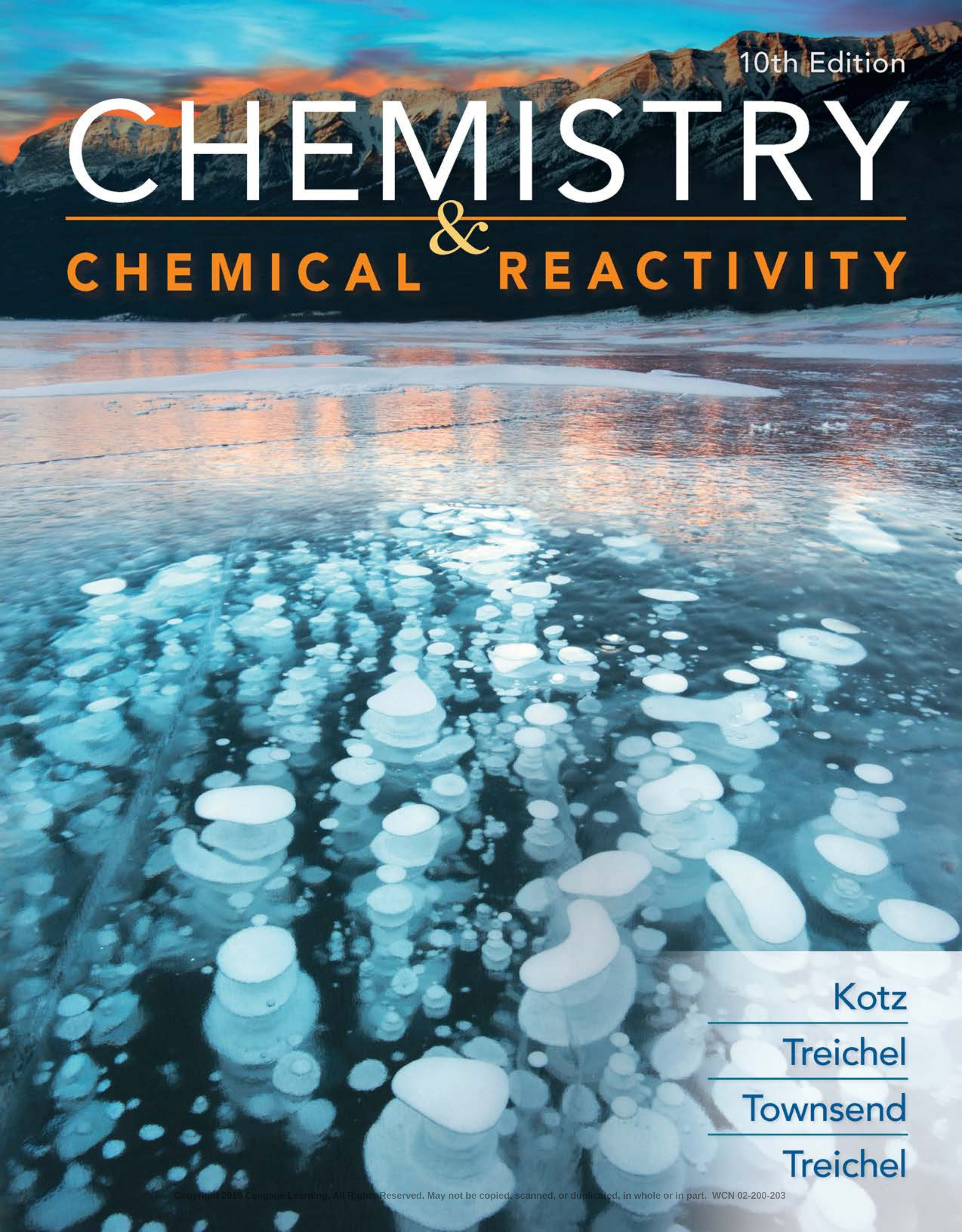
10th Edition

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
238.0289	Atomic weight

Period	1A (1)	2A (2)	3B (3)	4B (4)	5B (5)	6B (6)	7B (7)	8B (8)	8B (9)	8B (10)
1	Hydrogen 1 H 1.0079									
2	Lithium 3 Li 6.941	Beryllium 4 Be 9.0122								
3	Sodium 11 Na 22.9898	Magnesium 12 Mg 24.3050								
4	Potassium 19 K 39.0983	Calcium 20 Ca 40.078	Scandium 21 Sc 44.9559	Titanium 22 Ti 47.867	Vanadium 23 V 50.9415	Chromium 24 Cr 51.9961	Manganese 25 Mn 54.9380	Iron 26 Fe 55.845	Cobalt 27 Co 58.9332	Nickel 28 Ni 58.6934
5	Rubidium 37 Rb 85.4678	Strontium 38 Sr 87.62	Yttrium 39 Y 88.9059	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.9064	Molybdenum 42 Mo 95.96	Technetium 43 Tc (97.907)	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.9055	Palladium 46 Pd 106.42
6	Cesium 55 Cs 132.9055	Barium 56 Ba 137.327	Lanthanum 57 La 138.9055	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.9479	Tungsten 74 W 183.84	Rhenium 75 Re 186.207	Osmium 76 Os 190.23	Iridium 77 Ir 192.22	Platinum 78 Pt 195.084
7	Francium 87 Fr (223.02)	Radium 88 Ra (226.0254)	Actinium 89 Ac (227.0278)	Rutherfordium 104 Rf (265)	Dubnium 105 Db (268)	Seaborgium 106 Sg (271)	Bohrium 107 Bh (270)	Hassium 108 Hs (277)	Meitnerium 109 Mt (276)	Darmstadtium 110 Ds (281)

Lanthanides	Cerium 58 Ce 140.116	Praseodymium 59 Pr 140.9076	Neodymium 60 Nd 144.242	Promethium 61 Pm (144.91)	Samarium 62 Sm 150.36	Europium 63 Eu 151.964
Actinides	Thorium 90 Th 232.0381	Protactinium 91 Pa 231.0359	Uranium 92 U 238.0289	Neptunium 93 Np (237.0482)	Plutonium 94 Pu (244.664)	Americium 95 Am (243.061)

Note: Atomic masses are IUPAC values (up to four decimal places). Numbers in parentheses are atomic masses or mass numbers of the most stable isotope of an element.

