terms mean with respect to scientific research?
    (a) anecdotal evidence
    (b) sample size
    (c) replication
    (d) placebo
14. Scholars publish their research in a refereed (peer-reviewed) journal. These journals are like scholarly magazines. Scientists who submit their articles for publication have their research reviewed by their peers (experts in their field of study). Many research reports submitted for publication are rejected because of some fault in the study. As a referee (peer-reviewer), critique the following experimental designs.
    (a) One group of 10 patients is given experimental medication for an illness while another group of 10 patients is not given the medication. The health of all twenty patients is monitored for six months.
    (b) One chemistry teacher completes a unit of study without doing any laboratory work; another teacher completes the same unit of study by doing four laboratory investigations. Student achievement is compared on the results of a unit test.

**Table 3** Evidence for Chemical Reactions

| Mixture | Procedure | Evidence |
|---|---|---|
| 1 | A zinc strip is briefly dipped into a hydrochloric acid solution. | Colourless gas bubbles formed on the strip. |
| 2 | A couple of drops of blue bromothymol blue solution are added to hydrochloric acid. | The blue bromothymol blue solution turned yellow. |
| 3 | A few drops of silver nitrate solution are added to hydrochloric acid. | A white solid (precipitate) formed. |
| 4 | Hydrochloric acid is added to a sodium acetate solution. | The odour of vinegar was evident. |
| 5 | Ammonium nitrate crystals are stirred into water. | The water (solution) felt cool. |
| 6 | Hydrochloric acid is added to a sodium bicarbonate solution. | Colourless gas bubbles formed. |
| 7 | A couple of drops of phenolphthalein solution are added to an ammonia solution. | The colourless phenolphthalein turned red. |
| 8 | Sodium hydroxide solution is added to a cobalt(II) chloride solution. | A blue and/or pink solid (precipitate) formed. |
| 9 | Sodium nitrate solution is added to a potassium chloride solution. | No change was observed. |
| 10 | A copper wire is placed into a silver nitrate solution. | Silvery crystals formed on the wire. |

# Balancing Chemical Reaction Equations 2.3

You are already familiar with some terms used to define convenient numbers (**Table 1**). For example, a dozen is a convenient number referring to such items as eggs or doughnuts. Since atoms, ions, and molecules are extremely small entities, a convenient number for them must be much greater than a dozen. A convenient *amount of substance*—also called the **chemical amount**—is the SI quantity for the number of entities in a substance. It is measured in units of moles (SI symbol, mol). Modern methods of estimating this number of entities have led to the value $6.02 \times 10^{23}$. This value is called **Avogadro's number**, named after the Italian chemist, Amedeo Avogadro (1776–1856). (Avogadro did not determine the number, but he created the research idea.) A **mole** is the unit of chemical amount of substance with the number of entities corresponding to Avogadro's number. For example:

- one mole of sodium is $6.02 \times 10^{23}$ Na atoms
- one mole of chlorine is $6.02 \times 10^{23}$ $Cl_2$ molecules
- one mole of sodium chloride is $6.02 \times 10^{23}$ NaCl formula units

Essentially, a mole represents a number ($6.02 \times 10^{23}$, Avogadro's number), just as a dozen represents the number 12.

Although the mole represents an extraordinarily large number, a mole of a substance is an observable quantity that is convenient to measure and handle. **Figure 1** shows a mole of each of three common substances: one element, one ionic compound, and one molecular compound. In each case, a mole of entities is a sample size that is convenient for lab work.

**Table 1** Convenient Numbers

| Quantity | Number | Example |
|---|---|---|
| pair | 2 | shoes |
| dozen | 12 | eggs |
| gross | 144 | pencils |
| ream | 500 | paper |
| mole | $6.02 \times 10^{23}$ | molecules |

**EXTENSION**

**How Big Is a Mole?**
Extend your understanding of the magnitude of Avogadro's number using analogies.

www.science.nelson.com GO

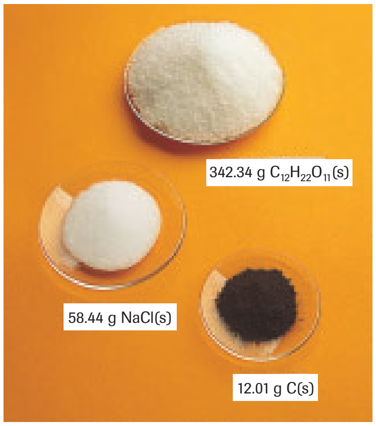



**Figure 1**
These amounts of carbon, table salt, and sugar each contain about a mole of entities (atoms, formula units, molecules) of the substance. The mole represents a convenient and specific quantity of a chemical. Note that equal numbers of entities can have very different volumes and masses.

## Translating Balanced Chemical Equations

A balanced chemical equation can be interpreted theoretically in terms of individual atoms, ions, or molecules, or groups of them. Consider the reaction equation for the industrial production of the fertilizer ammonia:

| $N_2(g)$ + | $3\,H_2(g)$ → | $2\,NH_3(g)$ |
|---|---|---|
| 1 molecule | 3 molecules | 2 molecules |
| 1 dozen molecules | 3 dozen molecules | 2 dozen molecules |
| 1 mol nitrogen | 3 mol hydrogen | 2 mol ammonia |
| $6.02 \times 10^{23}$ molecules | $3(6.02 \times 10^{23})$ molecules | $2(6.02 \times 10^{23})$ molecules |
| $6.02 \times 10^{23}$ molecules | $18.06 \times 10^{23}$ molecules | $12.04 \times 10^{23}$ molecules |

Note that the numbers in each row are *in the same ratio (1:3:2)* whether individual molecules, large numbers of molecules, or moles are considered. When moles are used to express the coefficients in the balanced equation, the ratio of reacting amounts is called the *mole ratio*.

A complete translation of the balanced chemical equation for the formation of ammonia is: "One mole of nitrogen gas and three moles of hydrogen gas react to form two moles of ammonia gas." This translation includes all the symbols in the equation, including coefficients and states of matter.

## DID YOU KNOW ?

**The Mole**

It is difficult for us to get an idea of how large a number the mole is and how small atoms and molecules are. Consider that one mole of water molecules occupies 18 mL of $H_2O(l)$, whereas one mole of marbles would cover planet Earth with a layer 80 km thick.

An experimental method for determining the number of molecules in a mole is to place a one-molecule-thick layer of an insoluble substance on water and use the measurements of mass and volume to calculate Avogadro's number.

## COMMUNICATION example

Translate the following chemical equation into an English sentence.

$$6\ CO_2(g) + 6\ H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6\ O_2(g)$$

### Solution

Six moles of carbon dioxide gas react with six moles of liquid water to produce one mole of aqueous glucose and six moles of oxygen gas.

## Balancing Chemical Equations

A chemical equation is a simple, precise, logical, and international method of communicating the experimental evidence of a reaction. The evidence used when writing a chemical equation is often obtained in stages. First there are some general observations that suggest a chemical change has occurred. These are likely followed by a series of diagnostic tests to identify the products of the reaction. At this stage an unbalanced chemical equation can be written, and then the theory of conservation of atoms can be used to predict the coefficients necessary to balance the reaction equation. In most cases, trial and error, as well as intuition and experience, play an important role in successfully balancing chemical equations. The following summary outlines a systematic approach to balancing equations. Use it as a guide as you study Sample Problem 2.1.

## SUMMARY Balancing Chemical Equations

Step 1: Write the chemical formula for each reactant and product, including the state of matter for each one.

Step 2: Try balancing the atom or ion present in the greatest number. Find the lowest common multiple to obtain coefficients to balance this particular atom or ion.

Step 3: Repeat step 2 to balance each of the remaining atoms and ions.

Step 4: Check the final reaction equation to ensure that all atoms and ions are balanced.

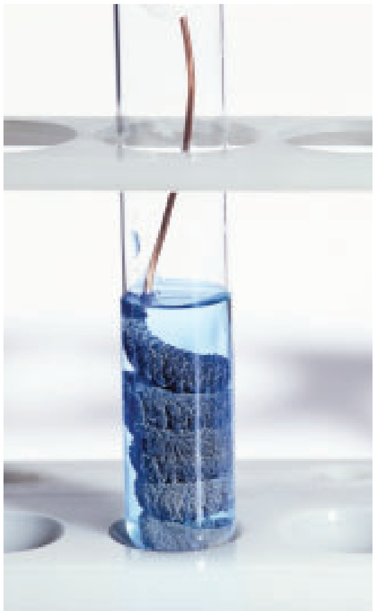


**Figure 2**
The chemical equation must represent the evidence from a reaction between copper and aqueous silver nitrate.

## SAMPLE problem 2.1

A simple technology for recycling silver is to trickle waste solutions containing silver ions over scrap copper. Copper metal reacts with aqueous silver nitrate to produce silver metal and aqueous copper(II) nitrate (**Figure 2**). Write the balanced chemical equation.

Step 1: $?\ Cu(s) + ?\ AgNO_3(aq) \rightarrow ?\ Ag(s) + ?\ Cu(NO_3)_2(aq)$

Step 2: Oxygen atoms are present in the greatest number as part of the nitrate ion, so balance this first. Balance the nitrate ion as a group.

$$?\ Cu(s) + 2\ AgNO_3(aq) \rightarrow ?\ Ag(s) + 1\ Cu(NO_3)_2(aq)$$

Step 3: Balance Ag and Cu atoms. (Always balance elements last.)

$$Cu(s) + 2\ AgNO_3(aq) \rightarrow 2\ Ag(s) + Cu(NO_3)_2(aq)$$

Step 4: The chemical amounts in moles of copper, silver, and nitrate are one, two, and two on both the reactant and the product sides of the equation arrow. (This is a mental check; no statement is required.)

