unit **Review**

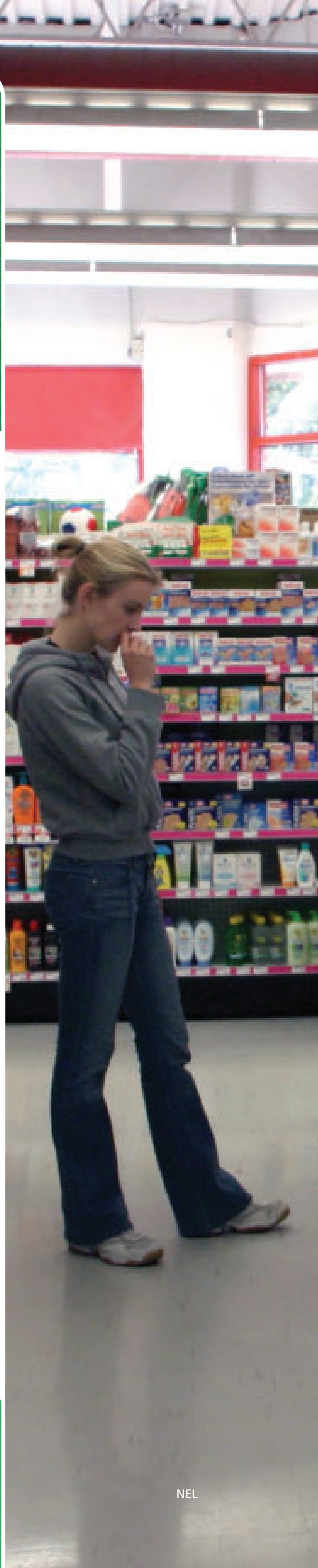
Chemistry Review

"As a high school chemistry teacher, I have had opportunities to be creative, tell stories, play, learn, and teach chemistry in everyday life. I have explored the chemistry of pottery, food and cooking, and silver-smithing, and toured local industrial plants in the coal, aluminium, iron, and oil industries. I have enjoyed the taste and chemistry of wine, beer, and chocolate with fellow colleagues, and learned about the properties and characteristics that make each of these products so special."

Figure 1
Peggy Au

Peggy Au, Winston Churchill High School
Lethbridge, Alberta

Chemistry is everywhere, from the colourful Canada Day fireworks display to the ingredients in toothpaste and cosmetics at the local pharmacy and grocery store. "Chemical" is one of those words that people often associate with negative feelings or dangerous consequences. In fact, the comfortable lives we lead are due in large part to our understanding and application of chemistry. Some chemicals are harmful to people or the environment, but many are integral to life, such as the carbon dioxide, oxygen, water, and glucose in the cycle of photosynthesis and cellular respiration. The air we breathe and the food we eat are all based on the elements of the periodic table and their combinations. The water we drink must be processed chemically and physically before it is considered safe. Rocks and minerals form the foundation of the non-living environment. For example, magnesium carbonate from the Rocky Mountains becomes a main component of sidewalks in our bustling cities. Mined metal ores become pots, pans, building components, and jewellery. Copper pans cannot be used for cooking acidic foods such as tomatoes and lemon juice because they cause the copper to oxidize. Cookies baked without baking soda are as hard as rocks. Chemistry is discovery, and a sense of wonder about how and why elements interact and combine in the natural and human-made world. Chemistry surrounds us.



GENERAL OUTCOMES

In this unit, you will

- use atomic theory and the periodic table to classify, describe, explain, and predict the properties of the elements
- use atomic, ionic, and bonding theories to describe, explain, and predict the properties and chemical formulas for compounds
- use reaction generalizations to describe, explain, and predict simple chemical reactions
- describe the processes of science and the nature of scientific knowledge
- describe the differences between and interdependence of science and technology
- employ decision-making processes on science–technology–society issues

Chemistry Review

ARE YOU READY?

These questions will help you find out what you already know, and what you need to review, before you continue with this unit.

Knowledge

1. To facilitate the use of this textbook as a reference, answer the following questions. Use the periodic table and the Appendices to help you find the answers in the most efficient way. Include with your answer the textbook section where you found the answer.
   (a) What is the atomic number and melting point for the element copper?
   (b) From the Appendix, what is the chemical formula and recommended name for baking soda?
   (c) Sketch an Erlenmeyer flask.
   (d) Which variable should be listed on the vertical (y) axis of a graph?
   (e) Write the definition for "science" as found in the textbook.
   (f) What is the melting point of aluminium?
   (g) Describe the first step in the procedure for lighting a laboratory burner.
   (h) From the Appendix, list the headings for writing a laboratory report.
   (i) Describe the WHMIS symbol for a flammable chemical.

Skills

Refer to the Appendices to help you answer the following questions.

2. A student attempting to identify a pure substance from its density obtained the evidence shown in **Table 1**.
   (a) Construct and label a mass–volume graph from the evidence in **Table 1**.
   (b) From the graph, what mass of the substance has a volume of 12.7 mL?
   (c) From the graph, describe the relationship of mass and volume for this solid.

Table 1 Mass and Volume of a Solid

Mass (g)	Volume (mL)
1.2	3.6
1.8	5.5
2.3	6.9
3.1	9.2
6.9	20.7

3. Imagine that a vacuum cleaner salesperson comes to your home to demonstrate a new model. The salesperson cleans a part of your carpet with your vacuum cleaner, and then cleans the same area again using the new model. A special attachment on the new model lets you see the additional dirt that the new model picked up. Analysis seems to indicate that the new model does a better job. Evaluate the experimental design and provide your reasoning.

4. List the manipulated and responding variables and one controlled variable of this experimental problem: "How does altitude affect the boiling point of pure water?"

5. Write an experimental design to answer the problem in question 4.

6. How must you dispose of the following substances in the laboratory?
   (a) broken beaker
   (b) corrosive solutions
   (c) toxic compounds

Prerequisites

Skills

- use a textbook, periodic table, and other references efficiently and effectively
- identify and know how to use basic chemistry laboratory equipment
- create and interpret a table of evidence and a graph of the evidence
- read and write laboratory reports
- create and critique experimental designs
- interpret WHMIS symbols and MSDS data sheets
- operate safely in a chemistry laboratory
- appropriately dispose of waste in a chemistry laboratory

You can review prerequisite concepts and skills on the Nelson Web site and in the Appendices.

A Unit Pre-Test is also available online.

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7. Draw a floor plan of the laboratory where you will be working. On your plan indicate the location of the following:
   (a) entrances (exits), including the fire exit
   (b) storage for aprons and eye protection
   (c) eyewash station
   (d) first-aid kit
   (e) fire extinguisher(s)
   (f) MSDS binders
   (g) container for broken glass

8. List the actions you should take if
   (a) your clothing catches fire
   (b) someone else's clothing catches fire

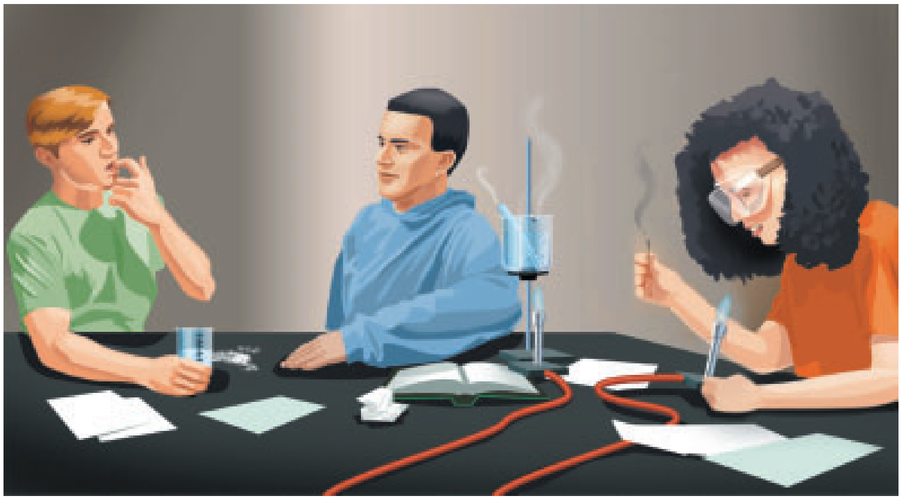

Figure 1
What is unsafe in this picture?

9. Examine **Figure 1**. What safety rules are the students breaking?

10. (a) Identify the WHMIS symbols in **Figure 2**.
    (b) What should you do immediately if any chemical comes in contact with your skin?

11. Describe the procedure for lighting a burner by giving the correct sequence for the photographs in **Figure 3**. You may use a photograph more than once.

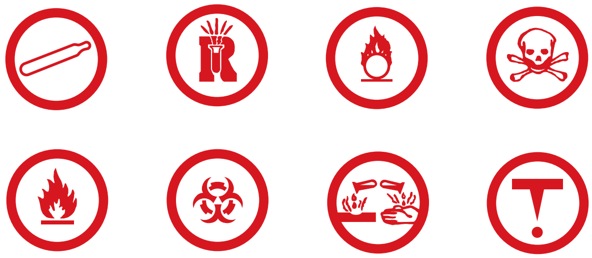

Figure 2
The Workplace Hazardous Materials Information System (WHMIS) provides information regarding hazardous products.

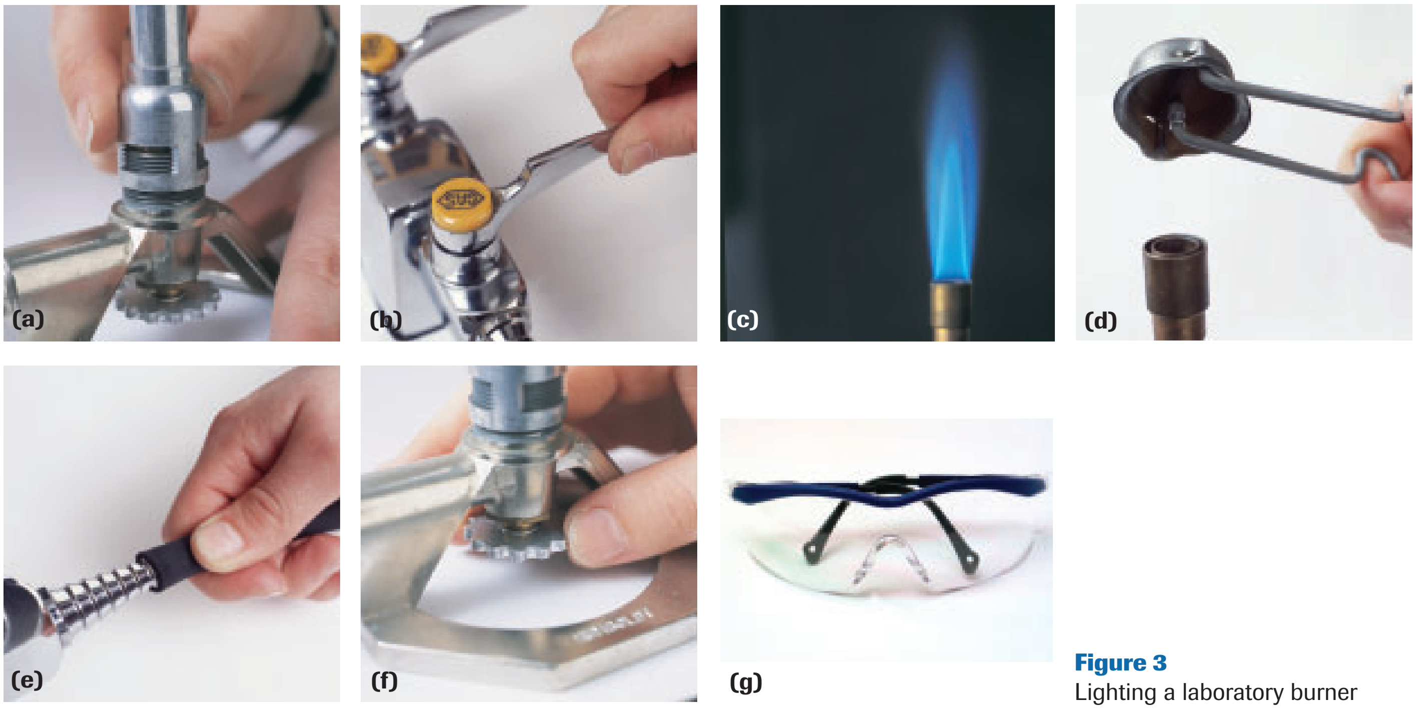

Figure 3
Lighting a laboratory burner

chapter

1 Elements and Compounds

In this chapter

- Exploration: Combustion of Magnesium (Demonstration)
- Web Activity: Groups of Elements
- Web Activity: The Rutherford Scattering Experiment
- Web Activity: Emission and Absorption Spectra for Hydrogen
- Web Activity: Harriet Brooks

We could argue that chemistry is responsible for some of the hazards of modern life: environmental damage resulting from resource extraction; the toxic effects of some products; and the challenge of garbage disposal. However, that argument ignores the underlying truth: Chemistry has been fundamental to the development of society as we know it. We now have cleaner fuel, more durable and safer paints, easy-care clothing, inexpensive fertilizers, life-saving pharmaceuticals, corrosion-resistant tools and machinery, and unusual new materials that we are using in interesting new ways. Much of this innovation has made our lives better to some degree.

Chemistry is just another way to say "the understanding of the nature of matter." Chemists through the ages and around the world have relied upon scientific inquiry, carrying out investigations and making careful observations. The periodic table sums up the results of many of those investigations and presents information about the elements (**Figure 1**). The observations that went into the creation of the periodic table also helped to create modern atomic theory. In turn, we can explain many of the patterns in the properties of the elements in terms of atomic theory. In this chapter, we will discuss the patterns used to classify elements and compounds, and consider how these patterns are explained by atomic theory.

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. Examine the periodic table on the inside front cover of this book. Identify and describe some similarities and differences between this table and the ones you used in previous grades.
2. Identify the parts of the atom and describe how they are arranged. According to this model, how do the atoms of the various elements differ from each other?
3. Identify and describe patterns in properties that you are aware of among the elements of the periodic table. Explain these patterns, using your model of the atom.
4. Why do elements form compounds? Use examples of compounds you are familiar with in your explanation.
5. Describe how the scientific community names and writes formulas for chemicals such as sodium, chlorine, table salt, sugar, and battery acid.

Career Connections:
Chemistry Teacher; Careers with Chemistry

Figure 1
Since phosphorus (shown) spontaneously ignites in air, it must be stored in water. Other metals react with both oxygen and water and so must be stored in oil. Magnesium oxidizes more slowly in air, but can be ignited with a flame (see the Exploration below). Each element has its own set of physical and chemical properties.

Exploration — Combustion of Magnesium (Demonstration)

We know things in several different ways. We might see something happening with our own eyes, or we might take a measurement of some variable. These are qualitative and quantitative observations, respectively. Interpretations are statements that go beyond direct observation; for example, the magnesium reacted with oxygen.

In this demonstration you will watch a reaction and classify what you see as a qualitative or quantitative observation or an interpretation. The reaction is the burning of magnesium.

Only observe the burning of the magnesium when it is within the glass beaker. Never look directly at burning magnesium. The bright flame emits ultraviolet radiation that could harm your eyes.

Due to possible reaction to bright light, persons known to have had seizures should not participate in the demonstration.

Because of its hazardous nature, this demonstration should never be carried out by students.

Materials: lab apron, eye protection, rubber gloves, magnesium ribbon (5 cm), steel wool, laboratory burner and striker, crucible tongs, large glass beaker

- Observe the magnesium before, during, and after it is burned in air. Record all your observations.
- Take safety precautions, then light the laboratory burner (Appendix C).
- Use rubber gloves when handling the steel wool.
- Clean the magnesium ribbon with steel wool. Record any observations.
- Use tongs to hold the magnesium ribbon.
- Light the magnesium ribbon in the burner flame and hold the burning magnesium inside the glass beaker to observe.

(a) Classify your observations as qualitative or quantitative observations.

(b) Indicate which, if any, of your written statements are interpretations.

1.1 Introduction: Science and Technology

Scientific Values

Besides the processes of describing, predicting, and explaining, science also includes specialized methods, such as designing investigations, attitudes, such as open-mindedness, and values, such as honesty.

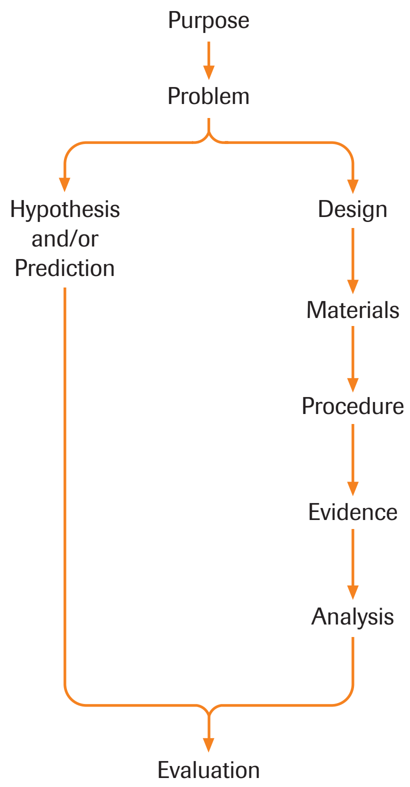

Figure 1
A model for reporting scientific problem solving. During laboratory investigations, the processes overlap and cycle back for modification. Although the reporting may look linear, the actual process of scientific problem solving is not linear and may involve many cycles. An hypothesis or prediction is not always present. In the evaluation section, the answer from the hypothesis or prediction is compared with the answer from the analysis. (See Appendix B.)