For the latest information see: http://www.chem.qmul.ac.uk/iupac/AtWt/

1B (11)	2B (12)	3A (13)	4A (14)	5A (15)	6A (16)	7A (17)	8A (18)
							Helium 2 He 4.0026
		Boron 5 B 10.811	Carbon 6 C 12.011	Nitrogen 7 N 14.0067	Oxygen 8 O 15.9994	Fluorine 9 F 18.9984	Neon 10 Ne 20.1797
		Aluminum 13 Al 26.9815	Silicon 14 Si 28.0855	Phosphorus 15 P 30.9738	Sulfur 16 S 32.066	Chlorine 17 Cl 35.4527	Argon 18 Ar 39.948
Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.63	Arsenic 33 As 74.9216	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.798
Silver 47 Ag 107.8682	Cadmium 48 Cd 112.411	Indium 49 In 114.818	Tin 50 Sn 118.710	Antimony 51 Sb 121.760	Tellurium 52 Te 127.60	Iodine 53 I 126.9045	Xenon 54 Xe 131.293
Gold 79 Au 196.9666	Mercury 80 Hg 200.59	Thallium 81 Tl 204.3833	Lead 82 Pb 207.2	Bismuth 83 Bi 208.9804	Polonium 84 Po (208.98)	Astatine 85 At (209.99)	Radon 86 Rn (222.02)
Roentgenium 111 Rg (280)	Copernicium 112 Cn (285)	Nihonium 113 Nh (286)	Flerovium 114 Fl (289)	Moscovium 115 Mc (289)	Livermorium 116 Lv (292)	Tennessine 117 Ts (293)	Oganesson 118 Og (294)

Gadolinium 64 Gd 157.25	Terbium 65 Tb 158.9254	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.9303	Erbium 68 Er 167.26	Thulium 69 Tm 168.9342	Ytterbium 70 Yb 173.045	Lutetium 71 Lu 174.9668
Curium 96 Cm (247.07)	Berkelium 97 Bk (247.07)	Californium 98 Cf (251.08)	Einsteinium 99 Es (252.08)	Fermium 100 Fm (257.10)	Mendelevium 101 Md (258.10)	Nobelium 102 No (259.10)	Lawrencium 103 Lr (262.11)

Standard Colors for Atoms in Molecular Models

- carbon atoms
- hydrogen atoms
- oxygen atoms
- nitrogen atoms
- chlorine atoms

10th Edition

CHEMISTRY & CHEMICAL REACTIVITY

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PART TWO ATOMS AND MOLECULES

Preface

The first edition of this book was conceived over 35 years ago. Since that time there have been nine editions, and over 1 million students worldwide have used the book to begin their study of chemistry. Over the years, and the many editions, our goals have 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 these goals, we have tried to show the close relation between the observations chemists make of chemical and physical changes in the laboratory and in nature and the way these changes are viewed at the atomic and molecular levels.


John C. Kotz

Hot air balloon. See Chapter 10 on the gas laws.

We have also tried to convey a sense that chemistry not only has a lively history but is also dynamic, with important new developments occurring every year. Furthermore, we want to provide some insight into the chemical aspects of the world around us.

The authors of this text have collectively taught chemistry for over 100 years, and we have engaged in years of fundamental research. As with thousands of scientists before and now, our goal has 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, many others, are put to use, perhaps only many years later, to make a better material or better pharmaceutical. Every person eventually benefits from the work of the worldwide community of scientists.

Recently, however, science has come under attack. Some distrust what the scientific community has done and dismiss results of carefully done research. Therefore, key among the objectives 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, 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 (both as a printed book and digital version) is designed for students interested in further study in science, whether that science is chemistry, biology, engineering, geology, physics, or related subjects. Our assumption is that students in a course using this book have had some preparation in algebra and in 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. The first was to write a book that students would enjoy reading and that would offer, at a reasonable level of rigor, chemistry and chemical principles in a format and organization typical of college and university courses today. Second, we wanted 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.
- Using *Applying Chemical Principles* study questions in each chapter 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, proteins, 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 have 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 of covering the behavior of gases** (Chapter 10). It has been placed with chapters on liquids, solids, and solutions (Chapters 10–13) because it logically fits with those topics. However, it can easily be read and understood after covering only the first four chapters of the book.

Similarly, chapters on atomic and molecular structure (Chapters 6–9) could 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.

John C. Kotz

Crystals of rhodochrosite, $MnCO_3$. See Chapters 12 and 17.

Also, the chapters on chemical equilibria (Chapters 15–17) can be covered before those on solutions and kinetics (Chapters 13 and 14).

Organic chemistry (Chapter 23) is one of the final chapters in the textbook. However, the topics of this chapter can also be presented to students following the chapters on structure and bonding.

The order of topics in the text was also devised to introduce as early as possible the background required for the laboratory experiments 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 so important in the study of chemistry, energy and its units are introduced in Chapter 1, and thermochemistry is introduced in Chapter 5.

ORGANIZATION AND PURPOSES OF THE SECTIONS OF THE BOOK

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 *Let's Review* section reviews units and mathematical methods. Chapter 2 introduces atoms, molecules, and ions, and 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 equilibrium. 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 involved in chemical processes.

PART TWO: Atoms and Molecules

The current theories of the arrangement of electrons in atoms are presented in Chapters 6 and 7. This discussion is tied closely to the arrangement of elements in the periodic table and to 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 of simple molecules. Finally, Chapter 9 considers the major theories of chemical bonding in more detail.

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.

WHAT'S NEW IN THIS EDITION

Numerous changes have been made from the previous edition, some small, some large. A few that stand out are listed here.

- *Goals* for each topic in a chapter are now given at the beginning of each section. A *Chapter Goals Revisited* section at the end of the chapter then links each goal to one or more Study Questions that relate to the goal.
- *Applying Chemical Principles* questions have been expanded from one per chapter to two or three. Some were *A Closer Look* or *Case Study* boxes in the ninth edition.
- We made a change in how significant figures are treated in problem solving (page 41).
- We reorganized the section on naming compounds in Chapter 2.
- A new section has been added to Chapter 2 on *Instrumental Analysis: Determining Compound Formulas.*
- At the suggestion of a user of the book, we added an *A Closer Look* box in Chapter 3 (page 141) on naming common acids and their related anions.
- We changed our approach to solving limiting reactant problems in Chapter 4.
- In Chapter 8 we expanded the discussion of van Arkel diagrams for bonding and added an *Applying Chemical Principles* question on the topic.
- In Chapter 12 we added a section on the Electron Sea Model for bonding in metals.
- The section on alloys in Chapter 12 was expanded.