Translation: One mole of solid copper reacts with two moles of aqueous silver nitrate to produce two moles of solid silver and one mole of aqueous copper(II) nitrate.

Use the following techniques for balancing chemical equations:

- Persevere and realize that, like solving puzzles, several attempts may be necessary for more complicated chemical equations.
- The most common student error is to use incorrect chemical formulas to balance the chemical equation. *Always write correct chemical formulas first and then balance the equation as a separate step.*
- If polyatomic ions remain intact, balance them as a single unit.
- Delay balancing any atom that is present in more than two substances in the chemical equation until all other atoms or ions are balanced. (Oxygen atoms in several entities is a common example.)
- Balance elements (entities with only one kind of atom) last.
- If a fractional coefficient is required to balance an atom, multiply all coefficients by the denominator of the fraction to obtain integer values. (Balancing with fractions is correct, but not preferred.)

For example, in balancing the following reaction equation, hydrogen atoms are balanced first, then nitrogen, and oxygen is balanced last. This equation requires 7 mol of oxygen atoms:

$$2\,NH_3(g) + ?O_2(g) \rightarrow 3\,H_2O(g) + 2\,NO_2(g)$$

The only number that can balance the oxygen atoms is $\frac{7}{2}$. By doubling all coefficients, the reaction equation can then be balanced using only integers:

$$4\,NH_3(g) + 7\,O_2(g) \rightarrow 6\,H_2O(g) + 4\,NO_2(g)$$

### DID YOU KNOW?

**Balancing Equations**

There are two general purposes for balancing chemical equations:

- to communicate that atoms/ions are neither created nor destroyed during a chemical reaction
- to calculate the masses and volumes of reactants and products by using the mole ratios of reactants and products (see Unit 4)

### Learning Tip

When water is a product of a reaction, it is often produced as a gas (vapour), $H_2O(g)$. The heat of combustion produces temperatures above the boiling point of water, 100 °C. If the temperature is low and/or the humidity is high, the water condenses to $H_2O(l)$ or freezes to $H_2O(s)$, as seen in vapour trails of cars and jets.

## Section 2.3 Questions

1. Translate the following English sentences into internationally understood balanced chemical equations:
   (a) Two moles of solid aluminium and three moles of aqueous copper(II) chloride react to form three moles of solid copper and two moles of aqueous aluminium chloride. (This reaction does not always produce the expected products listed here.)
   (b) One mole of solid copper reacts with two moles of hydrochloric acid to produce one mole of hydrogen gas and one mole of copper(II) chloride. (When tested in the laboratory, this prediction of products is falsified.)
   (c) Two moles of solid mercury(II) oxide decomposes to produce two moles of liquid mercury and one mole of oxygen gas. (This decomposition reaction is a historical but dangerous method of producing oxygen. Research an MSDS for mercury(II) oxide.)
   (d) Methanol (used in windshield washer antifreeze and as a fuel) is produced from natural gas in world-scale quantities in Medicine Hat, Alberta by the following reaction series:
      (i) One mole of methane gas reacts with one mole of steam to produce one mole of carbon monoxide gas and three moles of hydrogen gas.
      (ii) One mole of carbon monoxide gas reacts with two moles of hydrogen gas to produce one mole of liquid methanol.
2. Translate each of the following chemical equations into an English sentence including the chemical amounts and states of matter for all the substances involved:
   (a) Fire-starters for camp fires often involve the following reaction. Methanol is also a fondue fuel.

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

   (b) Phosphoric acid for fertilizer production is produced from rock phosphorus at Fort Saskatchewan, Alberta:

   $$Ca_3(PO_4)_2(s) + 3\,H_2SO_4(aq) \rightarrow 2\,H_3PO_4(aq) + 3\,CaSO_4(s)$$

   (c) The reaction of sodium with water is potentially dangerous.

   $$2\,Na(s) + 2\,H_2O(l) \rightarrow H_2(g) + 2\,NaOH(aq)$$

   (d) Sulfuric acid can be used as a catalyst to dehydrate sugar.

   $$C_{12}H_{22}O_{11}(s) \rightarrow 12\,C(s) + 11\,H_2O(g)$$

3. Which of the following chemical equations is balanced correctly?

(a) $H_2(g) + O_2(g) \rightarrow H_2O(g)$

(b) $2\ NaOH(aq) + Cu(ClO_3)_2(aq) \rightarrow Cu(OH)_2(s) + 2\ NaClO_3(aq)$

(c) $Pb(s) + AgNO_3(aq) \rightarrow Ag(s) + Pb(NO_3)_2(aq)$

(d) $2\ NaHCO_3(s) \rightarrow Na_2CO_3(s) + CO_2(g) + H_2O(l)$

4. Write a balanced chemical equation for each of the following reactions. Assume that substances are pure and at SATP unless the states of matter are given. Also classify the primary perspective presented in the accompanying statements: The possible perspectives are scientific, technological, ecological, economic, and political.

(a) Research indicates that sulfur dioxide gas reacts with oxygen in the air to produce sulfur trioxide gas.

(b) Sulfur trioxide gas travelling across international boundaries causes disagreements between governments.

sulfur trioxide + water → sulfuric acid

(c) The means exist for industry to reduce sulfur dioxide emissions; for example, by treatment with lime.

calcium oxide + sulfur dioxide + oxygen → calcium sulfate

(d) Restoring acidic lakes to normal pH (acid–base balance) is expensive; for example, adding lime to lakes using aircraft (**Figure 3**).

calcium oxide + sulfurous acid → water + calcium sulfite

**Figure 3**
Helicopters are used to add lime to acidic lakes.

(e) Fish in overly acidic lakes may die from mineral poisoning due to the leaching of, for example, aluminium ions from lake bottoms.

solid aluminium silicate + sulfuric acid → aqueous hydrogen silicate + aqueous aluminium sulfate

(f) Chemical engineers prepare sodium fluoride in large batches for city water or toothpaste distributors.

aqueous sodium chloride + hydrofluoric acid → aqueous sodium fluoride + hydrochloric acid

5. Balance the following equations that communicate reactions that occur before, during, and after the formation of acid rain.

(a) $C(s) + O_2(g) \rightarrow CO_2(g)$

(b) $S_8(s) + O_2(g) \rightarrow SO_2(g)$

(c) $CaSiO_3(s) + H_2SO_3(aq) \rightarrow H_2SiO_3(aq) + CaSO_3(s)$

(d) $CaCO_3(s) + HNO_3(aq) \rightarrow H_2CO_3(aq) + Ca(NO_3)_2(aq)$

(e) $Al(s) + H_2SO_4(aq) \rightarrow H_2(g) + Al_2(SO_4)_3(aq)$

(f) $SO_2(g) + H_2O(l) \rightarrow H_2SO_3(aq)$

(g) $Fe(s) + H_2SO_3(aq) \rightarrow H_2(g) + Fe_2(SO_3)_3(s)$

(h) $CO_2(g) + H_2O(l) \rightarrow H_2CO_3(aq)$

(i) $CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

(j) $FeS(s) + O_2(g) \rightarrow FeO(s) + SO_2(g)$

(k) $H_2S(g) + O_2(g) \rightarrow H_2O(g) + SO_2(g)$

(l) $CaCO_3(s) + SO_2(g) + O_2(g) \rightarrow CaSO_4(s) + CO_2(g)$

6. Balance the following chemical reaction equations and draw molecular models to represent the number and kind of atoms in each molecule.

(a) Hydrogen is used as fuel for the space shuttle.

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

(b) Ammonia fertilizer is produced for agricultural use.

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

(c) Hydrogen chloride gas is produced and then dissolved to make hydrochloric acid to etch concrete.

$H_2(g) + Cl_2(g) \rightarrow HCl(g)$

### Extension

7. Scientists have a high standard for accepting knowledge as valid/acceptable. Write a short procedure for a double blind experimental design to test the effectiveness of using lime to neutralize acid lakes. Reference Appendix B.4.

# Chemical Amount 2.4

Chemists created the concept of the mole. They needed a convenient unit for determining the quantities of chemicals that react and/or are produced in a chemical reaction. You have seen that the mole is a useful unit for communicating reacting amounts in a balanced chemical equation. Now you will learn how to measure chemical amount (in moles) indirectly, by measuring mass directly.

## Molar Mass

The **molar mass**, *M*, of a substance is the mass of one mole of the substance. The unit for molar mass is grams per mole (g/mol) (**Figure 1**). Each substance has a different molar mass, which can be calculated as follows:

1. Write the correct chemical formula for the substance.
2. Determine the chemical amount (in moles) of each atom (or monatomic ion) in one mole of the chemical.
3. Use the atomic molar masses from the periodic table and the chemical amounts (in moles) to determine the mass of one mole of the chemical.
4. Communicate the mass of one mole as the molar mass in units of grams per mole, precise to two decimal places; for example, 78.50 g/mol.

You may also think of the molar mass as a ratio of the mass of a particular chemical to the amount of the chemical in moles. Molar mass is a convenient factor to use when converting between mass and chemical amount. In Sample Problems 2.2 and 2.3, *M* represents the molar mass, and the numbers and atomic molar masses are written out.

When doing calculations involving molar masses, remember that the relevant SI quantities and units are:

- mass, *m*, in grams, g
- chemical amount, *n*, in moles, mol
- molar mass, *M*, in grams per mole, g/mol


**Figure 1**
The molar mass of water is 18.02 g/mol. One mole of water has a mass of 18.02 g and contains $6.02 \times 10^{23}$ molecules of $H_2O$. One mole of liquid water occupies about 18.0 mL.

