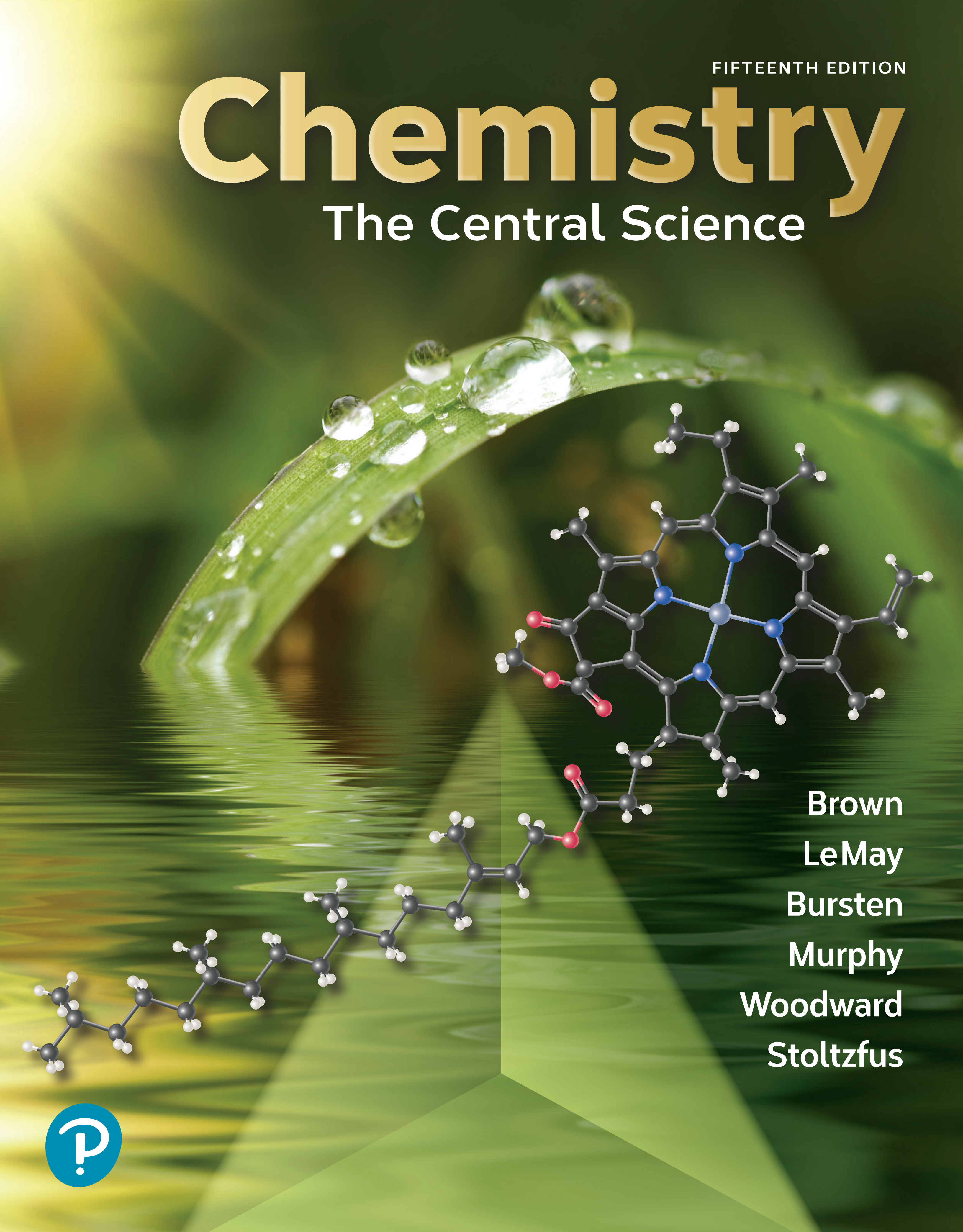
FIFTEENTH EDITION

Chemistry

The Central Science



Brown
LeMay
Bursten
Murphy
Woodward
Stoltzfus

This page intentionally left blank

Periodic Table of the Elements

Main Group Representative Elements (groups 1–2) · Transition metals (groups 3–12) · Main Group Representative Elements (groups 13–18)

Metals · Metalloids · Nonmetals

	1A[a] 1	2A 2	3B 3	4B 4	5B 5	6B 6	7B 7	8B 8	8B 9	8B 10	1B 11	2B 12	3A 13	4A 14	5A 15	6A 16	7A 17	8A 18
1	1 **H** 1.00794																	2 **He** 4.002602
2	3 **Li** 6.941	4 **Be** 9.0121831											5 **B** 10.811	6 **C** 12.0107	7 **N** 14.0067	8 **O** 15.9994	9 **F** 18.99840316	10 **Ne** 20.1797
3	11 **Na** 22.989770	12 **Mg** 24.3050											13 **Al** 26.981538	14 **Si** 28.0855	15 **P** 30.973762	16 **S** 32.065	17 **Cl** 35.453	18 **Ar** 39.948
4	19 **K** 39.0983	20 **Ca** 40.078	21 **Sc** 44.955908	22 **Ti** 47.867	23 **V** 50.9415	24 **Cr** 51.9961	25 **Mn** 54.938044	26 **Fe** 55.845	27 **Co** 58.933194	28 **Ni** 58.6934	29 **Cu** 63.546	30 **Zn** 65.39	31 **Ga** 69.723	32 **Ge** 72.64	33 **As** 74.92160	34 **Se** 78.971	35 **Br** 79.904	36 **Kr** 83.80
5	37 **Rb** 85.4678	38 **Sr** 87.62	39 **Y** 88.90584	40 **Zr** 91.224	41 **Nb** 92.90637	42 **Mo** 95.95	43 **Tc** [98]	44 **Ru** 101.07	45 **Rh** 102.90550	46 **Pd** 106.42	47 **Ag** 107.8682	48 **Cd** 112.414	49 **In** 114.818	50 **Sn** 118.710	51 **Sb** 121.760	52 **Te** 127.60	53 **I** 126.90447	54 **Xe** 131.293
6	55 **Cs** 132.905453	56 **Ba** 137.327	71 **Lu** 174.967	72 **Hf** 178.49	73 **Ta** 180.9479	74 **W** 183.84	75 **Re** 186.207	76 **Os** 190.23	77 **Ir** 192.217	78 **Pt** 195.078	79 **Au** 196.966569	80 **Hg** 200.59	81 **Tl** 204.3833	82 **Pb** 207.2	83 **Bi** 208.98038	84 **Po** [208.98]	85 **At** [209.99]	86 **Rn** [222.02]
7	87 **Fr** [223.02]	88 **Ra** [226.03]	103 **Lr** [262.11]	104 **Rf** [267.1]	105 **Db** [268.1]	106 **Sg** [269.1]	107 **Bh** [270.1]	108 **Hs** [269.1]	109 **Mt** [278.2]	110 **Ds** [281.2]	111 **Rg** [282.2]	112 **Cn** [285.2]	113 **Nh** [286.2]	114 **Fl** [289.2]	115 **Mc** [289.2]	116 **Lv** [293.2]	117 **Ts** [293.2]	118 **Og** [294.2]

Lanthanide series	57 **La** 138.9055	58 **Ce** 140.116	59 **Pr** 140.90766	60 **Nd** 144.24	61 **Pm** [145]	62 **Sm** 150.36	63 **Eu** 151.964	64 **Gd** 157.25	65 **Tb** 158.92534	66 **Dy** 162.50	67 **Ho** 164.93033	68 **Er** 167.259	69 **Tm** 168.93422	70 **Yb** 173.04
Actinide series	89 **Ac** [227.03]	90 **Th** 232.0377	91 **Pa** 231.03588	92 **U** 238.02891	93 **Np** [237.05]	94 **Pu** [244.06]	95 **Am** [243.06]	96 **Cm** [247.07]	97 **Bk** [247.07]	98 **Cf** [251.08]	99 **Es** [252.08]	100 **Fm** [257.10]	101 **Md** [258.10]	102 **No** [259.10]

[a] The labels on top (1A, 2A, etc.) are common American usage. The labels below these (1, 2, etc.) are those recommended by the International Union of Pure and Applied Chemistry (IUPAC).

Values in brackets are the atomic weights of the longest-lived or most important isotope of radioactive elements.

Further information is available at http://www.webelements.com

List of Elements with Their Symbols and Atomic Weights

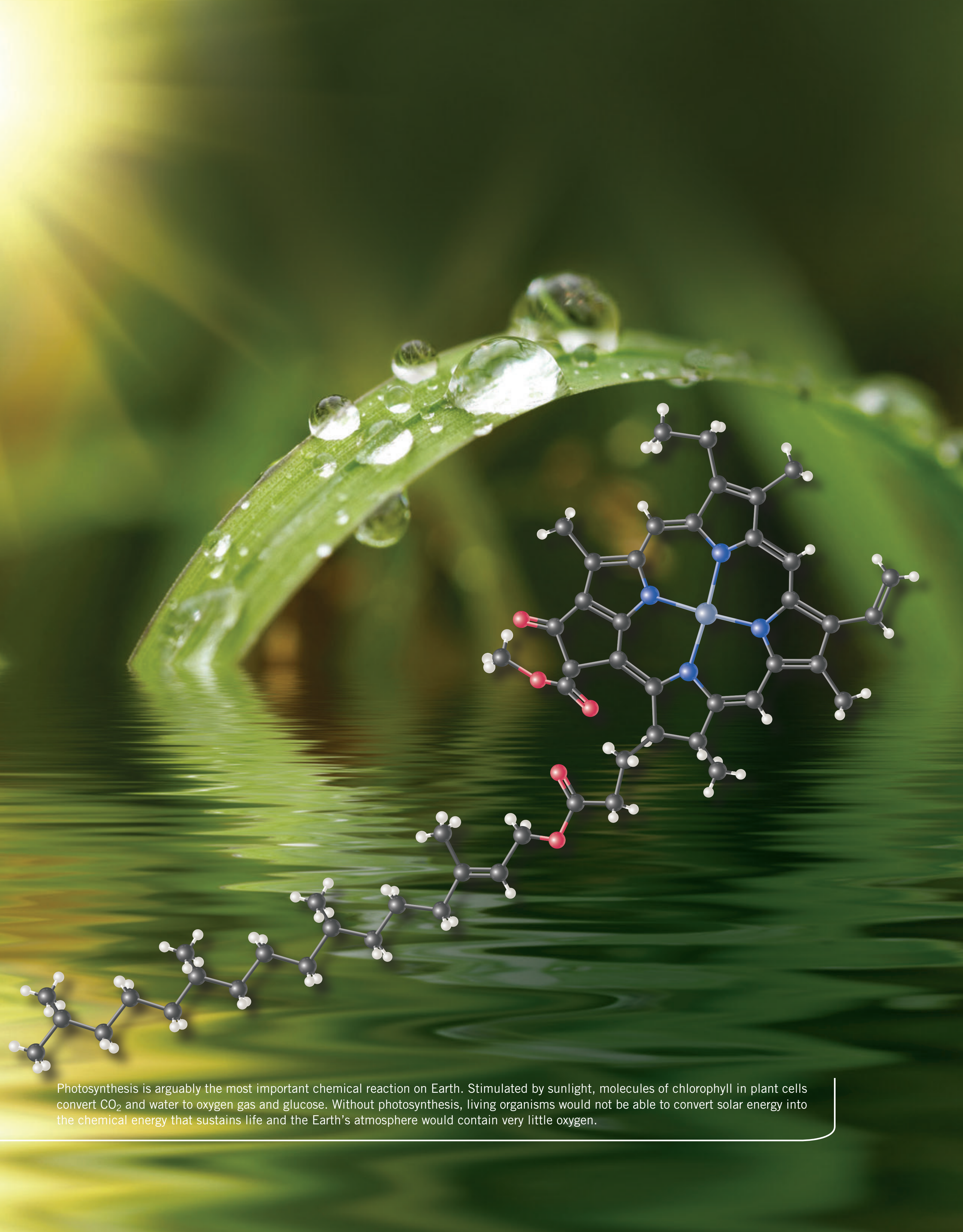
Element	Symbol	Atomic Number	Atomic Weight	Element	Symbol	Atomic Number	Atomic Weight	Element	Symbol	Atomic Number	Atomic Weight
Actinium	Ac	89	227.03[a]	Hafnium	Hf	72	178.49	Praseodymium	Pr	59	140.90766
Aluminum	Al	13	26.981538	Hassium	Hs	108	269.1[a]	Promethium	Pm	61	145[a]
Americium	Am	95	243.06[a]	Helium	He	2	4.002602	Protactinium	Pa	91	231.03588
Antimony	Sb	51	121.760	Holmium	Ho	67	164.93033	Radium	Ra	88	226.03[a]
Argon	Ar	18	39.948	Hydrogen	H	1	1.00794	Radon	Rn	86	222.02[a]
Arsenic	As	33	74.92160	Indium	In	49	114.818	Rhenium	Re	75	186.207[a]
Astatine	At	85	209.99[a]	Iodine	I	53	126.90447	Rhodium	Rh	45	102.90550
Barium	Ba	56	137.327	Iridium	Ir	77	192.217	Roentgenium	Rg	111	282.2[a]
Berkelium	Bk	97	247.07[a]	Iron	Fe	26	55.845	Rubidium	Rb	37	85.4678
Beryllium	Be	4	9.012183	Krypton	Kr	36	83.80	Ruthenium	Ru	44	101.07
Bismuth	Bi	83	208.98038	Lanthanum	La	57	138.9055	Rutherfordium	Rf	104	267.1[a]
Bohrium	Bh	107	270.1[a]	Lawrencium	Lr	103	262.11[a]	Samarium	Sm	62	150.36
Boron	B	5	10.81	Lead	Pb	82	207.2	Scandium	Sc	21	44.955908
Bromine	Br	35	79.904	Lithium	Li	3	6.941	Seaborgium	Sg	106	269.1[a]
Cadmium	Cd	48	112.414	Livermorium	Lv	116	293[a]	Selenium	Se	34	78.97
Calcium	Ca	20	40.078	Lutetium	Lu	71	174.967	Silicon	Si	14	28.0855
Californium	Cf	98	251.08[a]	Magnesium	Mg	12	24.3050	Silver	Ag	47	107.8682
Carbon	C	6	12.0107	Manganese	Mn	25	54.938044	Sodium	Na	11	22.989770
Cerium	Ce	58	140.116	Meitnerium	Mt	109	278.2[a]	Strontium	Sr	38	87.62
Cesium	Cs	55	132.905452	Mendelevium	Md	101	258.10[a]	Sulfur	S	16	32.065
Chlorine	Cl	17	35.453	Mercury	Hg	80	200.59	Tantalum	Ta	73	180.9479
Chromium	Cr	24	51.9961	Molybdenum	Mo	42	95.95	Technetium	Tc	43	98[a]
Cobalt	Co	27	58.933194	Moscovium	Mc	115	289.2[a]	Tellurium	Te	52	127.60
Copernicium	Cn	112	285.2[a]	Neodymium	Nd	60	144.24	Tennessine	Ts	117	293.2[a]
Copper	Cu	29	63.546	Neon	Ne	10	20.1797	Terbium	Tb	65	158.92534
Curium	Cm	96	247.07[a]	Neptunium	Np	93	237.05[a]	Thallium	Tl	81	204.3833
Darmstadtium	Ds	110	281.2[a]	Nickel	Ni	28	58.6934	Thorium	Th	90	232.0377
Dubnium	Db	105	268.1[a]	Nihonium	Nh	113	286.2[a]	Thulium	Tm	69	168.93422
Dysprosium	Dy	66	162.50	Niobium	Nb	41	92.90637	Tin	Sn	50	118.710
Einsteinium	Es	99	252.08[a]	Nitrogen	N	7	14.0067	Titanium	Ti	22	47.867
Erbium	Er	68	167.259	Nobelium	No	102	259.10[a]	Tungsten	W	74	183.84
Europium	Eu	63	151.964	Oganesson	Og	118	294.2[a]	Uranium	U	92	238.02891
Fermium	Fm	100	257.10[a]	Osmium	Os	76	190.23	Vanadium	V	23	50.9415
Flerovium	Fl	114	289.2[a]	Oxygen	O	8	15.9994	Xenon	Xe	54	131.293
Fluorine	F	9	18.9984016	Palladium	Pd	46	106.42	Ytterbium	Yb	70	173.04
Francium	Fr	87	223.02[a]	Phosphorus	P	15	30.973762	Yttrium	Y	39	88.90584
Gadolinium	Gd	64	157.25	Platinum	Pt	78	195.078	Zinc	Zn	30	65.39
Gallium	Ga	31	69.723	Plutonium	Pu	94	244.06[a]	Zirconium	Zr	40	91.224
Germanium	Ge	32	72.64	Polonium	Po	84	208.98[a]				
Gold	Au	79	196.966569	Potassium	K	19	39.0983				

[a]Mass of longest-lived or most important isotope.

CHEMISTRY

THE CENTRAL SCIENCE

15TH EDITION



Photosynthesis is arguably the most important chemical reaction on Earth. Stimulated by sunlight, molecules of chlorophyll in plant cells convert CO_2 and water to oxygen gas and glucose. Without photosynthesis, living organisms would not be able to convert solar energy into the chemical energy that sustains life and the Earth's atmosphere would contain very little oxygen.

CHEMISTRY

THE CENTRAL SCIENCE 15TH EDITION

Theodore L. Brown
University of Illinois at Urbana-Champaign

H. Eugene LeMay, Jr.
University of Nevada, Reno

Bruce E. Bursten
Worcester Polytechnic Institute

Catherine J. Murphy
University of Illinois at Urbana-Champaign

Patrick M. Woodward
The Ohio State University

Matthew W. Stoltzfus
The Ohio State University

Pearson

Content Development: Matt Walker, John Murdzek
Content Management: Jeanne Zalesky, Deborah Harden, Prudence Wei-Lin Huang
Content Production: Kristen Flathman, Beth Sweeten, Mary Tindle, Molly Montaro, Katie Foley, Jayne Sportelli, Lizette Faraji, Tod Regan, Chloe Veylit, Maria Guglielmo Walsh, Jerilyn Bockorick
Product Management: Chris Hess, Ian Desrosiers
Product Marketing: Candice Madden
Rights and Permissions: Ben Ferrini, Matthew Perry, Zosef Sotheo Herrero

Please contact https://support.pearson.com/getsupport/s/ with any queries on this content

Cover Image: Shutterstock

Library of Congress Cataloging-in-Publication Data
Cataloging-in-Publication Data is available on file at the Library of Congress.