John C. Kotz

Fireworks. See Chapter 6.

- In Chapter 13 we feature an excerpt from the book *Lab Girl* by Hope Jahren. The *A Closer Look* box on *Hardening Trees* applies to the colligative properties described in the chapter.
- In Chapter 14 a new *Problem Solving Tip* on *Determining a Rate Equation: A Logarithmic Approach* was added, and we expanded the discussion of enzyme catalysis.
- A *Problem Solving Tip* on *A Review of Concepts of Equilibrium* was added to Chapter 15.
- In Chapter 18 there is a new *A Closer Look* box titled *Entropy and Spontaneity?* This is based on some recent papers in the *Journal of Chemical Education*.
- In Chapter 18 there is a new section on *The Interplay of Kinetics and Thermodynamics.*
- Chapter 19 has a new section on *Corrosion: Redox Reactions in the Environment*.
- In Chapter 20 on environmental chemistry, much of the data have been updated, and a new *A Closer Look* box was added on *The Flint, Michigan Water Treatment Problem*.
- New research on understanding the dramatic reactivity of sodium with water is the subject of an *A Closer Look* box in Chapter 21. Other new *A Closer Look* boxes describe advances in boron chemistry, ammonium nitrate explosions, and new fluorine-based compounds. Finally, there are new *Applying Chemical Principles* questions on *Lead in the Environment* and *Hydrogen Storage*.
- For Chapter 24, *Biochemistry*, the section on *The RNA World* was dropped as was a box on *Reverse Transcriptase*. But, given the enormous interest in CRISPR, we added an *A Closer Look* box on *Genetic Engineering with CRISPR-Cas9*.
- Several new elements were added to the periodic table in the past few years. A new *A Closer Look* box in Chapter 25 describes those new elements and their production. There is also a new *A Closer Look* box, *A Real-Life Spy Thriller*, that describes a murder done with radioactive polonium.

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 the 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 involving the transfer of electrons and the use of these reactions in electrochemical cells.

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 brings together many of the concepts in earlier chapters into a discussion of *Environmental Chemistry—Earth's Environment, Energy, and Sustainability.* Chapter 21 is devoted to the chemistry of the main group elements, whereas Chapter 22 is a discussion of the transition elements and their compounds. Chapter 23 is a brief discussion of organic chemistry with an emphasis on molecular structure, basic reaction types, and polymers. Chapter 24 is an introduction to biochemistry, and Chapter 25 is an overview of nuclear chemistry.

FEATURES OF THE BOOK

Some years ago a student of one of the authors, now an accountant, shared his perspective on finishing 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. We were certainly pleased because we have always thought that, for many students, an important goal in general chemistry was 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 to 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.

For many students, a **visual *strategy map*** can be a useful tool in problem solving (as on page 46). There are approximately 60 strategy maps in the book accompanying *Example* problems.

Chapter Goals Revisited

The learning goals for each section are listed at the top of the section. The goals are revisited on the last page 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 40 to over 150 *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.

Study Questions are available in the OWLv2 online learning system. OWLv2 now has over 1800 of the roughly 2500 *Study Questions* in the book.

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

A CLOSER LOOK ESSAYS AND PROBLEM SOLVING TIPS

As in the ninth edition, there are boxed essays titled *A Closer Look* that take a more in-depth look at relevant chemistry. A few examples are *Mendeleev and the Periodic Table* (Chapter 2), *Amedeo Avogadro and His Number* (Chapter 2), *Measuring Molecular Polarity* (Chapter 8), *Hydrogen Bonding in Biochemistry* (Chapter 11), and *The Flint, Michigan Water Treatment Problem* (Chapter 20).

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 there are two or three longer questions that use the principles learned in the chapter to study examples of forensic chemistry, environmental chemistry, a problem in medicinal chemistry, or some other area. Examples are *Green Chemistry and Atom Economy* (Chapter 4), *What Makes the Colors in Fireworks* (Chapter 6), *A Pet Food Catastrophe* (Chapter 11), and *Lithium and "Green Cars"* (Chapter 12).

ANCHORING CONCEPTS IN CHEMISTRY

The American Chemical Society Examinations Institute has been writing assessment examinations for college chemistry for over 75 years. In 2012 the Institute began publishing papers in the *Journal of Chemical Education* on “anchoring concepts” or “big ideas” in chemistry. The purpose was to provide college instructors with a fine-grained content map of chemistry so that instruction can be aligned better with the content of the American Chemical Society examinations. The ACS map begins with “anchoring concepts,” which are subdivided into “enduring understandings” and then further broken down into detailed areas.

We believe these ideas are useful to both teachers and students of chemistry and are important enough to include them in this Preface.

The College Board, the publisher of Advanced Placement (AP®) examinations, has recently redesigned the AP chemistry curriculum along many of the same ideas. We have made sure that the present edition of *Chemistry & Chemical Reactivity* has included material that meets many of the criteria of the College Board curriculum while basing the text largely on the “anchoring concepts” of the Examinations Institute.

AMERICAN CHEMICAL SOCIETY EXAMINATIONS INSTITUTE’S ANCHORING CONCEPTS

The anchoring concepts are listed here with a notation of the chapters that describe or use those concepts.

1. **Atoms (Chapters 1, 2, 6, 7)**
2. **Bonding (Chapters 8, 9, 12, 23)**
3. **Structure and Function (Chapters 11, 12, 16, 24)**
4. **Intermolecular Interactions (Chapters 10, 11, 24)**
5. **Reactions (Chapters 3, 4, 16, 17, 19–24)**
6. **Energy and Thermodynamics (Chapters 1, 5–8, 12, 13, 18, 20)**
7. **Kinetics (Chapter 14, 24)**
8. **Equilibrium (Chapters 3, 15–19)**
9. **Experiments, Measurements, and Data (these appear throughout the book)**
10. **Visualizations (these appear throughout the book)**

MORE INFORMATION:

See the following articles by K. Murphy, T. Holme, and others in the *Journal of Chemical Education*:
Volume 89, pages 715-720 and 721-723, 2012
Volume 92, pages 993-1002 and 1115-1116, 2015

Acknowledgments

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

CENGAGE

The ninth edition of this book was published by Cengage, and we continue with much of the same excellent team we have had in place for a number of years.