What Is Science?

Science involves describing, predicting, and explaining nature and its changes in the simplest way possible. Scientists refine the descriptions of the natural world so that these descriptions are as precise and complete as possible. In science, reliable and accurate descriptions of phenomena become scientific laws.

In scientific problem solving, descriptions, predictions, and explanations are developed and tested through experimentation. In the normal progress of science, scientists ask questions, make predictions based on scientific concepts, and design and conduct experiments to obtain experimental answers. As shown in **Figure 1**, scientists evaluate this process by comparing the results they predicted with their experimental results.

Scientists make predictions that can be tested by performing experiments. Experiments that verify predictions lend support to the concepts on which the predictions are based. We try to explain events in order to understand them. Scientists, like young children, try to understand and explain the world by constructing concepts. Scientific explanations are refined to be as logical, consistent, and simple as possible.

Every investigation has a purpose—a reason why the experimental work is done. The purpose of scientific work is usually to create, test, or use a scientific concept. This order is chronological; for example, one scientist creates a concept, others test the concept, and, if the test is passed, many scientists (plus teachers and students) use the concept.

Scientific research is often very complex and involves, by analogy, many roadblocks, road repairs, and detours along the way. Scientists record all of their work, but the formal report submitted for publication often does not reflect the difficulties and circling back that is part of the process. The order of the report headings does not reflect a specific scientific method. **Figure 1** illustrates the sections and sequence of a laboratory report. Depending on the purpose of the investigation, some sections (Hypothesis, Prediction, and Evaluation) may not be required. See Appendix B.

The Natures of Science and Technology

Science and technology are two different but parallel and intertwined human activities. **Science** is the study of the natural world with the goal of describing, explaining, and predicting substances and changes. The purpose of scientific investigations is to create, test, and/or use scientific concepts. **Technology** is the skills, processes, and equipment required to manufacture useful products or to perform useful tasks. Technology employs a systematic trial-and-error process whose goal is to get process or equipment to work. Technology generally does not seek scientific explanations for why it works.

Technology is an activity that runs parallel to science (**Figure 2**). Technology often leads science as in the development of processes for creating fire, cooking, farming, refining metal, and the invention of the battery. The use of fire, cooking, farming, and refining preceded the scientific understanding of these processes by thousands of years. The invention of the battery in 1800 was not understood scientifically until the early 1900s. Seldom does technology develop out of scientific research, although as the growth of scientific knowledge increases, the number of instances of technology as applied science is increasing.

The discovery of fire and the invention of the battery provided science with sources of energy with which to conduct experimental designs that would not otherwise have been possible. Science would not progress very far without the increasingly advanced technologies available to scientists. Often scientific advances have to wait on the development of technologies for research to be done; for example, glassware, the battery, the laser, and the computer.

Often science is blamed for the effects of technology. Often people say, "Science did this, " or "Science did that." Most often, though, it was a technological development that was responsible. Technologies and scientific concepts are created by people and used by people. We have to learn how to intelligently control and evaluate technological developments and scientific research, but we can't unless we are scientifically and technologically literate.

Science is an intellectual pursuit founded on research. Concepts start as hypotheses (tentative explanations) and end as accepted or discarded theories or laws. Science meets its goal of concept creation by continually testing concepts. Old concepts are restricted, revised, or replaced when they do not pass the testing process. Scientific knowledge is one of many kinds of knowledge that is trusted and relied upon around the world. Scientists employ a skeptical attitude that results in scientific knowledge being constantly tested worldwide against the best evidence and logic available. Attitudes such as open-mindedness, a respect for evidence, and a tolerance of reasonable uncertainty are qualities found in a scientist. These attitudes represent a predisposition to act in a certain way, without claiming absolute knowledge.

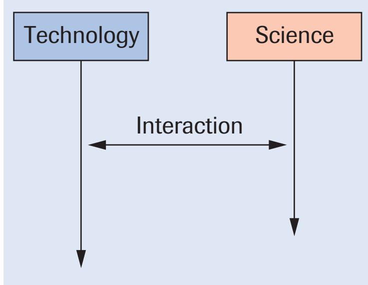

Figure 2
Science and technology are parallel streams of activity where, historically, the development of a technology has most often led the scientific explanation of the technology. Increasingly, technologies are being developed from an application of scientific knowledge. Certainly, science and technology feed off of one another.

What Is Chemistry?

Chemistry is the physical science that deals with the composition, properties, and changes in matter. Chemistry is everywhere around you, because you and your surroundings are composed of chemicals with a variety of properties. However, chemistry involves more than the study of chemicals. It also includes studying chemical reactions, chemical technologies, and their effects on the environment.

Chemistry is primarily the study of changes in matter. For example, coals burning, fireworks exploding, and iron rusting are all changes studied in chemistry. A *chemical change* or *chemical reaction* is a change in which one or more new substances with different properties are formed. Chemistry also includes the study of *physical changes*, such as water freezing to form ice crystals and boiling to form water vapour, during which no new substances are formed. (Physical changes are sometimes called phase changes or changes of state.)

CAREER CONNECTION

Chemistry Teacher
Chemistry teachers, like all science teachers, are in great demand in high schools, colleges, and universities. In large schools, a chemistry teacher may teach only chemistry. However, in smaller schools, the chemistry teacher may also teach other sciences and even other subjects. What education is required to become a high school chemistry teacher?

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Classifying Knowledge

Classification helps us to organize our knowledge. Classifying knowledge itself is an even more powerful tool. Here are some examples.

The Evidence section of an investigation report includes all observations related to a problem under investigation. An **observation** is a direct form of knowledge obtained by means of one of your five senses—seeing, smelling, tasting, hearing, or feeling. An observation might also be obtained with the aid of an instrument, such as a balance, a microscope, or a stopwatch.

Observations may also be classified as qualitative or quantitative. A *qualitative observation* describes qualities of matter or changes in matter; for example, a substance's colour, odour, or physical state. A *quantitative observation* involves the quantity of matter or the degree of change in matter; for example, a measurement of the length or mass of magnesium ribbon. All quantitative observations include a number; qualitative observations do not.

An **interpretation**, which is included in the Analysis section of an investigation report, is an indirect form of knowledge that builds on a concept or an experience to further

DID YOU KNOW ?

Scientific Attitudes
Scientific attitudes (also called habits of mind) represent a predisposition to act in a certain way when searching for an answer to a question. Examples of scientific attitudes include

- critical-mindedness
- suspended judgement
- respect for evidence
- honesty
- objectivity
- willingness to change
- open-mindedness
- questioning

CAREER CONNECTION

Careers with Chemistry

There are numerous careers and life experiences that require some knowledge of chemical composition and change. Some careers with chemistry are shown below. There are also many ways to find out about these careers.

pharmacist
forester
dental assistant
farmer
nurse
forensic chemist
nutritionist
veterinarian
cosmetologist
mechanic
miner
firefighter
pulp-mill worker
welder
toxicologist
baker
fertilizer salesperson
wine producer
petroleum engineer
environmental lawyer
chemistry teacher
science writer or reporter
environmental technologist

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describe or explain an observation. For example, observing the light and the heat from burning magnesium might suggest, based on your experience, that a chemical reaction is taking place. A chemist's interpretation might be more detailed: The oxygen molecules collide with the magnesium atoms and remove electrons to form magnesium and oxide ions. Clearly, this statement is not an observation. The chemist did not observe the exchange of electrons.

Observable knowledge is called **empirical knowledge**. Observations are always empirical. **Theoretical knowledge**, on the other hand, explains and describes scientific observations in terms of ideas; theoretical knowledge is *not observable*. Interpretations may be either empirical or theoretical, and depend to a large extent on your previous experience of the subject. **Table 1** gives examples of both kinds of knowledge.

Table 1 Classification of Knowledge

Type of knowledge	Example
empirical	• observation of the colour and size of the flame when magnesium burns
theoretical	• the idea that "magnesium atoms lose electrons to form magnesium ions, while oxygen atoms gain electrons to form oxide ions"

Communicating Empirical Knowledge in Science

Communication is an important aspect of science. Scientists use several means of communicating knowledge in their reports or presentations. Some ways of communicating empirical knowledge are presented below:

- *Empirical descriptions* communicate a single item of empirical knowledge, that is, an observation. For example, you might communicate the simple description that magnesium burns in air to form a white, powdery solid.
- *Tables of evidence* report a number of observations. The manipulated (independent) variable is usually listed first followed by the responding (dependent) variable. **Table 2** shows results from a quantitative experiment that involved burning magnesium.

Table 2 Mass of Magnesium Burned and Mass of Ash Produced

Trial	Mass of magnesium (g)	Mass of ash produced (g)
1	3.6	6.0
2	6.0	9.9
3	9.1	15.1

- *Graphs* are visual presentations of observations. According to convention, the manipulated variable is labelled on the *x*-axis, and the responding variable is labelled on the *y*-axis (Appendix F.4). For example, the evidence reported in **Table 2** is shown as a graph in **Figure 3**. Graphs appear in the Analysis section of a lab report.
- **Empirical hypotheses** are preliminary generalizations that require further testing. Based on **Figure 3**, for example, you might tentatively suggest that the mass of the product of a reaction will always vary directly with the mass of a reacting substance.
- **Empirical definitions** are statements that define an object or a process in terms of observable properties. For example, a metal is a shiny, flexible solid.

- **Generalizations** are statements that summarize a limited number of empirical results. Generalizations are usually broader in scope than empirical definitions and often deal with a minor or sub-concept. For example, many metals slowly react with oxygen from the air in a process known as corrosion.
- **Scientific laws** are statements of major concepts based on a large body of empirical knowledge. Laws are more important and summarize more empirical knowledge than generalizations. For example, the burning of magnesium, when studied in greater detail (**Table 3**), illustrates the law of conservation of mass.

Table 3 Mass of Magnesium, Oxygen, and Product of Reaction

Trial	Mass of magnesium (g)	Mass of oxygen (g)	Mass of product (g)
1	3.2	2.1	5.3
2	5.8	3.8	9.6
3	8.5	5.6	14.1

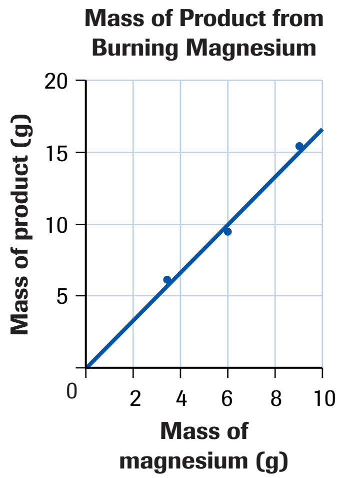

Figure 3
The relationship between the mass of magnesium that reacted and the mass of product obtained is a straight line (direct proportion).

According to the evidence in **Table 3**, the total mass of magnesium and oxygen is generally equal to the mass of the product. Similar studies of many different reactions reflect the **law of conservation of mass**: *In any physical or chemical change, the total initial mass of reactant(s) is equal to the total final mass of product(s).*

For a statement to become accepted as a scientific law, evidence must first be collected from many examples and replicated by many scientists. Even after the scientific community recognizes a new law, that law is subjected to continuous experimental tests based on the ability of the law to describe, explain, and predict nature. Laws must accurately describe and explain current observations and predict future events in a simple manner.

Section 1.1 Questions

1. Classify the following statements about carbon as observations or interpretations:
   (a) Carbon burns with a yellow flame.
   (b) Carbon atoms react with oxygen molecules to produce carbon dioxide molecules.
   (c) Global warming is caused by carbon dioxide.
2. Classify each of the following statements as one of the forms of empirical knowledge:
   (a) Elements are defined as substances that cannot be decomposed by heat or electricity.
   (b) The mass of products in a chemical reaction is always equal to the mass of reactants.
   (c) Graphite is a black powdery substance.
   (d) I believe that, in this case, the temperature will affect the rate of reaction.
   (e) Based upon the limited evidence available, the metals are all bendable.
3. Classify the following statements about carbon as empirical or theoretical:
   (a) Carbon in the form of graphite conducts electricity, whereas carbon in the form of diamond does not.
   (b) Graphite contains some loosely held electrons, whereas the electrons in diamond are all tightly bound in the atoms.
4. Scientific knowledge can be classified as empirical or theoretical.
   (a) What is the key distinction between these two types of knowledge?
   (b) How would you classify the knowledge in the Analysis section of an investigation report?
5. According to research by historians and philosophers, science and technology are related but different disciplines. Classify each of the following activities by Canadians as science or technology:
   (a) Aboriginal Canadians built birch bark canoes.
   (b) Harriet Brooks is the only person known to have worked in the laboratories of Ernest Rutherford, J. J. Thomson, and Marie Curie.
   (c) The telephone was invented by Alexander Graham Bell.
   (d) In 1990, Richard Taylor, who grew up in Medicine Hat, Alberta, was awarded the Nobel Prize for empirically testing and verifying the existence of quarks.
6. List the four characteristics of scientific communication.
7. Describe how a generalization differs from a scientific law.
8. Classify the following activities as science or non-science.
   (a) predicting the weather
   (b) fortune telling
   (c) astronomy
   (d) astrology
   (e) studying animal behaviour
   (f) observing the Northern Lights
   (g) ESP (extrasensory perception)

1.2 Classifying Matter

Matter is anything that has mass and occupies space. Anything that does not have mass or that does not occupy space—energy, happiness, and philosophy are examples—is not matter. To organize their knowledge of substances, scientists classify matter (**Figure 1**). A common classification differentiates matter as **pure substances**, whose composition is constant and uniform, and **mixtures**, whose composition is variable and may or may not be uniform throughout the sample. Empirically, **heterogeneous mixtures** are non-uniform and may consist of more than one phase. By analogy, your bedroom, for example, is a heterogeneous mixture because it consists of solids such as furniture, gases such as air, and perhaps liquids such as soft drinks. **Homogeneous mixtures** are uniform and consist of only one phase. Examples are alloys, tap water, aqueous solutions, and air.

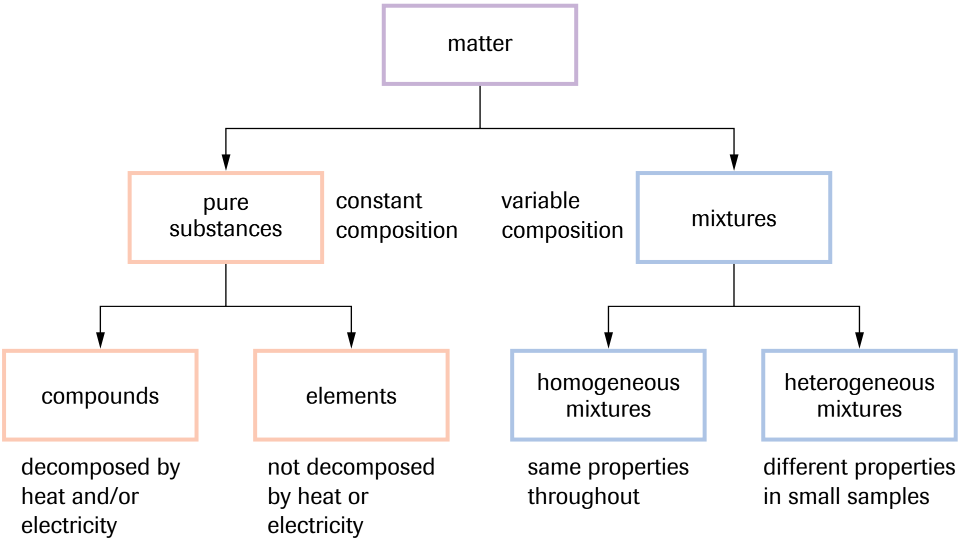

Figure 1
An empirical classification of matter

You can classify many substances as heterogeneous or homogeneous by making simple observations. However, some substances that appear homogeneous may, on closer inspection, prove to be heterogeneous (**Figure 2**). Introductory chemistry focuses on pure substances and homogeneous mixtures, commonly known as solutions.

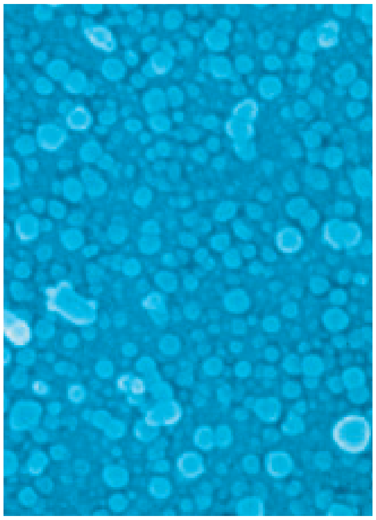

Figure 2
Although milk is called "homogenized," close examination through a microscope reveals solid and liquid phases. Milk is a heterogeneous mixture.

This empirical (observable) classification system is based on the methods used to separate matter. The parts of both heterogeneous mixtures and solutions can be separated by physical means, such as filtration; distillation; chromatography; mechanically extracting one component from the mixture; allowing one component to settle; or using a magnet to separate certain metals. A pure substance cannot be separated by physical methods. A compound can be separated into more than one substance only by means of a chemical change involving heat or electricity, called chemical decomposition. **Elements** cannot be broken down into simpler chemical substances by any physical or chemical means.