ScoutAutomatedPrintCode

Pearson

Access Code Card
ISBN-10: 0137542747
ISBN-13: 9780137542741

Rental
ISBN-10: 0137493606
ISBN-13: 9780137493609

Pearson's Commitment to Diversity, Equity, and Inclusion

Pearson is dedicated to creating bias-free content that reflects the diversity, depth, and breadth of all learners' lived experiences.

We embrace the many dimensions of diversity, including but not limited to race, ethnicity, gender, sex, sexual orientation, socioeconomic status, ability, age, and religious or political beliefs.

Education is a powerful force for equity and change in our world. It has the potential to deliver opportunities that improve lives and enable economic mobility. As we work with authors to create content for every product and service, we acknowledge our responsibility to demonstrate inclusivity and incorporate diverse scholarship so that everyone can achieve their potential through learning. As the world's leading learning company, we have a duty to help drive change and live up to our purpose to help more people create a better life for themselves and to create a better world.

Our ambition is to purposefully contribute to a world where:

- Everyone has an equitable and lifelong opportunity to succeed through learning.
- Our educational content accurately reflects the histories and lived experiences of the learners we serve.
- Our educational products and services are inclusive and represent the rich diversity of learners.
- Our educational content prompts deeper discussions with students and motivates them to expand their own learning (and worldview).

Accessibility

We are also committed to providing products that are fully accessible to all learners. As per Pearson's guidelines for accessible educational Web media, we test and retest the capabilities of our products against the highest standards for every release, following the WCAG guidelines in developing new products for copyright year 2022 and beyond.

You can learn more about Pearson's commitment to accessibility at **https://www.pearson.com/us/accessibility.html**

Pearson

Contact Us

While we work hard to present unbiased, fully accessible content, we want to hear from you about any concerns or needs with this Pearson product so that we can investigate and address them.

Please contact us with concerns about any potential bias at **https://www.pearson.com/report-bias.html.**

For accessibility-related issues, such as using assistive technology with Pearson products, alternative text requests, or accessibility documentation, email the Pearson Disability Support team at **disability.support@pearson.com**

To our students,
whose enthusiasm and curiosity
have often inspired us,
and whose questions and suggestions
have sometimes taught us.

BRIEF CONTENTS

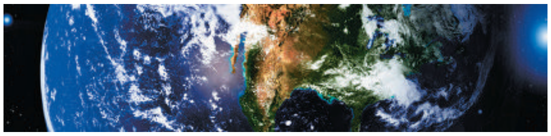
This page intentionally left blank

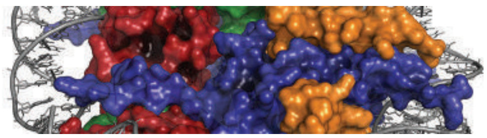
CONTENTS

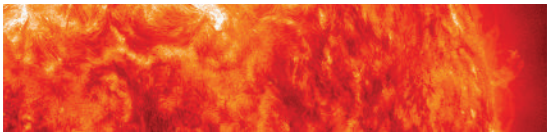
13 Properties of Solutions 521

14 Chemical Kinetics 565

15 Chemical Equilibrium 621







APPENDICES

CHEMICAL APPLICATIONS AND ESSAYS

A Closer Look

Chemistry and Sustainability

Chemistry and Life

Strategies for Success

PREFACE

To the Instructor

Philosophy

We authors of *Chemistry: The Central Science* are delighted and honored that you have chosen us as your instructional partners for your general chemistry class. Collectively we have taught general chemistry to multiple generations of students. Therefore, we understand the challenges and opportunities of teaching a class that so many students take. We have also been active researchers who appreciate both the learning and the discovery aspects of the chemical sciences. Our varied, wide-ranging experiences have formed the basis of the close collaborations we have enjoyed as coauthors. In writing our book, our focus is on the students: We try to ensure that the text is not only accurate and up-to-date but also clear and readable. We strive to convey the breadth of chemistry and the excitement that scientists experience in making new discoveries that contribute to our understanding of the physical world. We want the student to appreciate that chemistry is not a body of specialized knowledge that is separate from most aspects of modern life, but central to any attempt to address a host of societal concerns, including renewable energy, environmental sustainability, and improved human health. Most of all, we want to provide you and your students the most effective tools for teaching and learning.

Publishing the fifteenth edition of this text bespeaks an exceptionally long record of successful textbook writing. We are appreciative of the loyalty and support the book has received over the years, and we are mindful of our obligation to justify each new edition. We begin our approach to each new edition with an intensive author retreat in which we ask ourselves the deep questions that we must answer before we can move forward. What justifies yet another edition? What is changing in the world not only of chemistry, but with respect to science education and the qualities of the students we serve? How can we help your students not only learn the principles of chemistry, but also become critical thinkers who can think more like chemists?

Answers to these questions lie only partly in the changing face of chemistry itself. The introduction of many new technologies has changed the landscape in the teaching of sciences at all levels. The use of online resources in accessing information and presenting learning materials has markedly changed the role of the textbook as one element among many tools for student learning. Our challenge as authors is to maintain the text as the primary source of chemical knowledge and practice, while at the same time integrating it with the new avenues for learning made possible by technology. This book incorporates a number of technologies to improve pedagogy, including use of computer-based classroom tools, such as Mastering Chemistry, which is continually evolving to provide more effective means of testing and evaluating student performance, while giving the student immediate and helpful feedback. Video feedback for a select number of *Exam Prep* questions is also available in Mastering Chemistry, which is new to this edition

As authors, we want this text to be a central, indispensable learning tool for students. Whether as a physical book or in electronic form, it can be carried everywhere and used at any time. It is the best place students can go to obtain the information outside of the classroom needed for learning, skill development, reference, and test preparation. The text, more effectively than any other instrument, provides the depth of coverage and coherent background in modern chemistry that students need to serve their professional interests and, as appropriate, to prepare for more advanced chemistry courses.

If the text is to be effective in supporting your role as instructor, it must be addressed to the students. We strive to keep our writing clear and interesting, complemented by figures and illustrations wherever possible. The book has numerous in-text study aids for students, including student-friendly learning objectives and follow-up self-assessment exercises for each section of the book, carefully placed descriptions of problem-solving strategies, and a wealth of problems in varying formats at the end of each chapter. We hope our cumulative experience as teachers is evident in our pacing, choice of examples, and the types of study aids and motivational tools we have employed. We believe students are more enthusiastic about learning chemistry when they see its importance relative to their own goals and interests; therefore, we have highlighted many important applications of chemistry in everyday life. We hope you are able to make use of this material.

It is our philosophy, as authors, that the text and all the supplementary materials provided to support its use must work in concert with you, the instructor. A textbook is only as useful to students as the instructor permits it to be. This book is replete with features that help students learn and that can guide them as they acquire both conceptual understanding and problem-solving skills. There is a great deal here for the students to use, too much for all of it to be absorbed by any student in a one-year course. You will be the guide to the best use of the book. Only with your active help will the students be able to utilize most effectively all that the text and its supplements offer. Students care about grades, of course, and with encouragement they will also become interested in the subject matter and care about learning. Please consider emphasizing features of the book that can enhance student appreciation of chemistry, such as the *Chemistry and Sustainability* and *Chemistry and Life* boxes that show how chemistry impacts modern life and its relationship to health and life processes. Also consider emphasizing conceptual understanding (placing less emphasis on simple manipulative, algorithmic problem solving) and urging students to use the rich on-line resources available.

Organization and Contents

The first five chapters give a largely macroscopic, phenomenological view of chemistry. The basic concepts introduced—such as nomenclature, stoichiometry, and thermochemistry—provide necessary background for many of the laboratory experiments performed in general chemistry. We believe an early introduction to thermochemistry is desirable because so much of our understanding of chemical processes is based on considerations of energy changes. By incorporating bond enthalpies in the Thermochemistry chapter we aim to emphasize the connection between the macroscopic properties of substances and the submicroscopic world of atoms and bonds. We believe we have produced an effective, balanced approach to teaching thermodynamics in general chemistry, as well as providing students with an introduction to some of the global issues involving energy production and consumption. It is no easy matter to walk the narrow pathway between trying to teach too much at too high a level versus resorting to oversimplifications. For the book as a whole, the emphasis has been on imparting *conceptual* understanding, as opposed to presenting equations into which students are supposed to plug numbers.

The next four chapters (Chapters 6–9) deal with electronic structure and bonding. For more advanced students, *A Closer Look* boxes in Chapters 6 and 9 highlight radial probability functions and the phases of orbitals. Placing this latter discussion in *A Closer Look* box in Chapter 9 enables those who wish to cover this topic to do so, while others may decide to bypass it. For those instructors who wish to take an "atoms first" approach to teaching chemistry, starting with Chapters 1, 2, and 6 (while filling in concepts and problem-solving skills from Chapters 3–5 as they come up, especially in the laboratory) may work well.

In Chapters 10–13, the focus of the text changes to the next level of the organization of matter: examining the states of matter. Chapters 10 and 11 deal with gases, liquids, and intermolecular forces, while Chapter 12 is devoted to solids, presenting a contemporary view of the solid state as well as of modern materials accessible to general chemistry students. Chapter 12 provides an opportunity to show how abstract chemical bonding concepts impact real-world applications. The modular organization of the chapter allows you to tailor your coverage to focus on the materials (semiconductors, polymers, nanomaterials, and so forth) that are most relevant to your students and your own interests. This section of the book concludes with Chapter 13, which covers the formation and properties of solutions.

The next several chapters examine the factors that determine the speed and extent of chemical reactions: kinetics (Chapter 14), equilibria (Chapters 15–17), thermodynamics (Chapter 19), and electrochemistry (Chapter 20). Also in this section is a chapter on environmental chemistry (Chapter 18), in which the concepts developed in preceding chapters are applied to a discussion of the atmosphere and hydrosphere. This chapter has increasingly become focused on green chemistry and the impacts of human activities on Earth's water and atmosphere, and expands on many of the concepts first introduced in the *Chemistry and Sustainability* boxes.

After a discussion of nuclear chemistry (Chapter 21), the book ends with three survey chapters. Chapter 22 deals with nonmetals, Chapter 23 with the chemistry of transition metals, including coordination compounds, and Chapter 24 with the chemistry of organic compounds and elementary biochemical themes. These final four chapters are developed in an independent, modular fashion and can be covered in any order.

Our chapter sequence provides a fairly standard organization, however we recognize that not everyone teaches all the topics in the order we have chosen. We have, therefore, made sure instructors can make common changes in teaching sequence with no loss in student comprehension. In particular, many instructors prefer to introduce gases (Chapter 10) after stoichiometry (Chapter 3) rather than with states of matter. The chapter on gases has been written to permit this change with *no* disruption in the flow of material. It is also possible to treat balancing redox equations (Sections 20.1 and 20.2) earlier, after the introduction of redox reactions in Section 4.4. Finally, some instructors like to cover organic chemistry (Chapter 24) right after bonding (Chapters 8 and 9). This, too, is a largely seamless move.

We have brought students into greater contact with descriptive organic and inorganic chemistry by integrating examples throughout the text. You will find pertinent and relevant examples of "real" chemistry woven into all the chapters to illustrate principles and applications. Some chapters, of course, more directly address the "descriptive" properties of elements and their compounds, especially Chapters 4, 7, 11, 18, and 22–24. We also incorporate descriptive organic and inorganic chemistry in the end-of-chapter exercises.

Major Global Changes in This Edition

As with every new edition of *Chemistry: The Central Science,* the book has undergone a great many changes as we strive to keep the content current, and to improve the clarity and effectiveness of the text, the art, and the exercises. Among the myriad changes there are certain points of emphasis that we use to organize and guide the revision process. In creating the fifteenth edition, our revision was organized around the following points:

- We continue to use our in-classroom experiences with today's students to develop new tools that make the learning of chemistry more effective for students. In particular, we continue to develop new ways in which we can make our text a better, more indispensable learning tool for students. First, we have added *Learning Objectives* to each section of the text. These targeted goals are written in a student-friendly, easily understood manner which emphasizes the important concepts that provide students with achievable goals in their studies. Up to six learning objectives are placed in a margin box at the beginning of each section for ease of use. Then, at the end of each section, we have added a set of *Self-Assessment Exercises* for the students to complete as the equivalent of a low-stakes quiz as they proceed through the text. The author team was careful to ensure that each learning objective is covered by a self-assessment exercise. The self-assessment exercises, assignable in

Mastering, are structured as multiple-choice questions with wrong answers (distractors) chosen to probe common misconceptions and errors that students tend to make. Responses, both correct and incorrect, contain feedback written by the author team to help students recognize their mistakes and provides hints to get on the right track if they select the wrong answer. This organizational structural change has meant that some sections were combined with others, compared to previous editions of the book.

- At the end of each chapter are a series of *Exam Prep* questions. These multiple-choice questions, assignable in Mastering, are tied to each chapter's *Learning Objectives* and constitute what amounts to a practice exam for students to take on their own. As with the self-assessment exercises each answer contains clear, concise feedback written by the authors.

- Extensive effort has gone into creating enhanced content for the eText version of this book to make it so much more than just an electronic copy of the physical textbook. A select number of the Exam Prep questions include worked out solution videos, which allow students to check their work and solidify their understanding as they prepare for their midterm exams. These questions can also be assigned in Mastering Chemistry.

- Chemistry as the central science is intimately tied to larger issues such as climate change, humanity's use of energy, abundance of clean water, food insecurity, and more. Therefore, many of the former *Chemistry Put to Work* boxes have been reimagined and rewritten as *Chemistry and Sustainability* boxes, to showcase the means by which chemists contribute to the understanding of, and movement toward, a sustainable society. We maintain our focus on the positive aspects of chemistry without neglecting problems that can arise in an increasingly technological world. Our goal is to help students appreciate the real-world perspective of chemistry and the ways in which chemistry affects their lives. To address some of the most pressing societal issues of our time many new boxes have been added, including an introduction to these boxes in Chapter 1, which highlights the *UN Sustainability Development Goals*.

- The *Additional Exercises* at the end of each chapter are no longer separated into "additional exercises," and "integrative exercises," nor are brackets used to indicate problems that are abnormally difficult. For the student, this simulates the more real-world environment of an examination where such distinctions are not made.

- Throughout the text, updates to the periodic table and numerical constants have been implemented; for instance, in 2019, the values of Avogadro's number and a number of other physical constants were redefined, and we have included the most current values.

- Astute readers may notice the *Give It Some Thought* feature has been removed. The removal of this feature makes the reading experience less fragmented. The best *Give It Some Thought* questions have been reimagined as multiple-choice questions that are now part of the Self-Assessment Exercises and Exam Prep questions.

Chapter-Level Changes in This Edition

Chapter 1 continues the trend from the fourteenth edition to emphasize, early on, the importance of energy. The inclusion of energy in the opening chapter provides much greater flexibility for the order in which subsequent chapters can be covered. The *Chemistry and Sustainability* boxes are introduced in this chapter to frame the understanding that, historically, chemistry has had both positive and negative impacts on sustainability. More depth has been added to the discussion of significant figures compared to previous editions.

In Chapter 2, the treatment of organic chemistry nomenclature has been expanded to better match the long-standing section on inorganic nomenclature. This change involved moving some material, including end-of-chapter exercises, from Chapter 24. Inorganic acids such as HCl and organic acids such as acetic acid are now clearly distinguished.

In Chapter 5, the discussion of energy has been updated and expanded, especially regarding the section on foods and fuels, to connect directly to the focus on sustainability in the text.

In Chapter 6, a new (nearly) full-page figure has been added that shows the relationship between the wave function, the probability density, and the radial probability function for the 1*s*, 2*s* and 3*s* orbitals. By explicitly showing the wave functions, instructors who want to cover phases of orbitals have a better fundamental grounding with which to do so.

In Chapter 10, the average speed of gas molecules is now quantitatively described, in addition to the root-mean-square speed and the most probable speed. The discussion of diffusion and mean free path has been expanded to introduce the students to the concept of the random walk.

In Chapter 13, the explanation of why the solubility of gaseous and solid solutes typically change in the opposite direction with temperature is significantly expanded. The effects of entropy are emphasized, to the extent they can be in this chapter where entropy is first introduced but not covered in full detail. In acknowledgment of the complex interplay of enthalpy and entropy, some details are left to Chapter 19. New material that explores the use of reverse osmosis to desalinate ocean water has been added (some of this material was previously in Chapter 18).

In Chapter 14, sections have been renamed to better reflect their content. A new *Closer Look* box on diffusion-controlled reactions and activation-controlled reactions, highly relevant to reaction mechanisms, has been added.

In Chapter 15, the discussion of the Haber process has been expanded to show both the positive and negative implications of the process with respect to sustainability: the importance of the Haber process in addressing food insecurity vis-à-vis the enormous energy consumption and carbon footprint of the process.

In Chapter 16, the discussion of Lewis acids and bases has been moved from the end of the chapter to the first section where the Arrhenius and Brønsted-Lowry definitions of acids and bases are introduced. This rearrangement makes for a more natural discussion of the acidic properties of small, highly charged cations in the section on the acid–base properties of salt solutions.

Chapter 17 has been renamed to make its content (buffer, titrations, solubility equilibria) more clear.

Many aspects of Chapter 18 (ozone hole, atmospheric CO_2 levels, acid rain, ocean acidification, etc.) are constantly changing. This material has been revised to reflect the most up-to-date data and scientific consensus on future trends.

In Chapter 19, we have substantially rewritten the early sections to help students better understand the concepts of spontaneous, nonspontaneous, reversible, and irreversible processes and their relationships. These improvements have led to a clearer definition of entropy. The topical box on "Entropy and Human Society" has been revised as a *Chemistry and Sustainability* feature, with a greater emphasis on the sustainability aspects of the second law of thermodynamics.

In Chapter 21, the discussion of the various means of generating electricity has been revised, and a section on the health hazards of environmental radon has been added.