The ninth edition of the book was very successful, in large part owing to the work of Lisa Lockwood as the Product Manager. She has an excellent sense of the market and worked with us in planning this new edition. We have worked with Lisa through several editions and have become good friends.

Peter McGahey has been our Content Developer since he joined us to work on the fifth edition. Peter is blessed with energy, creativity, enthusiasm, intelligence, and good humor. He is a trusted friend and confidant and cheerfully answers our many questions during frequent phone calls and emails.

Our team at Cengage is completed with Teresa Trego, Content Project Manager. Schedules are very demanding in textbook publishing, and Teresa has helped to keep us on schedule. We certainly appreciate her organizational skills and good humor.

We have worked with Graphic World, Inc. for the production of the last several editions, and they have been excellent again. For this edition, Cassie Carey guided the book through months of production.

A team at Lumina Datamatics directed the photo research for the book and was successful in filling our sometimes offbeat requests for particular photos.

No book can be successful without proper marketing, and Janet del Mundo (Marketing Manager) is again involved with this book. She is knowledgeable about the market and has worked tirelessly to bring the book to everyone's attention.

With regard to marketing and sales, over the nine editions of this book we have met in person or through email the people from the company who visit universities and meet the faculty. They have been excellent over the years, work hard for us, and deserve our profound thanks.

Art, Design, and Photography

Many of the color photographs in our book have been beautifully created by Charles D. Winters, and he produced a few new images for this edition. We have worked with him for more than 30 years and have become close friends. We listen to his jokes, both new and old—and always forget them.

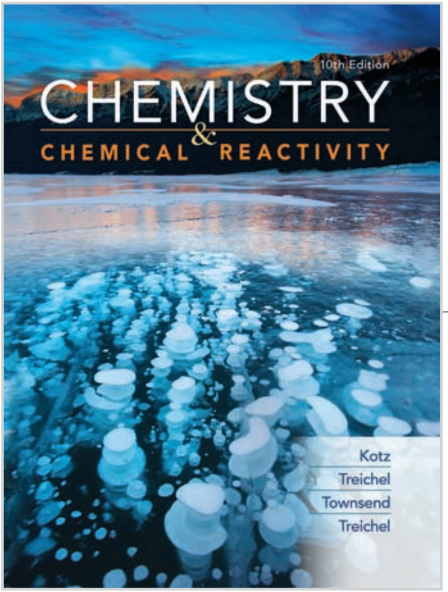
When the fifth edition was being planned some years ago, we brought in Patrick Harman as a member of the team. Pat designed the first edition of our *Interactive General Chemistry* CD-ROM (published in the 1990s), and we believe its success is in no small way connected to his design skill. For the fifth through the ninth editions of the book, Pat went over many of the figures to bring a fresh perspective to ways to communicate chemistry. Once again he has worked on designing and producing new illustrations for this edition, and his creativity is obvious in their clarity. Pat is also working with us on the digital version of this book.

Other Collaborators

We have been fortunate to have a number of other colleagues who have played valuable roles in this project. Several who have been important in this edition are:

- Alton Banks (North Carolina State University) has been involved for a number of editions preparing the *Student Solutions Manual*. Alton has been very helpful in ensuring the accuracy of the Study Question answers in the book, as well as in their respective manuals.
- David Shinn of the U.S. Merchant Marine Academy has been the accuracy reviewer for the text.
- David Sadeghi (University of Texas, San Antonio) reviewed the ninth edition and made suggestions that helped in the preparation of this new edition.

About the Cover



Kevin Schafer/Minden Pictures

Have you ever walked around a shallow lake or pond and watched as bubbles of gas rise to the surface? This is "marsh gas," and it is often responsible for the characteristic smell of a marshy area. This "marsh gas" is mostly methane (CH_4), and it is an extremely important and possibly dangerous feature of the worldwide environment.

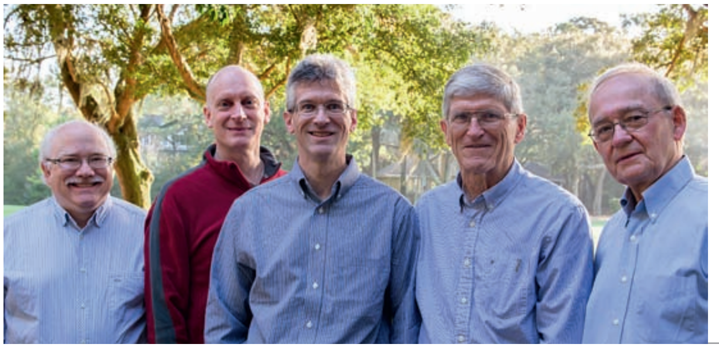
Bodies of water are usually surrounded by vegetation, which, over the years or centuries, will fall into the water and decay. The vegetation is consumed by bacteria that release methane as a product of the digestion. Some of the methane bubbles to the surface, and in the winter the bubbles can be trapped in the ice. The white patches you see in the photo on the cover of the book are trapped methane bubbles in a lake in northern Canada.

The methane can also be trapped as "methane hydrate," a white solid in which methane is encased in a lattice of water molecules (pages 925 and 936). Estimates are that there are millions upon millions of tons of methane trapped in the hydrated form under the world's oceans and in the Arctic regions.

Why should methane bubbles and methane hydrate be of interest? Methane hydrates could be a source of needed fuel. But, as we are in an era of climate change, likely brought on by excessive release of carbon dioxide (CO_2), scientists are interested in all possible effects on the climate. Many studies have found that methane is a far more potent "greenhouse gas" than CO_2. Some of the bubbles in a frozen lake come from slow methane release by methane hydrate. But what if methane is released explosively? This is of concern because the Arctic is clearly warming, which destabilizes the buried methane hydrate. The possibility of a catastrophic, explosive methane release is hotly debated by environmental scientists.

There is a lot of interesting information available on this topic from reputable journals and news sources. This would be a good topic for you to watch over the next few years.

About the Authors



Courtesy Katherine Kotz

(*left to right*) John Townsend, Pat Harman, David Treichel, Paul Treichel, John Kotz

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 SUNY College at Oneonta in 1970. He retired from SUNY in 2005 as a *State University of New York Distinguished Teaching Professor of Chemistry*.

