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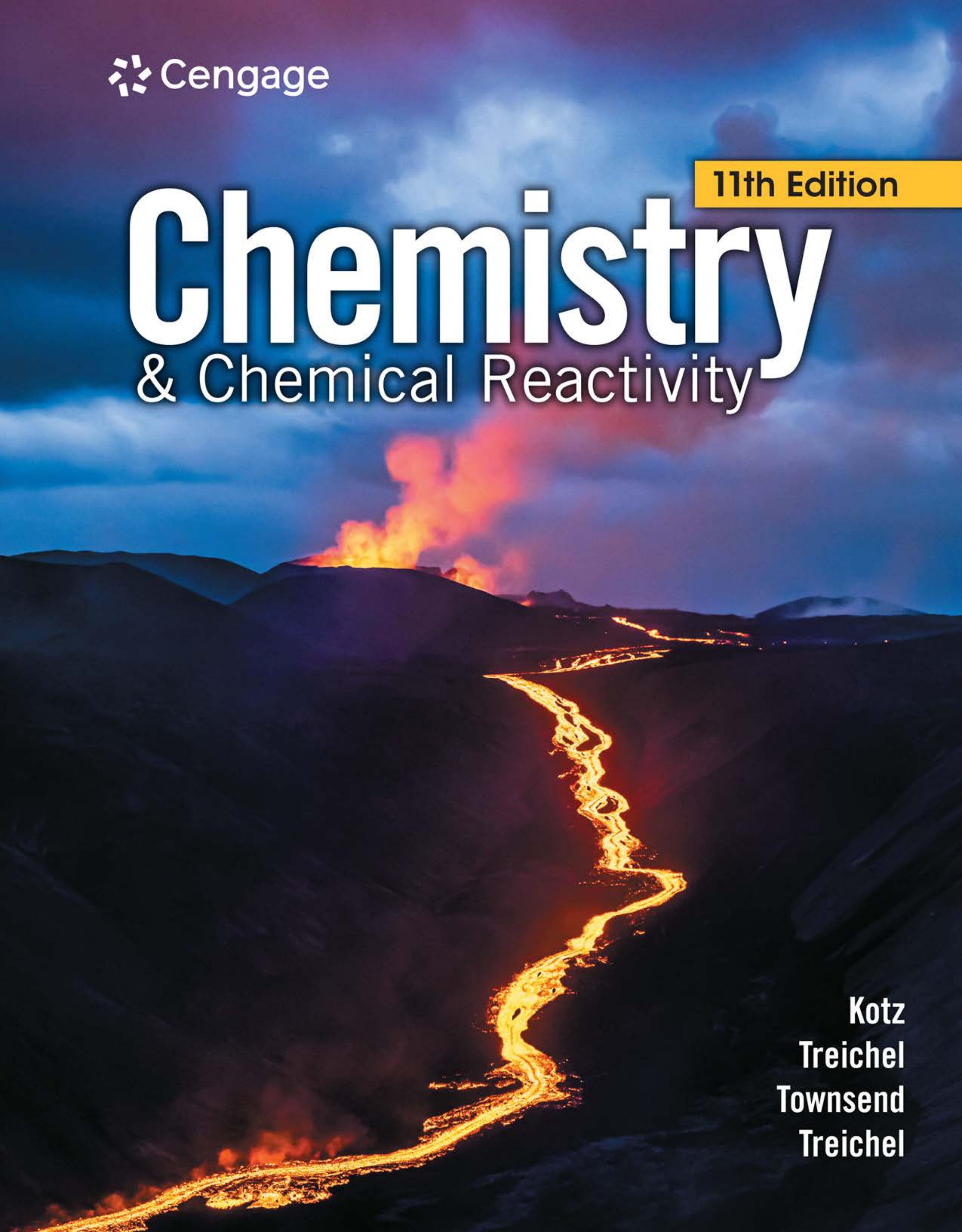
11th Edition

Chemistry
& Chemical Reactivity



Kotz
Treichel
Townsend
Treichel

Periodic Table of the Elements

- MAIN GROUP METALS
- TRANSITION METALS
- METALLOIDS
- NONMETALS

Uranium	
92	Atomic number
U	Symbol
238.03	Atomic weight

	1A (1)	2A (2)	3B (3)	4B (4)	5B (5)	6B (6)	7B (7)	8B (8)	8B (9)	8B (10)
1	Hydrogen 1 H 1.008									
2	Lithium 3 Li 6.94	Beryllium 4 Be 9.0122								
3	Sodium 11 Na 22.990	Magnesium 12 Mg 24.305								
4	Potassium 19 K 39.098	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956	Titanium 22 Ti 47.867	Vanadium 23 V 50.942	Chromium 24 Cr 51.996	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.693
5	Rubidium 37 Rb 85.468	Strontium 38 Sr 87.62	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.95	Technetium 43 Tc (98)	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42
6	Cesium 55 Cs 132.91	Barium 56 Ba 137.33	Lanthanum 57 La 138.91	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.95	Tungsten 74 W 183.84	Rhenium 75 Re 186.21	Osmium 76 Os 190.23	Iridium 77 Ir 192.22	Platinum 78 Pt 195.08
7	Francium 87 Fr (223)	Radium 88 Ra (226)	Actinium 89 Ac (227)	Rutherfordium 104 Rf (267)	Dubnium 105 Db (268)	Seaborgium 106 Sg (269)	Bohrium 107 Bh (270)	Hassium 108 Hs (277)	Meitnerium 109 Mt (276)	Darmstadtium 110 Ds (281)

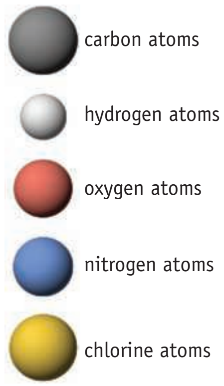
Lanthanides	Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Neodymium 60 Nd 144.24	Promethium 61 Pm (145)	Samarium 62 Sm 150.36	Europium 63 Eu 151.96
Actinides	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Neptunium 93 Np (237)	Plutonium 94 Pu (244)	Americium 95 Am (243)

Note: Atomic weights are IUPAC values. For elements for which IUPAC recommends ranges of atomic weights, conventional values are shown. Numbers in parentheses are mass numbers of the most stable isotope of an element.

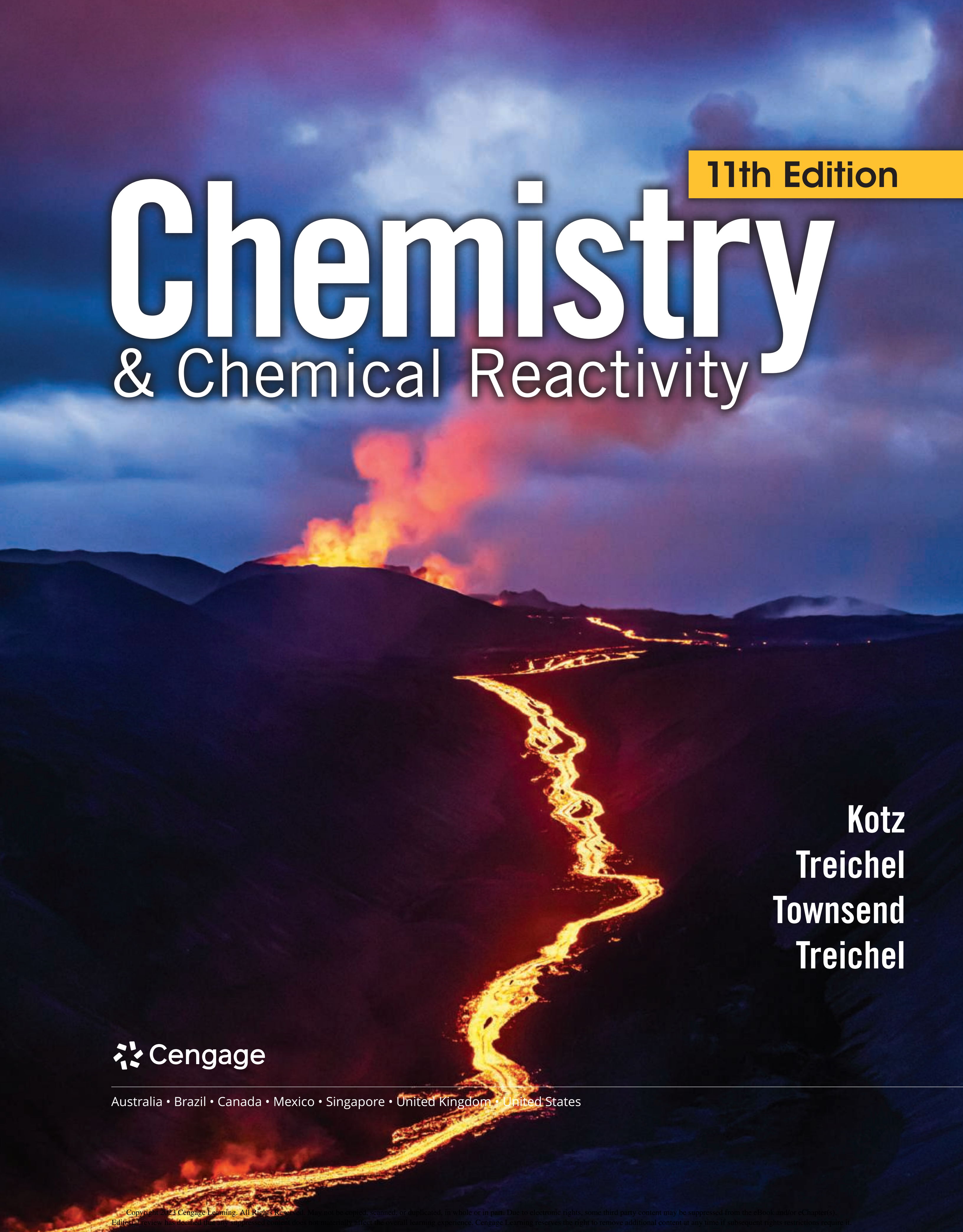
For the latest information see: https://iupac.org/what-we-do/periodic-table-of-elements/ and https://www.nist.gov/pml/periodic-table-elements