Finally, in Chapter 24 a new Chemistry and Life box on COVID-19 and mRNA vaccines has been added.

To the Student

Chemistry: The Central Science, Fifteenth Edition, has been written to introduce you to modern chemistry. As authors, we have, in effect, been engaged by your instructor to help you learn chemistry. Based on the comments of students and instructors who have used this book in its previous editions, we believe that we have done that job well. Of course, we expect the text to continue to evolve through future editions. We invite you to write to tell us what you like about the book so we will know where we have helped you most. We would also like to learn of any shortcomings in an effort improve the book in subsequent editions. Our addresses are given at the end of the Preface.

Advice for Learning and Studying Chemistry

Learning chemistry requires both the assimilation of many concepts and the development of analytical skills. In this text, we have provided you with numerous tools to help you succeed in both tasks. If you are going to succeed in your chemistry course, you will have to develop good study habits. Science courses, and chemistry in particular, make different demands on your learning skills than do other types of courses. We offer the following tips for success in your study of chemistry:

Don't fall behind! As the course moves along, new topics will build on material already presented. If you don't keep up with your reading and problem solving, you will find it much harder to follow the lectures and discussions on current topics. Experienced teachers know that students who read the relevant sections of the text *before* coming to a class learn more from the class and retain greater recall. "Cramming" just before an exam has been shown to be an ineffective way to study any subject, chemistry included.

Focus your study. The amount of information you will be expected to learn may seem overwhelming. We have tried to help you by incorporating *Learning Objectives* into the beginning of each section within each chapter; with accompanying *Self-Assessment Exercises* at the end each section so you can test your knowledge. At the end of each chapter, we provide you with *Exam Prep* questions, which you can think of as a multiple-choice practice exam. During your time with your instructor in the classroom, it is essential to recognize those concepts and skills that are particularly important. Pay attention to what your instructor is emphasizing. As you work through the *Sample Exercises* and homework assignments, try to see what general principles and skills they employ. Use the *What's Ahead* feature at the beginning of each chapter to help orient yourself to what is important in each chapter. A single reading of a chapter will generally not be enough for successful learning of chapter concepts and problem-solving skills. You will often need to go over assigned materials more than once. Don't skip the *Go Figure* features, *Sample Exercises,* and *Practice Exercises.* These are your guides to whether you are learning the material. They are also good preparation for test-taking. The *Key Equations* at the end of the chapter will also help you focus your study.

Keep good lecture notes. Your lecture notes will provide you with a clear and concise record of what your instructor regards as the most important material to learn. Using your lecture notes in conjunction with this text is the best way to determine which material to study.

Skim topics in the text before they are covered in lecture. Reviewing a topic before lecture will make it easier for you to take good notes. First read the *What's Ahead* points and the end-of-chapter *Summary;* then quickly read through the chapter, skipping Sample Exercises and supplemental sections. Paying attention to the titles of sections and subsections gives you a feeling for the scope of topics. Try to avoid thinking that you must learn and understand everything right away.

Do a certain amount of preparation before lecture. More than ever, instructors are using the lecture period not simply as a one-way channel of communication from teacher to student. Rather, they expect students to come to class ready to work on problem solving and critical thinking. Coming to class unprepared is not a good idea for any lecture environment, but it certainly is not an option for an active learning classroom if you aim to do well in the course.

After lecture, carefully read the topics covered in class. As you read, pay attention to the concepts presented and to the application of these concepts in the *Sample Exercises.* Once you think you understand a *Sample Exercise,* test your understanding by working the accompanying *Practice Exercise.*

Learn the language of chemistry. As you study chemistry, you will encounter many new words. It is important to pay attention to these words and to know their meanings or the entities to which they refer. Knowing how to identify chemical substances from their names is an important skill; it can help you avoid painful mistakes on examinations. For example, "chlorine" and "chloride" refer to very different things.

Attempt the assigned end-of-chapter exercises. Working the exercises selected by your instructor provides necessary practice in recalling and using the essential ideas of the chapter. You cannot learn merely by observing; you must be a participant. In particular, try to resist checking the *Solutions Manual* (if you have one) until you have made a sincere effort to solve the exercise yourself. If you get stuck on an exercise, however, get help from your instructor, your teaching assistant, or another student. Spending more than 20 minutes on a single exercise is rarely effective unless you know that it is particularly challenging.

Learn to think like a scientist. This book is written by scientists who love chemistry. We encourage you to develop your critical thinking skills by taking advantage of features in this new edition, such as exercises that focus on conceptual learning and the *Design an Experiment* exercises.

Use online resources. Some things are more easily learned by discovery, and others are best shown in three dimensions. If your instructor has included Mastering Chemistry with your book, take advantage of the unique tools it provides to get the most out of your time in chemistry.

The bottom line is to work hard, study effectively, and use the tools available to you, including this textbook. We want to help you learn more about the world of chemistry and why chemistry is the central science. If you really learn chemistry, you can be the life of the party, impress your friends and parents, and . . . well, also pass the course with a good grade.

Answers to Go Figures, Practice Exercises and Self Assessment Exercises are available as PDF files within Mastering Chemistry. We invite instructors to share these resources as needed.

Acknowledgments

The production of a textbook is a team effort requiring the involvement of many people besides the authors who contributed hard work and talent to bring this edition to life. Although their names don't appear on the cover of the book, their creativity, time, and support have been instrumental in all stages of its development and production.

Each of us has benefited greatly from discussions with colleagues and from correspondence with instructors and students both here and abroad. Colleagues have also helped immensely by reviewing our materials, sharing their insights, and providing suggestions for improvements. For this edition, we were particularly blessed with an exceptional group of accuracy checkers who read through our materials looking for both technical inaccuracies and typographical errors.

Reviewers of Chemistry: *The Central Science*

S. K. Airee, *University of Tennessee*
John J. Alexander, *University of Cincinnati*
Robert Allendoerfer, *SUNY Buffalo*
Patricia Amateis, *Virginia Polytechnic Institute and State University*
Sandra Anderson, *University of Wisconsin*
John Arnold, *University of California*
Socorro Arteaga, *El Paso Community College*
Margaret Asirvatham, *University of Colorado*
Todd L. Austell, *University of North Carolina, Chapel Hill*
Yiyan Bai, *Houston Community College*
Melita Balch, *University of Illinois at Chicago*
Rebecca Barlag, *Ohio University*
Christine Barnes, *University of Tennessee, Knoxville*
Rosemary Bartoszek-Loza, *The Ohio State University*
Hafed Bascal, *University of Findlay*
Boyd Beck, *Snow College*
Kelly Beefus, *Anoka-Ramsey Community College*
Amy Beilstein, *Centre College*
Donald Bellew, *University of New Mexico*
Phil Bennett, *Santa Fe Community College*
Victor Berner, *New Mexico Junior College*
Narayan Bhat, *University of Texas, Pan American*
Jo Blackburn, *Richland College*
Merrill Blackman, *United States Military Academy*
Salah M. Blaih, *Kent State University*
Carribeth Bliem, *University of North Carolina, Chapel Hill*
Stephen Block, *University of Wisconsin, Madison*
James A. Boiani, *SUNY Geneseo*
John Bookstaver, *St. Charles Community College*
Leon Borowski, *Diablo Valley College*
Simon Bott, *University of Houston*
Kevin L. Bray, *Washington State University*
Daeg Scott Brenner, *Clark University*
Gregory Alan Brewer, *Catholic University of America*
Karen Brewer, *Virginia Polytechnic Institute and State University*
Ron Briggs, *Arizona State University*
Edward Brown, *Lee University*
Gary Buckley, *Cameron University*
Scott Bunge, *Kent State University*
William Butler, *Rochester Institute of Technology*
Carmela Byrnes, *Texas A&M University*
B. Edward Cain, *Rochester Institute of Technology*
Kim Calvo, *University of Akron*
Donald L. Campbell, *University of Wisconsin*
Rachel Campbell, *Florida Gulf Coast University*
Gene O. Carlisle, *Texas A&M University*
David Carter, *Angelo State University*
Elaine Carter, *Los Angeles City College*
Robert Carter, *University of Massachusetts at Boston Harbor*
Ann Cartwright, *San Jacinto Central College*
David L. Cedeño, *Illinois State University*
Dana Chatellier, *University of Delaware*
Stanton Ching, *Connecticut College*
Paul Chirik, *Cornell University*
Ted Clark, *The Ohio State University*
Tom Clayton, *Knox College*
William Cleaver, *University of Vermont*
Beverly Clement, *Blinn College*
Robert D. Cloney, *Fordham University*
Doug Cody, *Nassau Community College*
John Collins, *Broward Community College*
Edward Werner Cook, *Tunxis Community Technical College*
Elzbieta Cook, *Louisiana State University*
Enriqueta Cortez, *South Texas College*
Jason Coym, *University of South Alabama*
Thomas Edgar Crumm, *Indiana University of Pennsylvania*

Dwaine Davis, *Forsyth Tech Community College*
Michelle Dean, *Kennesaw State University*
Nancy De Luca, *University of Massachusetts, Lowell North Campus*
Angel de Dios, *Georgetown University*
John M. DeKorte, *Glendale Community College*
Michael Denniston, *Georgia Perimeter College*
Marian DeWane, *University California Irvine*
Daniel Domin, *Tennessee State University*
James Donaldson, *University of Toronto*
Patrick Donoghue, *Appalachian State University*
Bill Donovan, *University of Akron*
Tom Dowd, *Harper College*
Stephen Drucker, *University of Wisconsin-Eau Claire*
Ronald Duchovic, *Indiana University–Purdue University at Fort Wayne*
Robert Dunn, *University of Kansas*
David Easter, *Southwest Texas State University*
Joseph Ellison, *United States Military Academy*
George O. Evans II, *East Carolina University*
Emmanue Ewane, *Houston Community College*
Jordan Fantini, *Denison University*
James M. Farrar, *University of Rochester*
Debra Feakes, *Texas State University at San Marcos*
Gregory M. Ferrence, *Illinois State University*
Clark L. Fields, *University of Northern Colorado*
Jennifer Firestine, *Lindenwood University*
Jan M. Fleischner, *College of New Jersey*
Paul A. Flowers, *University of North Carolina at Pembroke*
Michelle Fossum, *Laney College*
Roger Frampton, *Tidewater Community College*
Joe Franek, *University of Minnesota*
David Frank, *California State University*
Cheryl B. Frech, *University of Central Oklahoma*
Ewa Fredette, *Moraine Valley College*
Kenneth A. French, *Blinn College*
Karen Frindell, *Santa Rosa Junior College*
John I. Gelder, *Oklahoma State University*
Robert Gellert, *Glendale Community College*
Luther Giddings, *Salt Lake Community College*
Paul Gilletti, *Mesa Community College*
Peter Gold, *Pennsylvania State University*
Eric Goll, *Brookdale Community College*
John Gorden, *Auburn University*
James Gordon, *Central Methodist College*
John Gorden, *Auburn University*
Palmer Graves, *Florida International University*
Thomas J. Greenbowe, *University of Oregon*
Michael Greenlief, *University of Missouri*
Eric P. Grimsrud, *Montana State University*
Nathan Grove, *University of North Carolina, Wilmington*
Brian Gute, *University of Minnesota, Duluth*
Margie Haak, *Oregon State University*
John Hagadorn, *University of Colorado*
Randy Hall, *Louisiana State University*
John M. Halpin, *New York University*
Marie Hankins, *University of Southern Indiana*
Robert M. Hanson, *St. Olaf College*
Daniel Haworth, *Marquette University*
Michael Hay, *Pennsylvania State University*
Inna Hefley, *Blinn College*
David Henderson, *Trinity College*
Brad Herrick, *Colorado School of Mines*
Paul Higgs, *Barry University*
Carl A. Hoeger, *University of California, San Diego*
Gary G. Hoffman, *Florida International University*
Deborah Hokien, *Marywood University*
Robin Horner, *Fayetteville Tech Community College*
Roger K. House, *Moraine Valley College*
Amanda Howell, *Appalachian State University*
Michael O. Hurst, *Georgia Southern University*
William Jensen, *South Dakota State University*
Jeff Jenson, *University of Findlay*
Janet Johannessen, *County College of Morris*
Milton D. Johnston, Jr., *University of South Florida*
Andrew Jones, *Southern Alberta Institute of Technology*
Booker Juma, *Fayetteville State University*
Ismail Kady, *East Tennessee State University*
Siam Kahmis, *University of Pittsburgh*
Steven Keller, *University of Missouri*
John W. Kenney, *Eastern New Mexico University*
Neil Kestner, *Louisiana State University*
Angela King, *Wake Forest University*
Jesudoss Kingston, *Iowa State University*
Leslie Kinsland, *University of Louisiana*
Louis J. Kirschenbaum, *University of Rhode Island*
Donald Kleinfelter, *University of Tennessee, Knoxville*
Daniela Kohen, *Carleton University*
David Kort, *George Mason University*
Jeffrey Kovac, *University of Tennessee*
George P. Kreishman, *University of Cincinnati*
Paul Kreiss, *Anne Arundel Community College*
Manickham Krishnamurthy, *Howard University*
Sergiy Kryatov, *Tufts University*
Brian D. Kybett, *University of Regina*
William R. Lammela, *Nazareth College*
John T. Landrum, *Florida International University*
Richard Langley, *Stephen F. Austin State University*
Russ Larsen, *University of Iowa*
Joe Lazafame, *Rochester Institute of Technology*
N. Dale Ledford, *University of South Alabama*
Ernestine Lee, *Utah State University*
David Lehmpuhl, *University of Southern Colorado*
Robley J. Light, *Florida State University*
Donald E. Linn, Jr., *Indiana University–Purdue University Indianapolis*
David Lippmann, *Southwest Texas State*
Patrick Lloyd, *Kingsborough Community College*
Encarnacion Lopez, *Miami Dade College, Wolfson*
Ramón López de la Vega, *Florida International University*
Charity Lovett, *Seattle University*
Arthur Low, *Tarleton State University*
Rosemary Loza, *The Ohio State University*
Michael Lufaso, *University of North Florida*
Gary L. Lyon, *Louisiana State University*
Preston J. MacDougall, *Middle Tennessee State University*
Jeffrey Madura, *Duquesne University*
Larry Manno, *Triton College*
Asoka Marasinghe, *Moorhead State University*
Earl L. Mark, *ITT Technical Institute*
Pamela Marks, *Arizona State University*
Albert H. Martin, *Moravian College*
Przemyslaw Maslak, *Pennsylvania State University*
Hilary L. Maybaum, *ThinkQuest, Inc.*

Armin Mayr, *El Paso Community College*
Marcus T. McEllistrem, *University of Wisconsin*
Craig McLauchlan, *Illinois State University*
Jeff McVey, *Texas State University at San Marcos*
William A. Meena, *Valley College*
Joseph Merola, *Virginia Polytechnic Institute and State University*
Stephen Mezyk, *California State University*
Gary Michels, *Creighton University*
Diane Miller, *Marquette University*
Eric Miller, *San Juan College*
Gordon Miller, *Iowa State University*
Shelley Minteer, *Saint Louis University*
Massoud (Matt) Miri, *Rochester Institute of Technology*
Mohammad Moharerrzadeh, *Bowie State University*
Tracy Morkin, *Emory University*
Barbara Mowery, *York College*
Kathleen E. Murphy, *Daemen College*
Kathy Nabona, *Austin Community College*
Robert Nelson, *Georgia Southern University*
Al Nichols, *Jacksonville State University*
Ross Nord, *Eastern Michigan University*
Jessica Orvis, *Georgia Southern University*
Mark Ott, *Jackson Community College*
Jason Overby, *College of Charleston*
Robert H. Paine, *Rochester Institute of Technology*
Robert T. Paine, *University of New Mexico*
Sandra Patrick, *Malaspina University College*
Mary Jane Patterson, *Brazosport College*
Tammi Pavelec, *Lindenwood University*
Albert Payton, *Broward Community College*
Lee Pedersen, *University of North Carolina*
Christopher J. Peeples, *University of Tulsa*
Kim Percell, *Cape Fear Community College*
Gita Perkins, *Estrella Mountain Community College*
Richard Perkins, *University of Louisiana*
Nancy Peterson, *North Central College*
Robert C. Pfaff, *Saint Joseph's College*
John Pfeffer, *Highline Community College*
Lou Pignolet, *University of Minnesota*
Bernard Powell, *University of Texas*
Bob Pribush, *Butler University*
Jeffrey A. Rahn, *Eastern Washington University*
Steve Rathbone, *Blinn College*
Bhavna Rawal, *Houston Community College*
Scott Reeve, *Arkansas State University*
John Reissner Helen Richter Thomas Ridgway, *University of North Carolina, University of Akron, University of Cincinnati*
Al Rives, *Wake Forest University*
Gregory Robinson, *University of Georgia*
Mark G. Rockley, *Oklahoma State University*
Lenore Rodicio, *Miami Dade College*
Amy L. Rogers, *College of Charleston*
Jimmy R. Rogers, *University of Texas at Arlington*
Kathryn Rowberg, *Purdue University at Calumet*
Steven Rowley, *Middlesex Community College*
Kresimir Rupnik, *Louisiana State University*
Joel Russell, *Oakland University*
James E. Russo, *Whitman College*
Theodore Sakano, *Rockland Community College*
Michael J. Sanger, *University of Northern Iowa*
Jerry L. Sarquis, *Miami University*
James P. Schneider, *Portland Community College*
Mark Schraf, *West Virginia University*
Melissa Schultz, *The College of Wooster*
Gray Scrimgeour, *University of Toronto*
Paula Secondo, *Western Connecticut State University*
Stacy Sendler, *Arizona State University*
Michael Seymour, *Hope College*
Kathy Thrush Shaginaw, *Villanova University*
Susan M. Shih, *College of DuPage*
David Shinn, *University of Hawaii at Hilo*
Lewis Silverman, *University of Missouri at Columbia*
Vince Sollimo, *Burlington Community College*
David Soriano, *University of Pittsburgh-Bradford*
Richard Spinney, *The Ohio State University*
Eugene Stevens, *Binghamton University*
Jerry Suits, *University Northern Colorado*
James Symes, *Cosumnes River College*
Greg Szulczewski, *University of Alabama, Tuscaloosa*
Matt Tarr, *University of New Orleans*
Dennis Taylor, *Clemson University*
Iwao Teraoka, *Polytechnic University*
Domenic J. Tiani, *University of North Carolina, Chapel Hill*
Edmund Tisko, *University of Nebraska at Omaha*
Richard S. Treptow, *Chicago State University*
Harold Trimm, *Broome Community College*
Michael Tubergen, *Kent State University*
Claudia Turro, *The Ohio State University*
James Tyrell, *Southern Illinois University*
Michael J. Van Stipdonk, *Wichita State University*
Philip Verhalen, *Panola College*
Ann Verner, *University of Toronto at Scarborough*
Edward Vickner, *Gloucester County Community College*
John Vincent, *University of Alabama*
Maria Vogt, *Bloomfield College*
Emanuel Waddell, *University of Alabama, Huntsville*
Tony Wallner, *Barry University*
Lichang Wang, *Southern Illinois University*
Thomas R. Webb, *Auburn University*
Clyde Webster, *University of California at Riverside*
Karen Weichelman, *University of Louisiana-Lafayette*
Paul G. Wenthold, *Purdue University*
Laurence Werbelow, *New Mexico Institute of Mining and Technology*
Wayne Wesolowski, *University of Arizona*
Sarah West, *University of Notre Dame*
Linda M. Wilkes, *University at Southern Colorado*
Charles A. Wilkie, *Marquette University*
Darren L. Williams, *West Texas A&M University*
Kurt Winklemann, *Florida Institute of Technology*
Klaus Woelk, *University of Missouri, Rolla*
Steve Wood, *Brigham Young University*
Troy Wood, *SUNY Buffalo*
Kimberly Woznack, *California University of Pennsylvania*
Thao Yang, *University of Wisconsin*
David Zax, *Cornell University*
Bob Zelmer, *The Ohio State University*
Dr. Susan M. Zirpoli, *Slippery Rock University*
Edward Zovinka, *Saint Francis University*

We would also like to express our gratitude to our partners at Pearson whose hard work, imagination, and commitment have contributed so greatly to the final form of this edition: Deb Harden and Ian Desrosiers, our Content Analyst and Product Manager, respectively, for their unflagging enthusiasm, continuous encouragement, and support; John Murdzek, our Development Editor, whose depth of experience, deep knowledge of chemistry, and careful attention to detail were invaluable to this revision; Matt Walker, Content Development Manager, who has brought his experience and insight to oversight of the entire project; and Beth Sweeten, Senior Content Producer, for keeping us on task and helping us to prioritize the many tasks that go into a revision of this scope. This revision would not have been possible without their hard work and guidance.