He is the author or co-author of 15 chemistry textbooks, among them two in advanced chemistry and two introductory general chemistry books in numerous editions. The general chemistry book has been published as an interactive CD-ROM, as an interactive ebook, and has been translated into five languages. He also published a number of research papers in organometallic chemistry.

He has received a number of awards, among them the *SUNY Award for Research and Scholarship* and the *Catalyst Award in Education* from the Chemical Manufacturers Association. He was the *Estee Lecturer* at the University of South Dakota, the *Squibb Lecturer* at the University of North Carolina-Asheville, and an invited plenary lecturer at numerous chemical society meetings overseas. He was a Fulbright Senior Lecturer in Portugal and a member of Fulbright review boards. In addition, he has been a Mentor for the U.S. National Chemistry Olympiad team and the technical editor for *ChemMatters* magazine. He has served on the boards of trustees for the College at Oneonta Foundation, the Kiawah Nature Conservancy, and Camp Dudley. His email address is johnkotz@mac.com.

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Dedication

To Katherine (Katie) Kotz, who has patiently and lovingly worked with and helped her husband for over 56 years. She has tolerated late nights and missed weekends as Jack worked on manuscripts and spent time teaching and in the laboratory. And to his sons (David and Peter) who grew up in the lab and are now both very respected professionals in education.

1 Basic Concepts of Chemistry

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CHAPTER OUTLINE

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.

A Scientific Mystery: Ötzi the Iceman

In 1991 a hiker in the Alps on the Austrian-Italian border found a well-preserved human body encased in ice. It was first thought to be a person who had recently died, but a number of scientific studies over more than a decade concluded the man had lived 53 centuries ago and was about 46 years old when he died. He became known as Ötzi the Iceman.

The discovery of the Iceman's body, one of the oldest naturally-formed mummies, set off many scientific studies that brought together chemists, biologists, anthropologists, paleontologists, and others from all over the world. These studies give us a marvelous view of how science is done and the role that chemistry plays. Among the many discoveries made about the Iceman were the following:

- Some investigators looked for food residues in the Iceman's intestines. In addition to finding a few particles of grain, they located tiny flakes of mica believed to come from stones used to grind the grain the man ate. Their composition was like that of mica in a small area south of the Alps, thus establishing where the man lived in his later years. And, by analyzing animal fibers in his stomach, they determined his last meal was the meat of an Alpine ibex.

◀ **Ötzi the Iceman.** In 1991 a well-preserved body was found by a hiker in the Alps. The name "Ötzi" comes from the Ötz valley, the region of Europe (on the Austrian-Italian border) where the man was found. This discovery sparked a large number of studies, many involving chemistry, to discover how the Iceman lived and died.

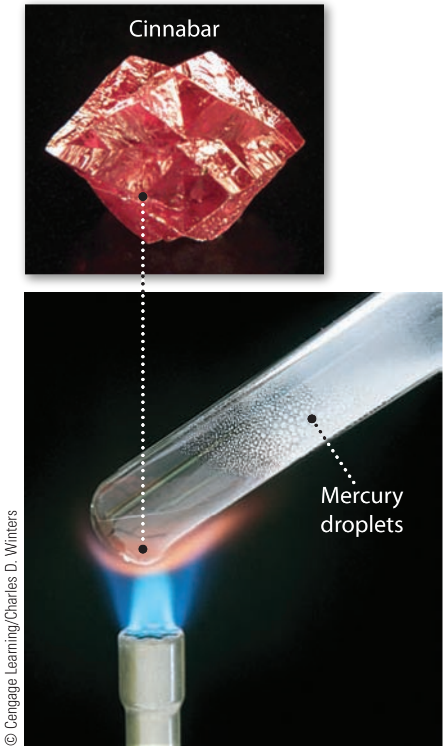

Figure 1.1 Cinnabar and mercury. Heating cinnabar (mercury(II) sulfide) in air changes it into orange mercury(II) oxide, which, on further heating, decomposes to the elements mercury and oxygen gas.

- High levels of copper and arsenic were incorporated into his hair. These observations, combined with the discovery that his ax was nearly pure copper, led the investigators to conclude he had been involved in copper smelting.
- One fingernail was still present on his body. Based on its condition, scientists concluded that he had been sick three times in the 6 months before he died and his last illness had lasted for 2 weeks. Finally, images of his teeth showed severe periodontal disease and cavities.
- Australian scientists took samples of blood residues from his stone-tipped knife, his arrows, and his coat. Using techniques developed to study ancient DNA, they found the blood came from four individuals. The blood on one arrow tip was from two individuals, suggesting that the man had killed or wounded two people using this arrow tip. Perhaps he had killed or wounded one person, retrieved the arrow, and used it again.

The many different methods used to reveal the life of the Iceman and his environment are used by scientists around the world, including present-day forensic scientists in their study of accidents and crimes. As you study chemistry and the chemical principles in this book, keep in mind that many areas of science depend on chemistry and that many different careers in the sciences are available.

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 carry out 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). As you will see, in modern chemistry, we now picture an exciting world of submicroscopic atoms and molecules interacting with each other. We have also developed ways to predict whether or not a particular reaction may occur.

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

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 someone else has decided it is an important part of preparing for a particular career. Chemistry is especially useful because it is central to our understanding of disciplines as diverse as biology, geology, materials science, medicine, physics, and some branches of engineering. In addition, chemistry plays a major role in the economy of developed nations, and chemistry and chemicals affect our daily lives in a wide variety of ways. A course in chemistry can also help you see how a scientist thinks about the world and how to solve problems. The knowledge and skills developed in such a course will benefit you in many career paths and will help you become a better informed citizen in a world that is becoming technologically more complex—and more interesting.

Hypotheses, Laws, and Theories

As scientists, we study questions of our own choosing or ones that someone else poses in the hope of finding an answer or discovering some useful information. When the Iceman was discovered, there were many questions that scientists could try to answer, such as where he lived. Considering what was known about humans living in that age, it seemed reasonable to assume that he was from an area on the border of what is now Austria and Italy. That is, regarding his origins, the scientists formed a **hypothesis**, a tentative explanation or prediction in accord with current knowledge.