### Learning Tip

When adding and subtracting measured values, the answer should have the same precision (number of decimal places) as the value with the least precision (number of decimal places). See Appendix F.3.

### SAMPLE problem 2.2

Determine the molar mass of water.

Step 1: Write the correct chemical formula for water: $H_2O(l)$.

Step 2: Determine the chemical amount of each atom in one mole of $H_2O(l)$: one mole of $H_2O$ is composed of $2\ mol_H + 1\ mol_O$

Step 3: Find the mass of one mole of water using the number of atoms and their atomic molar masses from the periodic table.

$$m_{H_2O} = 2\ M_H + 1\ M_O$$
$$= (2\ mol \times 1.01\ g/mol) + (1\ mol \times 16.00\ g/mol)$$
$$= 18.02\ g$$

Step 4: Since this quantity is the mass of one mole of water, the molar mass of water is 18.02 g/mol; that is,

$$M_{H_2O} = 18.02\ g/mol$$

### DID YOU KNOW?

**SI**

SI is the Système International d'Unités or International System of Units. SI is used in all languages to denote this system of units. SI was created by international agreement in 1960. Canada officially became an SI metric country in the early 1970s.

## SAMPLE problem 2.3

What is the molar mass of ammonium phosphate, a fertilizer?

Step 1: Write the correct chemical formula for ammonium phosphate: $(NH_4)_3PO_4(s)$.

Step 2: Determine the chemical amount of each atom in one mole of $(NH_4)_3PO_4(s)$:
One mole of $(NH_4)_3PO_4$ is composed of $3\ mol_N + 12\ mol_H + 1\ mol_P + 4\ mol_O$

Step 3: Find the mass of one mole of ammonium phosphate.

$$m_{(NH_4)_3PO_4} = 3\,M_N + 12\,M_H + 1\,M_P + 4\,M_O$$
$$= (3\text{ mol} \times 14.01\text{ g/mol}) + (12\text{ mol} \times 1.01\text{ g/mol}) + (1\text{ mol} \times 30.97\text{ g/mol}) + (4\text{ mol} \times 16.00\text{ g/mol})$$
$$= 149.12\text{ g}$$

Step 4: Since this quantity is the mass of one mole of ammonium phosphate, the molar mass of this chemical is 149.12 g/mol.

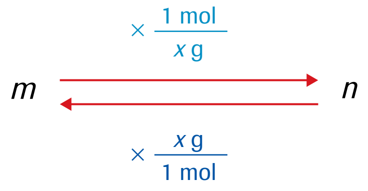



**Figure 2**
Chemists created the concept of molar mass to convert between mass and chemical amount.

## Mass–Amount Conversions

In order to use the mole ratio from the balanced equation to determine the masses of reactants and products in chemical reactions, you must be able to convert a mass to a chemical amount (an amount in moles) and vice versa. To do this, you use either the molar mass as a conversion factor in grams per mole (g/mol), or the reciprocal of the molar mass, in moles per gram (mol/g), and cancel the units (**Figure 2**). Examples of each conversion follow; $n$ represents chemical amount in moles and $m$ represents mass in grams.

For these Communication Examples, note that the molar mass is calculated separately (e.g., in your calculator) and inserted where needed. Your teacher may tell you whether you need to state it separately.

### Learning Tip

The certainty rule is presented in Appendix F.3. A value calculated by multiplying or dividing is no more certain than the least certain of the initial values. (A chain is no stronger than its weakest link.) Certainty is measured in significant digits. All digits except the zeros in front in a correctly measured or calculated value are counted; for example, 0.06 g has a certainty of one significant digit.

## COMMUNICATION example 1

Calcium carbonate helps to neutralize acidic soil under spruce trees. Convert a mass of 1500 g of calcium carbonate to a chemical amount.

### Solution

$$M_{CaCO_3} = 100.09\text{ g/mol}$$

$$n_{CaCO_3} = 1500\ \cancel{\text{g}} \times \frac{1\text{ mol}}{100.09\ \cancel{\text{g}}}$$

$$= 14.99\text{ mol}$$

In Communication Example 1, the appropriate conversion factor is the reciprocal of the molar mass. The certainty of the value for chemical amount (14.99 mol) is four significant digits, resulting from the least certain of four significant digits for 1500 g and five significant digits for 100.09 g/mol.

## COMMUNICATION example 2

Sodium sulfate is mined from lakes and deposits along the Alberta–Saskatchewan border. Convert a reacting amount of 3.46 mmol of sodium sulfate into mass in grams.

### Solution

$M_{Na_2SO_4} = 142.05$ g/mol

$m_{Na_2SO_4} = 3.46 \text{ mmol} \times \dfrac{142.05 \text{ g}}{1 \text{ mol}}$

$= 491$ mg

or

$m_{Na_2SO_4} = 3.46 \text{ mmol} \times \dfrac{1 \text{ mol}}{1000 \text{ mmol}} \times \dfrac{142.05 \text{ g}}{1 \text{ mol}}$

$= 0.491$ g

In Communication Example 2, the certainty of the value for mass (491 mg or 0.491 g) is three significant digits, resulting from the least certain of 3.46 mmol and 142.04 g/mol.

### DID YOU KNOW?

**Sodium Sulfate**

Sodium sulfate as a decahydrate is called Glauber's salt, $Na_2SO_4.10\ H_2O(s)$. The hydrate is used in solar energy storage units. Solar energy as heat is stored when the hydrate changes to an aqueous solution. Sodium sulfate is sometimes used by Alberta pulp and paper plants in the pulp bleaching process.

## Section 2.4 Questions

It helps to memorize the chemical formula or name for each technological or natural substance marked with an asterisk (*).

1. Calculate the molar mass of each of the following substances. The molar masses of water and of carbon dioxide should be memorized for efficient work:
   (a) $H_2O(l)$ (water)*
   (b) $CO_2(g)$ (respiration product)*
   (c) NaCl(s) (pickling salt, sodium chloride)*
   (d) $C_{12}H_{22}O_{11}(s)$ (table sugar, sucrose)*
   (e) $(NH_4)_2Cr_2O_7(s)$ (ammonium dichromate)
2. Communicate the certainty of the following measured or calculated values as a number of significant digits.
   (a) 16.05 g
   (b) 7.0 mL
   (c) 10 $cm^2$
   (d) 0.563 kg
   (e) 0.000 5 L
   (f) 90.00 g/mol
3. Perform the following calculations and express the answer to the correct certainty (number of significant digits).
   (a) $n_{Cu} = 7.46 \text{ g} \times \dfrac{1 \text{ mol}}{63.55 \text{ g}} =$
   (b) $m_C = 2.0 \text{ mol} \times \dfrac{12.01 \text{ g}}{1 \text{ mol}} =$
   (c) $n_{CuSO_4} = 100.0 \text{ mL} \times \dfrac{0.500 \text{ mol}}{1 \text{ L}} =$
   (d) $m_{CuSO_4 \cdot 5H_2O} = 0.05000 \text{ mol} \times \dfrac{249.71 \text{ g}}{1 \text{ mol}} =$
4. Perform the following more advanced calculations by using the precision and/or uncertainty rule where appropriate.
   (a) $m_{NH_3} = 101 \text{ mol} \times \dfrac{17.04 \text{ g}}{1 \text{ mol}} =$
   (b) $V_{n_{CuSO_4}} = 250.0 \text{ mol} \times \dfrac{1 \text{ L}}{5.00 \text{ mol}} =$
   (c) $c_{NaCl} = \dfrac{15.5 \text{ mmol}}{10.00 \text{ mL}} =$
   (d) $V_{avg} = \dfrac{13.6 \text{ mL} + 13.5 \text{ mL} + 13.6 \text{ mL}}{3} =$
   (e) $\% \text{ difference} = \dfrac{|3.67 \text{ g} - 3.61 \text{ g}|}{3.61 \text{ g}} \times 100 =$
   (f) $Q = 50.0 \text{ g} \times 4.19 \text{ J/(g·°C)} \times (34.2 - 15.4)\text{°C}$
5. Calculate the chemical amount of pure substance present in each of the following samples:
   (a) 40.0 g of propane, $C_3H_8(l)$, in a camp stove cylinder
   (b) A 500 g box of pickling salt*
   (c) A 10.00 kg bag of table sugar*
   (d) 325 mg of acetylsalicylic acid (ASA), $C_6H_4COOCH_3COOH(s)$, in a headache relief tablet
   (e) 150 g of isopropanol (rubbing alcohol), $CH_3CH_2OHCH_3(l)$, from a pharmacy
6. Calculate the mass of each of the following specified chemical amounts of pure substances:
   (a) 4.22 mol of ammonia in a window-cleaning solution*
   (b) 0.224 mol of sodium hydroxide (lye) in a drain-cleaning solution*
   (c) 57.3 mmol of water vapour produced by burning methane in a laboratory burner
   (d) 9.44 kmol of potassium permanganate fungicide
   (e) 0.77 mol of ammonium sulfate fertilizer
7. Calculate the mass of each reactant and product from the chemical amount shown in the following equations, and show how your calculations agree with the law of conservation of mass:
   (a) $H_2(g) + Cl_2(g) \rightarrow 2\ HCl(g)$
   (b) $2\ CH_3OH(l) + 3\ O_2(g) \rightarrow 2\ CO_2(g) + 4\ H_2O(g)$

# 2.5 Classifying Chemical Reactions

By analyzing the evidence obtained from many chemical reactions, it is possible to distinguish patterns. On the basis of these patterns, certain generalizations about reactions can be formulated. The generalizations in **Table 1** are based on extensive evidence and provide an empirical classification of most, but not all, common chemical reactions. The five types of reactions are described in the sections that follow. (For now, any reactions that do not fit these categories are classified as "other.")