There are many others who also deserve special recognition, including the following: Mary Tindle, our production editor, whose expertise, advice, flexibility, and commitment to accuracy have allowed us to produce a textbook that is both beautiful and of high quality; and Roxy Wilson (University of Illinois), who so ably coordinated the difficult job of working out solutions to the end-of-chapter exercises. Finally, we wish to thank our families and friends for their love, support, encouragement, and patience as we brought this fifteenth edition to completion.

Theodore L. Brown
Department of Chemistry
University of Illinois at Urbana-Champaign
Urbana, IL 61801
tlbrown@illinois.edu or tlbrown1@earthlink.net

H. Eugene LeMay, Jr.
Department of Chemistry
University of Nevada
Reno, NV 89557
lemay@unr.edu

Bruce E. Bursten
Department of Chemistry and Biochemistry
Worcester Polytechnic Institute
Worcester, MA 01609
bbursten@wpi.edu

Catherine J. Murphy
Department of Chemistry
University of Illinois at Urbana-Champaign
Urbana, IL 61801
murphycj@illinois.edu

Patrick M. Woodward
Department of Chemistry and Biochemistry
The Ohio State University
Columbus, OH 43210
woodward.55@osu.edu

Matthew W. Stoltzfus
Department of Chemistry and Biochemistry
The Ohio State University
Columbus, OH 43210
stoltzfus.5@osu.edu

ABOUT THE AUTHORS

The Brown/Lemay/Bursten/Murphy/Woodward/Stoltzfus Author Team values collaboration as an integral component to overall success. While each author brings unique talent, research interests, and teaching experiences, the team works together to review and develop the entire text. It is this collaboration that keeps the content ahead of educational trends and contributes to continuous innovations in teaching and learning throughout the text and technology. Some of the new key features in the fifteenth edition and accompanying Mastering Chemistry course are highlighted on the upcoming pages.

Theodore L. Brown received his Ph.D. from Michigan State University in 1956. Since then, he has been a member of the faculty of the University of Illinois, Urbana-Champaign, where he is now Professor of Chemistry, Emeritus. He served as Vice Chancellor for Research, and Dean of The Graduate College, from 1980 to 1986, and as Founding Director of the Arnold and Mabel Beckman Institute for Advanced Science and Technology from 1987 to 1993. Professor Brown has been an Alfred P. Sloan Foundation Research Fellow and has been awarded a Guggenheim Fellowship. In 1972 he was awarded the American Chemical Society Award for Research in Inorganic Chemistry and received the American Chemical Society Award for Distinguished Service in the Advancement of Inorganic Chemistry in 1993. He has been elected a Fellow of the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and the American Chemical Society.

H. Eugene Lemay, Jr., received his B.S. degree in Chemistry from Pacific Lutheran University (Washington) and his Ph.D. in Chemistry in 1966 from the University of Illinois, Urbana-Champaign. He then joined the faculty of the University of Nevada, Reno, where he is currently Professor of Chemistry, Emeritus. He has enjoyed Visiting Professorships at the University of North Carolina at Chapel Hill, at the University College of Wales in Great Britain, and at the University of California, Los Angeles. Professor LeMay is a popular and effective teacher, who has taught thousands of students during more than 40 years of university teaching. Known for the clarity of his lectures and his sense of humor, he has received several teaching awards, including the University Distinguished Teacher of the Year Award (1991) and the first Regents' Teaching Award given by the State of Nevada Board of Regents (1997).

Bruce E. Bursten received his Ph.D. in Chemistry from the University of Wisconsin in 1978. After two years as a National Science Foundation Postdoctoral Fellow at Texas A&M University, he joined the faculty of The Ohio State University, where he rose to the rank of Distinguished University Professor. In 2005, he moved to the University of Tennessee, Knoxville, as Distinguished Professor of Chemistry and Dean of the College of Arts and Sciences. In 2015, he moved to Worcester Polytechnic Institute as Provost and Professor of Chemistry and Biochemistry. Professor Bursten has been a Camille and Henry Dreyfus Foundation Teacher-Scholar and an Alfred P. Sloan Foundation Research Fellow, and he is a Fellow of both the American Association for the Advancement of Science and the American Chemical Society. At Ohio State he received the University Distinguished Teaching Award in 1982 and 1996, the Arts and Sciences Student Council Outstanding Teaching Award in 1984, and the University Distinguished Scholar Award in 1990. He received the Spiers Memorial Prize and Medal of the Royal Society of Chemistry in 2003, the Morley Medal of the Cleveland Section of the American Chemical Society in 2005, and the American Chemical Society Award for Distinguished Service in the Advancement of Inorganic Chemistry in 2020. He was President of the American Chemical Society for 2008 and Chair of the Section on Chemistry of the American Association for the Advancement of Science in 2015. Professor Bursten's research program focuses on theoretical studies of compounds of the transition-metal and actinide elements.

Catherine J. Murphy received two B.S. degrees, one in Chemistry and one in Biochemistry, from the University of Illinois, Urbana-Champaign, in 1986. She received her Ph.D. in Chemistry from the University of Wisconsin in 1990. She was a National Science Foundation and National Institutes of Health Postdoctoral Fellow at the California Institute of Technology from 1990 to 1993. In 1993, she joined the faculty of the University of South Carolina, Columbia, becoming the Guy F. Lipscomb Professor of Chemistry in 2003. In 2009 she moved to the University of Illinois, Urbana-Champaign, as the Peter C. and Gretchen Miller Markunas Professor of Chemistry. Professor Murphy has been honored for both research and teaching as a Camille Dreyfus Teacher-Scholar, an Alfred P. Sloan Foundation Research Fellow, a Cottrell Scholar of the Research Corporation, a National Science Foundation CAREER Award winner, and a subsequent NSF Award for Special Creativity. She has also received a USC Mortar Board Excellence in Teaching Award, the USC Golden Key Faculty Award for Creative Integration of Research and Undergraduate Teaching, the USC Michael J. Mungo Undergraduate Teaching Award, and the USC Outstanding Undergraduate Research Mentor Award. From 2006–2011, Professor Murphy served as a Senior Editor for the *Journal of Physical Chemistry*; in 2011, she became the Deputy Editor for the *Journal of Physical Chemistry C*. She is an elected Fellow of the American Association for the Advancement of Science (2008), the American Chemical Society (2011), the Royal Society of Chemistry (2014), and the U.S. National Academy of Sciences (2015). Professor Murphy's research program focuses on the synthesis, optical properties, surface chemistry, biological applications, and environmental implications of colloidal inorganic nanomaterials.

Patrick M. Woodward received B.S. degrees in both Chemistry and Engineering from Idaho State University in 1991. He received a M.S. degree in Materials Science and a Ph.D. in Chemistry from Oregon State University in 1996. He spent two years as a postdoctoral researcher in the Department of Physics at Brookhaven National Laboratory. In 1998, he joined the faculty of the Chemistry Department at The Ohio State University where he currently holds the rank of Professor. He has been a visiting professor at Durham University in the UK, the University of Sydney in Australia, and the University of Bordeaux in France. Professor Woodward is a Fellow of the American Chemical Society and has been recognized with an Alfred P. Sloan Foundation Research Fellowship and a National Science Foundation CAREER Award. He has served as Vice Chair for Undergraduate Studies in the Department of Chemistry and Biochemistry at Ohio State University, and director of the Ohio REEL program. Professor Woodward's research program focuses on understanding the links between bonding, structure, and properties of solid-state inorganic materials.

Matthew W. Stoltzfus received his B.S. degree in Chemistry from Millersville University in 2002 and his Ph.D. in Chemistry in 2007 from The Ohio State University. He spent two years as a teaching postdoctoral assistant for the Ohio REEL program, an NSF-funded center that works to bring authentic research experiments into the general chemistry lab curriculum in 15 colleges and universities across the state of Ohio. In 2009, he joined the faculty of Ohio State where he currently holds the position of Senior Lecturer. In addition to lecturing on general chemistry, he served as a Faculty Fellow for the Digital First Initiative, inspiring instructors to offer engaging digital learning content to students through emerging technology. Through this initiative, he developed an iTunes U general chemistry course, which has attracted over 220,000 students from all over the world. The iTunes U course, along with the videos at www.drfus.com, are designed to supplement the text and can be used by any general chemistry student. Stoltzfus has received several teaching awards, including the inaugural Ohio State University 2013 Provost's Award for Distinguished Teaching by a Lecturer, and he is recognized as an Apple Distinguished Educator.

1

INTRODUCTION: MATTER, ENERGY, AND MEASUREMENT

▲ THE MANUFACTURE OF SYNTHETIC PIGMENTS is one of the oldest examples of industrial chemistry. The impressionist artists made extensive use of the bold colors of the newly available pigments, as exemplified in van Gogh's painting *Road with Cyprus and Star*.

WHAT'S AHEAD

1.1 ▶ The Study of Chemistry Learn what chemistry is, what atoms and molecules are, and why it is useful to study chemistry.

1.2 ▶ Classifications of Matter Examine fundamental ways to classify matter; distinguish between *pure substances* and *mixtures*, and between *elements* and *compounds*.

1.3 ▶ Properties of Matter Use *properties* to characterize, identify, and separate substances; distinguish between chemical and physical properties.

1.4 ▶ The Nature of Energy Explore the nature of energy and the forms it takes, notably kinetic energy and potential energy.

1.5 ▶ Units of Measurement Learn how numbers and units of the metric system are used in science to describe properties.

1.6 ▶ Uncertainty in Measurement and Significant Figures Use significant figures to express the inherent uncertainty in measured quantities and in calculations.

1.7 ▶ Dimensional Analysis Learn to carry numbers and units through calculations; use units to check if a calculation is correct.

The title of this book is *Chemistry: The Central Science* because much of what goes on in the world around us involves chemistry. **Chemistry** is the study of matter, its properties, and the changes that matter undergoes. As you progress in your study, you will come to see how chemical principles operate in all aspects of our daily lives, including the ways our bodies process the food that we eat, the production of energy to power our vehicles and portable electronic devices, the brilliant color changes in fall leaves, and critical issues in our environment. We will also see that the properties of substances can be tailored for specific applications by controlling their composition and structure.

This first chapter provides an overview of what chemistry is about and what chemists do. The "What's Ahead" list in this and all of the chapters gives an overview of the chapter organization and of some of the ideas we will consider.

1.1 | The Study of Chemistry

Learning Objectives

When you finish Section 1.1, you should be able to:

- Explain the concepts of matter, atoms, and molecules.
- Demonstrate how molecules and the atoms that compose them are represented by molecular models.

Chemistry is at the heart of many changes we see in the world around us, and it accounts for the different properties we see in matter. To understand how these changes and properties arise, we need to look far beneath the surfaces of our everyday observations.

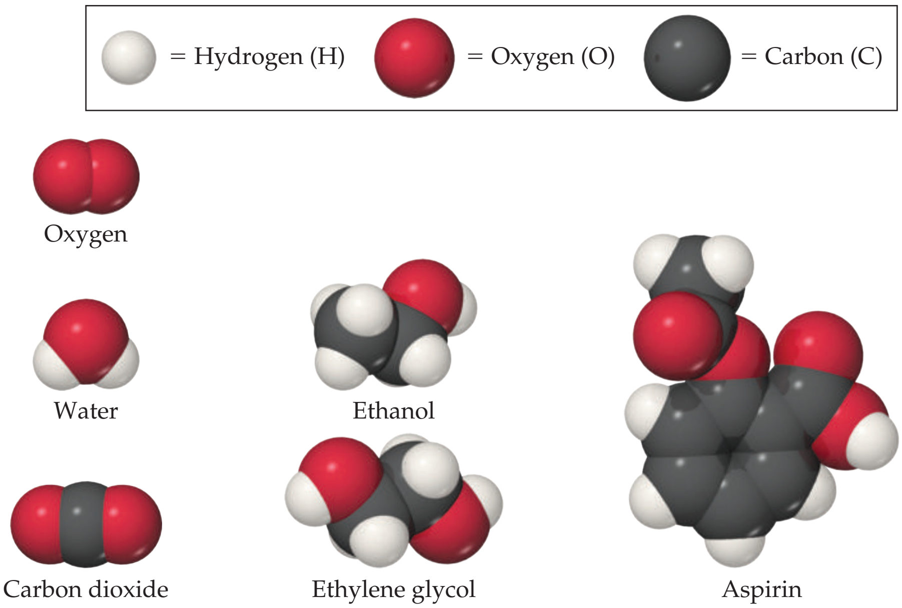
The Atomic and Molecular Perspective of Chemistry

Chemistry is the study of the properties and behavior of matter. **Matter** is the physical material of the universe; it is anything that has mass and occupies space. A **property** is any characteristic that allows us to recognize a particular type of matter and to distinguish it from other types. This book, your body, the air you are breathing, and the clothes you are wearing are all samples of matter. We observe a tremendous variety of matter in our world, but countless experiments have shown that all matter is composed of combinations of a little over 100 substances called **elements**. One of our major goals will be to relate the properties of matter to its composition—that is, to the specific elements it contains.

Chemistry also provides a background for understanding the properties of matter in terms of **atoms**, the exceedingly small building blocks of matter. Each element is composed of a unique kind of atom. We will see that the properties of matter relate to both the kinds of atoms the matter contains (*composition*) and the arrangements of these atoms (*structure*).

In a **molecule**, two or more atoms are joined in specific shapes. Throughout this text we represent molecules using colored spheres to show how the atoms are connected (Figure 1.1). The color provides a convenient way to distinguish between atoms of different elements. For example, notice that the molecules of ethanol and ethylene

Go Figure Which molecule has the most carbon atoms? How many carbon atoms does it contain?



▲ **Figure 1.1 Molecular models.** The white, black, and red spheres represent atoms of hydrogen, carbon, and oxygen, respectively.

glycol in Figure 1.1 have different compositions and structures. Ethanol contains one oxygen atom, depicted by one red sphere, whereas ethylene glycol contains two oxygen atoms.

Even apparently minor differences in the composition or structure of molecules can cause profound differences in properties. For example, ethanol and ethylene glycol (Figure 1.1) appear to be quite similar. Ethanol is the alcohol in beverages such as beer and wine, whereas ethylene glycol is a viscous liquid used as automobile antifreeze. The properties of these two substances differ in many ways, as do their biological activities. Ethanol is consumed throughout the world, but ethylene glycol is highly toxic. One of the challenges chemists undertake is to alter the composition or structure of molecules in a controlled way, creating new substances with different properties. For example, the common drug aspirin (Figure 1.1) was first synthesized in 1897 in a successful attempt to improve on a natural product extracted from willow bark that had long been used to alleviate pain.

Every change in the observable world—from boiling water to the changes that occur as our bodies combat invading viruses—has its basis in the world of atoms and molecules. Thus, as we proceed with our study of chemistry, we will find ourselves thinking in two realms: the *macroscopic* realm of ordinary-sized objects (*macro* means large) and the *submicroscopic* realm of atoms and molecules. We make our observations in the macroscopic world, but to understand that world, we must visualize how atoms and molecules behave at the submicroscopic level. Chemistry is the science that seeks to understand the properties and behavior of matter by studying the properties and behavior of atoms and molecules.

Why Study Chemistry?

Chemistry is all around us. Examples include the household chemicals used for cleaning and disinfecting that became so important during the COVID-19 pandemic (**Figure 1.2**). The chemical industry in the United States is nearly a $600 billion enterprise that employs over 500,000 people and accounts for nearly 10% of all U.S. exports.

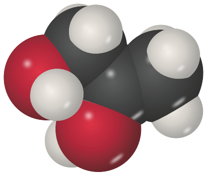
▲ **Figure 1.2 Household chemicals.** The cleansing and disinfecting properties of these household products used so extensively during the COVID-19 pandemic are due to the chemicals they contain.