After formulating one or more hypotheses, scientists perform experiments designed to give results that confirm or invalidate these hypotheses. In chemistry this usually requires that both quantitative and qualitative information be collected. **Quantitative** information is numerical data, such as the mass of a substance (Figure 1.3) or temperature at which it melts. **Qualitative** information, in contrast, consists of nonnumerical observations, such as the color of a substance or its physical appearance.

In the case of the Iceman, scientists assembled a great deal of qualitative and quantitative information on his body, his clothing, and his weapons. Among this was information on the ratio of oxygen isotopes in his tooth enamel and bones. Scientists know that the ratio of oxygen isotopes in water and plants differs from place to place. This ratio of isotopes showed that the Iceman must have consumed water from a relatively small location within what is now Italy.

This analysis using oxygen isotopes could be done because it is well known that oxygen isotopes in water vary with altitude in predictable ways. That is, the variation in isotope composition with location can be considered a law of science. After numerous experiments by many scientists over an extended period of time, these results have been summarized as a **law**—a concise verbal or mathematical statement of a behavior or a relation that seems always to be the same under the same conditions.

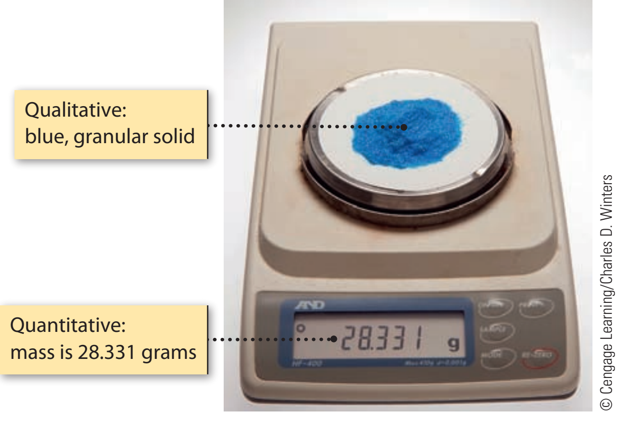

Figure 1.3 Qualitative and quantitative observations. Weighing a compound on a laboratory balance.

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

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

Once enough reproducible experiments have been conducted and experimental results have been generalized as a law or general rule, it may be possible to conceive a theory to explain the observation. A **theory** is a well-tested, unifying principle that explains a body of facts and the laws based on them. It is capable of suggesting 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. 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*. We do experiments and look for generalities because we want to be able to predict what may occur under other circumstances. We also want to know how we might control the outcome of a chemical reaction or process.

Understanding and *explaining* are two other important goals. We know, for example, that certain elements such as sodium react vigorously with water. But why should this be true? To explain and understand this, we 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 enough, and results can be inconclusive. Experiments often contain some level of uncertainty, and contradictory data can be collected. 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 the time they take will mean someone else could publish their results first and thus get the credit for a new scientific principle? Or should you consider that the two points not on the line might indicate that your original hypothesis is wrong and that you will have to 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 so that they can be used or reproduced by others.
- Research reports should be reviewed before publication by experts in the field to make sure that the experiments have been conducted properly and that the conclusions are logical. (Scientists refer to this as "peer review.")
- Conclusions should be reasonable and unbiased.
- Credit should be given where it is due.

1.2 Sustainability and Green Chemistry

Goal for Section 1.2

- Understand the principles of green chemistry.

The world's population is about 7.5 billion people, with about 80 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 a 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 we have paid an environmental price for it, with increases in 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 20 years ago and is now leading to new ways of doing things and to lower pollutant levels. Paul Anastas and John Warner stated the principles of green chemistry in their book *Green Chemistry: Theory and Practice* (Oxford, 1998). Among these are the ones stated below.

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- "It is better to prevent waste than to treat or clean up waste after it is formed."
- New pharmaceuticals or consumer chemicals are synthesized by a large number of chemical processes. "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."
- "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."

As you read *Chemistry & Chemical Reactivity,* we will remind you of these principles, and others, and how they can be applied. As you can see, they are simple ideas. The 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, microscopic, and symbolic levels.
- Recognize the different states of matter (solids, liquids, and gases) and give their characteristics.
- Recognize the difference between pure substances and mixtures and the difference between homogeneous and heterogeneous mixtures.

This chapter begins our discussion of how chemists think about science in general and about matter in particular. After looking at a way to classify matter, we will turn to some basic ideas about elements, atoms, compounds, and molecules and describe how chemists characterize these building blocks of matter.

States of Matter and Kinetic-Molecular Theory

An easily observed property of matter is its **state**—that is, whether a substance is a solid, liquid, or gas (Figure 1.5). You recognize a material as a solid because it has a rigid shape and a 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 more than the volume of a liquid with changes in temperature and pressure.

At low enough temperatures, virtually all matter is found 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 on melting—water being a significant exception—and then a large increase in volume occurs upon evaporation.

The **kinetic-molecular theory of matter** helps us 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.

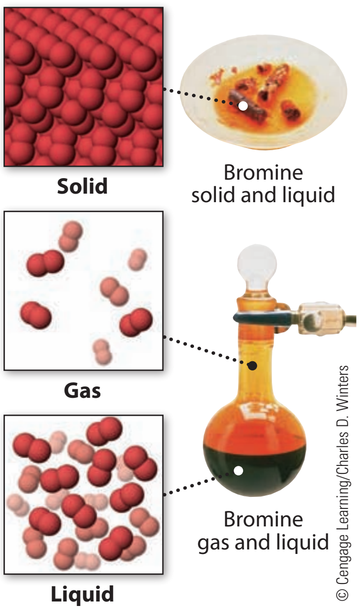

Figure 1.5 States of matter—solid, liquid, and gas. Elemental bromine exists in all three states near room temperature.

- 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.
- 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.
- 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—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 1.8) 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 can 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.