An **entity** is a general term that includes particles (sub-atomic entities such as protons, electrons, and neutrons), atoms, ions, molecules, and formula units. In this textbook, we restrict the use of the term "particle" to sub-atomic entities. Although the classification of matter is based on experimental work, theory lends support to this system. According to theory, elements are composed entirely of only one kind of atom. An **atom**, according to theory, is the smallest entity of an element that is still characteristic of that element. According to this same theory, **compounds** contain atoms of more than one element combined in a definite fixed proportion. Both elements and compounds may consist of molecules, distinct entities composed of two or more atoms. Solutions, unlike elements and compounds, contain entities of more than one substance, uniformly distributed throughout them.

A pure substance can be represented by a **chemical formula**, which consists of element symbols representing the entities and their proportions present in the substance. You can use chemical formulas to distinguish between elements, which are represented by a single symbol, and compounds, which are represented by two or more different symbols. Examples of formulas, along with empirical and theoretical definitions, are summarized in **Table 1**.

Table 1 Definitions of Elements and Compounds

Substance	Empirical definition	Theoretical definition	Examples
element	substance that cannot be broken down chemically into simpler units by heat or electricity	substance composed of only one kind of atom	Mg(s) (magnesium) O_2(g) (oxygen) C(s) (carbon)
compound	substance that can be decomposed chemically by heat or electricity	substance composed of two or more kinds of atoms	H_2O(l) (water) NaCl(s) (table salt) $C_{12}H_{22}O_{11}$(s) (sugar)

Section 1.2 Questions

1. Describe how to distinguish experimentally between each of the following pairs of substances:
   (a) heterogeneous and homogeneous mixtures
   (b) solutions and pure substances
   (c) compounds and elements
2. The purpose of the investigation in this problem is to test the Design of decomposition by electricity to determine whether a pure substance is an element or a compound. Complete the Analysis and Evaluation of the investigation report. In your Evaluation, evaluate the Design only (Part 1; see Appendix B.2).

   Problem
   Are water and table salt classified as elements or compounds?

   Prediction
   According to current theoretical definitions of element and compound, as well as the given chemical formulas, water and table salt are classified as compounds. The chemical formulas indicate that water, H_2O(l), and table salt, NaCl(s), are composed of more than one kind of entity.

   Design
   Electricity is passed through water and through molten salt. Any apparent evidence of decomposition is noted.

   Evidence

Table 2 Passing Electricity through Samples

Sample	Description	Observations after passing electricity through sample
water	colourless liquid	two colourless gases produced
molten table salt	colourless liquid	silvery solid and pale yellow-green gas formed (**Figure 3**)

3. Name two examples of each of the following:
   (a) pure substance
   (b) homogeneous mixture
   (c) heterogeneous mixture
4. Write a Design to determine whether a substance is an element or a compound. Make the Design extensive enough to provide a high degree of certainty in the answer.
5. John Dalton erroneously classified lime and several other compounds as elements because they would not decompose on heating. What does this indicate about the certainty of scientific knowledge?

Figure 3
(a) Sodium chloride (table salt)
(b) Sodium (dangerously reactive metal)
(c) Chlorine (poisonous, reactive gas)

1.3 Classifying Elements

Dmitri Mendeleev, a Russian chemist, created a periodic table in 1869. His periodic table communicated the **periodic law**: *chemical and physical properties of elements repeat themselves in regular intervals, when the elements are arranged in order of increasing atomic number*. (See the periodic table on the inside cover of this textbook.) A periodic table is a very useful tool upon which to base our chemical knowledge. The periodic table organizes the elements, for example, in groups and periods and as metals and nonmetals (**Figure 1**).

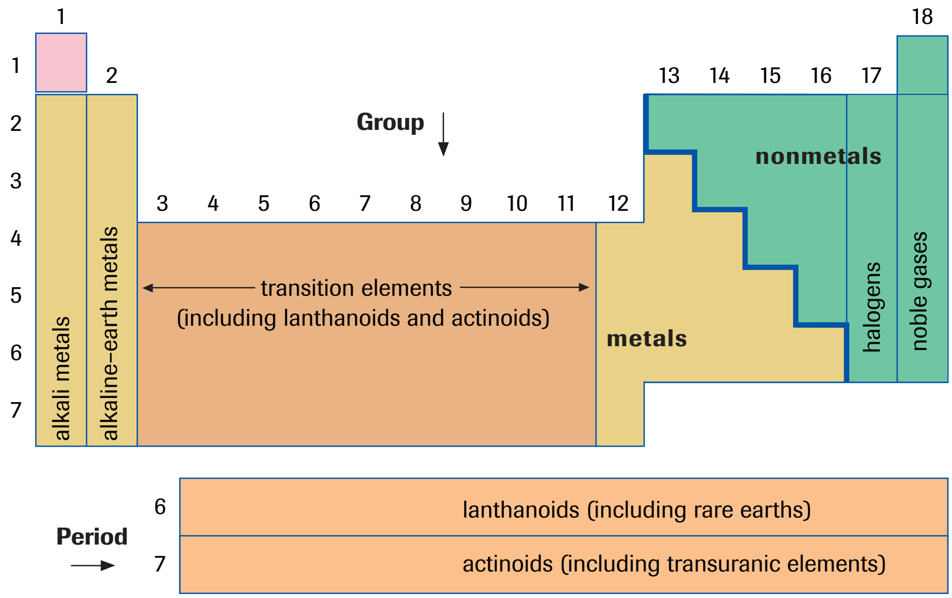

Figure 1
The periodic table is divided into sections, each with commonly used names. The main group, or representative, elements are those in Groups 1, 2, and 12 to 18.

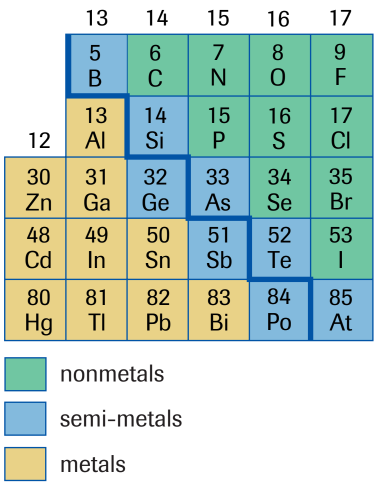

Figure 2
The properties of some elements have led to the creation of a class of elements called semi-metals.

- A **family** or **group** of elements has similar chemical properties and includes the elements in a vertical column in the main part of the table.
- A **period** is a horizontal row of elements whose properties gradually change from metallic to nonmetallic from left to right along the row.
- Metals are located to the left of the "staircase line" in the periodic table, and nonmetals are located to the right. **Semi-metals**—sometimes called metalloids—are a class of elements that are distributed along the staircase line (**Figure 2**).

When chemists investigate the properties of materials, they must specify the conditions under which the investigations were carried out. For example, water is a liquid under normal conditions indoors, but in subzero winter temperatures, it becomes a solid outdoors. Ordinarily, tin is a silvery-white metal, but at temperatures below 13 °C, it gradually turns grey and crumbles easily. For the sake of accuracy and consistency, the International Union of Pure and Applied Chemistry (IUPAC), a governing body for scientific communication, has defined a set of standard conditions. Unless other conditions are specified, descriptions of materials are assumed to be at **standard ambient temperature and pressure**. Under these ambient (surrounding) conditions, known as **SATP**, the materials are at a temperature of 25 °C and a pressure of 100 kPa.

From many observations of the properties of elements, scientists have found that **metals** are shiny, bendable, and good conductors of heat and electricity. The majority of the known elements are metals, and all metals except mercury are solids at SATP. The remaining known elements are mostly nonmetals. **Nonmetals** are not shiny, not bendable, and generally not good conductors of heat and electricity in their solid form. At SATP, most nonmetals are gases and a few are solids. Solid nonmetals are brittle and lack the lustre of metals. Most nonmetals exist in compounds rather than in element form.

In the definitions for metals and nonmetals, bendable, ductile, and malleable are often used interchangeably, although they are different properties. Ductile means that the metal can be drawn (stretched) into a wire or a tube, and malleable means that the metal can be hammered into a thin sheet. The word *lustrous* is often used in these definitions in place of shiny.

WWW WEB Activity

Case Study—Groups of Elements

Chemists classify elements, based on their similar physical and chemical properties, into (vertical) groups in our periodic table. Choose a vertical group to investigate. Report on similarities and differences among the elements of the group that you chose.

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Periodic tables usually include each element's symbol, atomic number, and atomic mass, along with other information that varies from table to table. The periodic table on the inside front cover features a box of data for each of the elements, and a key explaining the information in each box. The key is also shown in **Figure 3**. Note that theoretical data are listed in the column on the left, and empirically determined data are listed on the right.

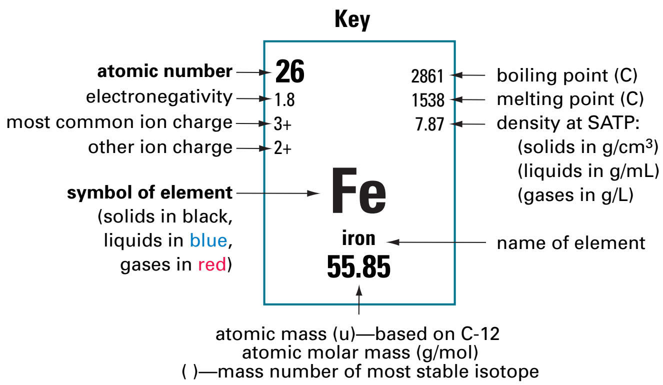

Figure 3
This key, which also appears on this book's inside front cover, helps you to determine the meaning of the numbers in the periodic table.

IUPAC specifies rules for chemical names and symbols. The IUPAC rules, which are summarized in many scientific references, are used all over the world.

SUMMARY *IUPAC Rules for Element Symbols and Names*

- Element names should differ as little as possible among different languages. However, only the symbols are truly international.
- The first letter (only) of the symbol is always an uppercase letter (e.g., the symbol for cobalt is Co, not CO, co, or cO).

DID YOU KNOW ?

Malleability of Gold

Gold is one of the most malleable metals. It is used when super-thin foil (~0.1 μm thick) is required in experiments and technologies. Gold foil is used for decorative gilding on cakes and books and for coating artificial satellites to reflect infrared radiation.

DID YOU KNOW ?

Ida Noddack, Discoverer of Rhenium

Ida Noddack (**Figure 4**) and her husband, Walter Karl Friedrich, predicted the properties of undiscovered elements in Group 7 and searched for these elements.

Less well-known among Noddack's scientific achievements is the initial concept of nuclear fission. Her idea conflicted with theories of atomic structure at that time, so it was ignored for several years.

Figure 4
Ida Noddack (1896–1978)

DID YOU KNOW ?

International Element Symbols

The Chinese character for hydrogen is unique to that language, but the symbol (on the right) is recognizable worldwide.

Table 1 IUPAC Element Roots

Number	Root
0	nil
1	un
2	bi
3	tri
4	quad
5	pent
6	hex
7	sept
8	oct
9	enn

- The name of any new metallic element after uranium should end in -ium.
- Artificial elements beyond atomic number 103 have IUPAC temporary names and symbols derived by combining (in order) the "element roots" for the atomic number and adding the suffix "-ium." The symbols of these elements consist of three letters, each being the first letter of the three element root names corresponding to the atomic number. (See **Table 1**.) For example, element 112 is called ununbium, Uub (one-one-two). The permanent names and symbols are determined by a vote of IUPAC representatives from each country.

Families and Series of Elements

Some groups of elements have family and series names that are commonly used in scientific communication. It is important to learn these family and series names (**Figure 1**).

- The **alkali metals** are Group 1 elements. They are soft, silver-coloured metals that react violently with water to form basic solutions. The most reactive alkali metals are cesium and francium.
- The **alkaline-earth metals** are the Group 2 elements. They are light, reactive metals that form oxide coatings when exposed to air.
- The **halogens** are the elements in Group 17. They are all extremely reactive, with fluorine being the most reactive.
- The **noble gases** are the elements in Group 18. They are special because of their extremely low chemical reactivity.
- The **main group elements** are the elements in Groups 1, 2, and 12 to 18. Of all the elements, the main group elements best follow the periodic law.
- The **transition elements** are the elements in Groups 3 to 11. These elements exhibit a wide range of chemical and physical properties.

In addition to the common classes of elements described above, the bottom two rows in the periodic table also have common names. The *lanthanoids* are the elements with atomic numbers 58 to 71. The *rare earth elements* include the lanthanoids, and yttrium and scandium. The *actinoids* are the elements with atomic numbers 90 to 103. The synthetic (not naturally occurring) elements that have atomic numbers of 93 or greater are referred to as *transuranic elements* (beyond uranium).

DID YOU KNOW ?

Naming the Classes of Elements

IUPAC, by international agreement, sets conventions of communication for the scientific community. In some older textbooks, you may find different names for some classes of elements. For example, the main group elements have been called representative elements, and semi-metals have been called metalloids. Even the definitions might change; for example, in the past, alkaline-earth elements have omitted beryllium and magnesium, and transition elements have included Group 12. Also, lanthanoids and actinoids have, in the past, been called lanthanides and actinides (although with a slightly different membership).

Section 1.3 Questions

1. What does the acronym IUPAC stand for?
2. Define SATP and state the reasons why IUPAC defined a set of standard conditions.
3. Classify the following chemicals as metals, semi-metals, or nonmetals:
   (a) iron
   (b) sulfur
   (c) silicon
   (d) gallium
4. List two physical and two chemical properties of the alkali metals.
5. Describe how the reactivity varies within the alkali metal family compared with the halogen family.
6. Nitrogen and hydrogen form a well-known compound, $NH_3(g)$, ammonia. According to the position of phosphorus in the periodic table, predict the most likely chemical formula for a compound of phosphorus and hydrogen.
7. Complete the Prediction, Analysis, and Evaluation (Parts 2 and 3; see Appendix B.2) of the investigation report.

Purpose
The purpose of this investigation is to test the empirical definitions of metals and nonmetals.

Problem
What are the properties of the selected elements?

Design
Each element is observed at SATP, and the malleability and electrical conductivity are determined for the solid form.

Evidence

Table 2 Properties of Selected Metals and Nonmetals

Element	Appearance	Malleability of solid	Electrical conductivity of solid
bromine	red-brown liquid	no	no
cadmium	shiny solid	yes	yes
chlorine	yellow-green gas	no	no
chromium	shiny solid	yes	yes
nickel	shiny solid	yes	yes
oxygen	colourless gas	no	no
platinum	shiny solid	yes	yes
phosphorus	white solid	no	no

8. **Table 3** lists modern element symbols and ancient technological applications. Write the English IUPAC name for each element symbol.

Table 3 Ancient Technological Applications of Elements

International symbol	Technological application
Sn	part of bronze (Cu and Sn) cutting tools, weapons, and mirrors used by Mayan and Inca civilizations
Cu	primary component of bronze and brass (Cu and Zn) alloys
Pb	used by Romans to make water pipes
Hg	a liquid metal used as a laxative by the Romans
Fe	produced by Egyptian iron smelters in 3000 B.C.E.
S	burned for fumigation by Greeks in 1000 B.C.E.
Ag	used in gold-silver alloys made by Greeks in 800 B.C.E.
Sb	an element in ground ore used in early Egyptian cosmetics
Co	used in Egyptian blue-stained glass in 1500 B.C.E.
Al	part of alum used as a fire retardant in 500 B.C.E.
Zn	part of brass mentioned by Aristotle in 350 B.C.E.

9. Copy and complete **Table 4**. Note that the SATP states of matter are solid (s), liquid (l), and gas (g).

Table 4 Elements and Mineral Resources

Mineral resource or use	Element name	Atomic number	Element symbol	Group number	Period number	SATP state
(a) high-quality ores at Great Bear Lake, NT	radium					
(b) potash deposits in Saskatchewan		19				
(c) extracted from Alberta sour natural gas			S			
(d) radiation source for cancer treatment				9	4	
(e) fuel in CANDU nuclear reactors			U	—		
(f) mined in the Northwest Territories				14	2	

Extension

10. Search the Internet for the latest information on the discovery and naming of element 104 and beyond.

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1.4 Theories and Atomic Theories

Empirical knowledge based on observation is the foundation for ideas in science. Usually, experimentation comes first and theoretical understanding follows. For example, the properties of some elements were known for thousands of years before a theoretical explanation was available.

So far in this chapter, you have encountered only empirical knowledge of elements, based on what has been observed. Curiosity leads scientists to try to explain nature in terms of what cannot be observed. This step—formulating ideas to explain observations—is the essence of theoretical knowledge in science. Albert Einstein (**Figure 1**) referred to theoretical knowledge as "free creations of the human mind."

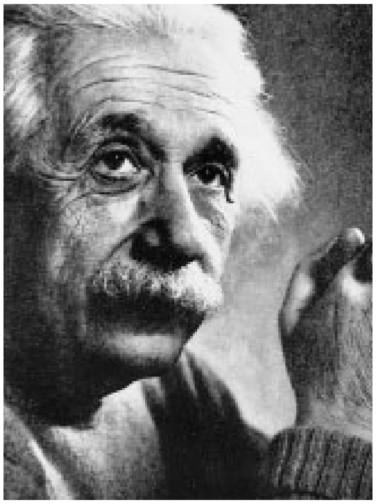

Figure 1
"No amount of experimentation can ever prove me right; a single experiment can prove me wrong." —Albert Einstein's view of the nature of science.