Chemistry lies near the heart of many matters of public concern, such as improvement of health care, conservation of natural resources, protection of the environment, and the supply of energy needed to keep society running. Using chemistry, we have discovered and continually improved upon pharmaceuticals, fertilizers and pesticides, plastics, solar panels, light-emitting diodes (LEDs), and building materials. We have also discovered that some chemicals are harmful to our health or the environment. This means that we must be sure that the materials with which we come into contact are safe. As a citizen and consumer, it is in your best interest to understand the effects, both positive and negative, that chemicals can have—we want you to have a balanced outlook regarding their uses.

You may be studying chemistry because it is an essential part of your curriculum. Your major might be chemistry, or it could be biology, engineering, pharmacy, agriculture, geology, or some other field. Chemistry is central to a fundamental understanding of governing principles in many science-related fields. For example, our interactions with the material world raise basic questions about the materials around us. We will see that chemistry is central to most realms of modern life.

Self-Assessment Exercises

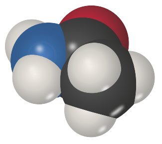
SAE 1.1 Which of the following statements is *false*? (**a**) All matter is composed of atoms of the elements. (**b**) The atoms of different elements must be different. (**c**) A molecule must contain atoms from two or more elements. (**d**) Different molecules can be made from the same elements. (**e**) Matter has mass and occupies space.



Propylene glycol

SAE 1.2 The molecule shown here is *propylene glycol*, a substance that is used extensively in the chemical industry. The color key is: White = hydrogen, red = oxygen, black = carbon. How many carbon atoms are in a molecule of propylene glycol? (**a**) 2 (**b**) 3 (**c**) 5 (**d**) 8 (**e**) 13

SAE 1.3 The molecule shown here is called *acetamide*. How many different elements and how many atoms are in a molecule of acetamide? (**a**) 3 elements, 4 atoms (**b**) 3 elements, 9 atoms (**c**) 4 elements, 4 atoms (**d**) 4 elements, 9 atoms (**e**) There is not enough information to answer the question.



Acetamide

1.2 | Classifications of Matter

Learning Objectives

When you finish Section 1.2, you should be able to:

- Compare and contrast the different states of matter: solid, liquid, and gas.
- Distinguish among elements, compounds, and mixtures.
- Identify the atomic symbols of common elements.

As we progress through this text, we will continue to learn more about the properties of matter and how the atoms and elements that comprise matter affect those properties. Let's begin our study of chemistry by examining two fundamental ways in which matter is classified. Matter is typically characterized by its physical state (gas, liquid, or solid) and its composition (whether it is an element, a *compound*, or a *mixture*).

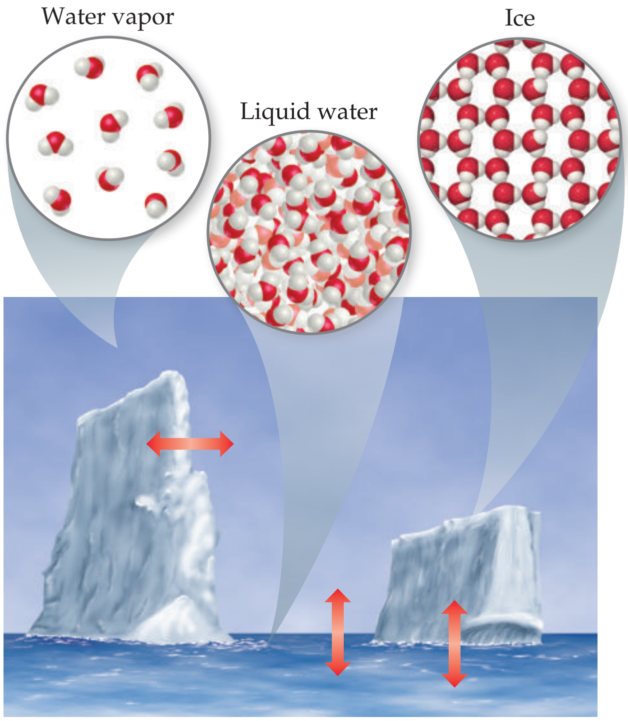
States of Matter

Think about what happens when liquid water freezes into ice. Both liquid water and ice consist of molecules of water, and yet we know there is a difference between them—one is liquid and one is solid. A sample of matter can be a gas, a liquid, or a solid. These three forms, called the **states of matter**, differ in some of their observable properties.

- A **gas** (also known as vapor) has no fixed volume or shape; rather, it uniformly fills its container. A gas can be compressed to occupy a smaller volume, or it can expand to occupy a larger one.
- A **liquid** has a distinct volume independent of its container, assumes the shape of the portion of the container it occupies, and is not easily compressed.
- A **solid** has both a definite shape and a definite volume and is not easily compressed.

The properties of the states of matter can be understood on the molecular level (Figure 1.3). In a gas, the molecules are far apart and moving at high speeds, colliding repeatedly with one another and with the walls of the container. Compressing a gas decreases the amount of space between molecules and increases the frequency of collisions between molecules but does not alter the size or shape of the molecules. In a liquid, the molecules are packed closely together but still move rapidly. The rapid movement allows the molecules to slide over one another; thus, a liquid pours easily. In a solid, the molecules are held tightly together, usually in definite arrangements in which the molecules can wiggle only slightly in their otherwise fixed positions. Thus, the distances between molecules are similar in the liquid and solid states, but while the molecules are for the most part locked in place in a solid, they retain considerable freedom of motion in a liquid. Changes in temperature and/or pressure can convert one state of matter to another, illustrated by such familiar processes as ice melting or water vapor condensing. We discuss these conversions from one state to another in greater detail in Chapter 11.

Go Figure In which form of water are the water molecules farthest apart?



▲ **Figure 1.3 The three physical states of water—water vapor, liquid water, and ice.** We can see the liquid and solid states but not the gas (vapor) state. The red arrows show that the three states of matter can interconvert.

Pure Substances

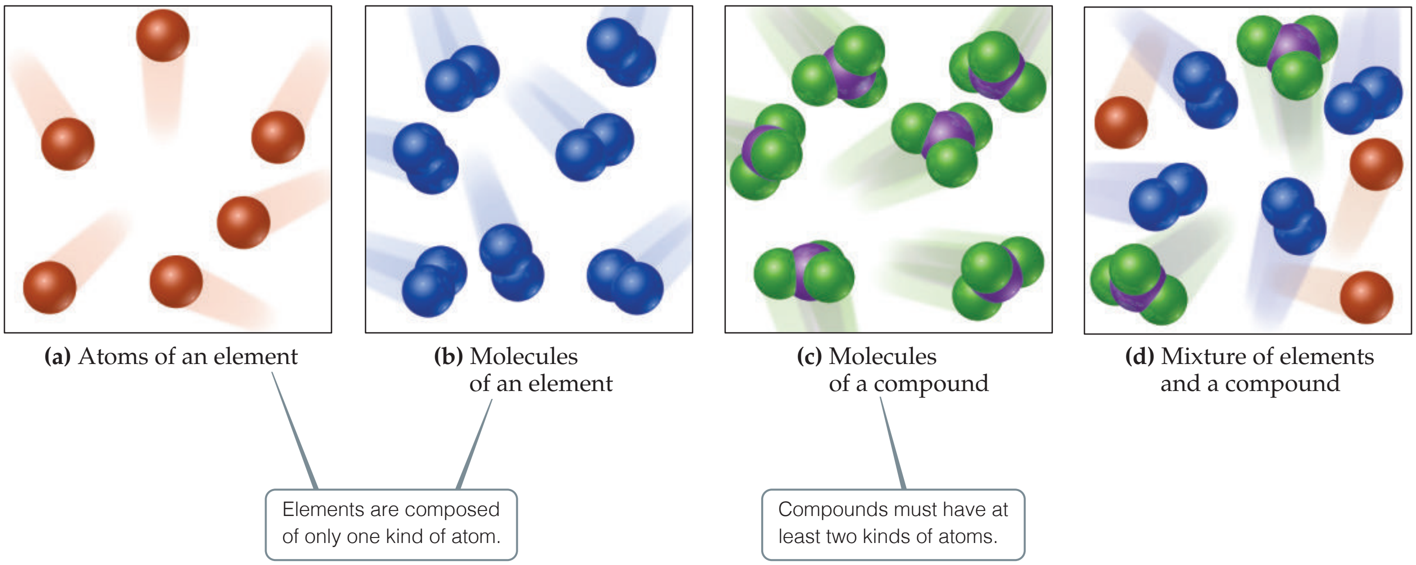
Most forms of matter we encounter—the air we breathe (a gas), the gasoline we burn in our cars (a liquid), and the sidewalk we walk on (a solid)—are not chemically pure. We can, however, separate these forms of matter into pure substances. A **pure substance** (usually referred to simply as a *substance*) is matter that has distinct properties and a composition that does not vary from sample to sample. Water and table salt (sodium chloride) are examples of pure substances.

All substances are either elements or compounds.

- *Elements* are substances that cannot be decomposed into simpler substances. On the molecular level, each element is composed of only one kind of atom [Figure 1.4(**a**) and (**b**)].
- **Compounds** are substances composed of two or more elements; they contain two or more kinds of atoms [Figure 1.4(**c**)]. Water, for example, is a compound composed of two elements: hydrogen and oxygen.

Figure 1.4(**d**) shows a mixture of substances. **Mixtures** are combinations of two or more substances in which each substance retains its chemical identity.

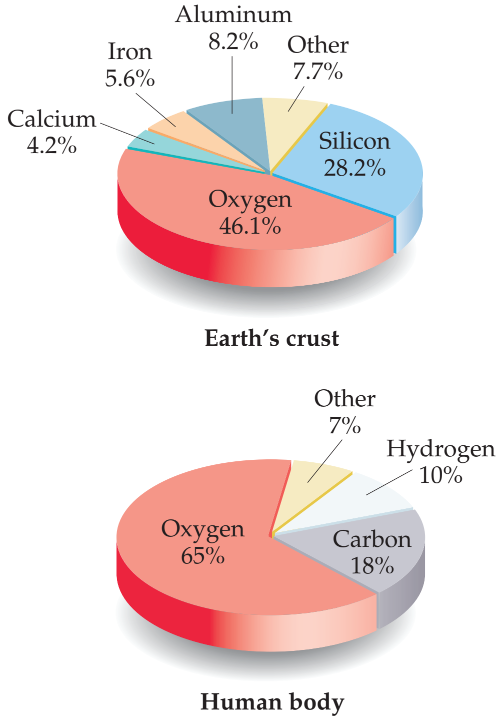
Go Figure How do the molecules of a compound differ from the molecules of an element?



▲ **Figure 1.4 Molecular comparison of elements, compounds, and mixtures.**

Go Figure

If the lower pie chart were drawn as the percentage in terms of number of atoms rather than the percentage in terms of mass, would the hydrogen slice of the pie get larger or smaller?



▲ **Figure 1.5 Relative abundances of elements.*** Elements in percent by mass in Earth's crust and in the human body.

TABLE 1.1 Some Common Elements and Their Symbols

Carbon	C	Aluminum	Al	Copper	Cu (from cuprum)
Fluorine	F	Bromine	Br	Iron	Fe (from ferrum)
Hydrogen	H	Calcium	Ca	Lead	Pb (from plumbum)
Iodine	I	Chlorine	Cl	Mercury	Hg (from hydrargyrum)
Nitrogen	N	Helium	He	Potassium	K (from kalium)
Oxygen	O	Lithium	Li	Silver	Ag (from argentum)
Phosphorus	P	Magnesium	Mg	Sodium	Na (from natrium)
Sulfur	S	Silicon	Si	Tin	Sn (from stannum)

Elements

Currently, 118 elements are known, though they vary widely in abundance. Hydrogen constitutes about 74% of the mass in the Milky Way galaxy, and helium constitutes 24%. Closer to home, only five elements—oxygen, silicon, aluminum, iron, and calcium—account for over 90% of the mass of Earth's crust, and only three—oxygen, carbon, and hydrogen—account for over 90% of the mass of the human body (**Figure 1.5**).

Table 1.1 lists some common elements, along with the chemical *symbols* used to denote them. The symbol for each element consists of one or two letters, with the first letter capitalized. These symbols are derived mostly from the English names of the elements, but sometimes they are derived from a foreign name instead (see the last column in Table 1.1). You will need to know these symbols and learn others as we encounter them in the text.

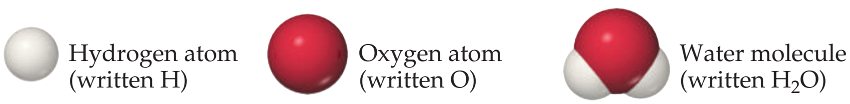
All of the known elements and their symbols are listed on the front inside cover of this text in a table known as the *periodic table*. In the periodic table, the elements are arranged in columns so that closely related elements are grouped together. We describe the periodic table in more detail in Section 2.5 and consider the periodically repeating properties of the elements in Chapter 7.

Compounds

Most elements can interact with other elements to form compounds. For example, when hydrogen gas burns in oxygen gas, the elements hydrogen and oxygen combine to form the compound water. Because each molecule of water contains two hydrogen atoms and one oxygen atom, we denote the molecule as H_2O. The subscript 2 indicates that there are two H atoms in the molecule. When there is only one atom of an element in a molecule, as is the case for O in water, we do not explicitly use the subscript 1.

Water can be decomposed back into its elements by passing an electrical current through it (**Figure 1.6**).

Decomposing pure water into its constituent elements shows that it contains 11% hydrogen and 89% oxygen by mass, regardless of its source. This ratio is constant because every water molecule is composed of two hydrogen atoms and one oxygen atom:

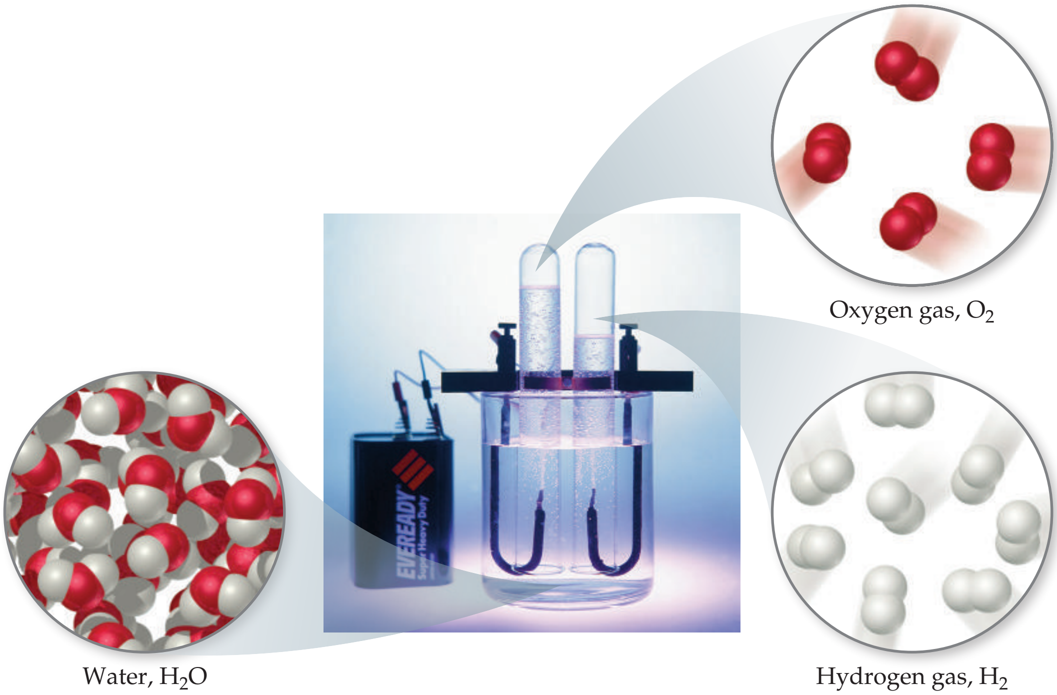


The amount of oxygen by mass is greater than the amount of hydrogen by mass because oxygen atoms are heavier than hydrogen atoms.

CRC Handbook of Chemistry and Physics, 97th ed. (2016–2017), pp. 14–17.

Go Figure

Is the volume of H_2 produced larger than the volume of O_2 produced because (**a**) hydrogen atoms are lighter than oxygen atoms, (**b**) hydrogen atoms are larger than oxygen atoms, or (**c**) each water molecule contains one oxygen atom and two hydrogen atoms?



▲ **Figure 1.6** **Electrolysis of water.** Water decomposes into its component elements, hydrogen and oxygen, when an electrical current is passed through it. The volume of hydrogen, collected in the right test tube, is twice the volume of oxygen.

The elements hydrogen and oxygen themselves exist naturally as *diatomic* (two-atom) molecules:

Oxygen molecule  (written O_2)

Hydrogen molecule  (written H_2)

As seen in **Table 1.2**, the properties of water bear no resemblance to the properties of its component elements. Hydrogen, oxygen, and water are each a unique substance, a consequence of the uniqueness of their respective molecules.

TABLE 1.2 Comparison of Water, Hydrogen, and Oxygen

	Water	Hydrogen	Oxygen
State[a]	Liquid	Gas	Gas
Normal boiling point	100 °C	−253 °C	−183 °C
Density[a]	1000 g/L	0.084 g/L	1.33 g/L
Flammable	No	Yes	No

[a]At room temperature and atmospheric pressure.

The observation that the elemental composition of a compound is always the same is known as the **law of constant composition** (or the **law of definite proportions**). French chemist Joseph Louis Proust (1754–1826) first stated the law in about 1800. Although this law has been known for 200 years, the belief persists among some people that a fundamental difference exists between compounds prepared in the laboratory and the corresponding compounds found in nature. This simply is not true. Regardless of its source—nature or a laboratory—a pure compound has the same composition and properties under the same conditions. Both chemists and nature must use the same elements and operate under the same natural laws. When two materials differ in composition or properties, either they are composed of different compounds or they differ in purity.