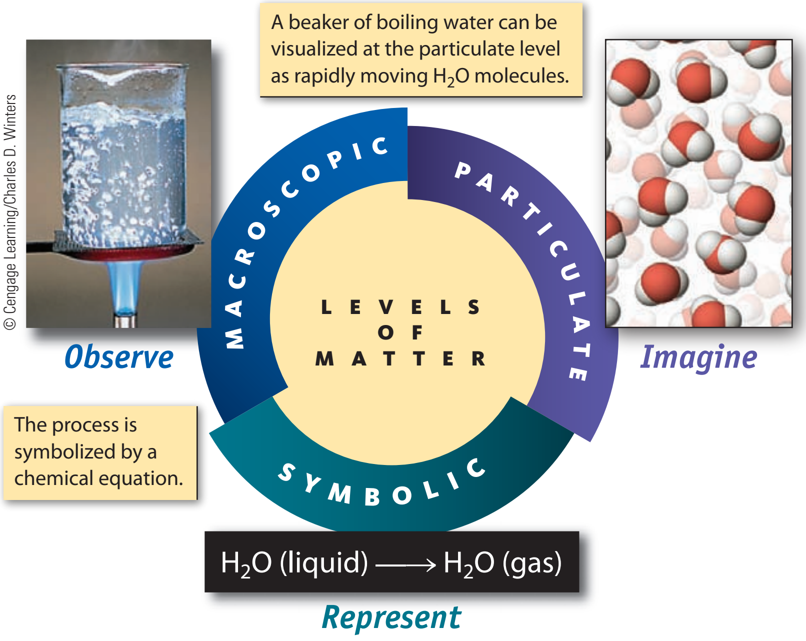

Figure 1.6 Levels of matter. We observe chemical and physical processes at the macroscopic level. To understand or illustrate these processes, scientists often imagine what has occurred at the particulate atomic and molecular levels and write symbols to represent these observations.

Now let us move to the level of atoms, molecules, and ions—a world of chemistry we cannot see. Take a macroscopic sample of material and divide it, again and again, past the point where the amount of sample can be seen by the naked eye, 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 (Figures 1.5 and 1.6).

Chemists are interested in the structure of matter at the particulate level. Atoms, molecules, and ions cannot be "seen" in the same way that one views the macroscopic world, but they are no less real. Chemists imagine what atoms must look like and how they might fit together to form molecules. They create models to represent atoms and molecules (Figures 1.5 and 1.6)—where tiny spheres are used to represent atoms—and then use these models to think about chemistry and to explain the observations they have made about the macroscopic world.

Chemists carry out experiments at the macroscopic level, but they think about chemistry at the particulate level. They then write down their observations as "symbols," the formulas (such as H_2O for water or NH_3 for ammonia molecules) and drawings that represent the elements and compounds involved. This is a useful perspective that will help you as you study chemistry. Indeed, one of our goals is to help you make the connections in your own mind among the symbolic, particulate, and macroscopic worlds of chemistry.

Pure Substances

A chemist looks at a glass of drinking water and sees a liquid. This liquid could be the pure chemical compound water. However, it is also possible the liquid is actually a homogeneous mixture of water and dissolved substances—that is, a **solution**. Specifically, we can classify a sample of matter as being either a pure substance or a mixture (Figure 1.7).

A pure substance has a set of unique properties by which it can be recognized. Pure water, for example, is colorless and odorless. If you want to identify a substance conclusively as water, however, you would have to examine its properties more carefully and compare them against the known properties of pure water. Melting point and boiling point serve the purpose well here. If you could show that the substance melts at 0 °C and boils at 100 °C at atmospheric pressure, you can be certain it is water. No other known substance melts and boils at precisely those temperatures.

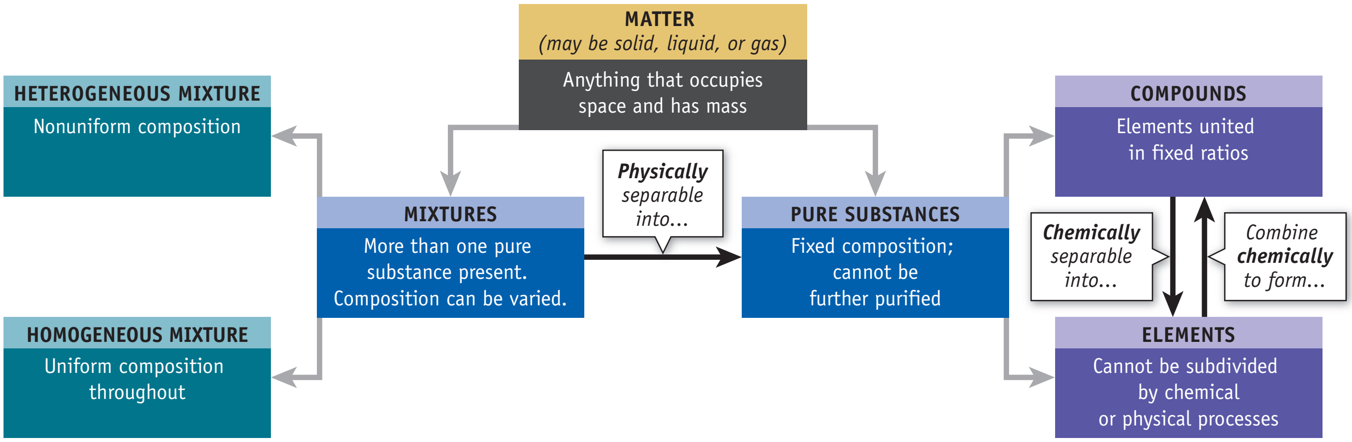

Figure 1.7 Classifying matter.

A second feature of a pure substance is that it cannot be separated into two or more different species by any physical technique at ordinary temperatures. If it could be separated, our sample would be classified as a mixture.

Mixtures: Heterogeneous and Homogeneous

A mixture consists of two or more pure substances that can be separated by physical techniques. In a **heterogeneous** mixture the uneven texture of the material can often be detected by the naked eye (Figure 1.8). However, keep in mind there are heterogeneous mixtures that may appear completely uniform but on closer examination are not. Milk, for example, appears smooth in texture to the unaided eye, but magnification would reveal fat and protein globules within the liquid. In a heterogeneous mixture the properties in one region are different from those in another region.

A **homogeneous** mixture consists of two or more substances in the same phase (Figure 1.8). No amount of optical magnification will reveal a homogeneous mixture to have different properties in different regions. Homogeneous mixtures are often called **solutions**. Common examples include air (mostly a mixture of nitrogen and oxygen gases), gasoline (a mixture of carbon- and hydrogen-containing compounds called *hydrocarbons*), and a soft drink in an unopened container.