**Figure 1**
A burning sparkler demonstrates the formation of magnesium oxide by the combustion of magnesium and oxygen. This reaction can be classified as a formation reaction and as a combustion reaction.

**Table 1** Chemical Reactions

| Reaction type | Generalization |
|---|---|
| formation | elements → compound |
| simple decomposition | compound → elements |
| complete combustion | substance + oxygen → most common oxides |
| single replacement | element + compound → element + compound<br>(metal + compound → metal + compound<br>or nonmetal + compound → nonmetal + compound) |
| double replacement | compound + compound → compound + compound |

## Formation Reactions

A **formation reaction** is the reaction of two or more elements to form either an ionic compound (from a metal and a nonmetal) or a molecular compound (from two or more nonmetals). An example of a reaction forming on ionic compound is the reaction of magnesium and oxygen shown in **Figure 1**.

word equation: magnesium + oxygen → magnesium oxide

chemical equation: $2\,Mg(s) + O_2(g) \rightarrow 2\,MgO(s)$

For chemical reactions producing molecular substances, the only products that you will be able to predict at this time are those whose formulas you memorized from **Table 3** in Section 1.6 (page 34); for example, $H_2O$.

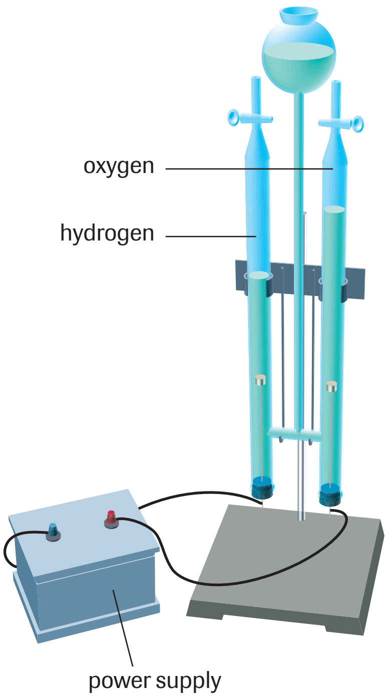



**Figure 2**
The simple decomposition of water is accomplished using a Hoffman apparatus.

## Simple Decomposition Reactions

A **simple decomposition reaction** is the breakdown of a compound into its component elements, that is, the reverse of a formation reaction. Simple decomposition reactions are important historically since they were used to determine chemical formulas. They remain important today in the industrial production of some elements from compounds available in the natural environment. A well-known example that is easy to demonstrate is the simple decomposition of water (**Figure 2**).

word equation: water → hydrogen + oxygen

chemical equation: $2\,H_2O(l) \rightarrow 2\,H_2(g) + O_2(g)$

## Combustion Reactions

A **complete combustion reaction** is the burning of a substance with sufficient oxygen available to produce the most common oxides of the elements making up the substance that is burned. Some combustions, like those in a burning candle or an untuned automobile engine, are incomplete, and also produce the less common oxides such as carbon monoxide. Combustion reactions (**Figure 3**) are exothermic; these reactions provide the major source of energy for technological use in our society.

To successfully predict the products of a complete combustion reaction, you must know the composition of the most common oxides. If the substance being burned contains

- carbon, then $CO_2(g)$ is produced
- hydrogen, then $H_2O(g)$ is produced
- sulfur, then $SO_2(g)$ is produced
- nitrogen, then assume $NO_2(g)$ is produced
- a metal, then the oxide of the metal with the most common ion charge is produced (**Figure 3**)

A typical example of a complete combustion reaction is the burning of butane, $C_4H_{10}(g)$:

word equation: butane + oxygen → carbon dioxide + water

chemical equation: $2\,C_4H_{10}(g) + 13\,O_2(g) \rightarrow 8\,CO_2(g) + 10\,H_2O(g)$

You will learn more about combustion reactions in Section 9.6.

**Figure 3**
A spectacular combustion of a metal is the burning of steel wool in pure oxygen. This reaction is used in fireworks; note that it is also a formation reaction for iron(III) oxide.
$4\,Fe(s) + 3\,O_2(g) \rightarrow 2\,Fe_2O_3(s)$

## Section 2.5 Questions

1. Rewrite each of the following reactions as a word or balanced chemical equation, and classify each reaction as formation, simple decomposition, or complete combustion. Assume the SATP states of matter unless otherwise indicated. For example,
   $2\,Na(s) + Cl_2(g) \rightarrow 2\,NaCl(s)$ (formation)
   sodium + chlorine → sodium chloride

   (a) lithium oxide → lithium + oxygen
   (b) $2\,KBr(s) \rightarrow 2\,K(s) + Br_2(l)$
   (c) $6\,K(s) + N_2(g) \rightarrow 2\,K_3N(s)$
   (d) magnesium oxide → magnesium + oxygen
   (e) $16\,Al(s) + 3\,S_8(s) \rightarrow 8\,Al_2S_3(s)$
   (f) methane + oxygen → carbon dioxide + water (vapour)

2. For each of the following reactions,
   - classify the reaction type as formation or simple decomposition,
   - predict the product(s) of the reaction,
   - complete and balance the chemical equation
   - complete the word equation.

   Assume the most common ion charges and that the products are at SATP.

   (a) Since the Bronze Age (about 3000 B.C.E.), copper has been produced by heating the ore that contains CuO(s).

   copper(II) oxide →

   (b) When aluminium reacts with air, a tough protective coating forms. This coating helps prevent acidic substances, such as soft drinks (**Figure 4**), from reacting with the acids and thereby corroding the aluminium.

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


**Figure 4**
Aluminium does not corrode in air because of a strongly adhering oxide coating.

   (c) Sodium hydroxide can be decomposed into its elements by melting it and passing electricity through it.

   $NaOH(l) \rightarrow$

   (d) Very reactive sodium metal reacts with the poisonous gas chlorine to produce an inert, edible chemical.

   $Na(s) + Cl_2(g) \rightarrow$

   (e) A frequent technological problem associated with the operation of swimming pools is that copper pipes react with aqueous chlorine.

   $Cu(s) + Cl_2(aq) \rightarrow$

(f) A major scientific breakthrough occurred in 1807 when Sir Humphry Davy isolated potassium by passing electricity through molten (melted) potassium oxide.

$K_2O(l) \rightarrow$

(g) When zinc is exposed to oxygen, a protective coating forms on the surface of the metal. This reaction makes zinc coating of metals (galvanizing) a desirable process for resisting corrosion.

zinc + oxygen →

(h) Translate the last equation above into an English sentence. Include the chemical amounts in moles.

**3.** State the names and chemical formulas for the most common oxides of carbon, hydrogen, sulfur, nitrogen, and iron.

**4.** For each of the following complete combustion reactions, complete and balance the chemical equation or complete the word equation. Assume the pure state of matter at SATP unless otherwise indicated.

(a) In Canada, many homes are heated by the combustion of natural gas (assume methane).

$CH_4(g) + O_2(g) \rightarrow$

(b) Nitromethane, $CH_3NO_2(l)$, is a fuel commonly burned in drag-racing vehicles.

nitromethane + oxygen →

(c) Mercaptans (assume $C_4H_9SH(g)$) are added to natural gas to give it a distinct odour. The mercaptan burns with the natural gas.

$C_4H_9SH(g) + O_2(g) \rightarrow$

(d) Ethanol from grain can be added to gasoline as a fuel and antifreeze. It burns along with the gasoline.

ethanol + oxygen →

(e) Write a balanced equation for (d), and then translate the equation into an English sentence. Include the chemical amounts and states of matter.

(f) Most automobiles currently burn gasoline (assume octane) as a fuel.

octane + oxygen →

**5.** Rewrite each of the following reactions as a word equation or a balanced chemical equation, and classify each reaction as formation, simple decomposition, or complete combustion. (Some reactions may have two classifications.)

(a) Electricity is used to produce elements from molten potassium bromide at a high temperature.

$2\,KBr(l) \rightarrow 2\,K(l) + Br_2(g)$

(b) Coal burns in a power plant to produce heat for generating electrical energy.

carbon + oxygen → carbon dioxide

(c) Gasoline antifreeze burns in an automobile engine.

methanol + oxygen → carbon dioxide + water

(d) Poisonous hydrogen sulfide from natural gas is eventually converted to elemental sulfur using this reaction as a first step in about 50 gas plants in Alberta.

$2\,H_2S(g) + 3\,O_2(g) \rightarrow 2\,SO_2(g) + 2\,H_2O(g)$

(e) Hydrogen gas may be the automobile fuel of the future.

hydrogen + oxygen → water

(f) Toxic hydrogen cyanide gas can be destroyed in a waste treatment plant, such as the one at Swan Hills, Alberta.

Four moles of hydrogen cyanide gas react with nine moles of oxygen gas to produce four moles of carbon dioxide gas, two moles of water vapour, and four moles of nitrogen dioxide gas.

**6.** Classify the following reactions as formation, simple decomposition, or complete combustion. Predict the products of the reactions, write the formulas and states of matter, and balance the reaction equations:

(a) $Al(s) + F_2(g) \rightarrow$

(b) $NaCl(s) \rightarrow$

(c) $S_8(s) + O_2(g) \rightarrow$

(d) methane + oxygen →

(e) aluminium oxide →

(f) propane burns

(g) $C_4H_{10}(g) + O_2(g) \rightarrow$

**7.** Describe a technological application for two of the chemical reactions in question 6.

**8.** Write a brief empirical description of reactants and products for two of the chemical reactions in question 6.

**9.** List two benefits and two risks of using combustion reactions. Use examples of a fuel used in your area. Try to use a variety of perspectives in your answer (see Section 2.1, page 45).