Mixtures

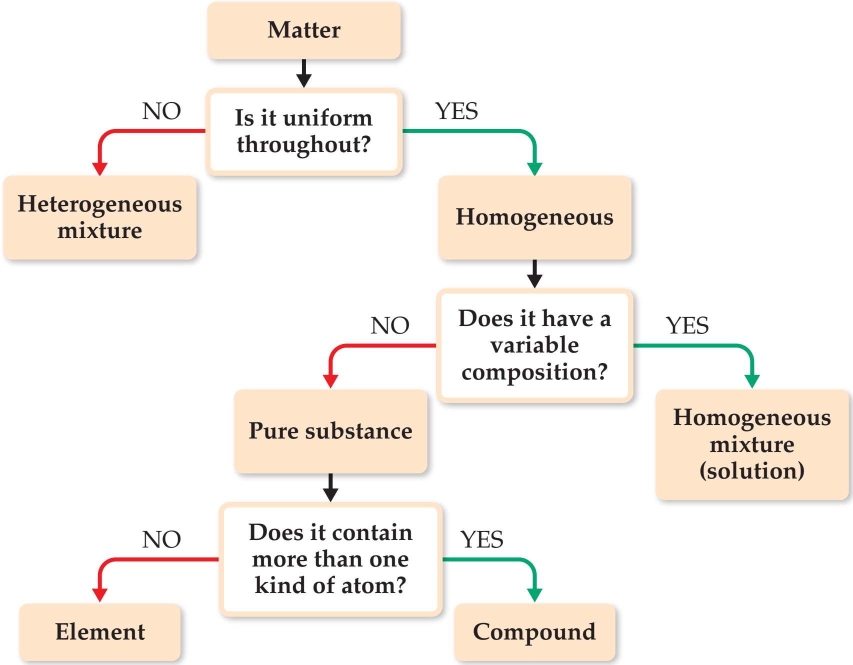
Most of the matter we encounter consists of mixtures of different substances. Each substance in a mixture retains its chemical identity and properties. In contrast to a pure substance, which by definition has a fixed composition, the composition of a mixture can vary. A cup of sweetened coffee, for example, can contain either a little sugar or a lot. The substances making up a mixture are called *components* of the mixture.

Some mixtures do not have the same composition, properties, and appearance throughout. Rocks and wood, for example, vary in texture and appearance in any typical sample. Such mixtures are *heterogeneous* [Figure 1.7(**a**)]. Mixtures that are uniform throughout are *homogeneous*. Air is a homogeneous mixture of nitrogen, oxygen, and smaller amounts of other gases. The nitrogen in air has all the properties of pure nitrogen because both the pure substance and the mixture contain the same nitrogen molecules. Salt, sugar, and many other substances dissolve in water to form homogeneous mixtures [Figure 1.7(**b**)]. Homogeneous mixtures are also called **solutions**. Although the term *solution* conjures up an image of a liquid, solutions can be solids, liquids, or gases.

In Figure 1.8 we summarize the classification of matter into elements, compounds, and mixtures. You should be comfortable in classifying substances among these three categories.

(a) (b)

▲ **Figure 1.7 Mixtures.** (a) Many common materials, including rocks, are heterogeneous mixtures. This photograph of granite shows a heterogeneous mixture of silicon dioxide and other metal oxides. (b) Homogeneous mixtures are called solutions. Many substances, including the blue solid shown here [copper(II) sulfate pentahydrate], dissolve in water to form solutions.



◀ **Figure 1.8 Classification of matter.** All pure matter is classified ultimately as either an element or a compound.

Sample Exercise 1.1

Distinguishing among Elements, Compounds, and Mixtures

Classify each of the following as an element, a compound, a homogeneous mixture, or a heterogeneous mixture: (**a**) molten iron; (**b**) a chocolate chip cookie; (**c**) a container of pure ethylene glycol (see Figure 1.1); (**d**) a cup of water with a teaspoon of sugar dissolved in it.

SOLUTION

We can follow the flowchart in Figure 1.8 to classify each substance: (**a**) Molten iron is simply iron heated to the point at which it melts into a liquid. It still contains only iron atoms and is therefore a pure substance that is an element. (**b**) A cookie contains several different substances in different amounts. It is not uniform throughout and is therefore a heterogeneous mixture. (**c**) As seen in Figure 1.1, an ethylene glycol molecule contains C, H, and O atoms. The sample of pure ethylene glycol is therefore a pure substance that is a compound. (**d**) The sugar water that results from dissolving sugar in water has the same composition throughout. It is a homogeneous mixture, also known as a solution.

▶ Practice Exercise

"White gold" contains gold and a "white" metal, such as palladium. Two samples of white gold differ in the relative amounts of gold and palladium they contain. Both samples are uniform in composition throughout. Use Figure 1.8 to classify white gold.

Self-Assessment Exercises

SAE 1.4 Which of the following processes is best described as a liquid turning into a gas? (**a**) snow melting (**b**) molten metal hardening upon cooling (**c**) rubbing alcohol evaporating from your skin (**d**) steam condensing on a cold surface (**e**) dry ice, which is frozen CO_2, evaporating

SAE 1.5 Which of the following characterizations is *incorrect*? (**a**) Chicken noodle soup is a heterogeneous mixture. (**b**) Aspirin is composed of 60.0% carbon, 4.5% hydrogen, and 35.5% oxygen by mass, regardless of its source. Aspirin is a compound. (**c**) The tanks that scuba divers use contain nitrogen and oxygen gas. The tanks contain a homogeneous mixture. (**d**) Yellow sulfur consists of molecules that contain eight-membered rings of sulfur atoms. Yellow sulfur is a compound. (**e**) The graphite in lead pencils consists entirely of sheets of carbon atoms. Graphite is a form of an element.

SAE 1.6 The compound called *heme* is present in red blood cells. Heme contains carbon, hydrogen, iron, nitrogen, and oxygen. Which of the following is the correct list of the symbols of the elements in a heme molecule? (**a**) Ca, Hy, Ir, Ni, Ox (**b**) C, H, Fe, N, O (**c**) C, H, I, N, O (**d**) C, H_2, Fe, N_2, O_2

SAE 1.7 A certain material has a fixed composition of S and Cl atoms regardless of its source. Which of the following statements about the material is *true*? (**a**) The material is a homogeneous mixture. (**b**) The material contains atoms of silicon and chlorine. (**c**) The material must contain equal numbers of S and Cl atoms. (**d**) The material is a heterogeneous mixture. (**e**) The material is a compound that contains two elements.

1.3 | Properties of Matter

Learning Objectives

When you finish Section 1.3, you should be able to:

- Distinguish between chemical and physical properties, and between intensive and extensive properties.
- Differentiate between chemical and physical changes.
- Describe how filtration, distillation, and chromatography can be used to separate mixtures of substances.

Every substance has unique properties. For example, the properties listed in Table 1.2 allow us to distinguish hydrogen, oxygen, and water from one another. The properties of a substance include everything that describes the substance, such as its color, its physical state, its mass, its ability to react with other substances, and numerous other characteristics. In this section, we look more closely at the types of properties that we typically use in describing substances

Types of Properties of Substances

The properties of matter can be categorized as physical or chemical. **Physical properties** can be observed without changing the identity and composition of the substance. These properties include color, odor, density, melting point, boiling point, and hardness. **Chemical properties** describe the way a substance may change, or *react*, to form other substances. A common chemical property is flammability, the ability of a substance to burn in the presence of oxygen.

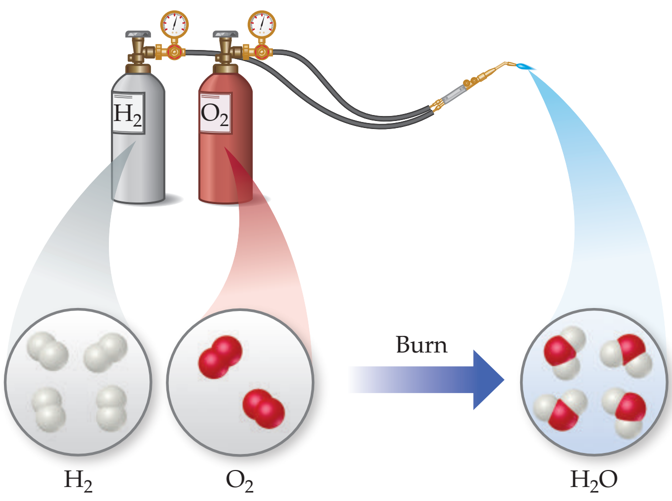
The properties of substances are further separated into two categories depending on whether the property depends on how much of the substance is being considered. Some properties, such as temperature and melting point, are *intensive properties*. **Intensive properties** do *not* depend on the amount of sample being examined and are particularly useful in chemistry because many intensive properties can be used to *identify* substances. **Extensive properties**, such as mass and volume, depend on the amount of sample. Extensive properties relate to the *amount* of substance present.

Physical and Chemical Changes

The changes substances undergo are either physical or chemical. During a **physical change**, a substance changes its physical appearance but not its composition: It is the same substance before and after the change. The evaporation of water is a physical change. When water evaporates, it changes from the liquid state to the gas state, but it is still composed of water molecules, as depicted in Figure 1.3. All **changes of state** (for example, from liquid to gas or from liquid to solid) are physical changes.

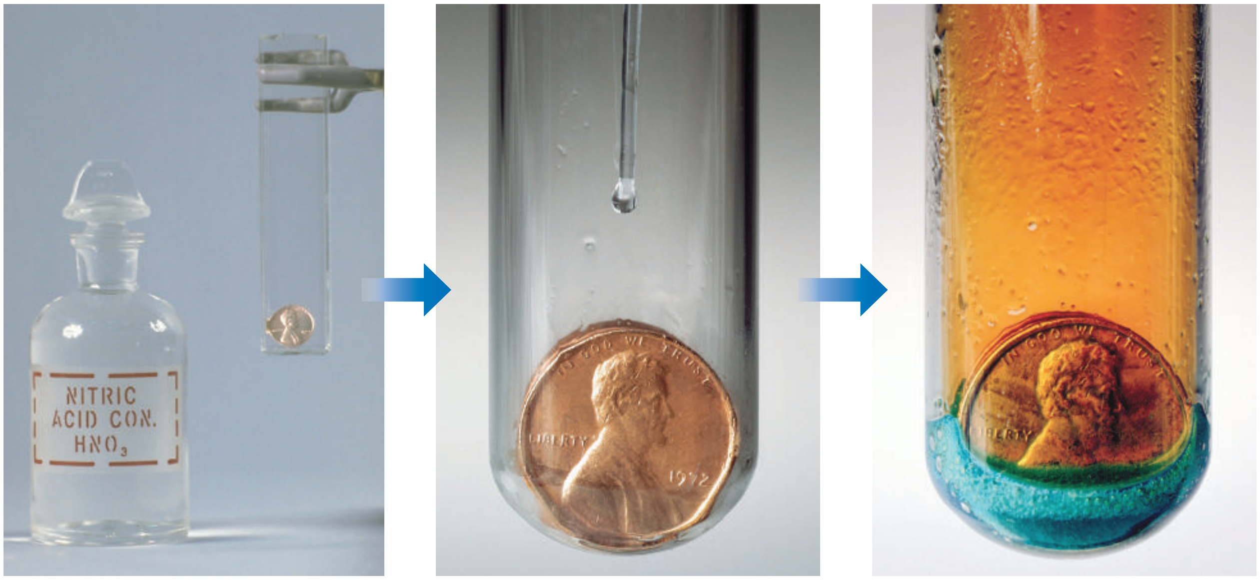
In a **chemical change** (also called a **chemical reaction**), a substance is transformed into a chemically different substance. When hydrogen burns in air, for example, it undergoes a chemical change because it combines with oxygen to form water (**Figure 1.9**).

Chemical changes can be dramatic. In the account given in **Figure 1.10**, Ira Remsen (1846–1927), author of a popular chemistry text, describes his first experiences with chemical reactions.



▲ **Figure 1.9 A chemical reaction.**

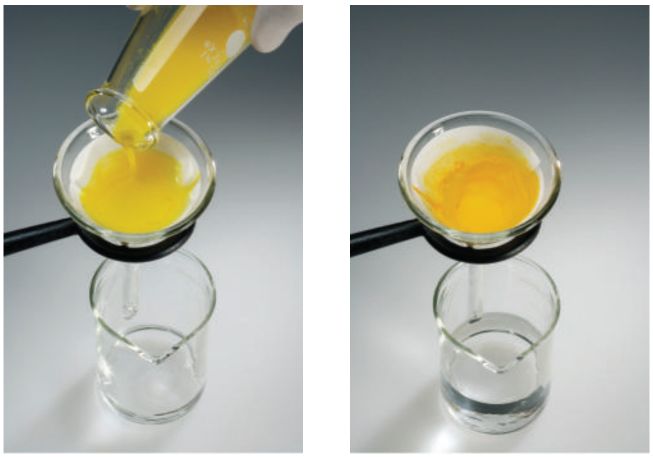
> While reading a textbook of chemistry, I came upon the statement "nitric acid acts upon copper," and I determined to see what this meant. Having located some nitric acid, I had only to learn what the words "act upon" meant. In the interest of knowledge I was even willing to sacrifice one of the few copper cents then in my possession. I put one of them on the table, opened a bottle labeled "nitric acid," poured some of the liquid on the copper, and prepared to make an observation. But what was this wonderful thing which I beheld? The cent was already changed, and it was no small change either. A greenish-blue liquid foamed and fumed over the cent and over the table. The air became colored dark red. How could I stop this? I tried by picking the cent up and throwing it out the window. I learned another fact: nitric acid acts upon fingers. The pain led to another unpremeditated experiment. I drew my fingers across my trousers and discovered nitric acid acts upon trousers. That was the most impressive experiment I have ever performed. I tell of it even now with interest. It was a revelation to me. Plainly the only way to learn about such remarkable kinds of action is to see the results, to experiment, to work in the laboratory.



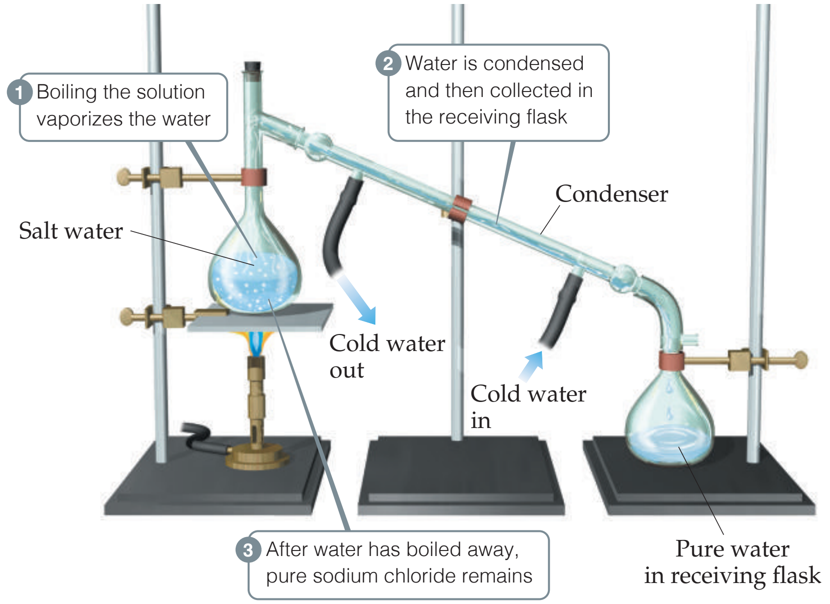
▲ **Figure 1.10** **The chemical reaction between a copper penny and nitric acid.** The dissolved copper produces the blue-green solution; the reddish-brown gas produced is nitrogen dioxide.

Separation of Mixtures

We can separate a mixture into its components by taking advantage of differences in their properties. For example, a heterogeneous mixture of iron filings and gold filings could be sorted by color into iron and gold. A less tedious approach would be to use a magnet to attract the iron filings, leaving the gold ones behind. We can also take advantage of an important chemical difference between these two metals: Many acids dissolve iron but not gold. Thus, if we put our mixture into an appropriate acid, the acid would dissolve the iron and the solid gold would be left behind. The two could then be separated by **filtration** (Figure 1.11). We would have to use other chemical reactions, which we describe later, to transform the dissolved iron back into metal.



◀ **Figure 1.11** **Separation by filtration.** A mixture of a solid and a liquid is poured through filter paper. The liquid passes through the paper while the solid remains on the paper.

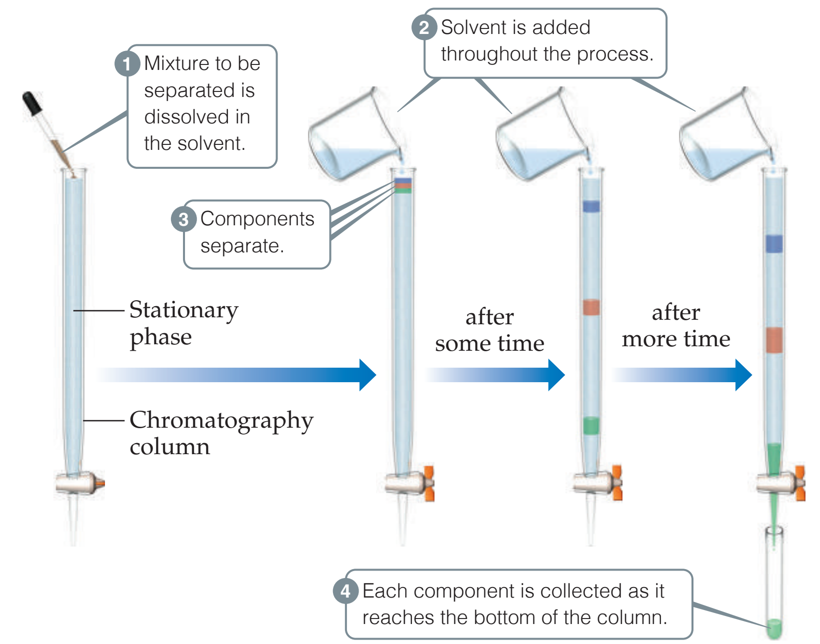


▶ **Figure 1.12 Distillation.** Apparatus for separating a sodium chloride solution (salt water) into its components.

An important method of separating the components of a homogeneous mixture is **distillation**, a process that depends on the different abilities of substances to form gases. For example, if we boil a solution of salt and water, the water evaporates, forming a gas, and the salt is left behind. The gaseous water can be converted back to a liquid on the walls of a condenser, as shown in **Figure 1.12**.