1B (11)	2B (12)	3A (13)	4A (14)	5A (15)	6A (16)	7A (17)	8A (18)
							Helium 2 He 4.0026
		Boron 5 B 10.81	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180
		Aluminum 13 Al 26.982	Silicon 14 Si 28.085	Phosphorus 15 P 30.974	Sulfur 16 S 32.06	Chlorine 17 Cl 35.45	Argon 18 Ar 39.95
Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.630	Arsenic 33 As 74.922	Selenium 34 Se 78.971	Bromine 35 Br 79.904	Krypton 36 Kr 83.798
Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Tin 50 Sn 118.71	Antimony 51 Sb 121.76	Tellurium 52 Te 127.60	Iodine 53 I 126.90	Xenon 54 Xe 131.29
Gold 79 Au 196.97	Mercury 80 Hg 200.59	Thallium 81 Tl 204.38	Lead 82 Pb 207.2	Bismuth 83 Bi 208.98	Polonium 84 Po (209)	Astatine 85 At (210)	Radon 86 Rn (222)
Roentgenium 111 Rg (282)	Copernicium 112 Cn (285)	Nihonium 113 Nh (286)	Flerovium 114 Fl (289)	Moscovium 115 Mc (290)	Livermorium 116 Lv (293)	Tennessine 117 Ts (294)	Oganesson 118 Og (294)

Standard Colors for Atoms in Molecular Models



Gadolinium 64 Gd 157.25	Terbium 65 Tb 158.93	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.93	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.05	Lutetium 71 Lu 174.97
Curium 96 Cm (247)	Berkelium 97 Bk (247)	Californium 98 Cf (251)	Einsteinium 99 Es (252)	Fermium 100 Fm (257)	Mendelevium 101 Md (258)	Nobelium 102 No (259)	Lawrencium 103 Lr (262)



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& Chemical Reactivity

Kotz
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Cengage

Australia • Brazil • Canada • Mexico • Singapore • United Kingdom • United States

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Chemistry and Chemical Reactivity,
Eleventh Edition
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Part Three States of Matter

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Part Five The Chemistry of the Elements

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Preface

The first edition of this book was conceived over 40 years ago. Since that time, there have been ten editions, and over one million students worldwide have used the book to begin their study of chemistry. Although the details of the book and its organization have changed over the years, our fundamental goal has remained the same: to provide a broad overview of the principles of chemistry, the reactivity of the chemical elements and their compounds, and the applications of chemistry. To reach this goal, we have tried to show the close relationship between the observations of chemical and physical changes made by chemists in the laboratory and in nature and the way these changes are viewed at the atomic and molecular levels. We have also tried to convey the sense that chemistry not only has a lively history but is also interesting and dynamic, with important new developments occurring every year. Furthermore, we wanted to provide some insight into the chemical aspects of the world around us.


David Kotz

Fireworks. See Chapter 6 for the chemistry of fireworks.

The authors of this text have collectively taught chemistry for over 100 years, and we have engaged in years of fundamental research. Like countless other scientists, our goals in our research and in writing this textbook have been to satisfy our curiosity about areas of chemistry, to document what we found, and to convey that to students and other scientists. Our results, and many others, may be used, perhaps only years later, to make a better material or better pharmaceutical. Every person eventually benefits from the work of the worldwide community of scientists.

In recent years, when people around the world have experienced various epidemics and increasing evidence of climate change has been published, science has come under attack. Some distrust the scientific community and dismiss the results of carefully done research. Therefore, a key objective of this book, and of a course in general chemistry, is to describe basic chemical "facts"—chemical processes and principles; how chemists came to understand those principles and new ideas; how they can be applied in industry, medicine, and the environment; and how to think about problems as a scientist. We have tried to provide the tools to help you become a chemically and scientifically literate citizen.

Audience for *Chemistry & Chemical Reactivity*

This textbook is designed for students interested in further study in science, whether that science is chemistry, biology, medicine, engineering, geology, physics, or related subjects. Our assumption is that students in a course using this book have had some preparation in algebra and general science. Although undeniably helpful, a previous exposure to chemistry is neither assumed nor required.

Philosophy and Approach of *Chemistry & Chemical Reactivity*

We have had several major but not independent objectives since the first edition of the book. Our first goal has been to write a book that students will find useful and interesting and that presents chemistry and chemical principles in a format and organization typical of college and university courses today. Second, we want to convey the utility and importance of chemistry by introducing the properties of the elements, their compounds, and their reactions.

The American Chemical Society has been urging educators to put *chemistry* back into introductory chemistry courses. We agree wholeheartedly. Therefore, we have tried to describe the elements, their compounds, and their reactions as early and as often as possible by:

- Bringing material on the properties of elements and compounds into the *Examples* and *Study Questions*.
- Using numerous photographs of the elements and common compounds, of chemical reactions, and of common laboratory operations and industrial processes.
- Each chapter incorporates *Applying Chemical Principles* questions that delve into the applications of chemistry.

General Organization

Through its many editions, *Chemistry & Chemical Reactivity* has had two broad themes: *Chemical Reactivity* and *Bonding and Molecular Structure*. The chapters on *Principles of Reactivity* introduce the factors that lead chemical reactions to be successful in converting reactants to products: common types of reactions, the energy involved in reactions, and the factors that affect the speed of a reaction. One reason for the enormous advances in chemistry and molecular biology in the last several decades has been an understanding of molecular structure. The sections of the book on *Principles of Bonding and Molecular Structure* lay the groundwork for understanding these developments. Particular attention is paid to an understanding of the structural aspects of such biologically important molecules as hemoglobin and DNA.

Flexibility of Chapter Organization

As we look at the introductory chemistry texts currently available and talk with colleagues at other universities, it is evident there is a generally accepted order of topics in the course. With minor variations, we followed that order. That is not to say that the chapters in our book cannot be used in some other order. We have written this book to be as flexible as possible. An example is the flexibility in covering the behavior of gases (Chapter 10). It has been placed with the chapters on liquids, solids, and solutions (Chapters 11–13) because it logically fits with those topics. However, it can also be read and understood after covering only the first four chapters of the book.