**Extension**

**10.** Hydrogen-burning cars may become common in the future. Write perspective statements, pro and/or con, to the resolution that most cars should be burning hydrogen in twenty years. Provide at least one statement from each of scientific, technological, ecological, economic, and political perspectives.

www.science.nelson.com GO

**11.** Dr. John Polanyi is a Canadian Nobel laureate. One reaction that he studied was that of atomic hydrogen gas, H(g), with chlorine gas. Read the story on the Web site and write the chemical equation for this reaction.

www.science.nelson.com GO

# Chemical Reactions in Solution 2.6

The reactions reviewed so far involve pure substances. The remaining two reaction types, single and double replacements, usually occur in aqueous solutions. As you know, substances dissolved in water are indicated by (aq).

A **solution** is a homogeneous mixture (page 12) of a **solute** (the substance dissolved) and a **solvent** (the substance, usually a liquid, that does the dissolving). **Figure 1** shows a common example involving table salt and water. The **solubility** of a substance, which is covered in more detail in Chapter 5, is the maximum quantity of the substance that will dissolve in a solvent at a given temperature. For substances like sodium chloride (in table salt), the maximum quantity that dissolves in certain solvents is large compared with other solutes. Such solutes are said to be very soluble. When very soluble substances are formed as products in a single or double replacement reaction, the maximum quantity of solute that can dissolve is rarely reached; thus, the new substance remains in solution, and an (aq) notation is appropriate. Other substances, such as calcium carbonate (in limestone and chalk), are only slightly soluble. When these substances are formed in a chemical reaction, the maximum quantity that can dissolve is usually reached and most of this substance settles to the bottom as a solid. Solid substances formed from reactions in solution are known as **precipitates** (**Figure 2**, on the next page). They are indicated in a chemical reaction equation by (s).

A *solubility chart* outlines solubility generalizations for a large number of ionic compounds; see **Table 1**. A major purpose of this chart is to predict the state of matter for ionic compounds formed as products of chemical reactions in solution. This summary of solubility evidence is listed in two categories—*very soluble (aq)* (for example, sodium chloride) and *slightly soluble (s)* (for example, calcium carbonate). The solubility of ionic compounds in water can be predicted from the solubility chart.

At this point, you will not be expected to predict the solubility of molecular compounds in water, but you should memorize the examples in **Table 2**. Some elements, like the alkali metals, react with water, but most elements do not react or dissolve in water to any noticeable extent. In general, if an element is a reactant or product in a chemical reaction in an aqueous solution then assume its pure state of matter unless otherwise indicated.

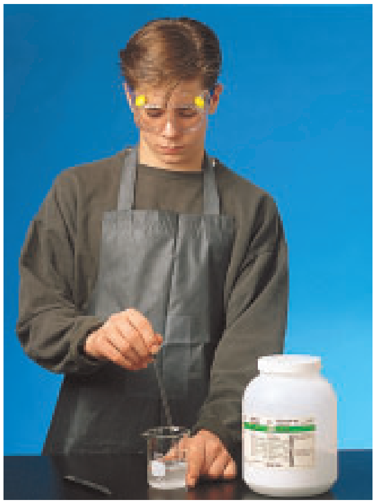


**Figure 1**
Table salt (the solute) is being dissolved in water (the solvent) to make a solution.

**Table 2** Solubility of Selected Molecular Compounds in Water

| Solubility | Examples |
|---|---|
| very soluble | $NH_3(aq)$, $H_2S(aq)$, $H_2O_2(aq)$, $CH_3OH(aq)$, $C_2H_5OH(aq)$, $C_{12}H_{22}O_{11}(aq)$, $C_6H_{12}O_6(aq)$ |
| slightly soluble | $CH_4(g)$, $C_3H_8(g)$,$C_8H_{18}(l)$ |

**Table 1** Solubility of Ionic Compounds at SATP—Generalizations*

| Ion | $Cl^-$ $Br^-$ $I^-$ | $S^{2-}$ | $OH^-$ | $SO_4^{2-}$ | $CO_3^{2-}$ $PO_4^{3-}$ $SO_3^{2-}$ | $CH_3COO^-$ | $NO_3^-$ $ClO_3^-$ $ClO_4^-$ | Group 1 $NH_4^+$ $H_3O^+$ $(H^+)$ |
|---|---|---|---|---|---|---|---|---|
| very soluble (aq) ≥ 0.1 mol/L | most | Group 1, $NH_4^+$, Group 2 | Group 1, $NH_4^+$, $Sr^{2+}$, $Ba^{2+}$, $Tl^+$ | most | Group 1, $NH_4^+$ | most | all | all |
| slightly soluble (s) < 0.1 mol/L (at SATP) | $Ag^+$, $Pb^{2+}$, $Tl^+$, $Hg_2^{2+}$, $Cu^+$ | most | most | $Ag^+$, $Pb^{2+}$, $Ca^{2+}$, $Ba^{2+}$, $Sr^{2+}$, $Ra^{2+}$ | most | $Ag^+$, $Hg_2^{2+}$ | none | none |

*Although these are particularly reliable, all generalizations have exceptions. This textbook specifically identifies any reference to an ionic compound solubility that is an exception to these generalizations.

**Figure 2**
When an iron(III) nitrate solution is added to a sodium phosphate solution, a yellow precipitate forms immediately. Diagnostic tests indicate that the low-solubility product is iron(III) phosphate, as predicted.

### SAMPLE problem 2.4

Iron(III) phosphate is predicted as a product in a chemical reaction. What is the solubility of $FePO_4$?

1. In the top row of the solubility chart, locate the column containing the negative ion $PO_4^{3-}$.
2. Look at the two boxes below this anion to determine in which category the positive ion $Fe^{3+}$ belongs. (A process of elimination may be necessary.)
3. Since $Fe^{3+}$ is not in Group 1, it must belong in the *slightly soluble* category.

We can predict that a precipitate of $FePO_4$(s) forms.

### COMMUNICATION example

Predict the solubility of each of the following ionic compounds by writing their chemical formulas with an (aq) or an (s), indicating very soluble or slightly soluble, respectively.

(a) copper(II) sulfate (b) magnesium carbonate (c) silver acetate (d) potassium iodide (e) ammonium chloride

#### Solution

(a) $CuSO_4$(aq) (b) $MgCO_3$(s) (c) $AgCH_3COO$(s) (d) KI(aq) (e) $NH_4Cl$(aq)

## Single Replacement Reactions

A **single replacement reaction** is the reaction of an element with a compound to produce a new element and an ionic compound. This reaction usually occurs in aqueous solutions. For example, silver can be produced from copper and a solution of silver ions (**Figure 3**):

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cu(s) | + | 2 $AgNO_3$(aq) | → | 2 Ag(s) | + | $Cu(NO_3)_2$(aq) |
| copper (metal) | + | silver nitrate (compound) | → | silver (metal) | + | copper(II) nitrate (compound) |

Iodine can be produced from chlorine and aqueous sodium iodide:

| | | | | | | |
|---|---|---|---|---|---|---|
| $Cl_2$(g) | + | 2 NaI(aq) | → | $I_2$(s) | + | 2 NaCl(aq) |
| chlorine (nonmetal) | + | sodium iodide (compound) | → | iodine (nonmetal) | + | sodium chloride (compound) |

We can predict the very soluble (aq) states for the two ionic products, copper(II) nitrate and sodium chloride, from the solubility chart (**Table 1**, page 61). Evidence shows that *a metal replaces a metal ion to liberate a different metal as a product* (as in the first preceding example) and *a nonmetal replaces a nonmetal ion to liberate a different nonmetal as a product* (as in the second example). Reactive metals, such as those in Groups 1 and 2, react with water to replace the hydrogen, forming hydrogen gas and a hydroxide compound. (In these reactions, hydrogen acts like a metal.)

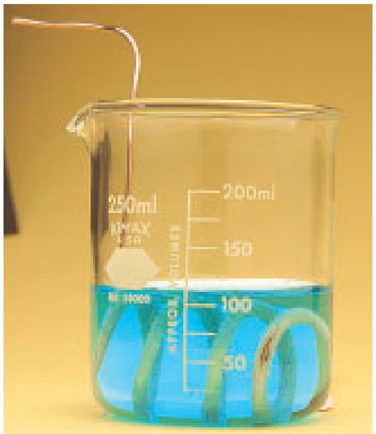



**Figure 3**
The blue solution verifies the prediction that the most common ion of copper, $Cu^{2+}$(aq), is formed.

## Double Replacement Reactions

A **double replacement reaction** can occur between two ionic compounds in solution. In the reaction, the ions, by analogy, "change partners" to form the products. If one of the products is slightly soluble, it may form a precipitate, as shown in **Figure 4**. As the term implies, **precipitation** is a double replacement reaction in which a solid substance forms. For example:

$$\begin{array}{lllllllll} CaCl_2(aq) & + & Na_2CO_3(aq) & \rightarrow & CaCO_3(s) & + & 2\,NaCl(aq) \\ \text{compound} & + & \text{compound} & \rightarrow & \text{compound} & + & \text{compound} \end{array}$$

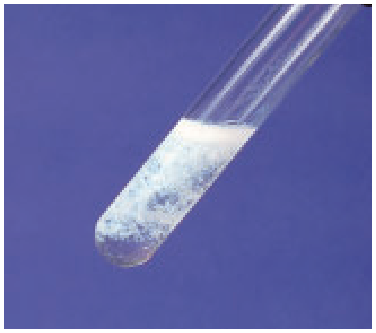


**Figure 4**
A white precipitate forms when colourless aqueous solutions of calcium chloride and sodium carbonate are mixed.