EXTENSION

Analogies in Science
An analogy is a comparison of a familiar object or process with something that is unfamiliar. Hear more about analogies in the world of science.

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DID YOU KNOW?

Earth, Air, Fire, and Water
"I do not find that anyone has doubted that there are four elements. The highest of these is supposed to be fire, and hence proceed the eyes of so many glittering stars. The next is that spirit, which both the Greeks and ourselves call by the same name, air. It is by the force of this vital principle, pervading all things and mingling with all, that the earth, together with the fourth element, water, is balanced in the middle of space."

– Pliny the Elder (Gaius Plinius Secundus), naturalist and historian (BCE 23–79)

Communicating Theoretical Knowledge in Science

Scientists communicate theoretical knowledge in several ways:

- *Theoretical descriptions* are specific descriptive statements based on theories or models. For example, "a molecule of water is composed of two hydrogen atoms and one oxygen atom."
- **Theoretical hypotheses** are ideas that are untested or extremely tentative. For example, "protons are composed of quarks that may themselves be composed of smaller particles."
- **Theoretical definitions** are general statements that characterize the nature of a substance or a process in terms of a non-observable idea. For example, a solid is theoretically defined as "a closely packed arrangement of atoms, each atom vibrating about a fixed location in the substance."
- **Theories** are comprehensive sets of ideas based on general principles that explain a large number of observations. For example, the idea that materials are composed of atoms is one of the principles of atomic theory; atomic theory explains many of the properties of materials. Theories are dynamic; they continually undergo refinement and change.
- *Analogies* are comparisons that communicate an idea in more familiar or recognizable terms. For example, an atom may be conceived as behaving like a billiard ball. All analogies "break down" at some level; that is, they have limited usefulness.
- *Models* are physical, graphic, or mental representations used to communicate an abstract idea. For example, marbles in a vibrating box could be used to study and explain the three states of matter. Like analogies, models are always limited in their application.

Theories that are acceptable to the scientific community must describe observations in terms of non-observable ideas, explain observations by means of ideas, predict results in future experiments that have not yet been tried, and be as simple as possible in concept and application.

Dalton's Atomic Theory

Recall that by the use of logic, the Greeks (Democritus) in about 300 BCE hypothesized that matter cut into smaller and smaller pieces would eventually reach what they called the atom—literally meaning indivisible. This idea was reintroduced over two thousand years later in 1805 by English chemist/schoolteacher John Dalton. Dalton created the modern theory of atoms to explain three important scientific laws—the laws of definite composition, multiple proportions, and conservation of mass (**Table 1**). Dalton's model of the atom was that of a featureless sphere—by analogy, a billiard ball (**Figure 2**). Dalton's atomic theory lasted for about a century, although it came under increasing criticism during the latter part of the 1800s.

Figure 2
In Dalton's atomic model, an atom is a solid sphere, similar to a billiard ball. This simple model is still used today to represent the arrangement of atoms in molecules.

SUMMARY *Creating Dalton's Atomic Theory (1805)*

Table 1 Empirical Work Leading to Dalton's Atomic Theory

Key experimental work	Theoretical explanation	Atomic theory
Law of definite composition: Elements combine in a characteristic mass ratio.	Each atom has a particular combining capacity.	Matter is composed of indestructible, indivisible atoms, which are identical for one element, but different from other elements.
Law of multiple proportions: There may be more than one mass ratio.	Some atoms have more than one combining capacity.	
Law of conservation of mass: Total mass remains constant (the same).	Atoms are neither created nor destroyed in a chemical reaction.	

Thomson's Atomic Model

Thomson's model of the atom (1897) was a hypothesis that the atom was composed of electrons (negative particles) embedded in a positively charged sphere (**Figure 3(a)**). Thomson's model of the atom is often communicated by using the analogy of a raisin bun (**Figure 3(b)**).

Table 2 summarizes the key experimental work that led to the creation of Thomson's atomic theory, along with the theoretical explanations. Although you are not required to describe the experimental work, you do need to know that theories are created to explain evidence.

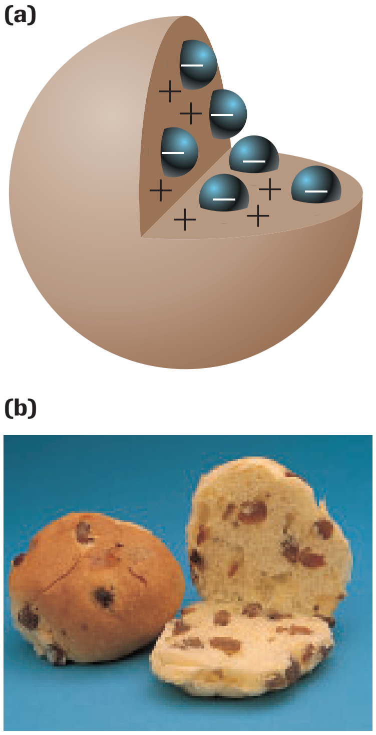

Figure 3
(a) In Thomson's atomic model, the atom is a positive sphere with embedded electrons.
(b) This model can be compared to a raisin bun, in which the raisins represent the negative electrons and the bun represents the region of positive charge.

SUMMARY *Creating Thomson's Atomic Theory (1897)*

Table 2 Empirical Work Leading to Thomson's Atomic Theory

Key experimental work	Theoretical explanation	Atomic theory
Arrhenius: the electrical nature of chemical solutions	Atoms may gain or lose electrons to form ions in solution.	Matter is composed of atoms that contain electrons (negatively charged particles) embedded in a positively charged material. The kind of element is characterized by the number of electrons in the atom.
Faraday: quantitative work with electricity and solutions	Particular atoms and ions gain or lose a specific number of electrons.	
Crookes: qualitative studies of cathode rays	Electricity is composed of negatively charged particles.	
Thomson: quantitative studies of cathode rays	Electrons are a component of all matter.	
Millikan: charged oil drop experiment	Electrons have a specific fixed electric charge.	

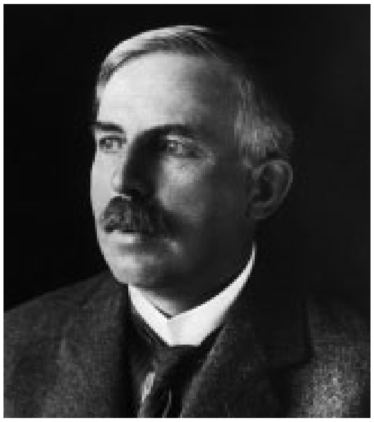

Figure 4
Rutherford's work with radioactive materials at McGill helped prepare him for his challenge to Thomson's atomic theory.

Rutherford's Atomic Theory

One of Thomson's students, Ernest Rutherford (**Figure 4**), eventually showed that some parts of Thomson's atomic theory were incorrect. Rutherford developed an expertise with nuclear radiation during the nine years he spent at McGill University in Montreal. Working with his team of graduate students, at Manchester in England, he devised an experiment to test Thomson's model of the atom. The prediction, based on Thomson's model, was that alpha particles should be deflected little, if at all. When some of the alpha particles were deflected at large angles and even backwards from the foil, the prediction was shown to be false, and Thomson's model judged unacceptable (**Figure 5**). Rutherford created a nuclear model of the atom to explain the evidence gathered in this scattering experiment. The theoretical explanations for the evidence gathered are presented in **Figure 6** and in **Table 3**.

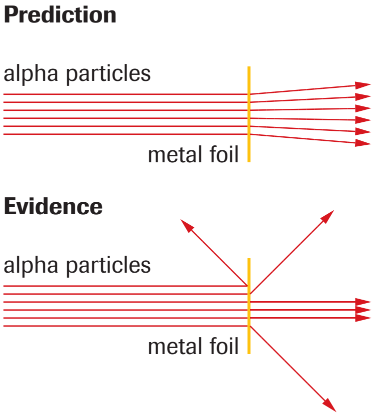

Figure 5
Rutherford's experimental observations were dramatically different from what he had expected based on Thomson's model.

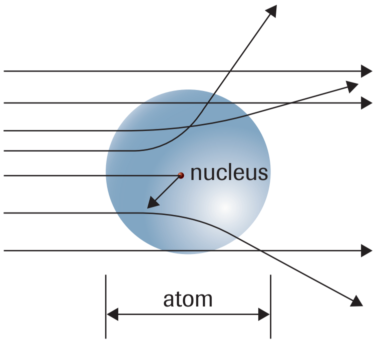

Figure 6
To explain his results, Rutherford suggested in his classic 1911 paper "that the atom consists of a central charge supposedly concentrated at a point."

WEB Activity

Simulation—The Rutherford Scattering Experiment

Find out how Rutherford conducted his gold foil experiment.

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DID YOU KNOW?

Gold

The Incas used the malleability of gold to create many functional works of art. Gold was not viewed as an economic commodity, but was valued partly because it did not rust (oxidize). Due to its malleability, gold was used as the super-thin foil in Rutherford's scattering experiment.

SUMMARY *Creating Rutherford's Atomic Theory (1911)*

Table 3 Empirical Work Leading to Rutherford's Atomic Theory

Key experimental work	Theoretical explanation	Atomic theory
Rutherford: A few positive alpha particles are deflected at large angles when fired at a gold foil.	The positive charge in the atom must be concentrated in a very small volume of the atom.	An atom is composed of a very tiny nucleus, which contains positive charges and most of the mass of the atom. Very small negative electrons occupy most of the volume of the atom.
Most materials are very stable and do not fly apart (break down).	A very strong nuclear force holds the positive charges within the nucleus.	
Rutherford: Most alpha particles pass straight through gold foil.	Most of the atom is empty space.	

Further research by several scientists led to creating the concepts of protons, neutrons, and isotopes (**Table 4**).

SUMMARY Creating the Concepts of Protons, Neutrons, and Isotopes

Table 4 Experimental Work Leading to Theories of New Particles

Key experimental work	Theoretical explanation	Atomic theory
Soddy (1913): Radioactive decay suggests different nuclei of the same element.	Isotopes of an element have a fixed number of protons, but varying stability and mass (**Figure 7**).	Atoms are composed of protons, neutrons, and electrons. Atoms of the same element have the same number of protons and electrons, but may have a varying number of neutrons (isotopes of the element).
Rutherford (1914): The lowest charge on an ionized gas particle is from the hydrogen ion.	The smallest particle of positive charge is the proton.	
Aston (1919): Mass spectrometer work indicates different masses for some atoms of the same element.	The nucleus contains neutral particles called neutrons.	
Radiation is produced by bombarding elements with alpha particles.		

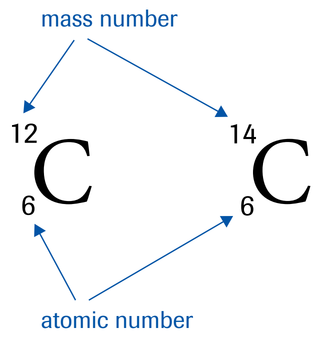

Figure 7
Two isotopes of carbon. Carbon-12 is stable, but carbon-14 is radioactive. Carbon-14 is used for carbon dating of ancient artifacts.

Table 5 Masses and Charges of Subatomic Entities

Particle	Relative mass	Relative charge
electron	1	1−
proton	1836.12	1+
neutron	1838.65	0

Still further empirical research with increasingly higher technologies allowed more precise determination of the relative masses of the subatomic particles. This more precise work confirmed that the electron and the proton had opposite charges, but that the charge was of the same magnitude (quantity) (**Table 5**).

The theoretical explanation for isotopes and the different masses of atoms of the same element is that atoms of elements can have a varying number of neutrons. Isotopes are designated by their **mass number**—the number of protons plus neutrons in their nucleus. The **atomic number** of an element could now be explained as the characteristic number of protons in the nucleus of atoms of that particular element. The number of neutrons can be calculated by subtracting the atomic number from the mass number. The atomic number and the mass number are shown in **Figure 7**.

Bohr's Atomic Theory

The genius of Niels Bohr lay in his ability to combine aspects of several theories and atomic models. He created a theory that, for the first time, could explain the periodic law. Bohr saw a relationship between the sudden end of a period in the periodic table and the quantum theory of energy proposed by German physicist Max Planck in 1900 and applied by Albert Einstein in 1905.

According to the Bohr atomic model, periods in the periodic table result from the filling of electron energy levels in the atom; for example, atoms in Period 3 have electrons in three energy levels. A period comes to an end when the maximum number of electrons is reached for the outer level. The maximum number of electrons in each energy level is given by the number of elements in each period of the periodic table; that is, 2, 8, 8, 18, etc. You may also recall that the last digit of the group number in the periodic table provides the number of electrons in the valence (outer) energy level. Although Bohr did his

DID YOU KNOW?

Canadian Diamonds

Diamonds are the hardest mineral on Earth. Scientists indicate that diamonds from the Canadian north were formed 2.5 to 3.3 Ga (billion years) ago from carbon under high pressure and temperature at depths of 150 to 225 km. Volcanic action has brought diamonds closer to the surface in structures called kimberlite pipes. Once the pipes are discovered, they are drilled to test for the presence of diamonds. Buffalo Head Hills in Alberta is a diamond exploration area.

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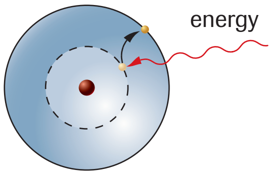
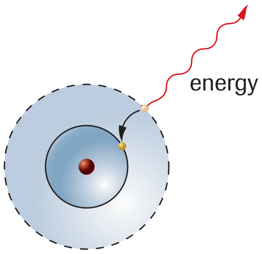
(a) An electron gains a quantum of energy and moves to a higher energy level.



(b) An electron loses a quantum of energy and falls to a lower energy level.



(c) A line spectrum indicates that several different electron jumps/transitions are possible.

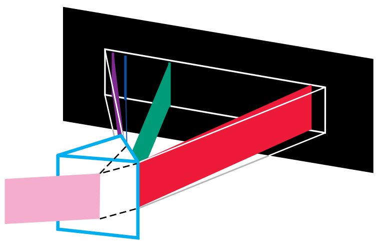


Figure 8
The theory of line spectra

calculations as if electrons were in circular orbits, the most important property of the electrons was their energy, not their motion. Energy-level diagrams for Bohr atoms are presented in the sample problem below. These diagrams have the same procedure and rationale as the orbit diagrams that you have drawn in past years. Since the emphasis here is on the energy of the electron, rather than the motion or position of the electron, orbits are not used.

SAMPLE problem 1.1

Use the Bohr theory and the periodic table to draw energy-level diagrams for the phosphorus atom.

First, refer to the periodic table to find the position of phosphorus. Use your finger or eye to move through the periodic table from the top left along each period until you get to the element phosphorus. Starting with Period 1, your finger must pass through 2 elements, indicating that there is the maximum of 2 electrons in energy level 1. Moving on to Period 2, your finger moves through the full 8 elements, indicating 8 electrons in energy level 2. Finally, moving on to Period 3, your finger moves 5 positions to phosphorus, indicating 5 electrons in energy level 3 for this element.

The position of 2, 8, and 5 elements per period for phosphorus tells you that there are 2, 8, and 5 electrons per energy level for this atom. The information about phosphorus atoms in the periodic table can be interpreted as follows:

atomic number 15:	15 protons and 15 electrons (for the atom)
period number 3:	electrons in 3 energy levels
group number 15:	5 valence electrons (the last digit of the group number)

To draw the energy-level diagram, work from the bottom up:

Sixth, the 3rd energy level:	$\underline{5\ e^-}$	(from group 15)
Fifth, the 2nd energy level:	$\underline{8\ e^-}$	(from eight elements in Period 2)
Fourth, the 1st energy level:	$\underline{2\ e^-}$	(from two elements in Period 1)
Third, the protons:	$15\ p^+$	(from the atomic number)
Second, the symbol:	P	(uppercase symbol from the table)
First, the name of the atom:	phosphorus atom	(lowercase name)

Although the energy levels in this energy-level diagram are, for convenience, shown as equal distances apart, this is contrary to the evidence. Line spectra evidence indicates that higher energy levels are increasingly closer together (**Figure 8**).

COMMUNICATION example

Use Bohr's theory and the periodic table to draw energy-level diagrams for hydrogen, carbon, and sulfur atoms.

Solution

		$\underline{6\ e^-}$
	$\underline{4\ e^-}$	$\underline{8\ e^-}$
$\underline{1\ e^-}$	$\underline{2\ e^-}$	$\underline{2\ e^-}$
$1\ p^+$	$6\ p^+$	$16\ p^+$
H	C	S
hydrogen atom	carbon atom	sulfur atom

Practice

1. Draw an electron energy-level diagram for each of the following:
   (a) an atom of boron
   (b) an atom of aluminium
   (c) an atom of helium

WEB Activity

Simulation—Emission and Absorption Spectra for Hydrogen

How do the transitions to and from the $n = 2$ energy level provide the emission and absorption spectra for the hydrogen atom? Try this simulation to find out.