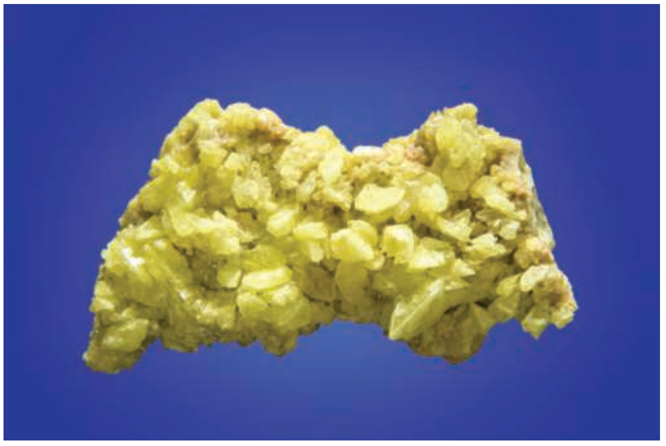
Similarly, the chapters on atomic and molecular structure (Chapters 6–9) can be used in an *atoms-first approach* before the chapters on stoichiometry and common reactions (Chapters 3 and 4). To facilitate this, there is an introduction to energy and its units in Chapter 1. Also, the chapters on chemical equilibria (Chapters 15–17) can be covered before those on solutions and kinetics (Chapters 13 and 14). Although organic chemistry (Chapter 23) is one of the final chapters in the textbook, the topics of this chapter can also be presented to students following the chapters on structure and bonding (Chapters 9 and 10).

The order of topics in the text was also devised to introduce as early as possible the background required for the laboratory experiments that are usually performed in introductory chemistry courses. For this reason, chapters on chemical and physical properties, common reaction types, and stoichiometry begin the book. In addition, because an understanding of energy is very important for the study of chemistry, energy and its units are introduced in Chapter 1, and thermochemistry is introduced in Chapter 5.

Sections of the Book — Organization and Purpose

Part One: The Basic Tools of Chemistry

The basic ideas and methods of chemistry are introduced in Part One. Chapter 1 defines important terms, and the accompanying Chapter 1R reviews measurement units and some fundamental mathematical methods used throughout the text. Chapter 2 introduces atoms, molecules, and ions as well as the most important organizational device in chemistry, the periodic table. In Chapter 3, we begin to discuss the principles of chemical reactivity. Writing chemical equations is covered here, and there is a short introduction to the concept of chemical equilibrium. In addition, some major types of chemical reactions in aqueous solution are introduced. Then, in Chapter 4, we describe the numerical methods used by chemists to extract quantitative information from chemical reactions. Chapter 5 is an introduction to the energy changes involved in chemical processes.



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Elemental sulfur.

Part Two: Atoms and Molecules

The current theories that explain the arrangement of electrons in atoms and monatomic ions are presented in Chapters 6 and 7. This discussion is tied closely to the arrangement of elements in the periodic table and to their periodic properties. In Chapter 8, we discuss the details of chemical bonding and the properties of these bonds. In addition, we show how to derive the three-dimensional structure and charge distribution of simple molecules. Finally, Chapter 9 considers the major theories of chemical bonding in more detail.

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Liquid oxygen is attracted to a strong magnet. See Chapter 9 for an explanation of the magnetic properties of oxygen.

Part Three: States of Matter

The behavior of the three states of matter—gases, liquids, and solids—is described in Chapters 10–12. The discussion of liquids and solids is tied to gases through the description of intermolecular forces in Chapter 11, with particular attention given to liquid and solid water. In Chapter 13, we describe the properties of solutions—intimate mixtures of gases, liquids, and solids.

John C. Kotz

Hot air balloon takes off. See Chapter 5 for an introduction to transfers of energy as heat and work. See Chapter 10 for a discussion of the gas laws.

Part Four: The Control of Chemical Reactions

This section is wholly concerned with the *Principles of Reactivity*. Chapter 14 examines the rates of chemical processes and the factors controlling these rates. Next, Chapters 15–17 describe chemical equilibrium. After an introduction to equilibrium in Chapter 15, we highlight reactions involving acids and bases in water (Chapters 16 and 17) and reactions leading to slightly soluble salts (Chapter 17). To tie together the discussion of chemical equilibria and thermodynamics, we explore entropy and free energy in Chapter 18. As a final topic in this section, we describe in Chapter 19 chemical reactions that involve the transfer of electrons and the use of these reactions in electrochemical cells.

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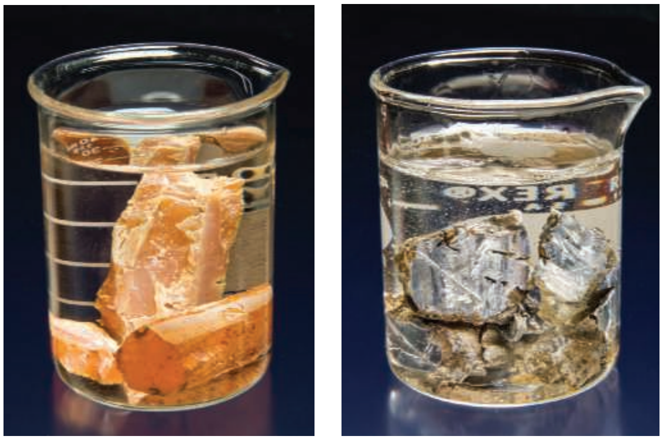
The explosive reaction of hydrogen and oxygen.

Part Five: The Chemistry of the Elements

Although the chemistry of many elements and compounds is described throughout the book, Part Five considers this topic in a more systematic way. Chapter 20 is an overview of nuclear chemistry. Chapter 21 is devoted to the chemistry of the main group elements, and Chapter 22 is a discussion of the transition elements and their compounds. Chapter 23 is a brief introduction to organic chemistry with an emphasis on molecular structure, basic reaction types, and polymers, and Chapter 24 is an introduction to biochemistry. Finally, Chapter 25 brings together many of the concepts in earlier chapters into a discussion of "Environmental Chemistry—Earth's Environment, Energy, and Sustainability."



Photos: © Charles D. Winters/Cengage

Elements: yellow phosphorus in water (left) and shiny potassium under oil (right).

What's New to this Edition?

The entire book was thoroughly reviewed. Many parts are rewritten, and new Study Questions were added. In addition, there are several new features that occur in each chapter.

Think–Pair–Share Questions

Many instructors have experimented with moving beyond simply lecturing in general chemistry. One approach that has worked especially well has been to take class time for students to work together on questions that help them learn course topics. This is the purpose of the *Think–Pair–Share* questions. Students work independently on the questions first, then form small groups to discuss their answers, and finally, present their results to the class. These questions do not generally require many calculations. Instead, they focus on helping students to think more deeply about the concepts of the chapter. They are placed after the *Applying Chemical Principles* questions and before the *Chapter Goals Revisited*.

Think–Pair–Share

1. You are tasked with determining the specific heat capacity (in J/g·K) for an unknown metal. The following equipment and supplies are available: a 25.0-g piece of the metal, a 200-mL insulated container, a graduated cylinder, water, ice, and a thermometer that can measure temperature changes accurately to ±0.02 °C.

(a) Outline the steps for an experimental procedure to determine the specific heat capacity of the metal using the available equipment and supplies.

(b) Identify possible sources of error in your experimental procedure that might cause an inaccurate result. (Assume the graduated cylinder and thermometer are both accurate and precise, and that human error is not a source of error.)

(c) Suggest some ideas for how to correct for some of these error sources.

2. For introductory laboratories, resealable plastic bags are a convenient way to conduct experiments involving gas-forming reactions. Energy as heat or work can transfer in or out of the plastic bag, but reactants and products remain trapped. In an experiment, nitric acid reacts with a small amount of copper in a sealed plastic bag according to the following balanced chemical equation:

$$Cu(s) + 4\ HNO_3(aq) \longrightarrow Cu(NO_3)_2(aq) + 2\ NO_2(g) + 2\ H_2O(\ell)$$

As the reaction proceeds, the contents of the bag become warm, and the bag inflates with a brown gas (NO_2).

(a) Define the system and the surroundings for this experiment.

(b) Does energy as heat (q) flow into the system or out of the system? What is the sign of q?

(c) Is work (w) done in this experiment? If so, is work done by the system on the surroundings, or by the surroundings on the system? What is the sign of w?

3. The following table shows the enthalpy of combustion for some fuels in units of kJ/mol, kJ/L, and kJ/g. The enthalpy of combustion per volume assumes a temperature of 25 °C and atmospheric pressure (1 atm). Note that although gasoline is a mixture of many hydrocarbons, it is often represented as octane.