The differing abilities of substances to adhere to the surfaces of solids can also be used to separate mixtures. For example, a mixture of substances can be separated by placing a sample of the mixture at the top of a column filled with a porous solid, as shown in **Figure 1.13**. When a suitable solvent is added to the top of the column, the mixture separates into its different components. This separation technique is called **chromatography** (literally "the writing of colors").

Go Figure Is the separation of the mixture shown here a physical or chemical process?



▲ **Figure 1.13 Separation of three substances using column chromatography.**

Self-Assessment Exercises

SAE 1.8 Imagine you have a gallon of the substance called *methanol*. Under usual conditions, methanol is a flammable colorless liquid. Which of the following statements about the properties of methanol is *correct*? (**a**) The fact that methanol is colorless is a chemical property. (**b**) The mass of the gallon of methanol is an intensive property. (**c**) The fact that methanol is flammable is a physical property. (**d**) The temperature at which the methanol freezes is an intensive property.

SAE 1.9 Each of the following describes either a physical change or a chemical change of a substance:

(**i**) An iron nail rusts when exposed to damp air.
(**ii**) Water vapor condenses on a cold window to form frost.
(**iii**) Plants make sugar from carbon dioxide and water.

Which of these processes are *chemical* changes? (**a**) Only one of the three is a chemical change (**b**) i and ii (**c**) i and iii (**d**) ii and iii (**e**) All three are chemical changes.

SAE 1.10 Which of the following statements about separation techniques is *incorrect*? (**a**) Filtration can be used to separate a solid substance from a liquid. (**b**) Distillation is a technique that depends on the differences in the evaporation of different substances. (**c**) Solid A dissolves in water and solid B does not dissolve in water. After adding a mixture of the two solids to water, filtration would be an effective way of separating a mixture of solids A and B. (**d**) Chromatography is a technique that depends on the differences in the rate of travel of different substances through a solid medium. (**e**) Chromatography can be used to separate a compound into its elements.

1.4 | The Nature of Energy

Learning Objectives

When you finish Section 1.4, you should be able to:

- Describe the concepts of *energy*, *work*, and *heat.*
- Distinguish between *kinetic* and *potential* energy.

All objects in the universe are made of matter, but matter alone is not enough to describe the behavior of the world around us. The water in an alpine lake and a pot of boiling water are both made from the same substance, but your body will experience a very different sensation if you put your hand in each. The difference between the two is their energy content; boiling water has more energy than chilled water. To understand chemistry, we must also understand energy and the changes in energy that accompany chemical processes.

Work and Heat

Unlike matter, energy does not have mass and cannot be held in our hands, but its effects can be observed and measured. **Energy** is defined as *the capacity to do work or transfer heat*. Both work and heat are means by which energy is transferred from one object to another. **Work** is *the energy transferred when a force exerted on an object causes a displacement of that object*. **Heat** is *the energy transferred to cause the temperature of an object to increase*. The concepts of work and heat are illustrated in the examples shown in **Figure 1.14**.

Although the temperature of an object is intuitive to most people, the definition of work is less apparent. We define work, w, as the product of the force exerted on the object, F, and the distance, d, that it moves:

$$w = F \times d \qquad [1.1]$$

The **force** F is defined as any push or pull exerted on the object.* Familiar examples include gravity and the attraction between opposite poles of a bar magnet. It takes work to lift an object off of the floor or to pull apart two magnets that have come together at the opposite poles. When you type on a keyboard, you are doing work on the keys as they are displaced by the force of your fingers.

Kinetic Energy and Potential Energy

To understand energy, we need to grasp its two fundamental forms, kinetic energy and potential energy. Objects, whether they are automobiles, baseballs, or molecules, can

*In using this equation, only the component of the force that is acting in the same direction as the distance traveled is used. That will generally be the case for problems we will encounter in this chapter.

possess **kinetic energy**, the energy of *motion*. The magnitude of the kinetic energy, E_k, of an object depends on its mass, m, and velocity, v:

$$E_k = \frac{1}{2}mv^2 \quad [1.2]$$

Thus, the kinetic energy of an object increases as its velocity or speed* increases. For example, a car has greater kinetic energy moving at 65 miles per hour (mi/h) than it does at 25 mi/h. For a given velocity, the kinetic energy increases with increasing mass. Thus, a large truck traveling at 65 mi/h has greater kinetic energy than a motorcycle traveling at the same velocity because the truck has the greater mass.

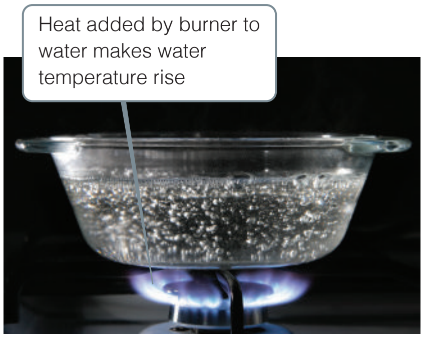
In chemistry, we are interested in the kinetic energy of atoms and molecules. Although these particles are too small to be seen, they have mass and are in motion, so they possess kinetic energy. When a substance is heated, be it a pot of water on the stove or a metal bench sitting in the Sun, the atoms and molecules in that substance gain kinetic energy and their average speed increases. Hence, we see that the transfer of heat is simply the transfer of kinetic energy at the molecular level. We return to this concept in later chapters of the book.

All other forms of energy—the energy stored in a stretched spring, in a weight held above your head, or in a chemical bond—are classified as potential energy. An object has **potential energy** by virtue of its position relative to other objects. Potential energy is, in essence, the "stored" energy that arises from the attractions and repulsions an object experiences in relation to other objects.

We are familiar with many instances in which potential energy is converted into kinetic energy. For example, think of a cyclist poised at the top of a hill (**Figure 1.15**). Because of the attractive force of gravity, the gravitational potential energy of the bicycle is greater at the top of the hill than at the bottom. As a result, the bicycle easily rolls down the hill with increasing speed. As it does so, gravitational potential energy is converted into kinetic energy. The gravitational potential energy decreases as the bicycle rolls down the hill, while at the same time its kinetic energy increases as it picks up speed (Equation 1.2). This example illustrates that kinetic and potential energy are interconvertible.

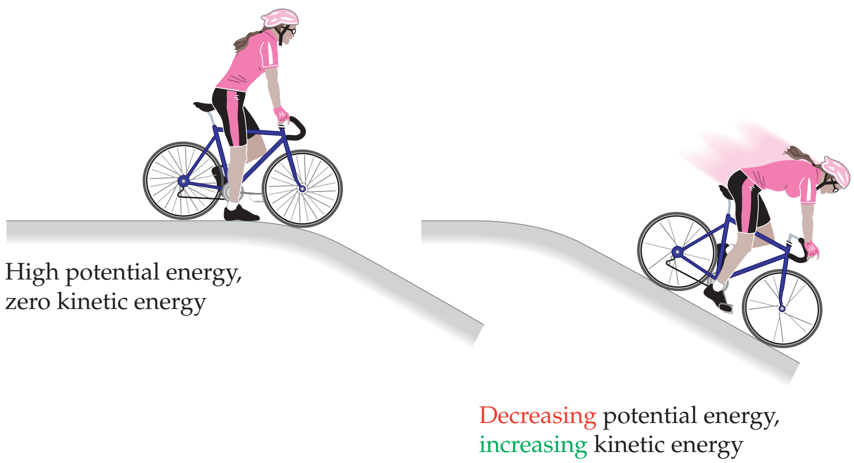
Gravitational forces play a negligible role in the ways that atoms and molecules interact with one another. Forces that arise from electrical charges are more important when dealing with atoms and molecules. One of the most important forms of potential

(a)



(b)

▲ **Figure 1.14** **Work and heat, two forms of energy.** (**a**) *Work* is energy used to cause an object to move against an opposing force. (**b**) *Heat* is energy used to increase the temperature of an object.



▲ **Figure 1.15** **Potential energy and kinetic energy.** The potential energy initially stored in the motionless bicycle and rider at the top of the hill is converted to kinetic energy as the bicycle moves down the hill and loses potential energy.

---

*Strictly speaking, velocity is a *vector* quantity that has a direction—that is, it tells you how fast an object is moving and in what direction. Speed is a *scalar* quantity that tells you how fast an object is moving but not the direction of the motion. Unless otherwise stated, we will not be concerned with the direction of motion, so velocity and speed are used interchangeably in this book.

energy in chemistry is *electrostatic potential energy*, which arises from the interactions between charged particles. Opposite charges attract each other, whereas like charges repel. The strength of this interaction increases as the magnitudes of the charges increase, and it decreases as the distance between charges increases. We return to electrostatic energy several times throughout the book.

One of our goals in chemistry is to relate the energy changes seen in the macroscopic world to the kinetic or potential energy of substances at the molecular level. Many substances, fuels for example, release energy when they react. The *chemical energy* of a fuel is due to the potential energy stored in the arrangements of its atoms. As we explain in later chapters, *chemical energy is released when bonds between atoms are formed, and it is consumed when bonds between atoms are broken*. When a fuel burns, some bonds are broken and others are formed, but the net effect is to convert chemical potential energy to thermal energy, the energy associated with temperature.

Self-Assessment Exercises

SAE 1.11 Which of the following statements about energy, work, and heat is *false*? (**a**) Energy can be classified into two fundamental forms: kinetic energy and potential energy. (**b**) Heat is energy transferred to increase the temperature of an object. (**c**) Energy is the capacity to do work or transfer heat. (**d**) Work causes the displacement of an object. (**e**) Energy has mass and occupies space.

SAE 1.12 A rocket takes off from the surface of Earth and accelerates into the sky. Which of the following correctly describes the changes in the kinetic and gravitational potential energy of the rocket as it takes off? (**a**) Its kinetic energy decreases and its gravitational potential energy decreases. (**b**) Its kinetic energy increases and its gravitational potential energy decreases. (**c**) Its kinetic energy decreases and its gravitational potential energy increases. (**d**) Its kinetic energy increases and its gravitational potential energy increases. (**e**) The kinetic and gravitational potential energies of the rocket are unchanged.

SAE 1.13 Consider the following three vehicles in motion:

(**i**) A compact car that weighs 2000 pounds and is traveling at 40 miles per hour.
(**ii**) A medium-sized car that weighs 3000 pounds and is traveling at 40 miles per hour.
(**iii**) A truck that weighs 4000 pounds and is traveling at 20 miles per hour.

Which of the following is the correct ordering of the vehicles from smallest to largest kinetic energy? (**a**) iii < i < ii (**b**) i < ii < iii (**c**) i = iii < ii (**d**) i < iii < ii (**e**) ii < iii = i

CHEMISTRY AND SUSTAINABILITY An Introduction

As the global population grows, we continue to consume Earth's resources and put strains on the capacity of the human race to provide essential needs to sustain its existence. The notion of *sustainability* is used to describe the intersection of economic, social, and environmental factors to determine the best ways in which we can exist on Earth while being responsible stewards of it.

In 1991, the World Conservation Union, the United Nations Environment Programme, and the World Wildlife Fund for Nature published a report entitled "Caring for the Earth: A Strategy for Sustainable Living."* In this report, they proposed a set of principles for a sustainable society, which began with the following sentences: "Living sustainably depends on accepting a duty to seek harmony with other people and with nature. The guiding rules are that people must share with each other and care for the Earth. Humanity must take no more from nature than nature can replenish." These guiding principles have become increasingly relevant in a world that is subject to greater climate change, food shortages, increasing scarcity of clean water, and global pandemics.

Undeniably, some applications of chemistry have had negative impacts on sustainability, such as industrial chemical spills, the use of chemical substances that were later found to be toxic, and the generation of chemical waste as technology has advanced. However, chemistry has also had some of the most positive effects in increasing the sustainability of our world. It promises even more as we head to the future.

Sustainability entails more than scientific and technological advances. In 2016, the United Nations introduced its 17 Sustainable Development Goals (**Figure 1.16**). These far-reaching goals address important issues of social justice and global economic issues. Chemistry, as the central science, has the capacity to improve global conditions in many of these important areas and will therefore have a major role in achieving these ambitious goals.

In this edition of our textbook, we are introducing a new set of feature boxes entitled "Chemistry and Sustainability." In these boxes, we highlight some of the ways in which applications of chemistry and related fields (such as chemical engineering and materials science) are making ours a more sustainable planet. We also present some of the new developments that promise to enhance sustainability in the near future. Many of you who are students of chemistry now will likely end up as practitioners of the chemical sciences and may very well end up working on these exciting new discoveries that make ours a better, and more sustainable, world. We hope you find these examples both instructive and inspiring.

Related Exercises: 1.41, 1.91

Continued

*David Munro and Martin Holdgate, eds. 1991. "Caring for the Earth: A Strategy for Sustainable Living," Gland, CH: International Union for the Conservation of Nature, United Nations Environmental Program, and World Wide Fund for Nature. Available at https://portals.iucn.org/library/node/6439.

▲ **Figure 1.16 The 17 UN Sustainable Development Goals.** In 2016, the United Nations proposed 17 goals for global sustainable development that span social, economic, and environmental issues. The UN has challenged the world to achieve these goals by 2030: https://www.un.org/sustainabledevelopment/sustainable-development-goals.

1.5 | Units of Measurement

Learning Objectives

When you finish Section 1.5, you should be able to:

- Identify the seven base units and the common prefixes used in the *metric system.*
- Convert temperatures between the Fahrenheit, Celsius, and Kelvin scales.
- Distinguish metric base units from derived units, such as volume.
- Interconvert among mass, volume, and density, given two of the three quantities.
- Calculate energy quantities in joules.

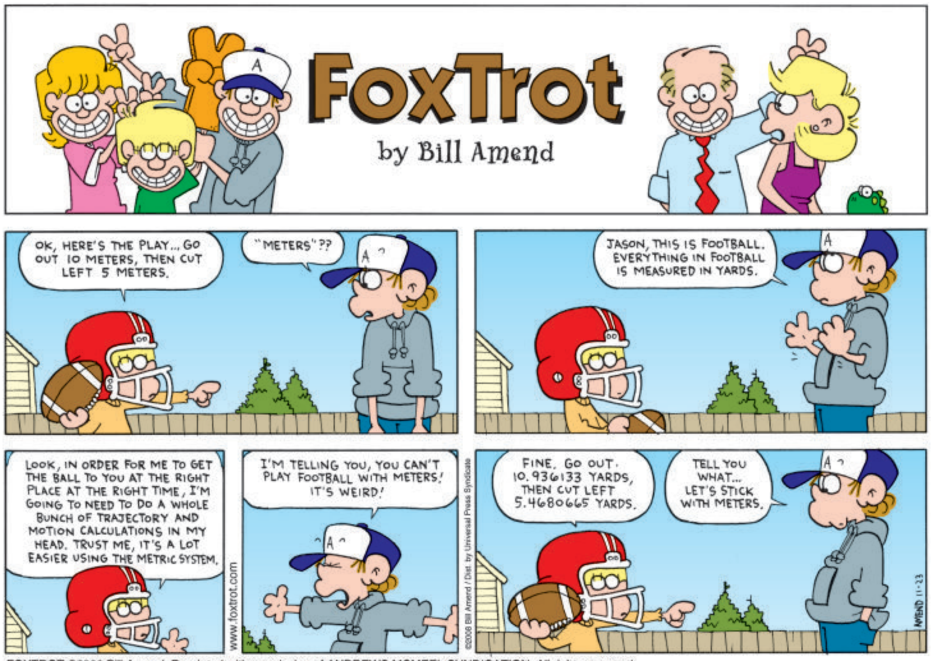
Many properties of matter are *quantitative;* that is, they are associated with numbers. When a number represents a measured quantity, the units of that quantity must be specified. To say that the length of a pencil is 17.5 is meaningless. Expressing the number with its units, 17.5 centimeters (cm), properly specifies the length. In this section, we look more closely at the units we use for measurement in science.

The Metric System and SI Units

The units used for scientific measurements are those of the **metric system**, developed in France during the late eighteenth century. Most countries use the metric system as their system of measurement. The United States has traditionally used the English system, although use of the metric system has become more common (Figure 1.17).

In 1960, an international agreement was reached specifying a particular choice of metric units for use in scientific measurements. These preferred units are called **SI units**, after the French *Système International d'Unités*. This system has seven *base units* from which all other units are derived (Table 1.3). In this chapter , we discuss the SI base units for length, mass, and temperature. The SI units for other measures, such as volume, can be derived from these fundamental base units.

With SI units, prefixes are used to indicate decimal fractions or multiples of various units. For example, the prefix *milli-* represents a 10^{-3} fraction, one-thousandth, of a unit: A milligram (mg) is 10^{-3} gram (g), a millimeter (mm) is 10^{-3} meter (m), and so forth. Table 1.4 lists the prefixes used in SI units; the prefixes most commonly encountered in chemistry are kilo-, centi-, milli-, micro-, and nano. In using SI units and in working



▲ **Figure 1.17 Metric units.** Metric measurements are increasingly common in the United States, as exemplified by the volume printed on this soda can in both metric units (liters, L) and English units (quarts, qt, and fluid ounces, fl oz).

TABLE 1.3 SI Base Units

Physical Quantity	Name of Unit	Abbreviation
Length	Meter	m
Mass	Kilogram	kg
Temperature	Kelvin	K
Time	Second	s or sec
Amount of substance	Mole	mol
Electric current	Ampere	A or amp
Luminous intensity	Candela	cd

TABLE 1.4 Prefixes Used in the Metric System and with SI Units

Prefix	Abbreviation	Meaning	Example	
Peta	P	10^{15}	1 petawatt (PW)	$= 1 \times 10^{15}$ watts[a]
Tera	T	10^{12}	1 terawatt (TW)	$= 1 \times 10^{12}$ watts
Giga	G	10^{9}	1 gigawatt (GW)	$= 1 \times 10^{9}$ watts
Mega	M	10^{6}	1 megawatt (MW)	$= 1 \times 10^{6}$ watts
Kilo	k	10^{3}	1 kilowatt (kW)	$= 1 \times 10^{3}$ watts
Deci	d	10^{-1}	1 deciwatt (dW)	$= 1 \times 10^{-1}$ watt
Centi	c	10^{-2}	1 centiwatt (cW)	$= 1 \times 10^{-2}$ watt
Milli	m	10^{-3}	1 milliwatt (mW)	$= 1 \times 10^{-3}$ watt
Micro	μ[b]	10^{-6}	1 microwatt (μW)	$= 1 \times 10^{-6}$ watt
Nano	n	10^{-9}	1 nanowatt (nW)	$= 1 \times 10^{-9}$ watt
Pico	p	10^{-12}	1 picowatt (pW)	$= 1 \times 10^{-12}$ watt
Femto	f	10^{-15}	1 femtowatt (fW)	$= 1 \times 10^{-15}$ watt
Atto	a	10^{-18}	1 attowatt (aW)	$= 1 \times 10^{-18}$ watt
Zepto	z	10^{-21}	1 zeptowatt (zW)	$= 1 \times 10^{-21}$ watt

[a]The watt (W) is the SI unit of power, which is the rate at which energy is either generated or consumed. The SI unit of energy is the joule (J); $1\ J = 1\ kg \cdot m^2/s^2$ and $1\ W = 1\ J/s$.