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SUMMARY Creating Bohr's Atomic Theory (1913)

Table 6 Experimental Work Leading to Bohr's Atomic Theory

Key experimental evidence	Theoretical explanation	Bohr's atomic theory
Mendeleev (1869–1872): There is a periodicity of the physical and chemical properties of the elements.	A new period begins in the periodic table when a new energy level of electrons is started in the atom.	• Electrons travel in the atom in circular orbits with quantized energy—energy is restricted to only certain discrete quantities. • There is a maximum number of electrons allowed in each orbit. • Electrons "jump" to a higher level when a photon is absorbed. A photon is emitted when the electron "drops" to a lower level.
Mendeleev (1872): There are two elements in the first period and eight elements in the second period of the periodic table.	There are two electrons maximum in the first electron energy level and eight in the next level.	
Kirchhoff and Bunsen (1859), Johann Balmer (1885): Gaseous elements have line spectra for emission and absorption, not continuous spectra.	Since the energy of light absorbed and emitted is quantized, the energy of electrons in atoms is quantized.	

DID YOU KNOW ?

Richard Taylor and Quarks

Richard Taylor, born in Medicine Hat, Alberta in 1929, was jointly awarded the 1990 Nobel Prize in Physics for his 1969 work in verifying the existence of quarks. From that point forward, common matter could be described as being composed of electrons, up quarks (u), and down quarks (d). A proton is composed of two up quarks and one down quark (uud), while a neutron is composed of one up quark and two down quarks (udd).

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Formation of Monatomic Ions

In the laboratory, sodium metal and chlorine gas can react violently to produce a white solid, sodium chloride, commonly known as table salt (**Figure 9**). Sodium chloride is very stable and unreactive compared with the elements sodium and chlorine. Bohr originally suggested that the stable, unreactive behaviour of the noble gases was explained by their full outer electron orbits. According to this theory, when the neutral atoms collide, an electron is transferred from one atom to the other, and both atoms become entities called **ions**, which have an electrical charge (**Figure 10**). Sodium ions and chloride ions are **monatomic ions**—single atoms that have gained or lost electrons.

The theory of monatomic ion formation can be used to predict the formation of ions by most representative elements. However, the theory is restricted to these elements. Predictions cannot be made about:

- transition metals. Information about the ions of these elements can be obtained from the data in the periodic table on the inside front cover of this book.
- boron, carbon, and silicon. Experimental evidence indicates that these elements rarely form ions.
- hydrogen. Hydrogen atoms usually form positive ions by losing an electron. Although unusual, a negative hydrogen ion can be formed.

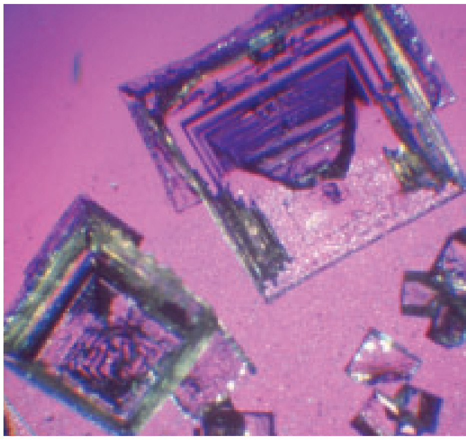

Figure 9
A very reactive metal (sodium) reacts with a poisonous, reactive nonmetal (chlorine) to produce a relatively inert compound (sodium chloride).

Learning Tip

Note that sodium (atomic number 11) has one more electron than the nearest noble gas, neon (atomic number 10). Chlorine (atomic number 17) has one fewer electron than its nearest noble gas, argon (atomic number 18). A transfer of one electron from a sodium atom to a chlorine atom will result in both entities having filled energy levels.

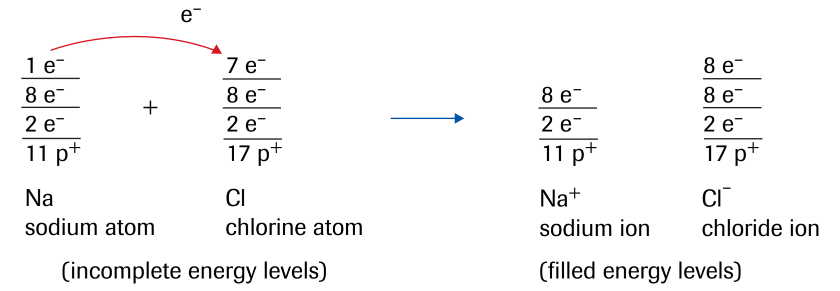

Figure 10
Energy-level models for the reaction of sodium and chlorine. The models are used to explain how two very reactive elements could react to form a relatively inert compound.

DID YOU KNOW?

Useful Isotopes

The following radioisotopes (radioactive isotopes) are produced artificially, for example, within the core of CANDU nuclear reactors. Most of the radioisotopes are used for medical diagnosis or therapy or for industrial or research work.

Ir-192 – analysis of welds
Co-60 – cancer treatment
Tc-99 – monitoring blood flow
I-131 – hyperthyroid treatment
C-14 – archeological dating
Hg-203 – dialysis monitoring
P-32 – white cell reduction
Co-57 – monitoring vitamin B_{12}
Tl-201 – monitoring blood flow
Sr-85 – bone scanning
In-111 – brain tumor scanning
Se-75 – pancreas tumor scanning

DID YOU KNOW?

Analogy for Electron Transitions

In an automobile, the transmission shifts the gears from lower to higher gears, such as from first to second, or downshifts from higher to lower gears. The gears are fixed: first, second, third. You cannot shift to "$2\frac{1}{2}$." Similarly, electron energies in the Bohr model are fixed and electron transitions can only be up or down between specific energy levels.

Positively charged ions are called **cations**. All of the monatomic cations are formed from the metallic and semi-metal elements when they lose electrons in an electron transfer reaction.

Negatively charged ions are called **anions**. All of the monatomic anions come from the nonmetallic and semi-metal elements. Names for monatomic anions use the stem of the English name of the element with the suffix "-ide" and the word "ion" (**Table 7**).

Table 7 Names and Symbols of Monatomic Anions

Group 15	Group 16	Group 17
nitride ion, N^{3-}	oxide ion, O^{2-}	fluoride ion, F^{-}
phosphide ion, P^{3-}	sulfide ion, S^{2-}	chloride ion, Cl^{-}
arsenide ion, As^{3-}	selenide ion, Se^{2-}	bromide ion, Br^{-}
	telluride ion, Te^{2-}	iodide ion, I^{-}

The symbols for monatomic ions include the element symbol with a superscript indicating the net charge. The symbols "+" and "−" represent the words "positive" and "negative." For example, the charge on a sodium ion Na^{+} is "positive one," an aluminium ion Al^{3+} is "positive three," and an oxide ion O^{2-} is "negative two."

Evaluation of Scientific Theories

"Physical concepts are free creations of the human mind, and are not, however it may seem, uniquely determined by the external world. In our endeavor to understand reality we are somewhat like a man trying to understand the mechanism of a closed watch. He sees the face and the moving hands, even hears its ticking, but he has no way of opening the case. If he is ingenious he may form some picture of a mechanism which could be responsible for all the things he observes, but he may never be quite sure his picture is the only one which could explain his observations. He will never be able to compare his picture with the real mechanism and he cannot even imagine the possibility of the meaning of such a comparison."

(Albert Einstein and Leopold Infeld, *The Evolution of Physics*, New York: Simon and Schuster, 1938, page 31.)

It is never possible to *prove* theories in science. A theory is accepted if it logically describes, explains, and predicts observations. A major endeavour of science is to make predictions based on theories and then to test the predictions. Once the evidence is collected, a prediction may be

- *verified* if the evidence agrees within reasonable experimental error with the prediction. If this evidence can be replicated, the scientific theory used to make the prediction is judged to be acceptable, and the evidence adds further support and certainty to the theory;
- *falsified* if the evidence obviously contradicts the prediction. If this evidence can be replicated, then the scientific theory used to make the prediction is judged to be unacceptable.

The ultimate authority in scientific work is the evidence (empirical knowledge) gathered during valid experimental work.

An unacceptable theory requires further action; there are three possible strategies.

- *Restrict* the theory. Treat the conflicting evidence as an exception and use the existing theory within a restricted range of situations.
- *Revise* the theory. This option is the most common. The new evidence becomes part of an improved theory.
- *Replace* the existing theory with a totally new concept.

These choices are often referred to as the three Rs.

SUMMARY Theoretical Descriptions of Atoms and Ions

Table 8 Cation and Anion Formation

	Atoms	Cations formed by metals	Anions formed by nonmetals
Name	element name	element name	element root + -ide
Nucleus	$\#p^+$ = atomic number	$\#p^+$ = atomic number	$\#p^+$ = atomic number
Electrons	$\#e^- = \#p^+$	$\#e^- < \#p^+$	$\#e^- > \#p^+$

WEB Activity

Canadian Achievers—Harriet Brooks

Ontario-born Harriet Brooks (**Figure 11**) was Rutherford's first graduate student at McGill University, Montreal. She was also the first woman at McGill to receive a Master of Science degree in physics. She made many contributions to science, including the discovery of radon as a radioactive by-product of radium. She was also the first person to realize that one element can change into another in a series of transformations. Research Brooks's other research interests, and what life was like for a female scientist in the early 20th century.

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DID YOU KNOW?

"Seeing" Atoms

In the 1980s, two kinds of microscopes were developed that can produce images of atoms and molecules. These microscopes have magnifications up to 24 million times. The scanning tunnelling microscope (STM) produces images indirectly by using feedback to draw electrons from a material's surface at a constant rate; the atomic force microscope (AFM) probes the surface of a specimen with a diamond stylus whose tip may be only one atom wide. Nanoscience and nanotechnology have advanced substantially due to the invention of these microscopes.

DID YOU KNOW?

Falsification

Karl Popper (1902–1994) is known as the Father of Falsification. He developed the concept of falsification to change scientific work from a conservative attitude of trying to verify to a critical attitude of trying to refute. The Popper concept of scientific work is used extensively in this textbook.

Figure 11
Harriet Brooks (1876–1933)

Section 1.4 Questions

1. What is the key difference between empirical and theoretical knowledge?
2. List four characteristics a theory must have to be accepted by the scientific community.
3. Describe the difference between a theory and a law.
4. According to the Bohr theory, what is the significance of full, outer electron orbits of atoms? Which chemical family has this unique property?
5. The alkali metals have similar physical and chemical properties (**Figure 12**). According to the Bohr theory, what theoretical similarity of alkali metal atoms helps to explain their empirical properties?

Figure 12
The alkali metals, such as potassium, are soft metals that react vigorously with water.

6. What is the ultimate authority in scientific work (what kind of knowledge is most trusted)?
7. Use the periodic table and theoretical rules to predict the number of occupied energy levels and the number of valence electrons for each of the following neutral atoms: beryllium, chlorine, krypton, iodine, lead, arsenic, and cesium.
8. If a scientific theory or other scientific knowledge is found to be unacceptable as a result of falsified predictions, what three options are used by scientists?
9. Write a theoretical definition of cation and anion.
10. The alkali metals all react violently with halogens to produce stable white solids. Draw energy-level diagrams (like **Figure 10**, page 24) for each of the following reactions:
    (a) lithium + chlorine → lithium chloride
    (b) potassium + fluorine → potassium fluoride
11. List the ion charges of the monatomic ions for the following families: alkali metals, alkaline-earth metals, Group 13, Group 15, Group 16, and halogens.
12. Draw energy-level diagrams for the following reactions between Group 2 elements and oxygen.
    (a) magnesium with oxygen (**Figure 13**)
    (b) calcium with oxygen

Figure 13
Magnesium burns vigorously in air, giving off visible and ultraviolet light. The reaction should, therefore, not be observed directly.

13. All the electron energy-level diagrams drawn in the previous questions have complete or filled outer energy levels. Describe the experimental evidence for these filled outer energy levels.
14. Write the symbols for the following atoms and ions (e.g., the sodium atom is Na, while the chloride ion is Cl^{-}).
    (a) sulfur atom
    (b) oxide ion
    (c) lithium ion
    (d) phosphide ion
    (e) aluminium atom
    (f) gallium ion
    (g) rubidium ion
    (h) iodide ion
15. The purpose of this investigation is to test the theory of ions presented in this section. Complete the Prediction and Evaluation (Parts 2 and 3) of the investigation report.

    Problem
    What is the chemical formula of the compound formed by the reaction of aluminium and fluorine?

    Prediction
    According to the Bohr theory of atoms and ions, the chemical formula of the compound formed by the reaction of aluminium and fluorine is [your answer]. The reasoning behind this prediction is [your reasoning, including electron energy-level diagrams].

    Design
    Aluminium and fluorine react in a closed vessel, and the chemical formula is calculated from the masses of reactants and products.

    Analysis
    According to the evidence gathered in the laboratory, the chemical formula of the compound formed by the reaction of aluminium and fluorine is AlF_3.

Extension

16. Describe some contributions Canadian scientists and/or scientists working in Canadian laboratories made to the advancement of knowledge about the nature of matter.

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Classifying Compounds 1.5

Before chemists could understand compounds, they had to devise ways to distinguish them from elements. Once they achieved this distinction, they could begin to organize their knowledge by classifying compounds. In this section, classification of compounds is approached in three different ways: by convention, empirically, and theoretically.

Classification of Compounds by Convention

Elements are commonly classified as metals or nonmetals. Given that compounds contain atoms of more than one kind of element, what combinations can result? Three classes of compounds are possible: *metal–nonmetal*, *nonmetal–nonmetal*, and *metal–metal* combinations (**Figure 1**).

- Metal–nonmetal combinations are called **ionic compounds**. An example is sodium chloride, NaCl (**Figures 1** and **2**).
- Nonmetal–nonmetal combinations are called **molecular compounds**. An example is sulfur dioxide, SO_2.
- Metal–metal combinations are called alloys and inter-metallic compounds. Alloys include common metal–metal solutions (silver–gold alloys in coins). Inter-metallic compounds include CuZn, Cu_5Zn_8, and $CuZn_3$ in brass at certain temperatures.

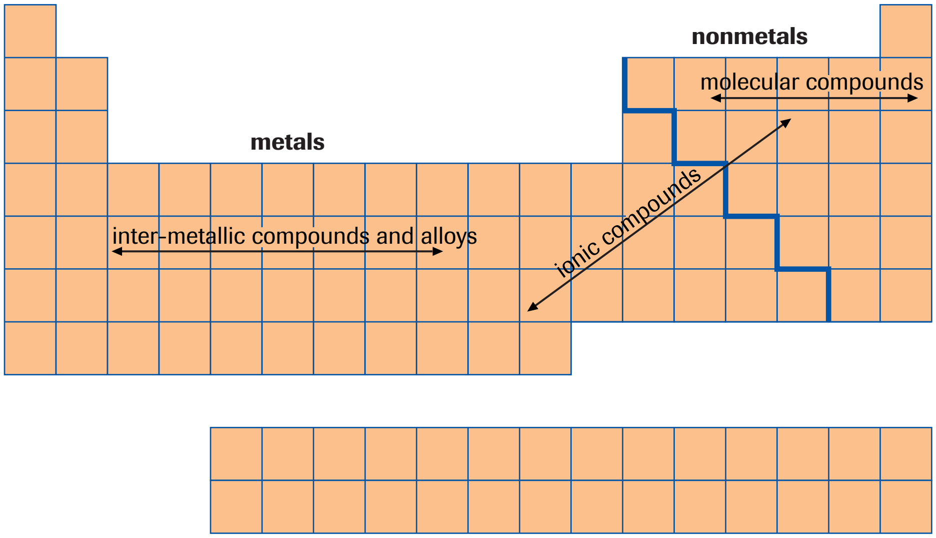

Figure 1
From two classes of elements, there can be three classes of compounds. This chapter covers ionic and molecular compounds.

Empirical Classification of Ionic and Molecular Compounds

The properties of compounds can be used to classify compounds as ionic or molecular. Many properties are common to each of these classes, but by restricting the properties of each empirical definition to those easiest to identify, we can design diagnostic tests for

DID YOU KNOW ?

Alternative Terms

- Molecular compounds are sometimes called *covalent compounds,* but in this textbook the preferred term is *molecular compounds.*
- *Alloys,* such as brass and amalgams, are solutions of a metal with other metals and, sometimes, nonmetals. Alloys do not combine in definite proportions whereas inter-metallic compounds do.

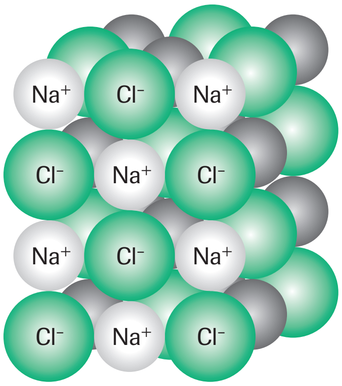

Figure 2
To agree with the explanation of the empirically determined formula for sodium chloride, the model of a sodium chloride crystal must represent both a 1:1 ratio of ions and the shape of the salt crystal. The chemical formula, NaCl(s), represents one formula unit of the crystal, representing a 1:1 ratio of ions.

ionic and molecular compounds. A *diagnostic test* is a laboratory procedure conducted to identify or classify chemicals. Some of the common diagnostic tests used in chemistry are described in Appendix C.3.

Empirical Definitions of Compounds

In a series of replicated investigations scientists have found that ionic compounds are all solids at SATP. When dissolved in water, these compounds form solutions that conduct electricity. Scientists have also discovered that molecular compounds at SATP are solids, liquids, or gases that, when dissolved in water, form solutions that generally do not conduct electricity. These *empirical definitions*—a list of empirical properties that define a class of chemicals—will prove helpful throughout your study of chemistry. For example, electrical conductivity of a solution is an efficient and effective diagnostic test that determines whether a compound is ionic or molecular (**Figure 3**).