Fuel	$\Delta H°$ (kJ/mol)	$\Delta H°$ (kJ/L)	$\Delta H°$ (kJ/g)
Hydrogen, $H_2(g)$	−285.8	−11.7	−141.8
Methane, $CH_4(g)$	−890.2	−36.4	−55.5
Ethane, $C_2H_6(g)$	−1560.6	−63.8	−51.9
Ethanol, $C_2H_6O(\ell)$	−1376.5	−23,590	−29.9
Octane, $C_8H_{18}(\ell)$	−5490	−33,814	−48.1

(a) When determining which fuel provides the most energy in a car engine, is it best to compare the enthalpy change in a combustion reaction by moles, volume, or mass? Explain your reasoning? Based on your decision, which fuel provides the most energy (at the given temperature and pressure).

(b) Gasoline sold in the United States is often a blend of 10%, 15%, or even up to 85% ethanol by volume. Identify at least one advantage and one disadvantage of using gasoline blended with ethanol versus ethanol-free gasoline?

(c) Why are the enthalpies of combustion per liter of hydrogen, methane, and ethane much lower than those of ethanol and octane?

(d) The enthalpy of combustion of hydrogen per gram is nearly three times that of a hydrocarbon. And unlike a hydrocarbon, which produces the greenhouse gas CO_2 upon combustion, the combustion of hydrogen produces only water. Unfortunately, there are multiple issues in replacing gasoline with hydrogen as a fuel. What are some of the problems that must be overcome if hydrogen is to compete with, or possibly replace, gasoline as a fuel in vehicles?

Chemistry in Your Career

All of us have students who have gone on to wonderful careers, some in traditional chemistry careers, but often in some other field where a background in chemistry is useful. Each chapter features a short biography of a person who studied chemistry and now works, perhaps as a chemist, but more generally in a profession where they use their background in chemistry. This feature highlights people from diverse backgrounds to show all students that they have a place in chemistry and STEM courses.

Redesigned Strategy Maps

For many students, a visual *Strategy Map* can be a useful tool in problem solving (as on page 194). These have been redesigned to be more fully incorporated into the Solution section of the *Example* problems. There are 44 *Strategy Maps* accompanying *Example* problems in the book.

Example 4.1

Strategy Map

Problem
Calculate mass of O_2 required for combustion of **25.0 g of glucose**.

Data/Information
Formulas for reactants and products and the **mass** of one reactant (glucose)

Mass Relations in Chemical Reactions

Problem Glucose, $C_6H_{12}O_6$, reacts with oxygen to give CO_2 and H_2O. What mass of oxygen (in grams) is required to completely react with 25.0 g of glucose? What masses of carbon dioxide and water (in grams) are formed?

What Do You Know? You are given the mass of one of the reactants (glucose) and are asked to determine the masses of the other substances in the reaction. You know formulas for the reactants and products and need to calculate their molar masses.

Strategy Write the balanced chemical equation for this reaction. Then, follow the scheme outlined in Problem Solving Tip 4.1 and in the Strategy Map for this example.

Solution

Step 1 **Write the balanced equation.**

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

Step 2 **Convert the given mass (grams) to amount (moles).**

Use the molar mass of glucose to convert its mass (25.0 g) to the amount of glucose.

$$25.0\ \text{g glucose} \times \frac{1\ \text{mol glucose}}{180.2\ \text{g glucose}} = 0.1387\ \text{mol glucose}$$

Step 3 **Use the stoichiometric factor to convert the amount (moles) of glucose to the amount (moles) of O_2.**

Use the coefficients of the balanced equation to obtain the stoichiometric factor of 6 mol O_2 per 1 mol glucose, and then convert the amount of glucose to the amount of O_2.

$$0.1387\ \text{mol glucose} \times \frac{6\ \text{mol}\ O_2}{1\ \text{mol glucose}} = 0.8324\ \text{mol}\ O_2$$

Step 4 **Convert the amount (moles) of the requested substance to its mass (grams).**

Use the molar mass of O_2 to convert from the amount of O_2 to the mass of O_2.

$$0.8324\ \text{mol}\ O_2 \times \frac{32.00\ \text{g}\ O_2}{1\ \text{mol}\ O_2} = 26.6\ \text{g}\ O_2$$

Some of the Other Changes for This Edition

- Recent changes to the definitions of the SI Base Units are explained in a new *Closer Look* box (page 34).
- The atomic weights of the elements on the periodic tables and other tables have been updated based on values from the International Union of Pure and Applied Chemistry (IUPAC) and the National Institute of Standards and Technology (NIST).
- The issue of ranges being recommended by IUPAC for the atomic weights of some elements is discussed in a new *Closer Look* box (page 70).
- References to element groups in the periodic table are now given in both the traditional system used in the United States (Group 5A, for example) and the 1–18 system recommended by IUPAC.
- Biographies of some important scientists and their discoveries have been prepared (Marie Curie [page 82]; Antoine and Marie-Anne Lavoisier [page 141]; Niels Bohr [page 314]; James Watson, Francis Crick, and Rosalind Franklin [page 439]; and Lise Meitner [page 1020]).
- A new subsection "Naming Common Acids" (page 157) was added.
- The classification scheme for acid–base and gas-forming acid–base reactions (Sections 3.6–3.7) has been revised as well as the overall classification scheme of reactions in aqueous solution (Section 3.9).
- A *Closer Look* box (page 208) on nuclear magnetic resonance spectroscopy has been added.
- A greater distinction between heat capacity and specific heat capacity was made in Chapter 5.
- A new *Closer Look* box "Enthalpy, Internal Energy and Non-Expansion Work" (page 270) was added.
- A new *Problem-Solving Tip* (page 355) was included about the different methods used for writing the electron configuration of an atom.
- Chapter 8, "Bonding and Molecular Structure," was restructured.
- The story of the unraveling of the structure of DNA was expanded in Chapter 8.
- Two *Closer Look* boxes were added in Chapter 12, one on using X-rays to determine crystal structure and the other about glass.
- The positions of the chapters about nuclear chemistry (Chapter 20 in the current edition) and environmental chemistry (Chapter 25) were swapped so that information about nuclear chemistry can inform the content of later chapters and so that the chapter on environmental chemistry can serve as an overarching conclusion to the book.
- A new *Closer Look* box about radioactive decay series (page 997) was added to Chapter 20.
- The section on the origin of the elements (in Chapter 20, "Nuclear Chemistry") was expanded and revised.
- In Chapter 24, "Biochemistry," new material has been added on mRNA vaccines, electron carriers in biochemical oxidation–reduction reactions, and the metabolism of glucose in respiration.
- Chapter 25, "Environmental Chemistry—Earth's Environment, Energy, and Sustainability" has been updated and reorganized.
- All *Examples* have been reviewed, some have been revised to make the steps of the strategy clearer, and nine new *Examples* were written (*Example R.3* "Precision and Standard Deviation;" *Example 2.5* "Binary Molecular Compounds;" *Example 2.8* "Naming Ionic Compounds;" *Example 3.5* "Separating a Mixture by Selective Precipitation;" *Example 3.9* "Recognizing Oxidation–Reduction Reactions;" *Example 4.3* "Calculating Percent Yield;" *Example 4.8* "Relating Amount and Molarity;" *Example 4.12* "Acid–Base Titration;" and *Example 6.6* "Orbitals and Quantum Numbers").
- There are now over 2650 *Study Questions* in the book. Of these, over 360 are either new or revised in this edition.
- All appendices have been updated to ensure they contain the latest information.
- Appendix N, "Answers to Study Questions, Check Your Understanding, and Applying Chemical Principles Questions," has been accuracy checked by the book authors and the author of the *Student Solutions Manual*, Professor Charles Atwood.
- An *Index of Names* has been added so readers can find the contributions of generations of chemists.

Features of the Book

Some years ago, a former student of one of the authors, now an accountant, shared his perspective on his experience in general chemistry. He said that, while chemistry was one of his hardest subjects, it was also the most useful course he had taken because it taught him how to solve problems in addition to having learned to appreciate a bit of chemistry. We were certainly pleased because we have always thought that an important goal in general chemistry is not only to teach students chemistry but also to help them learn critical thinking and problem-solving skills. Many of the features of the book are meant to support those goals.

Problem-Solving Approach: Organization and Strategy Maps

Worked-out *Examples* are an essential part of each chapter. To better help students follow the logic of a solution, all *Examples* are organized around the following outline:

Problem: A statement of the problem.