When a mixture is separated into its pure components, the components are said to be **purified**. Efforts at separation are often not complete in a single step, however,

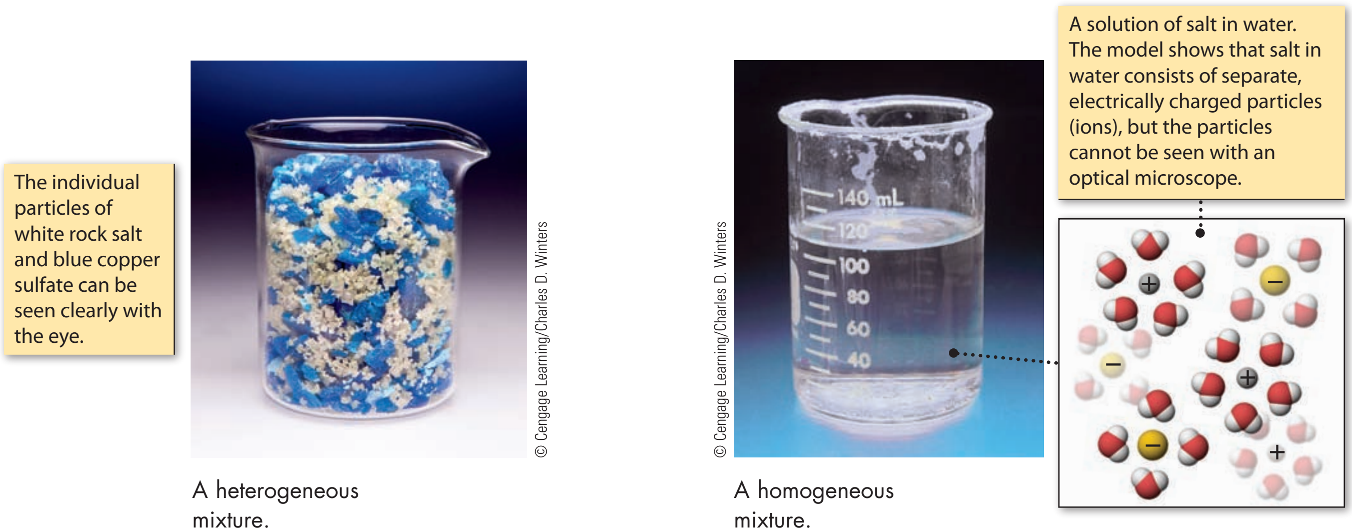

Figure 1.8 Heterogeneous and homogeneous mixtures.

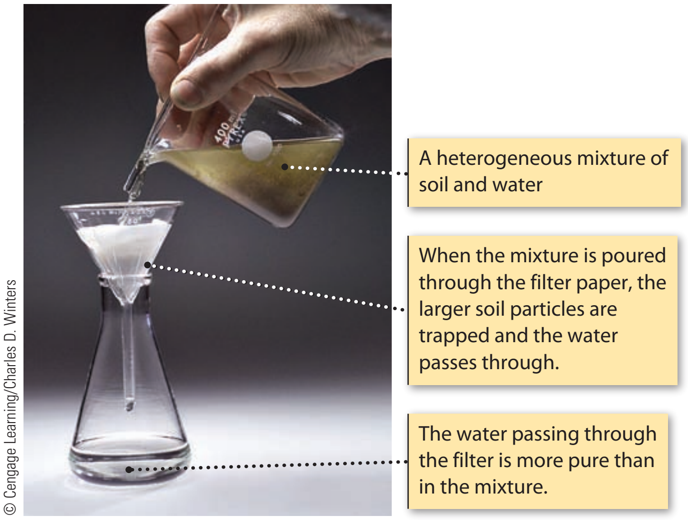

Figure 1.9 **Purifying a heterogeneous mixture by filtration.**

and repetition almost always gives an increasingly pure substance. For example, soil particles can be separated from water by filtration (Figure 1.9). When the mixture is passed through a filter, many of the particles are removed. Repeated filtrations will give water with a higher and higher state of purity. This purification process uses a property of the mixture, its clarity, to measure the extent of purification. When a perfectly clear sample of water is obtained, all of the soil particles are assumed to have been removed.

1.4 Elements

Goals for Section 1.4

- Identify the name or symbol for an element, given its symbol or name, respectively.
- Use the terms atom, element, and molecule correctly.

Passing an electric current through water can decompose it to gaseous hydrogen and oxygen (Figure 1.10). Substances like hydrogen and oxygen that are composed of *only one type of atom* are classified as **elements**. Currently 118 elements are known. Of these, only about 90—a few of which are illustrated in Figure 1.11—are found in nature. The remainder have been created by scientists. *Names and symbols for the elements are listed in the tables at the front and back of this book.* Carbon (C), sulfur (S), iron (Fe), copper (Cu), silver (Ag), tin (Sn), gold (Au), mercury (Hg), and lead (Pb) were known to the early Greeks and Romans and to the alchemists of ancient China, the Arab world, and medieval Europe. However, many other elements—such as aluminum (Al), silicon (Si), iodine (I), and helium (He)—were not discovered until the 18th and 19th centuries. Finally, scientists in the 20th and 21st centuries have made elements that do not exist in nature, such as technetium (Tc) and plutonium (Pu).

The stories behind some of the names of the elements are fascinating. Many elements have names and symbols with Latin or Greek origins. Examples include helium (He), from the Greek word *helios* meaning "sun," and lead, whose symbol, Pb, comes from the Latin word for "heavy," *plumbum*. More recently discovered elements have been named for their place of discovery or place of significance. Americium (Am),

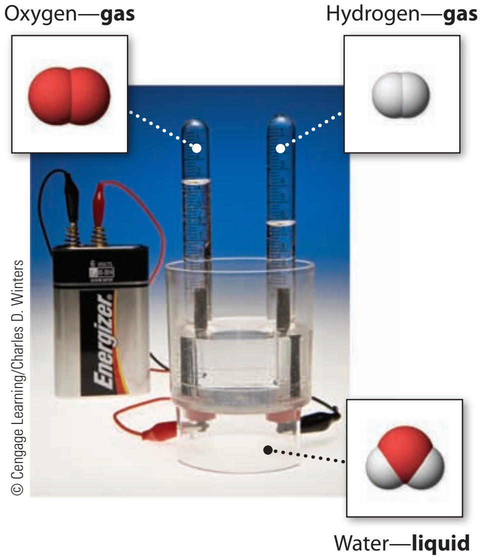

Figure 1.10 **Decomposing water to yield hydrogen and oxygen gases.**