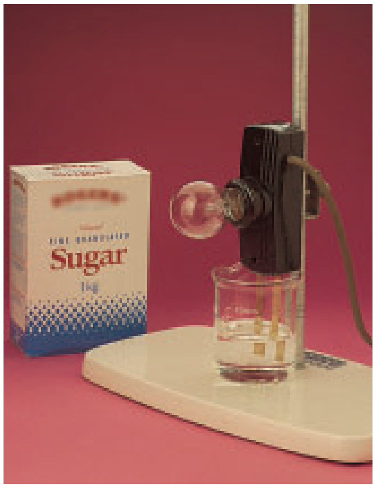

Figure 3
Conductivity is used to distinguish between aqueous solutions of soluble ionic and molecular compounds. Solutions of ionic compounds conduct electricity, but solutions of molecular compounds do not.

Empirical Definition of Acids, Bases, and Neutral Compounds

In science, it is not uncommon for new evidence to conflict with widely known and accepted theories, laws, and generalizations. Rather than viewing this as a problem, it is best regarded as an opportunity to improve our understanding of nature. As a result of the new evidence, the scientific concept is either restricted, revised, or replaced.

Not all compounds are either ionic or molecular. For example, aqueous hydrogen citrate (citric acid)—whose chemical formula is $C_3H_4OH(COOH)_3$—is a compound composed of nonmetals. You might predict that this compound is molecular. However, a citric acid solution conducts electricity, which might lead you to predict that the compound is ionic (**Figure 4**). This conflicting evidence necessitates a revision of the classification system. A third class of compounds, called acids, has been identified, and the three classes together provide a more complete description of the chemical world.

Acids are solids, liquids, or gases as pure compounds at SATP that form conducting aqueous solutions that make blue litmus paper turn red. Acids exhibit their special properties only when dissolved in water. As pure substances, all acids, at this point in your chemistry education, have the properties of molecular compounds.

Experimental work has also shown that some substances make red litmus paper turn blue. This evidence has led to another class of substances: **bases** are empirically defined as compounds whose aqueous solutions make red litmus paper turn blue. Compounds whose aqueous solutions do not affect litmus paper are said to be **neutral**. These empirical definitions will be expanded in Chapter 6.

The properties of ionic compounds, molecular compounds, acids, and bases are summarized in **Tables 1** and **2**.

Learning *Tip*

general properties
↓
defining properties
↓
empirical definitions
↓
diagnostic tests

Table 1 Properties of Ionic and Molecular Compounds and Acids

	Ionic	Molecular	Acids
State at SATP (pure substance)	(s) only	(s), (l), or (g)	(s), (l), or (g)
Conductivity of aqueous solution	high to low	none	high to low

Table 2 Properties of Aqueous Solutions of Acids, Bases, and Neutral Compounds

	Acidic	Basic	Neutral
Effect on blue litmus paper	turns red	none	none
Effect on red litmus paper	none	turns blue	none

Names and Formulas of Ionic Compounds

Communication systems in chemistry are governed by IUPAC. This organization establishes rules of communication to facilitate the international exchange of chemical knowledge. However, even when a system of communication is international, logical, precise, and simple, it may not be generally accepted if people prefer to use old names and are reluctant to change. There are many examples of chemicals that have both traditional names and IUPAC names. Chemical *nomenclature* is the systematic method for naming substances. Although names of chemicals are language-specific, the rules for each language are governed by IUPAC.

States of Matter in Chemical Formulas

Chemical formulas include information about the numbers and kinds of atoms or ions in a compound. It is also common practice in a formula to specify the state of matter: (s) to indicate "solid"; (l) to indicate "liquid"; (g) to indicate "gas"; and (aq) to indicate "aqueous," which refers to solutions in water. Substances that readily form **aqueous solutions** are very soluble in water. Some examples of chemical formulas with states of matter are:

$NaCl(s)$	pure table salt
$CH_3OH(l)$	pure methanol
$O_2(g)$	pure oxygen
$C_{12}H_{22}O_{11}(aq)$	aqueous sugar solution

Predicting and Naming Ionic Compounds

Besides *explaining* empirically determined formulas, an acceptable theory must also be able to predict future empirical formulas correctly. Experimental evidence provides the test for a prediction made from a theory. A major purpose of scientific work is to test concepts by making predictions.

Binary Compounds

To predict an ionic formula from the name of a binary (two-element) compound, write the chemical symbol, with its charge, for each of the two ions. Then predict the simplest whole-number ratio of ions to obtain a net charge of zero. For example, for the compound aluminium chloride, the ions are Al^{3+} and Cl^-. For a net charge of 0, the ratio of aluminium ions to chloride ions must be 1:3. The formula for aluminium chloride is, therefore, $AlCl_3$. This prediction agrees with the chemical formula determined empirically in the laboratory.

A complete chemical formula should also include the state of matter at SATP. Recall the generalization that all ionic compounds are solids at SATP. The complete formula is therefore, $AlCl_3(s)$.

$$Al(s) + Cl_2(g) \rightarrow Al^{3+}Cl^-\ Cl^-\ Cl^- \text{ or } AlCl_3(s)$$
$$\text{aluminium} + \text{chlorine} \rightarrow \text{aluminium chloride}$$

The name of a binary ionic compound is the name of the cation followed by the name of the anion. The name of the metal ion is stated in full and the name of the nonmetal ion has an *-ide* suffix, for example, magnesium oxide, sodium fluoride, and aluminium sulfide. Remember, name the two ions.

Multi-Valent Metals

Most transition metals and some main group metals can form more than one kind of ion, that is, they are multi-valent. For example, iron can form an Fe^{3+} ion or an Fe^{2+} ion, although Fe^{3+} is more common. In the reaction between iron and oxygen, two

Figure 4
Aqueous hydrogen citrate (citric acid)—an acid in the juice of citrus fruits such as oranges and grapefruits—might be predicted to be molecular, but it forms a conducting solution. It is, therefore, classified as an acid.

DID YOU KNOW?

Logical Consistency
Explanations are judged on their ability to explain an observation, generalization, or law in a logical, consistent, and simple fashion. For example, the inert character of noble gases and the inert chemical properties of ionic compounds (relative to elements) are explained logically and consistently by using the *same* atomic theory. This atomic theory suggests that there is a magic number of electrons to fill each energy level. When this maximum number is reached, the entity is inert—a nice, simple concept.

Learning Tip
Note that the focus here is on writing the correct chemical formulas for reactants and products, not on balancing the equation. The chemical equation is shown here along with the word equation.

Learning Tip

You can use the most common ion to help you predict the product of a chemical reaction; for example, iron(III) oxide in preference to iron(II) oxide. This indicates that iron(III) oxide is more commonly found in nature than is iron(II) oxide. Common occurrence, thermal stability, and electrochemical stability are considered when determining the most common ion.

possible products form stable compounds. We can predict the chemical formulas for the possible ionic compounds formed by the reaction by examining ion charges and balancing charges—the total positive charge plus the total negative charge equals zero.

$$\overset{2(3+)\;\;3(2-)}{Fe^{3+}{}_2O^{2-}{}_3} \qquad \overset{2+\;\;2-}{Fe^{2+}O^{2-}}$$

$$Fe_2O_3(s) \qquad FeO(s)$$

In the periodic table on this book's inside front cover, selected ion charges are shown, with the most common (stable) charge listed first (**Figure 5**). If the ion of a multi-valent metal is not specified in a description or an exercise question, you can assume the charge on the ion is the most common one.

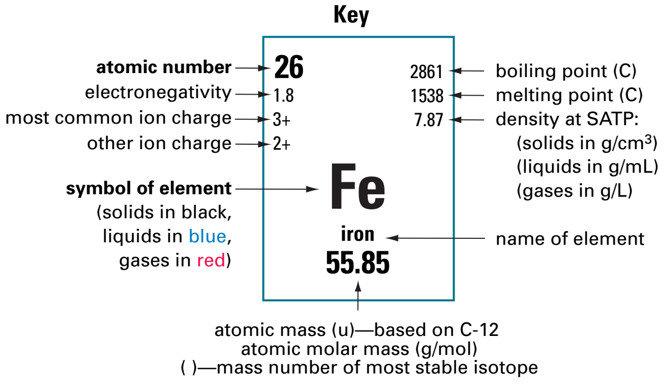

Figure 5
This information from the periodic table indicates that the most stable ion formed from Fe atoms is Fe^{3+}. Some metals have more than two possible ion charges, but only the most common two are listed in the periodic table.

To name the compounds, name the two ions. In the IUPAC system, the name of the multi-valent metal includes the ion charge. The ion charge is given in Roman numerals in brackets; for example, iron(III) is the name of the Fe^{3+} ion and iron(II) is the name of the Fe^{2+} ion. The Roman numerals indicate the charge on the ion, not the number of ions in the formula. The names of the previously mentioned compounds are

$Fe_2O_3(s)$, iron(III) oxide and $FeO(s)$, iron(II) oxide

DID YOU KNOW ?

Classical System

An older (classical) system for naming ions of multi-valent metals uses the Latin name for the element with an *-ic* suffix for the larger charge and an *-ous* suffix for the smaller charge. In this system, iron(III) oxide is "ferric oxide" and iron(II) oxide is "ferrous oxide."

Fe^{3+}	ferric	Fe^{2+}	ferrous
Sn^{4+}	stannic	Sn^{2+}	stannous
Pb^{4+}	plumbic	Pb^{2+}	plumbous
Cu^{2+}	cupric	Cu^{+}	cuprous
Sb^{5+}	stibnic	Sb^{3+}	stibnous

Compounds with Polyatomic Ions

Charges on **polyatomic ions**—ions containing a group of atoms with a net positive or negative charge—can be found in a table of polyatomic ions (see the inside back cover). Predicting the formula of ionic compounds involving polyatomic ions is done in the same way as for binary ionic compounds. Write the ion charges and then use a ratio of ions that yields a net charge of zero. For example, to predict the formula of a compound containing copper ions and nitrate ions, write the following:

$$\overset{2+\;\;\;2(1-)}{Cu^{2+}(NO_3{}^{-})_2} \qquad Cu(NO_3)_2(s) \qquad \text{copper(II) nitrate}$$

Two nitrate ions are required to balance the charge on one copper(II) ion (**Figure 6**). Note that parentheses are used in the formula to indicate the presence of more than one polyatomic ion. Do not use parentheses with one polyatomic ion or with simple ions. Do not write: $Ag_2(SO_4)(s)$ or $(Ag)_2SO_4(s)$.

A **formula unit** of an ionic compound is a representation of the simplest whole number ratio of ions; for example, NaCl is a formula unit of sodium chloride. There is no such thing as a molecule of NaCl, only a formula unit. (See Figure 2, page 27.) The simplest ratio formula is also referred to as the **empirical formula**. All ionic formulas are empirical formulas.

Learning Tip

Recognize the difference between the chemical formula for the element oxygen, $O_2(g)$, and the oxide ion, O^{2-}. Oxide ions occur in compounds such as aluminium oxide, $Al_2O_3(s)$, but not in elemental oxygen, $O_2(g)$.

Ionic Hydrates

Empirical work indicates that some ionic compounds exist as hydrates; for example, white $CuSO_4(s)$ also exists as blue $CuSO_4 \cdot 5H_2O(s)$ (**Figure 7**). **Hydrates** are compounds that decompose at relatively low temperatures to produce water and an associated compound. You cannot predict the number of water molecules added to the ionic formula unit. You need to be given or to reference this information. The following examples illustrate the nomenclature of ionic hydrates that is recommended by IUPAC, with older nomenclature in parentheses.

$CuSO_4 \cdot 5H_2O(s)$ is copper(II) sulfate—water (1/5) (copper(II) sulfate pentahydrate)

$Na_2CO_3 \cdot 10H_2O(s)$ is sodium carbonate—water (1/10) (sodium carbonate decahydrate)

sodium sulfate—water (1/7) is $Na_2SO_4 \cdot 7H_2O(s)$ (sodium sulfate heptahydrate)

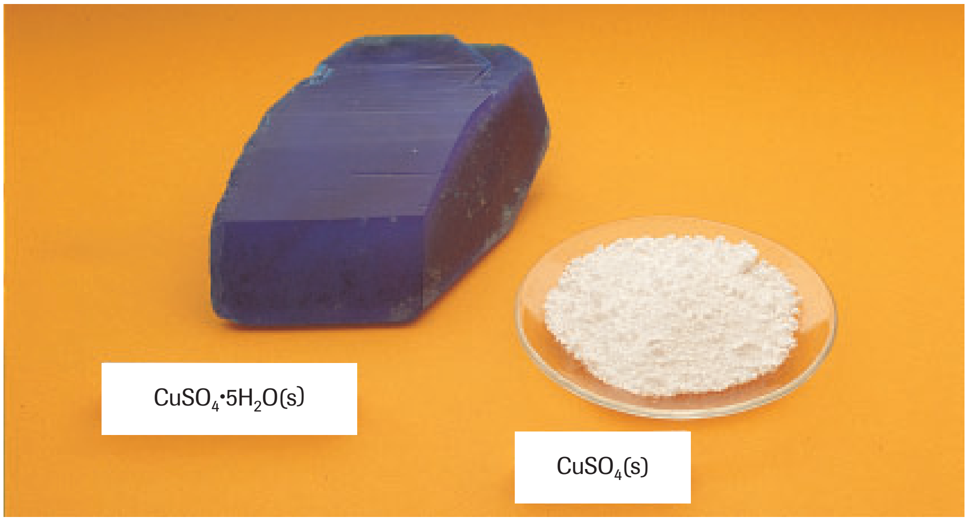

Figure 7
Heating bluestone crystals, $CuSO_4 \cdot 5H_2O(s)$, produces a white powder, $CuSO_4(s)$, according to the reaction $CuSO_4 \cdot 5H_2O(s) + \text{heat} \rightarrow CuSO_4(s) + 5\ H_2O(g)$
Adding water to the white powder produces bluestone.

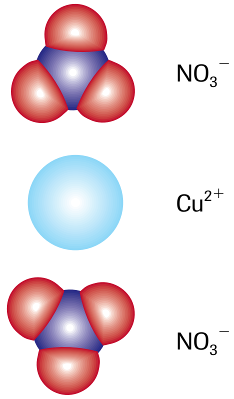

Figure 6
According to theory, two nitrate groups are required to balance the charge on one copper(II) ion. This theory agrees with observations.

Learning Tip

The convention for naming ionic hydrates has undergone a couple of changes in the last few decades. For example, copper(II) sulfate pentahydrate became copper(II) sulfate-5-water and now is copper(II) sulfate–water (1/5).

SUMMARY Ionic Compounds

Laboratory investigations indicate that there are classes of ionic compounds:
- binary ionic compounds such as NaCl, $MgBr_2$, and Al_2S_3
- polyatomic ionic compounds such as Li_2CO_3 and $(NH_4)_2SO_4$
- compounds of multi-valent metals such as $CoCl_2$ and $CoCl_3$

The empirically determined formulas of these types of compounds can be explained theoretically in a logically consistent way, using two concepts:
- Ionic compounds are composed of two kinds of ions: cations and anions.
- The sum of the charges on all the ions is zero.

Naming ionic compounds and writing ionic formulas:
- To name an ionic compound, name the two ions: first the cation and then the anion.
- To write an ionic formula, determine the ratio of ions that yields a net charge of zero.

DID YOU KNOW ?

Baking Soda

Baking soda (**Figure 8**) is one of the most versatile chemicals known. If you were to be deserted on an isolated island, baking soda would be a chemical of choice. Baking soda can be used for bathing, for brushing your teeth, for cleaning pots, for baking, and for extinguishing fires.