[b]Greek letter mu, pronounced "mew."

problems throughout this text, you must be comfortable using exponential notation. If you are unfamiliar with exponential notation or want to review it, refer to Appendix A.1.

Although non-SI units are being phased out, some are still commonly used by scientists. Whenever we first encounter a non-SI unit in the text, the SI unit will also be given. The relationships between the non-SI and SI units we use most frequently in this text appear on the back inside cover. We discuss how to convert from one to the other in Section 1.7.

Length and Mass

The SI base unit of *length* is the meter, which is a distance slightly longer than a yard. **Mass*** is a measure of the amount of material in an object. The SI base unit of mass is the kilogram (kg), which is equal to about 2.2 pounds (lb). This base unit is unusual because it uses a prefix, *kilo-*, instead of the word *gram* alone. We obtain other units for mass by adding prefixes to the word *gram*.

Sample Exercise 1.2
Using SI Prefixes

What is the name of the unit that equals (**a**) 10^{-9} gram, (**b**) 10^{-6} second, (**c**) 10^{-3} meter?

SOLUTION

We can find the prefix related to each power of ten in Table 1.4: (**a**) nanogram, ng; (**b**) microsecond, μs; (**c**) millimeter, mm.

Practice Exercise

(**a**) How many picometers are there in 1 m? (**b**) Express 6.0×10^3 m using a prefix to replace the power of ten. (**c**) Use exponential notation to express 4.22 mg in grams. (**d**) Which of the following lengths is greatest: 12.0 m, 2.0×10^3 mm, 1.5×10^{-3} km, or 1.8×10^{10} nm?

Temperature

Temperature, a measure of the hotness or coldness of an object, is a physical property that determines the direction of heat flow. Heat always flows spontaneously from a substance at higher temperature to one at lower temperature. Thus, the influx of heat we feel when we touch a hot object tells us that the object is at a higher temperature than our hand.

The temperature scales commonly employed in science are the Celsius and Kelvin scales. The **Celsius scale** was originally based on the assignment of 0 °C to the freezing point of water and 100 °C to its boiling point at sea level (**Figure 1.18**).

The **Kelvin scale** is the SI temperature scale, and the SI unit of temperature is the *kelvin* (K). Zero on the Kelvin scale is the temperature at which all thermal motion ceases, a temperature referred to as **absolute zero**. On the Celsius scale, absolute zero has the value −273.15 °C. The Celsius and Kelvin scales have equal-sized units; that is, a kelvin is the same size as a degree Celsius. Thus, the Kelvin and Celsius scales are related according to

$$K = {}^\circ C + 273.15 \qquad [1.3]$$

The freezing point of water, 0 °C, is 273.15 K (Figure 1.18). Notice that we do not use a degree sign (°) with temperatures on the Kelvin scale.

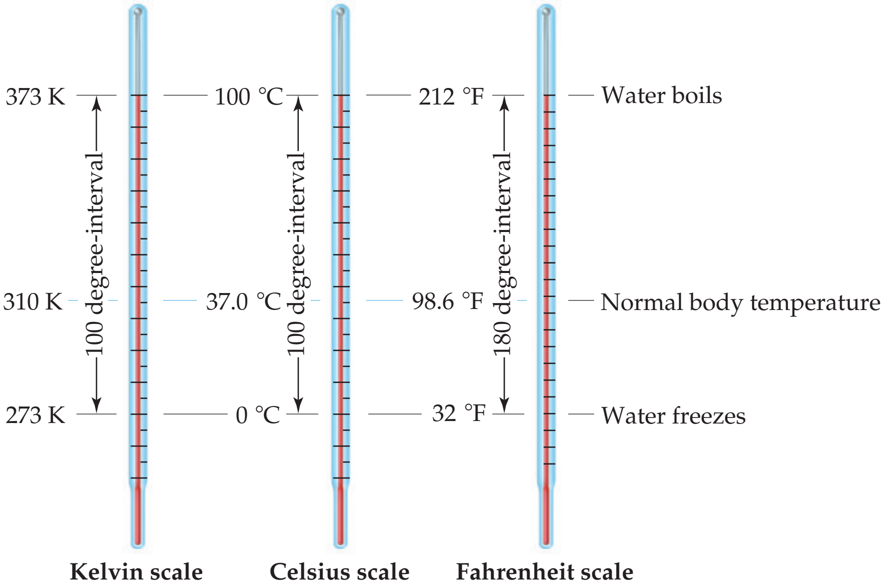
The common temperature scale in the United States is the *Fahrenheit scale*, which is not generally used in science. Water freezes at 32 °F and boils at 212 °F. The Fahrenheit and Celsius scales are related according to

$${}^\circ C = \frac{5}{9}({}^\circ F - 32) \quad \text{or} \quad {}^\circ F = \frac{9}{5}({}^\circ C) + 32 \qquad [1.4]$$

*Mass and weight are not the same thing. Mass is a measure of the amount of matter, whereas weight is the force exerted on this mass by gravity. For example, an astronaut weighs less on the Moon than on Earth because the Moon's gravitational force is less than Earth's. The astronaut's mass on the Moon, however, is the same as it is on Earth.

Go Figure

True or false: The "size" of a degree on the Celsius scale is the same as the "size" of a degree on the Kelvin scale.



▲ **Figure 1.18 Comparison of the Kelvin, Celsius, and Fahrenheit temperature scales.**

Derived SI Units

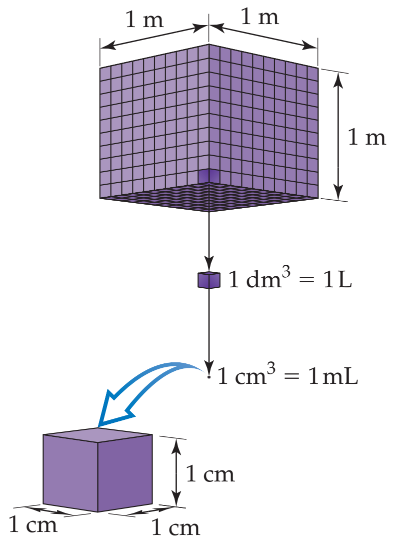
The SI base units are used to formulate *derived units*. A **derived unit** is obtained by multiplication or division of one or more of the base units. We begin with the defining equation for a quantity and, then substitute the appropriate base units. For example, *speed* is defined as the ratio of distance traveled to elapsed time. Thus, the derived SI unit for speed is the SI unit for distance (length), m, divided by the SI unit for time, s, which gives m/s, read "meters per second." Two common derived units in chemistry are those for volume and density.

The *volume* of a cube is its length cubed, length^3. Thus, the derived SI unit of volume is the SI unit of length, m, raised to the third power. The cubic meter, m^3, is the volume of a cube that is 1 m on each edge (**Figure 1.19**). Smaller units, such as cubic centimeters, cm^3 (sometimes written cc), are more frequently used in chemistry. The volume unit most commonly used in chemistry is the *liter* (L), which equals a cubic decimeter, dm^3, and is slightly larger than a quart. (The liter is the first metric unit we have encountered that is *not* an SI unit.) There are 1000 milliliters (mL) in a liter, and 1 mL is the same volume as 1 cm^3: 1 mL = 1 cm^3.

In the lab, you will likely use the devices in **Figure 1.20** to measure and deliver volumes of liquids. Syringes, burettes, and pipettes deliver amounts of liquids with more precision than graduated cylinders. Volumetric flasks are used to contain specific volumes of liquid.

Go Figure

How many 1-L bottles are required to contain 1 m^3 of liquid?



▲ **Figure 1.19 Volume relationships.** The volume occupied by a cube 1 m on each edge is one cubic meter, 1 m^3. Each cubic meter contains 1000 dm^3, 1 m^3 = 1000 dm^3. One liter is the same volume as one cubic decimeter, 1 L = 1 dm^3. Each cubic decimeter contains 1000 cubic centimeters, 1 dm^3 = 1000 cm^3. One cubic centimeter equals one milliliter, 1 cm^3 = 1 mL.

Sample Exercise 1.3
Converting Units of Temperature

A weather forecaster predicts the temperature will reach 30 °C. What is this temperature (**a**) in K and (**b**) °F?

SOLUTION

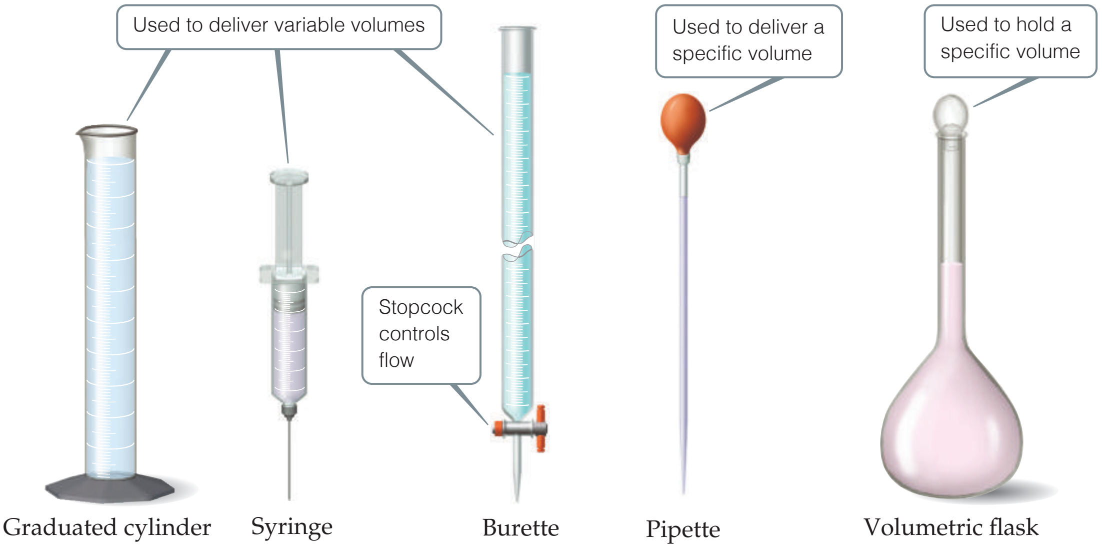
(**a**) Using Equation 1.3, we have K = 30 + 273 = 303 K.

(**b**) Using Equation 1.4, we have

$$°F = \frac{9}{5}(30) + 32 = 54 + 32 = 86\ °F.$$

▶ **Practice Exercise**

Ethylene glycol, the major ingredient in antifreeze, freezes at 260 K. What is the freezing point in (**a**) °C and (**b**) °F?



▶ **Figure 1.20** **Common volumetric glassware.**

TABLE 1.5 Densities of Selected Substances at 25 °C

Substance	Density (g/cm^3)
Air	0.001
Balsa wood	0.16
Ethanol	0.79
Olive oil	0.92
Water	1.00
Ethylene glycol	1.09
Table sugar	1.59
Table salt	2.16
Iron	7.9
Gold	19.32

Density is defined as the amount of mass in a unit volume of a substance:

$$\text{density} = \frac{\text{mass}}{\text{volume}} \qquad [1.5]$$

The densities of solids and liquids are commonly expressed in either grams per cubic centimeter (g/cm^3) or grams per milliliter (g/mL). The densities of some common substances are listed in **Table 1.5**. It is no coincidence that the density of water is 1.00 g/mL; the gram was originally defined as the mass of 1 mL of water at a specific temperature. Because most substances change volume when they are heated or cooled, densities are temperature dependent, and so temperature should be specified when reporting densities. If no temperature is reported, we assume 25 °C, close to normal room temperature.

The terms *density* and *weight* are sometimes confused. A person who says that iron weighs more than air generally means that iron has a higher density than air—1 kg of air has the same mass as 1 kg of iron, but the iron occupies a smaller volume, thereby giving it a higher density. If we combine two liquids that do not mix, such

Sample Exercise 1.4

Determining Density and Using Density to Determine Volume or Mass

(a) Calculate the density of mercury if 1.00×10^2 g occupies a volume of $7.36\ cm^3$.

(b) Calculate the volume of 65.0 g of liquid methanol (wood alcohol) if its density is 0.791 g/mL.

(c) What is the mass in grams of a cube of gold (density = $19.32\ g/cm^3$) if the length of the cube is 2.00 cm?

SOLUTION

(a) We are given mass and volume, so Equation 1.3 yields

$$\text{Density} = \frac{\text{mass}}{\text{volume}} = \frac{1.00 \times 10^2\ g}{7.36\ cm^3} = 13.6\ g/cm^3$$

(b) Solving Equation 1.3 for volume and then using the given mass and density gives

$$\text{Volume} = \frac{\text{mass}}{\text{density}} = \frac{65.0\ \cancel{g}}{0.791\ \cancel{g}/mL} = 82.2\ mL$$

(c) We can calculate the mass from the volume of the cube and its density. The volume of a cube is given by its length cubed:

$$\text{Volume} = (2.00\ cm)^3 = (2.00)^3\ cm^3 = 8.00\ cm^3$$

Solving Equation 1.3 for mass and substituting the volume and density of the cube, we have

$$\text{Mass} = \text{volume} \times \text{density} = (8.00\ \cancel{cm^3})(19.32\ g/\cancel{cm^3}) = 155\ g$$

▶ **Practice Exercise**

(a) Calculate the density of a 374.5-g sample of copper if it has a volume of $41.8\ cm^3$. **(b)** A student needs 15.0 g of ethanol for an experiment. If the density of ethanol is 0.789 g/mL, how many milliliters of ethanol are needed?

as olive oil and water, the less dense liquid (in this case the oil) will float on the denser liquid (the water).

Units of Energy

The SI unit for energy is the **joule** (pronounced "jool"), J, in honor of James Joule (1818–1889), a British scientist who investigated work and heat. If we return to Equation 1.2, where kinetic energy was defined, we see that the units of energy are (mass) × (velocity)^2. Thus, it follows that joules are a derived unit, $1\,J = 1\,(kg) \times (m/s)^2 = 1\,kg\text{-}m^2/s^2$. Numerically, a 2-kg mass moving at a velocity of 1 m/s possesses a kinetic energy of 1 J:

$$E_k = \frac{1}{2}mv^2 = \frac{1}{2}(2\,kg)(1\,m/s)^2 = 1\,kg\text{-}m^2/s^2 = 1\,J$$

Because a joule is not a very large amount of energy, we often use *kilojoules* (kJ) in discussing the energies associated with chemical reactions. For example, the amount of heat released when hydrogen and oxygen react to form 1 g of water is 16 kJ.

It is still quite common in chemistry, biology, and biochemistry to find energy changes associated with chemical reactions expressed in the non-SI unit of calories. A **calorie** (cal) was originally defined as the amount of energy required to raise the temperature of 1 g of water from 14.5 to 15.5 °C. It has since been defined in terms of a joule:

$$1\,cal = 4.184\,J\ (exactly)$$

A related energy unit that is familiar to anyone who has read a food label is the nutritional *Calorie* (note the capital C), which is 1000 times larger than *calorie* with a lowercase c: 1 Cal = 1000 cal = 1 kcal.

Sample Exercise 1.5

Identifying and Calculating Energy Changes

A standard propane (C_3H_8) tank used in an outdoor grill holds approximately 9.0 kg of propane. When the grill is operating, propane reacts with oxygen to form carbon dioxide and water. For every gram of propane that reacts with oxygen in this way, 46 kJ of energy is released as heat. (**a**) How much energy is released if the entire contents of the propane tank react with oxygen? (**b**) As the propane reacts, does the potential energy stored in chemical bonds increase or decrease? (**c**) If you were to store an equivalent amount of potential energy by pumping water to an elevation of 75 m above the ground, what mass of water would be needed? (Note: The force due to gravity acting on the water, which is the water's weight, is $F = m \times g$, where m is the mass of the object and g is the gravitational constant, $g = 9.8\,m/s^2$.)

SOLUTION

(**a**) We can calculate the amount of energy released from the propane as heat by converting the mass of propane from kg to g and then using the fact that 46 kJ of heat are released per gram:

$$E = 9.0\,\cancel{kg} \times \frac{1000\,\cancel{g}}{1\,\cancel{kg}} \times \frac{46\,kJ}{1\,\cancel{g}} = 4.1 \times 10^5\,kJ = 4.1 \times 10^8\,J$$

(**b**) When propane reacts with oxygen, the potential energy stored in the chemical bonds is converted to an alternate form of energy, heat. Therefore, the potential energy stored as chemical energy must decrease.

(**c**) The amount of work done to pump the water to a height of 75 m can be calculated using Equation 1.1:

$$w = F \times d = (m \times g) \times d$$

Equation 1.1 can then be rearranged to solve for the mass of water:

$$m = \frac{w}{g \times d} = \frac{4.1 \times 10^8\,J}{(9.8\,m/s^2)(75\,m)} = \frac{4.1 \times 10^8\,kg\text{-}\cancel{m^2}/\cancel{s^2}}{(9.8\,\cancel{m}/\cancel{s^2})(75\,\cancel{m})}$$

$$= 5.6 \times 10^5\,kg$$

At 25 °C, this mass of water would have a volume of 560,000 L, or roughly 150,000 gallons. Thus, we see that large amounts of potential energy can be stored as chemical energy.

Practice Exercise

A 12-oz vanilla milkshake at a fast-food restaurant contains 547 Calories. What quantity of energy is this in joules?