What Do You Know?: The information given is outlined.

Strategy: The information available is combined with the objective, and we begin to devise a pathway to a solution.

Solution: We work through the steps, both logical and mathematical, to the answer.

Think About Your Answer: We ask if the answer is reasonable or what it means.

Check Your Understanding: This is a similar problem for the student to try. A solution to the problem is in Appendix N.

Chapter Goals Revisited

The learning goals for each chapter section are listed at the beginning of the section. The goals are revisited on the last pages of the chapter, and specific end-of-chapter *Study Questions* are listed that can help students determine if they have met those goals.

End-of-Chapter Study Questions

There are between 48 and 178 *Study Questions* for each chapter, and answers to the odd-numbered questions are given in Appendix N. Questions are grouped as follows:

Practicing Skills: These questions are grouped by the topic covered by the questions.

General Questions: There is no indication regarding the pertinent section of the chapter. They generally cover several chapter sections.

In the Laboratory: These are problems that may be encountered in a laboratory experiment on the chapter material.

Summary and Conceptual Questions: These questions use concepts from the current chapter as well as preceding chapters.

Finally, some questions are marked with a small red triangle (▲). These are more challenging than other questions.

A Closer Look Essays and Problem-Solving Tips

As in the tenth edition, there are boxed essays titled *A Closer Look* that take a more in-depth look at relevant chemistry. While retaining and updating many from previous editions, we wrote several new ones and heavily revised some others including: "The SI Base Units" (Chapter 1R), "Isotopic Abundances and Atomic Weights" (Chapter 2), "Marie Curie (1867–1934)" (Chapter 2), "Amedeo Avogadro and His Number" (Chapter 2), "Nuclear Magnetic Resonance (NMR) Spectroscopy" (Chapter 4), "Enthalpy, Internal Energy, and Non-Expansion Work" (Chapter 5), "Niels Bohr (1885–1962)" (Chapter 6), "Lise Meitner (1878–1968)" (Chapter 20), "Hydrogen in Transportation" (Chapter 21), "mRNA Vaccines" (Chapter 24), "Methane Hydrates" (Chapter 25), and "Perfluoroalkyl Substances (PFAS)" (Chapter 25).

From our teaching experience, we have learned some "tricks of the trade" and try to pass on some of those in *Problem-Solving Tips*.

Applying Chemical Principles

At the end of each chapter are longer questions that use the principles learned in the chapter to study examples of forensic chemistry, environmental chemistry, medicinal chemistry, or other areas. Examples are "Atom Economy" (Chapter 4), "What Makes the Colors in Fireworks" (Chapter 6), "A Pet Food Catastrophe" (Chapter 11), "Lithium and Electric Vehicles" (Chapter 12), "The Age of Meteorites" (Chapter 20), and "Blue!" (Chapter 22).

Online Learning

Created by teaching chemists, *OWLv2* is a powerful online learning solution for chemistry with a unique Mastery Learning approach. It enables students to practice at their own pace, receive meaningful feedback, and access a variety of learning resources to help them master chemistry and achieve better grades.

The textbook's *Study Questions* are available in the *OWLv2* online learning system. *OWLv2* now has over 1800 of the roughly 2650 *Study Questions* in the book.

The *OWLv2* course and MindTap eReader both contain nearly 300 videos on specific topics narrated by the authors to help students visualize concepts and master difficult problems by watching them be solved on screen.

Acknowledgments

Preparing this new edition of *Chemistry & Chemical Reactivity* took about two years of continuous effort. As was true for our work on the first ten editions, we have had the support and encouragement of our colleagues at Cengage and our families, friends, faculty colleagues, and students.

Cengage

The ten previous editions of this book have been published by Cengage and its predecessor companies, and once again we had an excellent production team in place for this, the eleventh edition. Maureen McLaughlin and Helene Alfaro led the team with Mona Zeftel overseeing many aspects of book design. Various people helped with content organization: James Nash, Breanna Holmes, and Kelly Aull. They were invaluable.

The first half of the book in this edition was thoroughly reviewed and edited by Margy Kuntz. This is the eleventh edition of a book that has been used successfully in its previous editions by over a million students. Nonetheless, Margy found ways to better organize and clarify sections in these chapters.

The *Chemistry in Your Career* boxes are a new feature of the book, and we want to acknowledge the many people who told us their stories. We hope these will help the many students who take a chemistry course see how it can be important in their careers. Rebecca Heider at Cengage was masterful in putting their stories into small, readable vignettes.

Chemistry & Chemistry Reactivity has been supported by OWL for many editions. The relationship of the book and OWL has continued to be very well managed by Theresa Dearborn.

Art, Design, and Photography

Many of the color photographs in this book have been beautifully created by Charles D. Winters over many years and ten editions.

The book still profits from the design and illustration skills of Patrick Harman. Pat designed the first edition of our *Interactive General Chemistry CD-ROM* (published in the 1990s). For the fifth through the tenth editions of the book, Pat revised many of the figures in the book to bring a fresh perspective to ways to communicate chemistry. All these illustrations remain in use in this edition.

Other Collaborators

We have been fortunate to have had several colleagues play valuable roles in this project over its many editions. One who has been especially important to this edition is Professor Charles (Butch) Atwood. He has been very helpful in ensuring the accuracy of the *Study Question* answers in the book and producing the *Student Solutions Manual*.

Eleventh Edition Reviewers

We encourage users, both faculty and students, to contact us about book content and with suggestions for improvement. There have been many instances of this over the years and they have improved the book. In particular, we would like to thank Roger Barth (West Chester University of Pennsylvania) for many useful comments that assisted us as we planned changes for this edition. The following reviewed the book for this edition:

- John M. Farrar, *Northern Kentucky University*
- Bernard Majdi, *South Georgia State College*
- Danica A. Nowosielski, *Hudson Valley Community College*
- Jessica A. Parr, *University of Southern California*
- Dr. Jeff Seyler, *University of Southern Indiana*
- Jeffrey Stephens, *North Iowa Area Community College*
- Tarek Trad, *Sam Houston State University*
- Saul R. Trevino, *Houston Christian University*

About the Authors

John (Jack) Kotz graduated from Washington and Lee University in 1959 and earned a Ph.D. in chemistry at Cornell University in 1963. He was a National Institutes of Health postdoctoral fellow at the University of Manchester in England and at Indiana University. He was an Assistant Professor of Chemistry at Kansas State University before moving to the State University of New York at Oneonta in 1970. He taught general chemistry and inorganic chemistry, and in 1986 was appointed a State University of New York Distinguished Teaching Professor of Chemistry. He retired from active teaching in 2005. He is the author or co-author of sixteen chemistry textbooks, among them two in advanced inorganic chemistry, two introductory general chemistry books in numerous editions, and various manuals and study guides. The general chemistry book has been published as an interactive CD-ROM, as an interactive ebook, and has been translated into five languages. He has also published research papers in organometallic chemistry, and among his awards are the *SUNY Award for Research and Scholarship* and the *Catalyst Award in Education* from the Chemical Manufacturers Association. He was a Fulbright Senior Lecturer in Portugal and a mentor for the U.S. National Chemistry Olympiad team. He has served on the boards of trustees for the College at Oneonta Foundation, the Kiawah Island Nature Conservancy, and Camp Dudley. He is also an avid photographer, primarily of wildlife (www.greensward.smugmug.com). His email address is johnkotz@mac.com.

Paul M. Treichel received his B.S. degree from the University of Wisconsin in 1958 and a Ph.D. from Harvard University in 1962. After a year of postdoctoral study in London, he assumed a faculty position at the University of Wisconsin–Madison. He served as department chair from 1986 through 1995 and was awarded a Helfaer Professorship in 1996. He has held visiting faculty positions in South Africa (1975) and in Japan (1995). Retiring after 44 years as a faculty member in 2007, he is currently Emeritus Professor of Chemistry. During his faculty career he taught courses in general chemistry, inorganic chemistry, organometallic chemistry, and scientific ethics. Professor Treichel's research in organometallic and metal-cluster chemistry and in mass spectrometry, aided by 75 graduate and undergraduate students, has led to more than 170 papers in scientific journals. He may be contacted by email at treichelpaul@me.com.