Remember that chemists have created solubility generalizations to help us organize our knowledge. The generalizations serve our purpose and are only approximations of what is found in nature. There are always exceptions to generalizations.

In another kind of double replacement reaction, an acid reacts with a base, producing water and an ionic compound. This kind of double replacement reaction is known as **neutralization**. The reaction between hydrochloric acid and potassium hydroxide is an example:

$$\begin{array}{lllllllll} HCl(aq) & + & KOH(aq) & \rightarrow & H_2O(l) & + & KCl(aq) \\ \text{acid} & + & \text{base} & \rightarrow & \text{water} & + & \text{ionic compound (a salt)} \end{array}$$

When writing chemical equations for both precipitation and neutralization reactions, consult the solubility chart (**Table 1**, page 61) to determine the state of matter of the ionic products. For neutralization reactions, it may be easier to balance the equation if you temporarily write the chemical formula for water as HOH(l) rather than $H_2O(l)$.

## SUMMARY Predicting Chemical Reactions

**Table 3** Reaction Generalizations

| Type of reaction | Generalization | Notes |
|---|---|---|
| formation | element + element → compound | metal + nonmetal → ionic compound<br>nonmetal + nonmetal → molecular compound |
| simple decomposition | compound → element + element | |
| complete combustion | element or compound + oxygen → oxide | assume most common oxides are formed |
| single replacement | element + compound → element + compound | metal + compound → metal + compound<br>nonmetal + compound → nonmetal + compound<br>metal + acid → hydrogen + compound |
| double replacement | compound + compound → compound + compound | precipitation reaction:<br>solution + solution → precipitate + solution<br>neutralization reaction:<br>acid + base → water + aqueous ionic compound |

To write the correct chemical equation for a reaction, follow these steps:

Step 1: Use the reaction generalizations to classify the reaction.

Step 2: Use the reaction generalizations to predict the products of the chemical reaction and write the chemical equation.

(a) Predict, from theory, the chemical formulas for ionic compounds, and write the formulas from memory for molecular compounds and elements.

(b) Include states of matter, using the rules and generalizations.

Step 3: Balance the equation without changing the chemical formulas.

**+ EXTENSION**

### Hard and Soft Water

Precipitation reactions affect our water supply. Extend your understanding of precipitation by hearing about the everyday chemistry of hard and soft water.

www.science.nelson.com GO

## Section 2.6 Questions

1. The following chemical reactions occur in a water environment (e.g., in water in a beaker). Write the balanced chemical equation, including the states of matter, (s) or (aq), for each reaction:
   (a) lead(II) nitrate + lithium chloride → lead(II) chloride + lithium nitrate
   (b) ammonium iodide + silver nitrate → silver iodide + ammonium nitrate
   (c) The net reaction during the discharge cycle of a car battery is one mole of lead and one mole of solid lead(IV) oxide reacting with two moles of sulfuric acid to produce two moles of water and two moles of lead(II) sulfate.

2. The following reactions occur in a water environment. Write the balanced chemical equation, including SATP states of matter, for each chemical.
   (a) Copper can be extracted from solution by reusing cans that contain iron.
   iron + copper(II) sulfate → copper + iron(III) sulfate
   (b) Water can be clarified by producing a gelatinous precipitate.
   aluminium sulfate + calcium hydroxide → aluminium hydroxide + calcium sulfate
   (c) Chlorine is used to extract bromine from sea water.
   $Cl_2(g) + NaBr(aq) \rightarrow Br_2(l) + NaCl(aq)$
   (d) During photosynthesis in a plant, carbon dioxide reacts with water to produce glucose and oxygen.
   carbon dioxide + water → glucose + oxygen

3. Use the solubility table (**Table 1**, page 61), the generalization that all elements (except chlorine) are slightly soluble in water, and the molecular solubility in **Table 2** to predict the solubility of the following chemicals in water. Classify the chemical and then write the chemical formula with (aq) to indicate that the chemical is very soluble and with the pure state of matter, (s), (l), or (g), to indicate that the chemical is slightly soluble.
   (a) Zn (dry cell container and reactant)
   (b) $P_4$ (white phosphorus)
   (c) $C_{12}H_{22}O_{11}$ (sugar)
   (d) methanol (windshield and gasoline antifreeze)
   (e) octane (gasoline component)
   (f) barium sulfate (gastric X-rays)
   (g) sodium hydroxide (drain cleaner)
   (h) ammonia (window and general cleaner)
   (i) hydrogen fluoride (used to etch glass)

4. Communication systems are very important in chemistry. Describe the difference in what is being communicated in the following sets of symbols.
   (a) $P_4$ and 4 P
   (b) $Cl_2(g)$ and $Cl(g)$
   (c) Hg(l) and Hg(g)
   (d) $H_2O_2$ and $H_2 + O_2$
   (e) NaCl(l) and NaCl(aq)
   (f) Mg and $Mg^{2+}$

5. For each of the following reactions, classify the reaction, predict the products of the reaction, and complete and balance the chemical equation. (Assume the most common ion charge and state at SATP if not indicated otherwise.)
   (a) Expensive silver metal is recovered in a lab by placing inexpensive aluminium foil in aqueous silver nitrate.
   $Al(s) + AgNO_3(aq) \rightarrow$
   (b) When aqueous potassium hydroxide is added to a well-water sample, the formation of a rusty-brown precipitate indicates the presence of an iron(III) compound in the water.
   $KOH(aq) + FeCl_3(aq) \rightarrow$
   (c) A chemist in a consumer-protection laboratory adds aqueous sodium hydroxide to determine the concentration of acetic acid, $CH_3COOH(aq)$, in a vinegar sample.
   (d) A dishonest 16th-century alchemist, who tried to fool people into believing that iron could be changed into gold, dipped an iron strip into aqueous copper(II) sulfate.
   (e) Translate equation (d) into an English sentence. Include the chemical amounts and states of matter.

6. Complete the Prediction and diagnostic tests of the investigation report. Write up the diagnostic tests (Appendix C.4), including any controls, as part of the Design.

   **Problem**

   What are the products of the reaction of sodium metal and water?

   **Design**

   A very small piece of sodium metal is placed in distilled water and some diagnostic tests are carried out to identify the products....

7. State diagnostic tests for each of the product(s) in the following chemical reactions. Use the "If (procedure) and (evidence), then (analysis)" format.
   (a) $2\,H_2O(l) \rightarrow 2\,H_2(g) + O_2(g)$
   (b) $H_2(g) + Cl_2(aq) \rightarrow 2\,HCl(aq)$
   (c) $NH_3(g) + H_2O(l) \rightarrow NH_4OH(aq)$

### Extension

8. Critiquing and creating experimental designs are important skills for scientific literacy. Create experimental designs to test at least two of the claims made by the following individuals.
   (a) A salesperson claims that wrapping magnets around water pipes will reduce the amount of hard-water scaling that accumulates on the inside of the pipes.
   (b) A psychic claims that he can see halos over the heads of some identified individuals in the audience and not over others.
   (c) A psychic claims to be able to bend spoons with his mind—a feat of psychokinesis.
   (d) A salesperson claims that a copper bracelet relieves pain in the wrist.

# Chapter 2 SUMMARY

## Outcomes

### Knowledge

- use kinetic molecular theory and collision theory to explain how chemical reactions occur (2.2)
- write balanced chemical equations (2.2, 2.3)
- interpret balanced chemical equations in terms of chemical amount (in moles) (2.3)
- convert between chemical amount and mass (2.4)
- classify chemical reactions (2.5, 2.6)
- predict the solubility of elements and ionic and molecular compounds in water (2.6)
- predict products for chemical reactions (2.5, 2.6)

### STS

- state the technological application of important chemicals and chemical reactions (2.1, 2.3, 2.4, 2.5, 2.6)
- identify risks and benefits of some important chemical reactions (2.1, 2.3, 2.5)

### Skills

- read and write laboratory reports (2.6)
- create and critique experimental designs (2.6)

## Key Terms

**2.1**
STS
perspective
scientific
technological
ecological
economic
political

**2.2**
physical change
chemical change
nuclear change
kinetic molecular theory
diagnostic test
balanced chemical equation
coefficient

**2.3**
chemical amount
Avogadro's number
mole

**2.4**
molar mass

**2.5**
formation reaction
simple decomposition reaction
complete combustion reaction

**2.6**
solution
solute
solvent
solubility
precipitate
single replacement reaction
double replacement reaction
precipitation
neutralization

## MAKE a summary

1. Use the Key Terms to prepare concept maps that are centred on chemical reactions. Include, along with an example of each:
   (a) evidence for the occurrence of chemical reactions
   (b) classes of chemical reactions
   (c) solubility of elements, ionic compounds, and molecular compounds
   (d) perspectives on an STS issue
2. Search for ways to link the concept maps prepared in the previous question.
3. Refer back to your answers to the Starting Points questions at the beginning of this chapter. How has your thinking changed?

## Go To

www.science.nelson.com GO

The following components are available on the Nelson Web site. Follow the links for *Nelson Chemistry Alberta 20–30*.

- an interactive Self Quiz for Chapter 2
- additional Diploma Exam-style Review questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in the chapter.