Figure 8
Baking soda

Section 1.5 Questions

1. Distinguish, empirically and theoretically, between an element and a compound.
2. Distinguish, empirically and theoretically, between a metal and a nonmetal.
3. Classify each of the following as an element or compound:
   (a) $C_{12}H_{22}O_{11}(s)$ (sugar)
   (b) Fe(s) (in steel)
   (c) CO(g) (poisonous)
   (d) oxygen (20% of air)
4. Classify each of the following as a metal or nonmetal:
   (a) lead (poisonous)
   (b) chlorine (poisonous)
   (c) Hg(l)
   (d) $Br_2(l)$
5. Classify each of the following as ionic or molecular:
   (a) $C_6H_{12}O_6(s)$ (glucose)
   (b) $Fe_2O_3 \cdot 3H_2O(s)$ (rust)
   (c) $H_2O(l)$ (water)
   (d) potassium chloride (fertilizer)
6. Once empirical definitions of compounds are established, what kind of knowledge about compounds is likely to follow?
7. State the general names given to a positive ion and a negative ion.
8. Write the symbol, complete with charge, for each of the following ions:
   (a) chloride
   (b) chlorate
   (c) nitride
   (d) iron(III)
   (e) ammonium
   (f) hydroxide
9. Use IUPAC rules to name the following binary ionic compounds:
   (a) lime, CaO(s)
   (b) road salt, $CaCl_2(s)$
   (c) potash, KCl(s)
   (d) a hydride, $CaH_2(s)$
10. Write the chemical formulas and IUPAC names for the binary ionic products of the following chemical reactions. Do not get distracted by the formulas for the nonmetals or try to balance the equations. For example,

    $Li(s) + Br_2(l) \rightarrow Li^+Br^-(s)$ or LiBr(s) (lithium bromide)

    (a) $Sr(s) + O_2(g) \rightarrow$
    (b) $Ag(s) + S_8(s) \rightarrow$
11. Write the chemical formula and IUPAC name of the most common ionic product for each of the following chemical reactions. Do not get distracted by the formulas for the nonmetals or try to balance the equations. For example,

    $Bi(s) + O_2(g) \rightarrow Bi_2O_3(s)$ (bismuth(III) oxide)

    (a) $Ni(s) + O_2(g) \rightarrow$
    (b) $Pb(s) + S_8(s) \rightarrow$
    (c) $Sn(s) + I_2(s) \rightarrow$
    (d) $Fe(s) + O_2(g) \rightarrow$
12. Sketch diagrams of the sulfate and carbonate polyatomic ions.
13. Write empirical and theoretical definitions of an ionic compound.
14. For the IUPAC chemical names in each of the following word equations, write the corresponding chemical formulas (including the state at SATP) to form a chemical equation. (It is not necessary to balance the chemical equation.)
    (a) Sodium hypochlorite is a common disinfectant and bleaching agent. This compound is produced by the reaction of chlorine, $Cl_2(g)$, with lye:
    chlorine gas + aqueous sodium hydroxide →
    aqueous sodium chloride + liquid water +
    aqueous sodium hypochlorite
    (b) Sodium hypochlorite solutions are unstable when heated and slowly decompose:
    aqueous sodium hypochlorite →
    aqueous sodium chloride + aqueous sodium chlorate
    (c) The calcium oxalate produced in the following reaction is used in a further reaction to produce oxalic acid, a common rust remover:
    aqueous sodium oxalate + solid calcium hydroxide →
    solid calcium oxalate + aqueous sodium hydroxide
15. Predict the international chemical formulas with states at SATP for the compounds formed from the following elements. Unless otherwise indicated, assume that the most stable metal ion is formed. (Write the full chemical equations, but do not balance the equations.) Also write the IUPAC name of the product.
    (a) $Mg(s) + O_2(g) \rightarrow$
    (b) $Ba(s) + S_8(s) \rightarrow$
    (c) $Sc(s) + F_2(g) \rightarrow$
    (d) $Fe(s) + O_2(g) \rightarrow$
    (e) $Hg(l) + Cl_2(g) \rightarrow$
    (f) $Pb(s) + Br_2(l) \rightarrow$
    (g) $Co(s) + I_2(s) \rightarrow$
16. For the chemical formulas in each of the following equations, write the corresponding IUPAC names to form a word equation. (Refer to the table of polyatomic ions.)
    (a) The main product of the following reaction (besides table salt) is used as a food preservative.
    $NH_4Cl(aq) + NaC_6H_5COO(aq) \rightarrow$
    $NH_4C_6H_5COO(aq) + NaCl(aq)$
    (b) Aluminium compounds, such as the one produced in the following reaction, are important constituents of cement:
    $Al(NO_3)_3(aq) + Na_2SiO_3(aq) \rightarrow$
    $Al_2(SiO_3)_3(s) + NaNO_3(aq)$
    (c) Sulfides are foul-smelling compounds that can react with water to produce basic solutions:
    $Na_2S(s) + H_2O(l) \rightarrow NaHS(aq) + NaOH(aq)$
    (d) Nickel(II) fluoride may be prepared by the reaction of nickel ore with hydrofluoric acid:
    $NiO(s) + HF(aq) \rightarrow NiF_2(aq) + H_2O(l)$
17. Use current IUPAC rules to name the following hydrates. An older name is provided for reference, if possible.
    (a) $FeSO_4 \cdot 7H_2O(s)$ (ferrous sulfate heptahydrate)
    (b) $NiNO_3 \cdot 6H_2O(s)$ (nickelous nitrate hexahydrate)
    (c) $Al_2(SO_4)_3 \cdot 18H_2O(s)$ (aluminium sulfate-18-water)
    (d) $3CdSO_4 \cdot 8H_2O(s)$ (no name possible under older systems of nomenclature for hydrates)

Extension

18. Why do systems of nomenclature change over time?
19. Why is it important to have internationally accepted systems of communication?

Molecular Elements and Compounds 1.6

Many molecular formulas, such as H_2O, NH_3, and CH_4, had been determined empirically in the laboratory by the early 1800s, but chemists could not explain or predict molecular formulas using the same theory as for ionic compounds. The theory that was accepted for these compounds was the idea that nonmetal atoms share electrons and that the sharing holds the atoms together in a group called a **molecule**. The chemical formula of a molecular substance—called a **molecular formula**—indicates the number of atoms of each kind in a molecule (**Figure 1**).

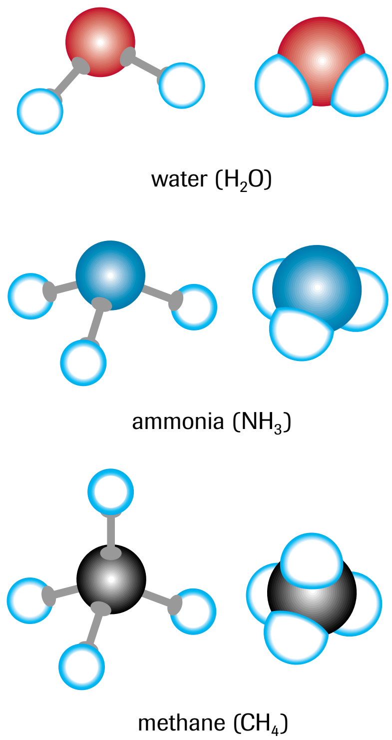

Figure 1
Molecular models of H_2O, NH_3, and CH_4 help us understand the theoretical explanation for the empirically determined formulas of water, ammonia, and methane. Ball-and-stick and space-filling models, as above, are types of molecular models.

Molecular Elements

As you have seen from the given chemical formulas for elements in the preceding examples and exercises, the chemical formula of all metals is shown as a single atom, whereas nonmetals frequently form **diatomic molecules** (i.e., molecules containing two atoms). Some useful rules are provided in **Table 1**. (Memorize the examples in this table.) An explanation of these rules is given in Unit 1. The diatomic elements end in *-gen*; for example, hydro*gen*, nitro*gen*, oxy*gen*, and the halo*gens*. $O_3(g)$ is a special unstable form of oxygen called ozone. $S_8(s)$ is called cycloöctasulfur, octasulfur, or usually just sulfur. **Figure 2** (on the next page) illustrates models of some of these molecules.

Table 1 Chemical Formulas of Metallic and Molecular Elements

Class of elements	Chemical structure	Examples
metals	all are monatomic	Na(s), Hg(l), Zn(s), Pb(s)
molecular elements (nonmetals)	some are diatomic	$H_2(g)$, $N_2(g)$, $O_2(g)$, $F_2(g)$, $Cl_2(g)$, $Br_2(l)$, $I_2(s)$
	some have molecules containing more than two atoms	$O_3(g)$, $P_4(s)$, $S_8(s)$
	all noble gases are monatomic	He(g), Ne(g), Ar(g)
other elements (semi-metals)	the rest of the elements can be assumed to be monatomic	C(s), Si(s)

Molecular Compounds

The names of some compounds communicate the number of atoms in a molecule. IUPAC has assigned Greek numerical prefixes to the names of molecular compounds formed from two different elements (**Table 2**). Other naming systems are used when a molecule has more than two kinds of atoms.

The following are examples of names of *binary molecular compounds*. Recall that *binary* refers to compounds composed of only two kinds of atoms and that *molecular* refers to compounds composed only of nonmetals.

Reactants		Product	Name
$C(s) + S_8(s)$	$\rightarrow$	$CS_2(l)$	carbon disulfide
$N_2(g) + I_2(s)$	$\rightarrow$	$NI_3(s)$	nitrogen triiodide
$N_2(g) + O_2(g)$	$\rightarrow$	$NO_2(g)$	nitrogen dioxide
$P_4(s) + O_2(g)$	$\rightarrow$	$P_4O_{10}(s)$	tetraphosphorus decaoxide

You will predict the chemical formulas for molecular compounds in Unit 1.

Table 2 Prefixes Used in Chemical Names

Prefix	Number of atoms
mono	1
di	2
tri	3
tetra	4
penta	5
hexa	6
septa	7
octa	8
nona	9
deca	10

Naming Molecular Compounds

According to IUPAC rules, the prefix system is used only for naming binary molecular compounds—molecular compounds composed of two kinds of atoms.

For hydrogen compounds such as hydrogen sulfide, $H_2S(g)$, the common practice is *not* to use the prefix system. In other words, we do not call this compound dihydrogen sulfide.

The molecular formulas and names of many molecular compounds must be memorized, referenced, or given. Some common molecular compounds whose names and formulas should be memorized are given in **Table 3**.

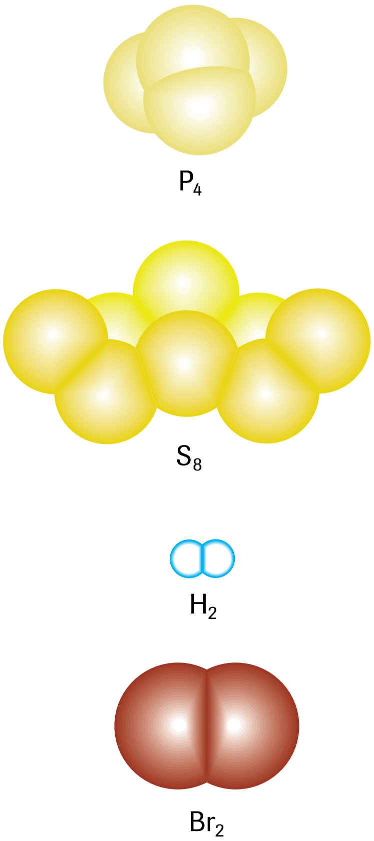

Figure 2
Models representing the molecular elements $P_4(s)$, $S_8(s)$, $H_2(g)$, and $Br_2(l)$.

SUMMARY *Elements and Molecular Compounds*

- Empirically, molecular elements and compounds as pure substances are solids, liquids, or gases at SATP. If they dissolve in water, their aqueous solutions do not conduct electricity.
- Theoretically, molecular elements and compounds are formed by nonmetal atoms bonding covalently to share electrons in an attempt to obtain the same number of electrons as the nearest noble gas.
- The chemical formulas for molecular elements should be memorized from **Table 1** on page 33. SATP states of matter are obtained from the periodic table.
- The chemical names and formulas for most binary molecular compounds are obtained from the memorized prefixes (see **Table 2** on page 33); for example, $N_2S_5(l)$ is dinitrogen pentasulfide and dinitrogen tetraoxide gas is $N_2O_4(g)$.
- Memorize the chemical formulas, names, and states of matter at SATP for common binary and ternary molecular compounds in **Table 3**. For other molecular compounds referred to in questions, you are given the states of matter.

Table 3 Common Molecular Compounds

IUPAC name	Molecular formula
water	$H_2O(l)$ or $HOH(l)$
hydrogen peroxide	$H_2O_2(l)$
ammonia	$NH_3(g)$
glucose	$C_6H_{12}O_6(s)$
sucrose	$C_{12}H_{22}O_{11}(s)$
methane	$CH_4(g)$
propane	$C_3H_8(g)$
octane	$C_8H_{18}(l)$
methanol	$CH_3OH(l)$
ethanol	$C_2H_5OH(l)$
hydrogen sulfide	$H_2S(g)$

Naming and Writing Formulas for Acids and Bases

In this chapter, acids and bases are given very restricted empirical and theoretical definitions. Aqueous hydrogen compounds that make blue litmus paper turn red are classified as acids and are written with the hydrogen appearing first in the formula. For example, $HCl(aq)$ and $H_2SO_4(aq)$ are acids. $CH_4(g)$ and $NH_3(g)$ are not acids, so hydrogen is written last in the formula. In some cases, hydrogen is written last if it is part of a group such as the COOH group; for example, $CH_3COOH(aq)$. These –COOH acids are organic acids and are described in more detail in Chapter 9.

Acids

Empirically, acids as pure substances are molecular compounds, as evident from their solid, liquid, and gas states of matter. Theoretically, they are composed of nonmetals that share electrons. However, the formulas of acids can be explained and predicted by assuming that they are ionic compounds. For example, the chemical formulas for the acids HCl(aq), H_2SO_4(aq), and CH_3COOH(aq) can be *explained* as follows:

H^+Cl^-(aq), $H^+{}_2SO_4{}^{2-}$(aq), $CH_3COO^-H^+$(aq)

The chemical formulas for acids can also be *predicted* by assuming that these aqueous molecular compounds of hydrogen are ionic:

aqueous hydrogen sulfide is $H^+{}_2S^{2-}$(aq), or H_2S(aq)
aqueous hydrogen sulfate is $H^+{}_2SO_4{}^{2-}$(aq), or H_2SO_4(aq)
aqueous hydrogen sulfite is $H^+{}_2SO_3{}^{2-}$(aq), or H_2SO_3(aq)

Acids are often named according to more than one system because they have been known for so long that the use of traditional names persists (**Figure 3**). IUPAC suggests that names of acids should be derived from the IUPAC name for the compound. In this system, sulfuric acid would be named aqueous hydrogen sulfate. However, the classical system of nomenclature is well entrenched, so it is necessary to know two or more names for many acids, especially the common ones.

The classical names for acids are based on anion names, according to three simple rules:

- If the anion name ends in "-ide," the corresponding acid is named as a "hydro —— ic" acid. Examples are hydrochloric acid, HCl(aq), hydrosulfuric acid, H_2S(aq), and hydrocyanic acid, HCN(aq).
- If the anion name ends in "-ate," the acid is named as a " —— ic" acid. Examples are nitric acid, HNO_3(aq), sulfuric acid, H_2SO_4(aq), and phosphoric acid, H_3PO_4(aq).
- If the anion name ends in "-ite," the acid is named as a " —— ous" acid. Sulfurous acid, H_2SO_3(aq), nitrous acid, HNO_2(aq), and chlorous acid, $HClO_2$(aq), are examples.

Figure 3
In addition to classical and systematic scientific names, many acids also have common commercial names. For example, muriatic acid is the commercial name for HCl(aq).

The classical system of acid nomenclature is part of a system for naming a series of related compounds. **Table 4** lists the acids formed from five different chlorine-based anions to illustrate this naming system.

Table 4 Classical Acid Nomenclature System of Chlorine Anion Acids

Ion Formula	IUPAC Ion name	Classical Acid name	Systematic IUPAC Acid name	Acid Formula
$ClO_4{}^-$	perchlorate ion	perchloric acid	aqueous hydrogen perchlorate	$HClO_4$(aq)
$ClO_3{}^-$	chlorate ion	chloric acid	aqueous hydrogen chlorate	$HClO_3$(aq)
$ClO_2{}^-$	chlorite ion	chlorous acid	aqueous hydrogen chlorite	$HClO_2$(aq)
ClO^-	hypochlorite ion	hypochlorous acid	aqueous hydrogen hypochlorite	HClO(aq)
Cl^-	chloride ion	hydrochloric acid	aqueous hydrogen chloride	HCl(aq)

Learning Tip

For oxy-ions such as $ClO_4{}^-$, the most common ion has an "... ate" suffix (e.g., chlorate). One extra oxygen is "per ... ate"; one less oxygen is "... ite"; and two less oxygens is "hypo ... ite".

Bases

Chemists have discovered that all aqueous solutions of ionic hydroxides make red litmus paper turn blue; that is, these compounds are *bases*. Other solutions have been classified as bases, but for the time being, restrict your definition of bases to aqueous ionic hydroxides such as NaOH(aq) and $Ba(OH)_2$(aq). The name of the base is the name of the ionic hydroxide; for example, aqueous sodium hydroxide and aqueous barium hydroxide.

Learning Tip

Scientists create classification systems to help them organize their knowledge. These classification systems also help you to organize the knowledge being learned.

SUMMARY Acids and Bases

- Empirically, acids are aqueous molecular compounds of hydrogen that form electrically conductive solutions and turn blue litmus paper red.
- By convention, the formula for an empirically identified acid is written as H___(aq) or ___COOH(aq).
- As pure substances, acids are molecular compounds, and, thus, can be solids, liquids, or gases; $HCl(g)$, $CH_3COOH(l)$, and $C_3H_4OH(COOH)_3(s)$.
- The chemical formulas and electrical conductivity of aqueous solutions of acids can be explained and predicted by assuming that these molecular compounds are ionic; for example, $H^+{}_2SO_4{}^{2-}(aq)$ or $H_2SO_4(aq)$.
- The classical names for acids follow this pattern: hydrogen _____ide becomes a "hydro_____ ic" acid; hydrogen _____ate is a "______ic" acid; hydrogen _____ite is a "_______ous" acid; and hydrogen hypo_____ite is a "hypo_______ous" acid.
- The IUPAC name for an acid is aqueous hydrogen _______; for example, aqueous hydrogen sulfate for $H_2SO_4(aq)$.
- Empirically, bases are aqueous ionic hydroxides that form electrically conductive solutions and turn red litmus paper blue.
- There is no special nomenclature system for bases. They are named as ionic hydroxides; for example, KOH(aq) is aqueous potassium hydroxide.