John R. Townsend completed his B.A. in Chemistry as well as the Approved Program for Teacher Certification in Chemistry at the University of Delaware. After a career teaching high school science and mathematics, he earned his M.S. and Ph.D. in biophysical chemistry at Cornell University, where he also received the DuPont Teaching Award for his work as a teaching assistant. After teaching at Bloomsburg University of Pennsylvania, he joined the faculty at West Chester University of Pennsylvania where he coordinated the chemistry education program for prospective high school teachers and the general chemistry lecture programs, taught undergraduate courses in general chemistry and biochemistry, and was the university supervisor for 78 prospective high school chemistry teachers during their student teaching semester. In 2021, he was the recipient of the Award for Excellence in Undergraduate Teaching in Chemical Science from the Philadelphia (Pennsylvania) Section of the American Chemical Society. Retiring in 2021, he is an Emeritus Professor of Chemistry at West Chester University. He may be contacted by email at jtownsend@wcupa.edu.

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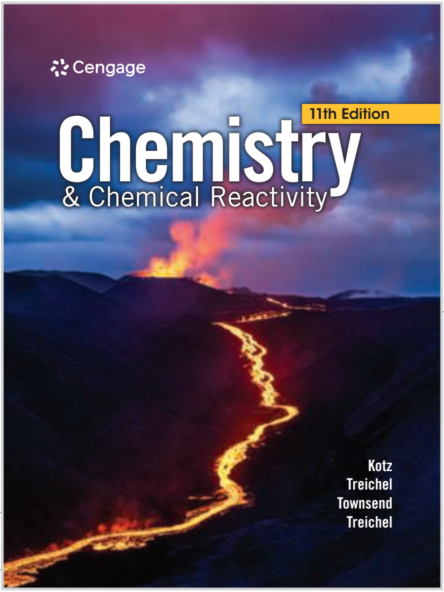
About the Cover



Ralph Lee Hopkins

Cover photo by Ralph Lee Hopkins, Fagradalsfjall volcano, Iceland, 2021.

Fagradalsfjall volcano, on the Reykjanes Peninsula not far from Reykjavik in Iceland, started erupting on March 19, 2021, and continued to erupt for six months. The volcano erupted again August 3, 2022, but went quiet after only 10 days.

For many observers, the most spectacular part of a volcanic eruption is the lava or molten rock that comes from the Earth's mantle during an eruption. For others, particularly scientists, volcanic activity provides opportunities to explore the chemical makeup of the Earth's mantle and to study the effects of volcanic activity on the environment.

Volcanoes are part of the story of the history and chemistry of the Earth. Volcanic events have always occurred and continue to occur around the globe as the result of tectonic plate activity. One massive volcanic event occurred in 1883 on the island of Krakatoa in Indonesia. Thousands of people in the volcano's vicinity perished quickly, but the eruption also had global consequences. For example, temperatures across the northern hemisphere dropped by an average of 0.4 °C in the year following the eruption.

Environmental scientists study the effects of volcanic activity. Scientists know that volcanic activity injects large amounts of water vapor, carbon dioxide, and sulfur dioxide into the atmosphere. Other gases released include hydrogen chloride and stinky "sewer gas" or hydrogen sulfide. There is a significant cooling effect in the atmosphere, partly from the conversion of sulfur dioxide to sulfuric acid and sulfate aerosols. These reflect sunlight back into space and cool the Earth. You might think that the carbon dioxide from volcanoes would increase global warming, a topic of current concern. However, scientists have shown that volcanoes emit less than 1% of the massive amount of carbon dioxide put into the atmosphere by human activities today.

The elements and compounds that arise from volcanic activity are fundamentally important. You will encounter these substances and many others in this general introduction to the field of chemistry.

Personal statement from Ralph Lee Hopkins, the photographer: It was a dream come true for a geologist-photographer to trek to an active volcano in Iceland. Words can't describe the sights, sounds, and smells of new earth being created. I spent two weeks and made five treks in between bad weather and poison gas warnings. I was very lucky to witness flowing lava up close and a sinuous river of lava spilling from the crater at sundown.

Dedication

We wish to dedicate this edition of *Chemistry & Chemical Reactivity* to our colleagues who have contributed to our knowledge of chemistry and teaching and to our many students, some of whom became good friends and who helped us understand better how to communicate our science. We also acknowledge and thank Professor Paul Treichel who helped shape this book with his work on many of the previous editions. His expertise, good humor, and friendship over the years are appreciated. And, finally, we thank our families who supported the years of work needed to produce this book and for their support throughout our careers.

1 Basic Concepts of Chemistry

Dnsphotography/iStock/Getty Images

Chapter Outline

Chemistry is the scientific study of the composition, structure, and properties of **matter** and the changes in both composition and energy that matter undergoes during reactions. Although chemistry is endlessly fascinating—at least to chemists—why should you study chemistry? Each person probably has a different answer, but many students take a chemistry course because those who are professional scientists, who teach and are involved daily in scientific work, realize how important chemistry is in any curriculum leading to a career in a science-related discipline. You will come to appreciate that chemistry is central to understanding disciplines as diverse as biology, geology, materials science, medicine, physics, and some branches of engineering. This is why chemistry is sometimes referred to as the *central science*. In addition, chemistry plays a major role in national economies, and chemistry and chemicals affect our daily lives in a wide variety of ways.

Matter Anything that occupies space and has mass — all substances and mixtures in the universe are composed of matter.

A course in chemistry can also help you see how a scientist thinks about the world and solves problems. The knowledge and skills developed in chemistry courses will benefit you in many career paths and help you become a better-informed citizen in a world that is becoming technologically more complex—and more interesting.

1.1 Chemistry and Its Methods

Goal for Section 1.1

- Recognize the difference between a hypothesis and a theory, and understand how laws are established.

This book provides a foundation for learning chemistry, a discipline that has developed over many centuries through the work of people around the planet. However, chemistry is about far more than historical knowledge. New

◀ **Methane Bubbles Trapped in Ice.** Bodies of water are often filled with and surrounded by vegetation. Over time, the vegetation will decay, slowly being digested by bacteria that release methane, a greenhouse gas, as a product of the digestion. Some of the methane bubbles rise to the surface, and in the winter the bubbles can be trapped in ice. The white patches in the photo are trapped methane bubbles in a lake in Alberta, Canada.

discoveries occur frequently, and many recent discoveries are highlighted in this book. As you read, please do not overlook the special features that explore some of these discoveries, in particular "A Closer Look" boxes and "Applying Chemical Principles" sections.

Are you interested in medicine or medical advances? Do not miss the story on the development of mRNA vaccines ("A Closer Look: mRNA Vaccines," page 1228) that have been valuable in the fight against the COVID-19 viruses or the story on how gene editing holds the promise for correcting genetic mutations that lead to diseases ("A Closer Look: Genetic Engineering with CRISPR-Cas9," page 1222).

Chemists, physicists, and material scientists work together to develop electrical devices using atomically thin films of pure carbon ("Applying Chemical Principles 12.2: Nanotubes and Graphene: Network Solids," page 614), create high-temperature superconductors that may one day replace inefficient power transmission lines ("Applying Chemical Principles 3.1: Superconductors," page 177), and find ways to create naturally occurring, but rare materials, such as diamonds in laboratories ("Applying Chemical Principles 18.2: Are Diamonds Forever?," page 917).

Perhaps most importantly, scientists across multiple disciplines are studying ways to slow climate change. Increasing levels of carbon dioxide, methane, and other greenhouse gases are changing the conditions on earth, both on land and in the oceans ("Applying Chemical Principles 1.1: CO_2 in the Oceans," page 21). It is accepted by the scientific community that significant changes to the environment will continue to occur if greenhouse gas emissions are not reduced. Some hope comes from sequestering greenhouse gases ("Applying Chemical Principles 3.2: Sequestering Carbon Dioxide," page 177) and reducing our reliance on fossil fuels ("Applying Chemical Principles 5.2: The Fuel Controversy—Alcohol and Gasoline," page 287). The environment is so important that an entire chapter (Chapter 25) is devoted to the subject.

As you use this book in your study of chemistry and chemical principles, be sure to understand that it is just the beginning. It provides an introduction to the most important topics of chemistry, but we hope that it will also help you appreciate those topics and their interconnections as well as their uses and importance in your lives.