## EXTENSION

CBC radio ONE QUIRKS & QUARKS

### Science and the Courts

Scientific evidence is increasingly being introduced into legal cases: DNA, blood alcohol levels, psychological profiles—all are intended to support either the prosecution's or the defence's case. But are the "facts" beyond doubt? Three experts give their opinions about interpreting scientific evidence for the courts.

www.science.nelson.com GO

**Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix H. Exam study tips and test-taking suggestions are on the Nelson Web site. Science Directing Words used in Diploma Exams are in bold type.**

www.science.nelson.com GO

**DO NOT WRITE IN THIS TEXTBOOK.**

## Part 1

**1.** NR Pentane, $C_5H_{12}(g)$, is a major component of naptha, the fuel manufactured by chemical engineers for camp stoves (**Figure 1**). The complete combustion of pentane is represented by the chemical equation

__ $C_5H_{12}(g)$ + __ $O_2(g) \rightarrow$ __$CO_2(g)$ + __ $H_2O(g)$

When the equation is balanced, the coefficients are ____, ____, ____, ____.


**Figure 1**
Naphtha is a popular camp fuel because it is easy to transport. It does, however, require careful handling, as the HHP symbols indicate.

**2.** NR Environmental chemists have found that nitrogen oxides, $NO_x$, can cause acid rain, as shown by the chemical equation

__ $NO_2(g)$ + __ $H_2O(l) \rightarrow$ __ $HNO_3(aq)$ + __ $NO(g)$

When the equation is balanced the coefficients are ____, ____, ____, ____.

**3.** Classification systems help us organize our knowledge. A reaction in which a precipitate is formed when two solutions of ionic compounds are mixed is classified as a
A. formation reaction
B. single replacement reaction
C. double replacement reaction
D. simple decomposition reaction

**4.** Research indicates that manufactured chemicals are among the most persistent pollutants on Earth. Scientists have found some chemicals in the tissues of polar bears, seals, tropical birds, dolphins, and humans. The primary perspective of this research is
A. technological
B. ecological
C. economic
D. scientific

**5.** The concept that the smallest entities of a substance are in continuous motion is central to
A. Dalton's atomic theory
B. Rutherford's atomic theory
C. the kinetic molecular theory
D. the law of conservation of mass

**6.** Chemists classify an acid–base neutralization reaction as a
A. formation reaction
B. single replacement reaction
C. double replacement reaction
D. simple decomposition reaction

## Part 2

**7.** Use the solubility table (**Table 1** on page 61 or inside back cover), the generalization that all elements (except chlorine) are only slightly soluble in water, and the molecular solubilities in **Table 2** (page 61) to **predict** the solubility of the following chemicals in water. Classify the chemical and then write the chemical formula with (aq) if chemical is very soluble and with the pure state of matter, (s), (l), or (g), if the chemical is slightly soluble in a water environment.
(a) sucrose (table sugar)
(b) methane (natural gas)
(c) calcium sulfate (gypsum)
(d) carbon (charcoal/graphite)
(e) sulfuric acid (car batteries)
(f) sodium carbonate (water softener)
(g) ammonium nitrate (fertilizer)
(h) sulfur (from $H_2S$ in sour gas)
(i) silver bromide (photographic film)
(j) magnesium hydroxide (milk of magnesia)

**8.** For each of the following word equations, write a balanced chemical equation, and classify the reaction.
(a) aqueous sodium hydroxide + sulfuric acid → water + sodium sulfate
(b) propane + oxygen → carbon dioxide + water
(c) aluminium + aqueous copper(II) chloride → copper + aluminium chloride
(d) molten sodium hydroxide → sodium + oxygen + hydrogen
(e) calcium + chlorine → calcium chloride
(f) aqueous lead(II) nitrate + aqueous sodium chloride → lead(II) chloride + sodium nitrate

**9.** Classify each of the following reactions as formation, simple decomposition, complete combustion, single replacement, or double replacement. **Predict** the products of the reactions, write the chemical formulas and states of matter, and balance the reaction equations.
(a) $KCl(s) \rightarrow$
(b) $Cu(s) + Cl_2(g) \rightarrow$
(c) $C_5H_{12}(g) + O_2(g) \rightarrow$
(d) $AgNO_3(aq) + NaCl(aq) \rightarrow$
(e) $Al(s) + Cu(NO_3)_2(aq) \rightarrow$
(f) $C_8H_{18}(l) + O_2(g) \rightarrow$
(g) $Al_2O_3(s) \rightarrow$
(h) $Fe(s) + Br_2(l) \rightarrow$
(i) $Cu(NO_3)_2(aq) + NaOH(aq) \rightarrow$
(j) $H_3PO_4(aq) + Ca(OH)_2(aq) \rightarrow$

**10.** Translate each of the following balanced equations into an English sentence. Include the chemical amounts and the states of matter for all the substances involved.
(a) $4\ NH_3(g) + 7\ O_2(g) \rightarrow 4\ NO_2(g) + 6\ H_2O(g)$
(b) $3\ CaCl_2(aq) + 2\ Na_3PO_4(aq) \rightarrow Ca_3(PO_4)_2(s) + 6\ NaCl(aq)$
(c) $2\ NaCl(l) \rightarrow 2\ Na(l) + Cl_2(g)$

**11.** **Describe** diagnostic tests for each of the product(s) in the following chemical reactions. Use the "If (procedure) and (evidence), then (analysis)" format (Appendix C.4).
(a) $2\ K(s) + 2\ H_2O(l) \rightarrow 2\ KOH(aq) + H_2(g)$
(b) $SO_3(g) + H_2O(l) \rightarrow H_2SO_4(aq)$
(c) $Cl_2(g) + 2\ NaI(aq) \rightarrow 2\ NaCl(aq) + I_2(s)$

**12.** Complete the Prediction and diagnostic tests of the investigation report. **Describe** the diagnostic tests, including any controls, as part of the Design. Use the "If (procedure) and (evidence), then (analysis)" format for the diagnostic tests.

### Problem
What are the products of the reaction of iron metal and hydrochloric acid?

### Design
A short piece of iron wire is placed in a dilute solution of hydrochloric acid and some diagnostic tests are carried out to identify the products.…

# Unit REVIEW

**Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix H. Exam study tips and test-taking suggestions are on the Nelson Web site. Science Directing Words used in Diploma Exams are in bold type.**

www.science.nelson.com GO

**DO NOT WRITE IN THIS TEXTBOOK.**

## Part 1

**1.** The modern periodic table was developed from evidence of periodicity in chemical and physical properties. The periodic table is an efficient means of organizing a vast body of empirical knowledge of the elements.

The scientist who created the first periodic table was

A. Niels Bohr
B. John Dalton
C. Albert Einstein
D. Dmitri Mendeleev

Use a periodic table to answer questions 2 to 6.

**2.** The family of elements listed in Group 2 of the periodic table is known as the

A. actinoids
B. alkali metals
C. alkaline-earth metals
D. transition elements

**3.** All the members of a certain family of elements are soft, silver-coloured conductors of electricity that react violently with water and form ions with a 1+ charge. The family name for this group of elements is

A. halogens
B. noble gases
C. alkali metals
D. alkaline-earth metals

**4.** All the members of a certain family of elements are very reactive and form ions with a 1– charge. The family name for this group of elements is

A. actinides
B. halogens
C. alkali metals
D. lanthanoids

**5.** NR The number of protons, electrons, and neutrons, respectively in an ion of lithium-7 are

___ ___ ___ ___

**6.** NR The number of protons, electrons, and neutrons, respectively in an atom of carbon-14 are

___ ___ ___ ___

**7.** Chemists often classify changes in matter as physical change, chemical change, or nuclear change. An example of a physical change is

A. formation
B. combustion
C. evaporation
D. neutralization

**8.** An equation that represents a physical change is

A. $H_2O(g) \rightarrow H_2O(l)$
B. $2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$
C. $2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(l)$
D. $2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$

Use this information to answer questions 9 and 10. Some descriptors may be used more than once.

Physical and chemical changes can be described empirically. The empirical descriptions include:

1. odour change
2. state change
3. colour change

List, in numerical order, the description(s) that applies/apply to each of the following reactions.

**9.** NR $2\ C_8H_{18}(l) + 25\ O_2(g) \rightarrow 16\ CO_2(g) + 18\ H_2O(g)$

___ ___ ___ ___

**10.** NR $Zn(s) + CuSO_4(aq) \rightarrow Cu(s) + ZnSO_4(aq)$

___ ___ ___ ___

**11.** NR Knowledge can be classified as

1. empirical
2. theoretical

Use the above classes of knowledge (i.e., 1 and 2) to classify the following statements, in order:

- A yellow precipitate formed.
- Atoms/ions were rearranged.
- Chemical bonds were broken and formed.
- The solution changed from purple to colourless.

___ ___ ___ ___

**12.** NR The multiple-step industrial process for producing sodium carbonate uses common salt (sodium chloride) and limestone (calcium carbonate) as raw material.

$\_\_NaCl(s) + \_\_CaCO_3(s) \rightarrow \_\_CaCl_2(s) + \_\_Na_2CO_3(s)$

The coefficients for balancing the overall reaction equation are, in order, ___ ___ ___ ___

**13.** NR Propane is widely used as fuel for heating and cooking.

$\_\_C_3H_8(g) + \_\_O_2(g) \rightarrow \_\_CO_2(g)\ \_\_H_2O(g)$

The coefficients for balancing the reaction equation for the complete combustion of propane are, in order,

___ ___ ___ ___

**14.** NR A spontaneous chemical reaction occurs when a crumpled piece of aluminium foil is dropped into a beaker of aqueous copper(II) sulfate.

$\_\_Al(s) + \_\_CuSO_4(aq) \rightarrow \_\_Cu(s) + \_\_Al_2(SO_4)_3(aq)$

The coefficients for the balanced reaction equation are, in order, ___ ___ ___ ___

**15.** NR An early industrial process for producing sodium metal involved the electrolysis of molten sodium hydroxide.

$\_\_NaOH(l) \rightarrow \_\_Na(l) + \_\_H_2(g) + \_\_O_2(g)$

The coefficients for the balanced reaction equation are, in order, ___ ___ ___ ___

**16.** The basic SI unit for chemical amount is the
A. gram
B. litre
C. metre
D. mole

**17.** The units for the molar mass of a chemical are
A. g/mol
B. g/L
C. mol/L
D. mol/g

**18.** NR An alcohol lamp uses 2.50 mol of methanol, $CH_3OH(l)$, while providing emergency lighting. The mass of methanol burned is _______________ g.