EXTENSION

Naming Compounds
Improve your understanding of naming ionic and molecular compounds.

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Section 1.6 Questions

1. Until a theoretical way of knowing molecular formulas is available, you must be given the formula or name and then rely on memory or use the prefix system to provide the name or formula as required. Provide the names or formulas (complete with the SATP states of matter) for the following substances:
   (a) chlorine (toxic)
   (b) phosphorus (reacts with air)
   (c) $C_2H_5OH(l)$ (alcohol)
   (d) methane (fuel)
   (e) helium (inert)
   (f) carbon (black)
   (g) $NH_3(g)$ (smelling salts)
2. Write the chemical formulas for the following molecular substances emitted as gases from the exhaust system of an automobile. Some of these substances may produce acid rain:
   (a) carbon dioxide
   (b) carbon monoxide
   (c) nitrogen dioxide
   (d) sulfur dioxide
   (e) nitrogen
   (f) octane
   (g) nitrogen monoxide
   (h) dinitrogen oxide
   (i) dinitrogen tetraoxide
   (j) water
3. Write unbalanced chemical equations to accompany the given statements or word equations, including the states at SATP. For example,

   nitrogen + oxygen → nitrogen dioxide

   $N_2(g) \quad + \quad O_2(g) \quad \rightarrow \quad NO_2(g)$

   (a) Solid silicon reacts with gaseous fluorine to produce gaseous silicon tetrafluoride.
   (b) Solid boron reacts with gaseous hydrogen to produce gaseous diboron tetrahydride.
   (c) Aqueous sucrose and water react to produce aqueous ethanol and carbon dioxide gas.
   (d) Methane gas reacts with oxygen gas to produce liquid methanol.
   (e) nitrogen + oxygen → nitrogen monoxide
   (f) nitrogen monoxide + oxygen → nitrogen dioxide
   (g) octane + oxygen → carbon dioxide + water vapour
   (h) octane + oxygen → carbon dioxide + carbon monoxide + carbon + water vapour
4. Classify the following as acidic, basic, neutral ionic, or neutral molecular:
   (a) KCl(aq) (fertilizer component)
   (b) HCl(aq) (in stomach)
   (c) sodium hydroxide (oven/drain cleaner)
   (d) ethanol (beverage alcohol)
5. Write the chemical formulas for the following acids:
   (a) aqueous hydrogen chloride (from a gas)
   (b) hydrochloric acid (stomach acid)
   (c) aqueous hydrogen acetate (from a liquid)
   (d) acetic acid (vinegar)
   (e) aqueous hydrogen sulfate (from a liquid)
   (f) sulfuric acid (car battery)
   (g) aqueous hydrogen nitrite (from a gas)
   (h) nitric acid (for making fertilizers)

6. Write accepted names for the following acids:
   (a) $H_2SO_3(aq)$ (acid rain)
   (b) HF(aq) (used for etching glass)
   (c) $H_2CO_3(aq)$ (carbonated beverages)
   (d) $H_2S(aq)$ (rotten egg odour)
   (e) $H_3PO_4(aq)$ (rust remover)
   (f) HCN(aq) (rat killer)
   (g) $H_3BO_4(aq)$ (insecticide)
   (h) $C_6H_5COOH(aq)$ (preservative)
7. Write chemical equations, including the states at SATP, for the following reactions involved in the manufacture and use of sulfuric acid:
   (a) Sulfur reacts with oxygen to produce sulfur dioxide gas.
   (b) Sulfur dioxide reacts with oxygen to produce sulfur trioxide gas.
   (c) Sulfur trioxide gas reacts with water to produce sulfuric acid.
   (d) Sulfuric acid reacts with ammonia gas to produce aqueous ammonium sulfate (a fertilizer).
   (e) Sulfuric acid reacts with rock phosphorus, $Ca_3(PO_4)_2(s)$, to produce phosphoric acid and solid calcium sulfate (gypsum).
8. Write chemical equations, including states at SATP, for the following reactions involved in the destructive reactions of acid rain:
   (a) Sulfuric acid in rain reacts with limestone (see Appendix J), causes deterioration of buildings, statues, and gravestones, and produces aqueous hydrogen carbonate (carbonic acid) and solid calcium sulfate.
   (b) Sulfuric acid from rain reacts with solid aluminium silicate in the bottom of a lake and releases aqueous hydrogen silicate (silicic acid) and toxic (to the fish) aqueous aluminium sulfate.
9. Write chemical equations, including states at SATP, for each of the following reactions involved in the control of acid rain:
   (a) Sulfur dioxide emissions can be reduced in the exhaust stack of an oil sands refinery by reacting the sulfur dioxide gas with lime (see Appendix J) and oxygen to produce solid calcium sulfate (gypsum).
   (b) Sulfuric acid in an acid lake can be neutralized by adding slaked lime (see Appendix J) to produce water and solid calcium sulfate.
10. An investigation is planned to explore the conductivity of various categories of substances. Complete the Analysis and Evaluation sections (Parts 2 and 3) of the investigation report.

Purpose
The purpose of this investigation is to extend the previously determined empirical definitions of ionic and molecular compounds to include the electrical conductivity of the solid, liquid, and aqueous states of matter.

Problem
What are the empirical definitions of ionic and molecular compounds?

Prediction
According to the current definitions of ionic and molecular compounds, ionic compounds are all solids at SATP that form electrically conductive solutions, whereas molecular compounds are solids, liquids, or gases at SATP that form non-conductive solutions.

Design
Pure samples of water (H_2O), calcium chloride ($CaCl_2$), sucrose ($C_{12}H_{22}O_{11}$), methanol (CH_3OH), sodium hydroxide (NaOH), and potassium iodide (KI) are tested for electrical conductivity in the pure state at SATP, in the pure molten state, and in aqueous solution.

manipulated variable:	compound tested
responding variable:	electrical conductivity
controlled variables:	temperature quantity of chemical quantity of water conductivity apparatus conductivity of the water

Evidence

Table 5 Electrical Conductivity of Compounds in Different States

Chemical formula	Pure state at SATP	Conductivity		
		Pure at SATP	Molten	Aqueous
H_2O	liquid	none	none	n/a*
$CaCl_2$	solid	none	high	high
$C_{12}H_{22}O_{11}$	solid	none	none	none
CH_3OH	liquid	none	none	none
NaOH	solid	none	high	high
KI	solid	none	high	high

*not applicable

Chapter 1 SUMMARY

Outcomes

Knowledge

- classify matter as pure and mixtures as homogeneous and heterogeneous (1.2)
- interpret the periodic table of the elements (1.3)
- use atomic theory to explain the periodic table (1.4)
- classify elements and compounds and know the properties of each class (1.3, 1.4)
- explain and predict chemical formulas for and name ionic and molecular compounds, acids, and bases (1.5, 1.6)
- identify the state of matter of substances (1.5, 1.6)
- write chemical equations when given reactants and products (1.5, 1.6)
- classify scientific knowledge as qualitative and quantitative, as observations and interpretations, and as empirical and theoretical (1.1)

STS

- describe the natures of science and technology (1.1)
- describe the application of some common chemicals (1.3, 1.5, 1.6)

Skills

- use a textbook, a periodic table, and other references efficiently and effectively (1.1–1.6)
- interpret and write laboratory reports (1.1, 1.2, 1.3, 1.4, 1.6)
- select and use diagnostic tests (1.2, 1.3, 1.4, 1.5, 1.6)

Key Terms

1.1
science
technology
chemistry
observation
interpretation
empirical knowledge
theoretical knowledge
empirical hypothesis
empirical definition
generalization
scientific law
law of conservation of mass

1.2
matter
pure substance
mixture
heterogeneous mixture
homogeneous mixture
element
entity
atom
compound
chemical formula

1.3
periodic law
family
group
period
semi-metal
standard ambient temperature and pressure (SATP)
metal
nonmetal
alkali metal
alkaline-earth metal
halogen
noble gas
main group element
transition element

1.4
theoretical hypothesis
theoretical definition
theory
mass number
atomic number
ion
monatomic ion
cation
anion

1.5
ionic compound
molecular compound
acid
base
neutral
aqueous solution
polyatomic ion
formula unit
empirical formula
hydrate

1.6
molecule
molecular formula
diatomic molecule

MAKE a summary

1. Prepare a concept map that is centred on pure substances. Include classes of substances along with their properties and nomenclature. See the Key Terms list.
2. Revisit your answers to the Starting Points questions at the start of this chapter. How has your thinking changed?

Go To

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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 1
- 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

Lightning
This video looks into the mystery of lightning from a scientific perspective. An understanding of positive and negative charges, related to the atomic theory, explains the phenomenon.

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Chapter 1 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.

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DO NOT WRITE IN THIS TEXTBOOK.

Part 1

Scientists not only classify natural objects and phenomena, but they also classify knowledge. In both cases, the process of classifying helps them (and us) to better organize knowledge.

1. The classification of knowledge includes
NR 1. interpretations 2. observations
Use the above classes of knowledge to classify the following statements, in order.
- Carbon (as graphite) conducts electricity.
- Aluminium can pass electrons from atom to atom.
- Sodium is a metal.
- Magnesium has two valence electrons.

___ ___ ___ ___

2. The classification of knowledge also includes
NR 1. quantitative observation 2. qualitative observation
Use the classes of observations to classify the following statements in order:
- To form an ion, the chlorine atom gains one electron.
- Gold is malleable.
- A sodium carbonate solution conducts electricity.
- The mass of magnesium burned is 2.0 g.

___ ___ ___ ___

3. Scientific knowledge can also be classified as
NR 1. empirical 2. theoretical
Use the above classes of knowledge to classify the following statements:
- Molecular compounds form nonconducting aqueous solutions.
- Ionic compounds dissolve as ions.
- Acids form conducting aqueous solutions.
- Bases dissolve to increase the hydroxide ion concentration.

___ ___ ___ ___

4. A substance that cannot be decomposed is _i_ definition for _ii_.
The above sentence is completed by the information in which row?

Row	i	ii
A.	an empirical	a compound
B.	an empirical	an element
C.	a theoretical	a compound
D.	a theoretical	an element

Science and technology are influential disciplines in our developed country. Understanding the natures of science and technology and their relationship to each other is important to being a citizen of Canada.

5. The purpose of scientific investigations does **not** include
A. creating a concept
B. verifying a concept
C. using a concept
D. testing a concept

6. The criterion that is **not** used to evaluate a scientific concept is its ability to
A. explain
B. predict
C. describe
D. prove

7. The relationship of science and technology is best described as
A. science leading technology
B. parallel supporting activities
C. science involving more trial and error
D. adversarial (in conflict)

Use this information to answer questions 8 and 9.

The format of a laboratory report reflects the basic pattern of scientific research. The following sections of a laboratory report are listed in random order.

1. Analysis
2. Evaluation
3. Evidence
4. Design
5. Materials
6. Problem
7. Procedure
8. Purpose
9. Prediction

8. Once the Purpose and Problem have been chosen, **identify**,
NR in order, the parts of an investigation report that are done before the work in a laboratory begins.

___ ___ ___ ___

9. **Identify**, in order, the parts of the investigation report that
NR are completed during and after the work in a laboratory.

___ ___ ___ ___

10. The Evaluation of an investigation does **not** involve
A. evaluating the evidence based upon whether the prediction is verified or falsified
B. evaluating the evidence based upon whether the design, materials, and procedure are adequate
C. evaluating the prediction by comparing the answer in the Analysis with the answer in the Prediction
D evaluating the hypothesis by comparing the answer in the Analysis with the answer in the Prediction

Use this information and the periodic table to answer questions 11 to 13.

Scientific research shows that heavy metals such as cadmium, lead, and mercury damage the human nervous and reproductive systems. This research has led to legislation restricting the use of these metals in Canada.

11. The name for an entity containing 48 electrons and 48 protons is
A. cadmium atom
B. cadmium ion
C. mercury atom
D. mercury ion

12. The symbol for an entity containing 80 electrons and 82 protons is
A. Hg(l)
B. Pb(s)
C. Hg^{2+}(aq)
D. Pb^{2+}(aq)

13. NR Chemical and Physical Properties of Elements
1. brittleness
2. form cations
3. solid at SATP
4. good insulators
5. silvery-grey colour
6. good conductors of heat
7. good conductors of electricity

The four properties shared by cadmium, lead, and mercury, listed in numerical order, are:

___ ___ ___ ___

Use this information to answer questions 14 to 16.

Some of the chemicals produced in Alberta are listed below.

1. ammonium sulfate, $(NH_4)_2SO_4$(s)
2. ammonia, NH_3(g)
3. caustic soda, NaOH(s)
4. chlorine gas, Cl_2(g)
5. ethene, C_2H_4(g)
6. methane, CH_4(g)
7. methanol, CH_3OH(l)
8. sodium chlorate, $NaClO_3$(s)
9. sulfur, S_8(s)

14. NR **Identify** the molecular compounds in numerical order.

___ ___ ___ ___

15. NR **Identify** the ionic compounds in numerical order.

___ ___ ___ ___

16. NR **Identify** the elements in numerical order.

___ ___ ___ ___

Use a periodic table to answer questions 17 to 19.

17. The element that has the **least** similar properties to the rest is
A. oxygen
B. sulfur
C. bromine
D. silver

18. The element that does **not** fit with the chemical properties of the rest is
A. sodium
B. potassium
C. lithium
D. cerium

19. NR The melting point of aluminium is

__________ °C.

Part 2

Scientific concepts can be defined in empirical terms or theoretical terms.

20. **Define** the following concepts empirically:
(a) metals
(b) nonmetals
(c) molecular compounds
(d) ionic compounds

21. **Define** the following concepts theoretically:
(a) atomic number
(b) mass number
(c) isotopes
(d) anion
(e) cation

22. Draw energy-level diagrams for the following entities:
(a) silicon atom
(b) potassium ion
(c) fluoride ion
(d) calcium atom
(e) sulfide ion

23. Table salt is often used in cooking. Many cook books recommend using salt in the water for cooking green beans. Some books suggest that the salt is necessary for maintaining the green colour of the beans.
(a) **Plan** a simple experimental design to test the hypothesis that salt is necessary to maintain the colour of green beans. (Refer to Appendix B.)
(b) If you know about single and double blind studies (see Appendix B.4), **plan** a more sophisticated experimental design for this research.

24. Copy and complete **Table 1** by classifying the compounds as ionic or molecular and writing the chemical formulas or IUPAC names.

Table 1 Ionic and Molecular Compounds

Use	IUPAC name	Ionic or molecular?	Formula
leavening agent	sodium hydrogen carbonate		
home heating fuel	methane		
bleach			NaClO(s)
masonry	calcium oxide		
dry ice			CO_2(s)
gas-line antifreeze	methanol		
in laundry detergent	sodium carbonate		
melts ice on sidewalks			$CaCl_2$(s)
sweetener			$C_{12}H_{22}O_{11}$(s)
fungicide	copper(II) sulfate		
prevents tooth decay			SnF_2(s)
car batteries	lead(IV) oxide		
food seasoning	sodium chloride		
solvent for oils and fats			CCl_4(l)
produces nitric acid	nitrogen dioxide		

25. A qualitative analysis of four compounds is carried out. Complete the Analysis of the following investigation report.

Purpose
The purpose of this investigation is to use evidence and empirical definitions to identify four solutions.

Problem
Which of the solutions labelled 1, 2, 3, and 4 is KCl(aq), C_2H_5OH(aq), HCl(aq), and $Ba(OH)_2$(aq)?

Design
Each solution is tested with a conductivity apparatus and with litmus paper to determine its identity. A sample of the water used for preparing the solutions is tested for conductivity as a control. Taste tests are ruled out because they are unsafe.

Evidence

Table 2 Qualitative Analysis Results

Solution	Conductivity	Litmus paper
water	none	no change
1	high	no change
2	high	blue to red
3	none	no change
4	high	red to blue

26. Memorizing is often an initial way of knowing something, such as a chemical formula. What other ways of knowing are available to you?

27. Chemistry is one way of knowing about nature. What are some other ways of knowing about natural phenomena?

Extension

28. Use the Internet to investigate how the modern view of fluctuating electrons in an atom compares with an Aboriginal view of a fluctuating universe. Briefly **describe** your findings.

www.science.nelson.com GO

29. Search for high-technology images, similar to **Figure 1**, of atoms in elements and molecules, and ions in ionic compounds.

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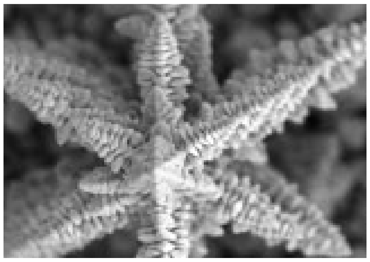

Figure 1
Image of a silver crystal taken with a scanning electron microscope (SEM).

30. Niels Bohr introduced his quantum model of the atom in his 1913 paper. In the last paragraph of the paper, Bohr wrote: "The foundation of the hypothesis has been sought entirely in its relation with Planck's theory of radiation; ... later it will be attempted to throw some further light on the foundation of it from another point of view."

The other point of view that Bohr refers to in this paragraph is that of testing the explanatory power of his quantum-model hypothesis by explaining the periodicity of the elements as displayed in the periodic table.

In your own words, use the Bohr theory of the atom to **explain** the periodic law. You can read Bohr's classic paper on the Nelson Web site.

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