Chemistry and Change

Chemistry is about change. It was once only about changing one natural substance into another—wood and oil burn, grape juice turns into wine, and cinnabar (Figure 1.1), a red mineral, ultimately changes into shiny quicksilver (mercury) when heated. The emphasis was largely on finding a recipe to complete a desired change with little understanding of the underlying structure of the materials or explanations for why particular changes occurred. Chemistry is still about change, but now chemists focus on the change of one pure substance, whether natural or synthetic, into another and on understanding that change (Figure 1.2). Chemists now picture an exciting world of submicroscopic atoms and molecules interacting with each other, and they have developed ways to predict whether or not a particular reaction may occur.

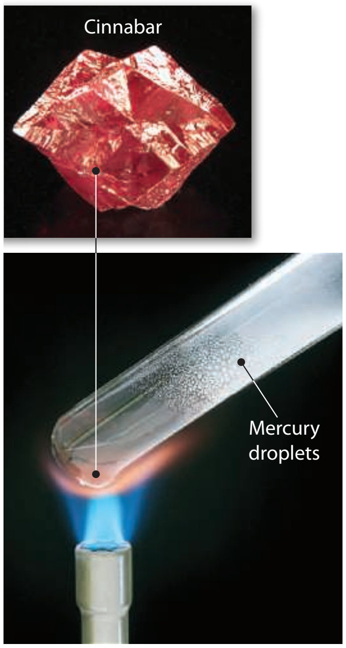


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Figure 1.1 Cinnabar and mercury. Heating cinnabar (mercury(II) sulfide) in air changes it into orange mercury(II) oxide, which, upon further heating, decomposes into the elements mercury and oxygen gas.

Methods of Science

Neil deGrasse Tyson, noted physicist, author, and TV personality once said "Science is a method of inquiry. Science is a way of expressing doubt and knowing when it's time to embrace what's discovered and move on to something else to doubt."

While there is no one scientific method by which all scientists conduct their studies, there are certain common practices. You almost always start the process by asking questions. These can be questions of your own choosing or ones that someone else poses. Having posed a reasonable question, the next step is often to look at the experimental work done in the field so that you have some notion of the possible answers. Based on this work, you may form a **hypothesis**, a tentative explanation or prediction of experimental observations.

Figure 1.2 Forming a chemical compound. Combining sodium metal (Na) and yellow chlorine gas (Cl_2) gives sodium chloride.

After formulating a hypothesis, systematic investigations are conducted, which may include formal experiments designed to give results that will confirm or invalidate the hypothesis. Systematic investigations require the collection of information or data, which may be either quantitative or qualitative. **Quantitative** information is numerical data, such as the mass of a substance (Figure 1.3) or the temperature at which it melts. **Qualitative** information, in contrast, consists of nonnumerical observations, such as the color of a substance or its physical appearance.

The data from your investigations must be analyzed and interpreted in order to derive meaning. Based on the analysis of your investigations, and perhaps studies from other researchers, you may have evidence supporting your hypothesis. However, it is also possible, and quite common, that you will need to revise your hypothesis and continue to test it with more experiments, or that the investigation will end up raising more questions for you to answer. After you have checked to ensure that your results are truly reproducible, a pattern of behavior or results might begin to emerge. At this point, you may be able to summarize your observations in the form of a **law**, a concise verbal or mathematical statement of a relation that is always the same under any condition.

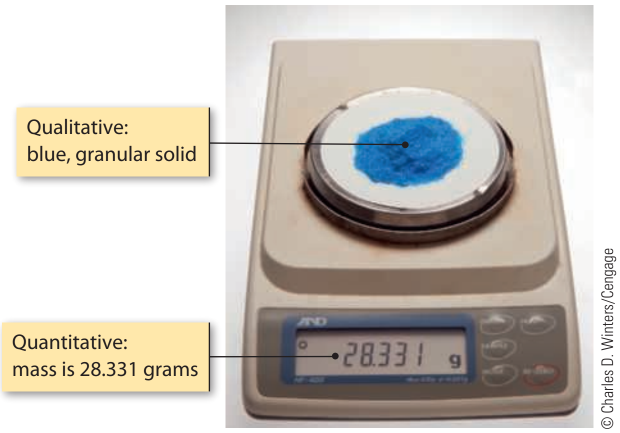


Figure 1.3 Qualitative and quantitative observations. Weighing a compound on a laboratory balance.

Figure 1.4 **The metallic element sodium reacts with water.**

Much of the work in science is based on laws because they help predict what may occur under a new set of circumstances. For example, chemists know from experience that if the element sodium comes in contact with water, a violent reaction occurs and new substances are formed (Figure 1.4). They also know the mass of the substances produced in the reaction is the same as the mass of the sodium and water used in the reaction. That is, mass is always conserved in chemical reactions, a statement of **the law of conservation of matter**.

Once enough reproducible studies are conducted and experimental results generalized as a law or general rule, it may be possible to conceive a theory to *explain* the observations. A **theory** is a well-tested, unifying principle that explains a body of facts and the laws based on them. Theories can suggest new hypotheses that can be tested experimentally.

Sometimes nonscientists use the word *theory* to imply that someone has made a guess and that an idea is not yet substantiated. To scientists, however, a theory is based on carefully determined and reproducible evidence that is being continuously tested. Theories are the cornerstone of our understanding of the natural world at any given time. Remember, though, that theories are inventions of the human mind. Theories can and do change as new facts are uncovered.

Goals of Science

Scientists, including chemists, have several goals. Two of these are *prediction* and *control*. Scientists do experiments and look for generalities because they want to predict what may occur under other circumstances. They also want to learn how to control the outcome of a chemical reaction or process.

Understanding and *explaining* are two other important goals. For example, certain elements such as sodium react vigorously with water. But why is this true? To explain and understand this, you need a background in chemical concepts.

Dilemmas and Integrity in Science

You may think research in science is straightforward: Do experiments, collect information, and draw a conclusion. But, research is seldom that easy. Frustrations and disappointments are common, and results can be inconclusive. Experiments always have some level of uncertainty, and sometimes the data collected are contradictory. For example, suppose you do an experiment expecting to find a direct relation between two experimental quantities. You collect six data sets. When plotted on a graph, four of the sets lie on a straight line, but two others lie far away from the line. Should you ignore the last two sets of data? Or should you do more experiments when you know that others could publish their results first and thus get the credit? Or should you consider that the two points not on the line might indicate that your original hypothesis is wrong and abandon a favorite idea you have worked on for many months? Scientists have a responsibility to remain objective in these situations, but sometimes it is hard to do.

It is important to remember that a scientist is subject to the same moral pressures and dilemmas as any other person. To help ensure integrity in science, some simple principles have emerged over time that guide scientific practice:

- Experimental results should be reproducible. Furthermore, these results should be reported in the scientific literature in enough detail to be used or reproduced by others.
- Research reports should be reviewed before publication by experts in the field to ensure that the experiments were conducted properly and that the conclusions are logical. (Scientists call this *peer review*.)
- Conclusions should be reasonable and unbiased.
- Credit should be given where it is due.

Chemistry in Your Career

Darius Z. Brown

Darius Z. Brown

Darius Z. Brown (he/him/his) began his journey in the world of chemistry by obtaining a B.S. (University of Buffalo) and M.S. (University of Illinois), with a focus on materials chemistry. He first put his degrees to use in a variety of industrial and research settings, including with a food manufacturer, university, and a paint producer.

Missing something in his industry work, Brown returned to school to become a high school chemistry teacher. "Having a solid educational background in chemistry, along with adequate industry experience in various fields as a chemist, has allowed me to focus on the relationships needed to teach high school students," says Brown, who believes that his own disadvantaged background helps him connect with students who face similar challenges. "I believe that once you can see the world in terms of atoms and chemical reactions, your perspective . . . changes, and you become more conscious and aware of the little things in life, which ultimately helps . . . with problem-solving and working together."

1.2 Sustainability and Green Chemistry

Goal for Section 1.2

- Understand the principles of green chemistry.

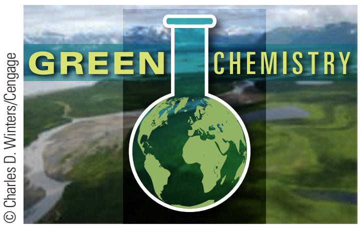
The world's population is over 8.0 billion people, with about 99 million added per year. Each new person needs shelter, food, and medical care, and each uses increasingly scarce resources like fresh water and energy. And each produces by-products in the act of living and working that can affect our environment. With such a large population, these individual effects can have large consequences for our planet. The focus of scientists, planners, and politicians is increasingly turning to the concept of sustainable development.