**19.** NR A student obtains 150 g of ammonium sulfate, $(NH_4)_2SO_4(s)$, to prepare a fertilizer solution. The chemical amount of ammonium sulfate obtained is _______________ mol.

**20.** NR A laboratory technician needs 7.50 mmol of potassium permanganate, $KMnO_4(s)$, to prepare a solution for use in a chemical analysis. The mass of potassium permanganate required is _______________ g.

**21.** NR The lead(II) ions in a waste laboratory solution precipitate as lead(II) carbonate, $PbCO_3(s)$. If 285 g of dry lead(II) carbonate is produced, the chemical amount of lead(II) ions precipitated is _______________ mol.

## Part 2

Use a periodic table to answer questions 22 to 24.

**22.** The periodic table summarizes and organizes a wealth of empirical and theoretical knowledge about chemical elements. **Define** the following terms associated with the periodic table:
(a) group
(b) period
(c) staircase line

**23.** Copy and complete the following table of atoms and ions.

**Table 1** Atoms and Ions

| Symbol | Name | # protons | # electrons | Net charge |
|---|---|---|---|---|
| | sulfide ion | | | |
| | | 35 | 36 | |
| $Ca^{2+}$ | | | | |
| | | 23 | 23 | |
| | | 26 | | 3+ |
| | | | 18 | 0 |

**24.** Many radioisotopes are produced artificially for use in medical diagnosis or therapy. Copy and complete the following table of radioisotopes assuming they are used as atoms.

**Table 2** Radioisotopes

| Name | Use | # protons | # electrons | # neutrons |
|---|---|---|---|---|
| cobalt-60 | cancer treatment | | | |
| | hyperthyroid treatment | 53 | | 78 |
| | reduces white cell count | | 15 | 17 |
| strontium-85 | bone scanning | | | |

**25.** For each of the following word equations, write a balanced chemical equation and classify the reaction.
(a) Butane, $C_4H_{10}(g)$, is a convenient fuel for camping (**Figure 1**).
butane + oxygen → carbon dioxide + water vapour

**Figure 1**
Many campers cook with a butane camp stove.

(b) Beautiful crystals form when copper objects are immersed in silver nitrate solutions.
copper + silver nitrate → copper(II) nitrate + silver
(c) Toxic cadmium ions can be removed from industrial effluent by sodium carbonate.
cadmium nitrate + sodium carbonate → sodium nitrate + cadmium carbonate
(d) Sir Humphry Davy discovered potassium by using electricity to decompose molten potassium hydroxide.
potassium hydroxide → potassium + oxygen + hydrogen
(e) Very pure or freshly cleaned aluminium forms a protective oxide coating when it is exposed to air.
aluminium + oxygen → aluminium oxide

**26.** Balance the following reaction equations, and then write the equation in words, including the states of matter and chemical amounts.

(a) Methanol burners keep food warm at a buffet.
$CH_3OH(l) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

(b) Phosphate ions can be removed from solution by adding calcium chloride.
$Na_3PO_4(aq) + CaCl_2(aq) \rightarrow NaCl(aq) + Ca_3(PO_4)_2(s)$

**27.** Complete and then balance the following chemical equations.

(a) Magnesium burns with a brilliant white light.
$Mg(s) + O_2(g) \rightarrow$

(b) The industrial production of sodium metal involves using electricity to decompose molten sodium chloride.
$NaCl(l) \rightarrow$

(c) Aluminium sulfate and sodium hydroxide solutions react to form a gelatinous precipitate.
$Al_2(SO_4)_3(aq) + NaOH(aq) \rightarrow$

(d) When its protective coating is removed, aluminium reacts vigorously with hydrochloric acid.
$Al(s) + HCl(aq) \rightarrow$

(e) Candles are included in emergency kits because they can produce both heat and light.
$C_{25}H_{52}(s) + O_2(g) \rightarrow$

**28.** Complete the Prediction and Design of the investigation report. Include three diagnostic tests in the Design to determine whether the predicted reaction has taken place and the predicted products have formed.

### Problem

What are the products of the reaction of aqueous copper(II) chloride and sodium hydroxide solution?

**29.** For each of the following reactions, translate the information into a balanced reaction equation. Then classify the main perspective—scientific, technological, ecological, economic, or political—suggested by the introductory statement.

(a) Oxyacetylene torches are used to produce high temperatures for cutting and welding metals such as steel (**Figure 2**). This process involves burning acetylene, $C_2H_2(g)$, in pure oxygen.

(b) During chemical research conducted in 1808, Sir Humphry Davy produced magnesium metal by decomposing molten magnesium chloride using electricity.

(c) An inexpensive application of single replacement reactions uses scrap iron to produce copper metal from waste copper(II) sulfate solutions.

(d) The emission of sulfur dioxide into the atmosphere creates problems between different levels of government, both nationally and internationally. Sulfur dioxide is produced when zinc sulfide is roasted in a combustion-like reaction in a zinc smelter.

(e) Burning leaded gasoline added toxic lead compounds to the environment, which damaged both plants and animals. Leaded gasoline contained tetraethyl lead, $Pb(C_2H_5)_4(l)$, which undergoes a complete combustion reaction in a car engine.

**Figure 2**
The flame of an oxyacetylene torch is hot enough to melt most metals.

**30.** Classify the perspective being communicated by each of the following statements about global warming.

(a) An invention is needed to remove carbon dioxide from gases emitted from oil refineries and power plants.

(b) More research is needed to confirm or refute the causes of global warming.

(c) The cost for stopping global warming is enormous.

(d) Votes can be won or lost over global warming.

(e) Profits will be reduced if greenhouse gas emissions are to be reduced.

**31.** Critiquing and creating experimental designs are important skills for scientific literacy. Create experimental designs to test at least two of the claims made by the following individuals. (See Appendix B.4.)

(a) A believer in the power of magnets claims that sleeping with flexible and padded magnets in your pillow provides a more restful sleep.

(b) A group of disbelievers claims that the photos and video from the 1969 Apollo 11 landing on the moon are fake because the shadows created by the Sun are not parallel in the video and photos.

(c) A psychic claims to be able to reproduce simple drawings made by a person who comes up from the audience.

(d) An alternative medical care provider claims to be able to cure a disease that standard medical practices cannot.

(e) A commercial for a shampoo claims that your hair will have more body if you use this shampoo.

(f) A commercial claims that a particular detergent removes grass stains from clothes better than other leading detergents.

**32.** Complete the Prediction (including possible diagnostic tests), Analysis (including reaction types), and Evaluation (Parts 2 and 3) for the following investigation report.

### Purpose
To test the single and double replacement reaction generalizations.

### Problem
What reaction products are formed when the following substances are mixed?
(a) aqueous chlorine and potassium iodide solution
(b) solutions of magnesium chloride and sodium hydroxide
(c) solutions of aluminium nitrate and sodium phosphate
(d) magnesium metal and hydrochloric acid
(e) sodium hydroxide solution and chromium(III) chloride solution
(f) lithium metal and water
(g) a clean cobalt strip and a silver nitrate solution
(h) nitric acid and an ammonium acetate solution

### Design
Diagnostic test information such as evidence of chemical reactions (**Table 2**, page 48), ion colours and solubilities (reference tables, inside back cover), and specific tests for products (Appendix C.4), are predicted, for convenience, along with the balanced chemical equations in the Prediction. The general plan is to observe the substances before and after mixing, and conduct the appropriate diagnostic tests.

### Evidence

**Table 3** Single and Double Replacement Reactions

| Reaction | Observations |
|---|---|
| (a) | • The colourless solutions produced a yellow-brown colour when mixed (**Figure 3**).<br>• A violet-purple colour appeared in the chlorinated layer when a hydrocarbon was added. |
| (b) | • The colourless solutions produced a white precipitate when mixed. |
| (c) | • The colourless solutions produced a white precipitate when mixed. |
| (d) | • The silvery solid added to the colourless solution produced gas bubbles and a green solution.<br>• The gas produced a pop sound when ignited. |
| (e) | • The colourless sodium hydroxide and green chromium(III) chloride solutions produced a dark precipitate and a colourless solution. |
| (f) | • The soft, silvery solid and colourless liquid produced gas bubbles and a colourless solution (**Figure 4**).<br>• The gas produced a pop sound when ignited.<br>• Red litmus turned blue in the final solution.<br>• The final solution produced a bright red flame colour. |
| (g) | • The silvery solid and colourless solution produced a pink solution and silvery needles. |
| (h) | • The colourless solutions remained colourless when mixed.<br>• A vinegar odour was produced. |

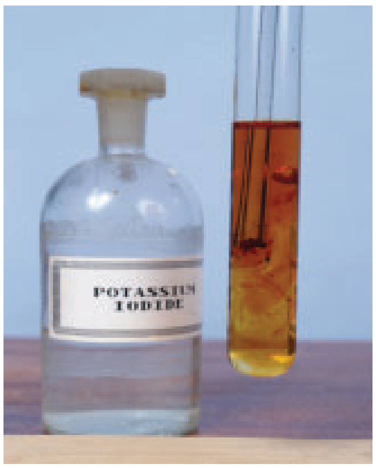



**Figure 3**
Chlorine reacting with potassium iodide.

**Figure 4**
The reaction of lithium with water.