James Cusumano, a chemist and former president of a chemical company, said that "On one hand, society, governments, and industry seek economic growth to create greater value, new jobs, and a more enjoyable and fulfilling lifestyle. Yet, on the other, regulators, environmentalists, and citizens of the globe demand that we do so with *sustainable development*—meeting today's global economic and environmental needs while preserving the options of future generations to meet theirs. How do nations resolve these potentially conflicting goals?" This conflict is even more evident now than it was in 1995 when Dr. Cusumano made this statement in the *Journal of Chemical Education*.

Much of the increase in life expectancy and quality of life, at least in the developed world, is derived from advances in science. But it comes at a cost to the environment, with increases in polluting gases such as nitrogen oxides and sulfur oxides in the atmosphere, acid rain falling in many parts of the world, and waste pharmaceuticals entering the water supply. Among many others, chemists are seeking answers to these problems, and one response has been to practice *green chemistry.*

The concept of green chemistry began to take root more than 30 years ago and now leads to new chemical methods and lower pollutant levels. Paul Anastas and John Warner stated 12 principles of green chemistry in their book *Green Chemistry: Theory and Practice* (Oxford, 1998) that have become hallmarks for chemists attempting to devise processes and products that are more environmentally sustainable. Among these are

- "It is better to prevent waste than to treat or clean up waste after it is formed."
- "Synthetic methods should be designed to maximize the incorporation of all materials used in the final product."
- Synthetic methods "should be designed to use and generate substances that possess little or no toxicity to human health or the environment."
- "Chemical products should be designed to [function effectively] while still reducing toxicity."



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- "Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure."
- Raw materials "should be renewable whenever technically and economically practical."
- "Chemical products should be designed so that at the end of their function, they do not persist in the environment or break down into dangerous products."
- "Substances used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires."

You will be reminded about these principles at various points in *Chemistry & Chemical Reactivity* as they are applied to modern applications in chemistry. Stating these fundamental ideas is good, but the real challenge is to put them into practice.

1.3 Classifying Matter

Goals for Section 1.3

- Understand the basic ideas of kinetic-molecular theory.
- Recognize the importance of representing matter at the macroscopic, submicroscopic, and symbolic levels.
- Recognize the different states of matter (solids, liquids, and gases) and know their characteristics.
- Recognize the difference between pure substances and mixtures as well as the difference between homogeneous and heterogeneous mixtures.

This section is an introduction to how chemists think about science in general and about matter in particular. Terms such as atom, element, molecule, and compound may appear to describe similar things, but each term has a unique definition. It is important that you know these definitions as they will be used throughout the book.

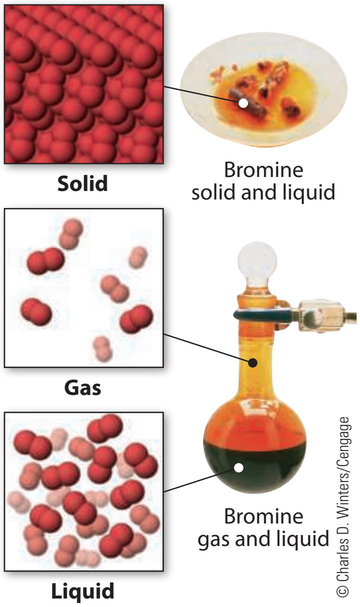

Figure 1.5 States of matter—solid, liquid, and gas. Elemental bromine exists in all three states near room temperature.

States of Matter and Kinetic-Molecular Theory

One key property of matter is its **state**—that is, whether a substance is a solid, liquid, or gas (Figure 1.5). A solid has a rigid shape and fixed volume that changes little as temperature and pressure change. Like solids, liquids have a fixed volume, but a liquid is fluid—it takes on the shape of its container and has no definite shape of its own. Gases are fluid as well, but the volume of a gas is determined by the size of its container. The volume of a gas varies with changes in temperature and pressure.

At low enough temperatures, virtually all matter is in the solid state. As the temperature is raised, solids usually melt to form liquids. Eventually, if the temperature is high enough, liquids evaporate to form gases. Volume changes typically accompany changes in state. For a given mass of material, there is usually a small increase in volume upon melting—water being a significant exception—and then a large increase in volume occurs upon evaporation.

The **kinetic-molecular theory of matter** helps you interpret the properties of solids, liquids, and gases. According to this theory, all matter consists of extremely tiny particles (atoms, molecules, or ions) in constant motion.

Solids: In solids, particles are packed closely together, usually in a regular pattern. The particles vibrate back and forth about their average positions, but seldom do particles in a solid squeeze past their immediate neighbors to come into contact with a new set of particles.

Liquids: The particles in liquids are arranged randomly rather than in the regular patterns found in solids. Liquids and gases are fluid because the particles are not confined to specific locations and can move past one another.

Gases: Under normal conditions, the particles in a gas are far apart. Gas molecules move extremely rapidly and are not constrained by their neighbors. The molecules of a gas fly about, colliding with one another and with the container walls. This random motion allows gas molecules to fill their container, so the volume of the gas sample is the volume of the container.

There are net forces of attraction between particles in all states—they are generally small in gases and large in liquids and solids. These forces have a significant role in determining the properties of matter. An important aspect of the kinetic-molecular theory is that the higher the temperature, the faster the particles move. The energy of motion of the particles (their **kinetic energy**, Section 1.7) acts to overcome the forces of attraction between particles. A solid melts to form a liquid when the temperature of the solid is raised to the point at which the particles vibrate fast enough and far enough to push one another out of the way and move out of their regularly spaced positions. As the temperature increases even more, the particles move faster still until finally they escape the clutches of their neighbors and enter the gaseous state.

Matter at the Macroscopic and Particulate Levels

The characteristic properties of gases, liquids, and solids can be observed by the unaided human senses. They are determined using samples of matter large enough to be seen, measured, and handled. You can determine, for example, the color of a substance, whether it dissolves in water, whether it conducts electricity, and if it reacts with oxygen. Observations such as these generally take place in the **macroscopic** world of chemistry (Figure 1.6). This is the world of experiments and observations.

Now imagine taking a macroscopic sample of material and dividing it again and again, past the point that the sample can be seen by the naked eye, and past the point where it can be seen using an optical microscope. Eventually, you reach the level of individual particles that make up all matter, a level that chemists refer to as the **submicroscopic** or **particulate** world of atoms and molecules (Figure 1.6).

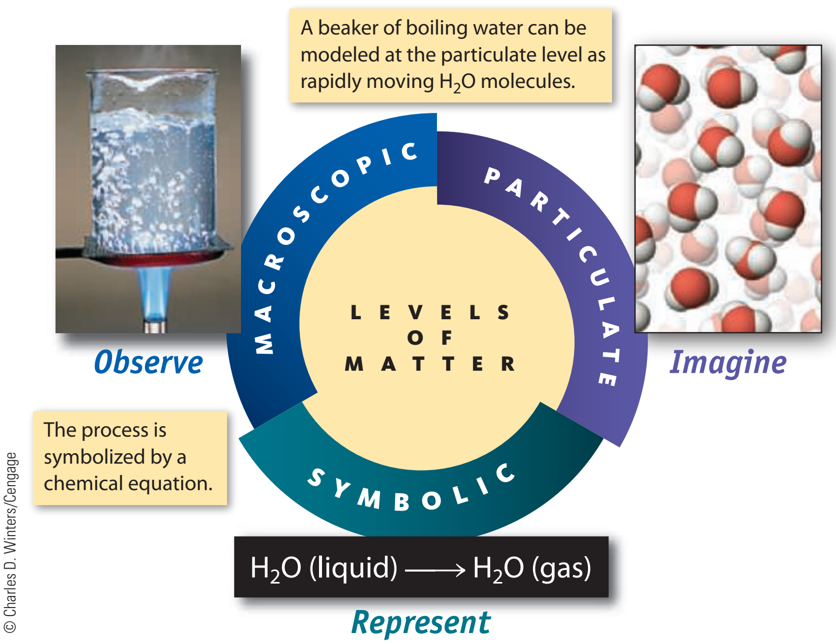

Figure 1.6 Levels of matter. Chemical and physical processes are observed at the macroscopic level. To understand or illustrate these processes, scientists often imagine what has occurred at the particulate atomic and molecular levels and write symbols to represent these observations.