

 Cengage

11th Edition

Chemistry

& Chemical Reactivity

Kotz
Treichel
Townsend
Treichel

Periodic Table of the Elements

1	Hydrogen 1 H 1.008									Uranium 92 U 238.03		
	1A (1)	2A (2)										
2	Lithium 3 Li 6.94	Beryllium 4 Be 9.0122										
3	Sodium 11 Na 22.990	Magnesium 12 Mg 24.305	3B (3)	4B (4)	5B (5)	6B (6)	7B (7)	8B (8) (9) (10)				
4	Potassium 19 K 39.098	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956	Titanium 22 Ti 47.867	Vanadium 23 V 50.942	Chromium 24 Cr 51.996	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.693		
5	Rubidium 37 Rb 85.468	Strontium 38 Sr 87.62	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.95	Tchnetium 43 Tc (98)	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42		
6	Cesium 55 Cs 132.91	Barium 56 Ba 137.33	Lanthanum 57 La 138.91	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.95	Tungsten 74 W 183.84	Rhenium 75 Re 186.21	Osmium 76 Os 190.23	Iridium 77 Ir 192.22	Platinum 78 Pt 195.08		
7	Francium 87 Fr (223)	Radium 88 Ra (226)	Actinium 89 Ac (227)	Rutherfordium 104 Rf (267)	Dubnium 105 Db (268)	Seaborgium 106 Sg (269)	Bohrium 107 Bh (270)	Hassium 108 Hs (277)	Meitnerium 109 Mt (276)	Darmstadtium 110 Ds (281)		

- MAIN GROUP METALS
- TRANSITION METALS
- METALLOIDS
- NONMETALS

Uranium
92 ----- Atomic number
U ----- Symbol
238.03 ----- Atomic weight

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

Lanthanides

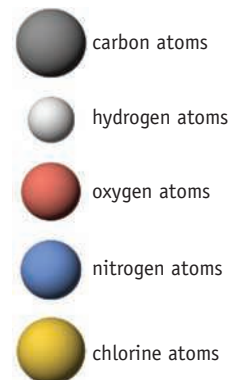
Actinides

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

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

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

Standard Colors for Atoms
in Molecular Models



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

11th Edition

Chemistry & Chemical Reactivity

Kotz
Treichel
Townsend
Treichel

 Cengage

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

This is an electronic version of the print textbook. Due to electronic rights restrictions, some third party content may be suppressed. Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. The publisher reserves the right to remove content from this title at any time if subsequent rights restrictions require it. For valuable information on pricing, previous editions, changes to current editions, and alternate formats, please visit www.cengage.com/highered to search by ISBN#, author, title, or keyword for materials in your areas of interest.

Important Notice: Media content referenced within the product description or the product text may not be available in the eBook version.

Chemistry and Chemical Reactivity,
Eleventh Edition

John C. Kotz, Paul M. Treichel,
John R. Townsend, and David A. Treichel

SVP, Product: Cheryl Costantini

VP, Product: Thais Alencar

Portfolio Product Director: Maureen McLaughlin

Portfolio Product Manager: Helene Alfaro,
Corey Smith

Product Assistant: Ellie Purgavie

Learning Designer: Mona ZefTEL, Courtney
Wolstoncroft

Technical Editor: Lumina Datamatics Ltd.

Content Manager: Kelly Aull

Digital Project Manager: Nikkita Kendrick

Technical Content Program Manager:
Ivan Corriher

Developmental Editor: Margy Kuntz

VP, Product Marketing: Jason Sakos

Sr Director, Product Marketing: Danae April

Product Marketing Manager: Andrew Stock

Sr Product Development Researcher:
Nicole Hurst

Subject Matter Expert: Theresa Dearborn

Content Acquisition Analyst: Ann Hoffman

Production Service: Lumina Datamatics Ltd.

Creative Studio Designer: Chris Doughman

Cover Image Source: Ralph Lee Hopkins

Other Course contributors: Charles Atwood,
Rebecca Heider

© 2023, 2019, 2015 Cengage Learning, Inc. ALL RIGHTS RESERVED.

WCN: 02-300

No part of this work covered by the copyright herein may be reproduced or distributed in any form or by any means, except as permitted by U.S. copyright law, without the prior written permission of the copyright owner.

Unless otherwise noted, all content is © Cengage Learning, Inc.

The names of all products mentioned herein are used for identification purposes only and may be trademarks or registered trademarks of their respective owners. Cengage Learning disclaims any affiliation, association, connection with, sponsorship, or endorsement by such owners.

For product information and technology assistance, contact us at
Cengage Customer & Sales Support, 1-800-354-9706
or **support.cengage.com**.

For permission to use material from this text or product, submit all
requests online at **www.copyright.com**.

Library of Congress Control Number: 2023904802

Student Edition:

ISBN: 978-0-357-85140-1

Loose-leaf Edition:

ISBN: 978-0-357-85141-8

Cengage

200 Pier 4 Boulevard
Boston, MA 02210
USA

Cengage is a leading provider of customized learning solutions. Our employees reside in nearly 40 different countries and serve digital learners in 165 countries around the world. Find your local representative at **www.cengage.com**.

To learn more about Cengage platforms and services, register or access your online learning solution, or purchase materials for your course, visit **www.cengage.com**.

Brief Contents

Part One The Basic Tools of Chemistry

- 1 Basic Concepts of Chemistry 2
- 1R Let's Review: The Tools of Quantitative Chemistry 30
- 2 Atoms, Molecules, and Ions 62
- 3 Chemical Reactions 138
- 4 Stoichiometry: Quantitative Information about Chemical Reactions 190
- 5 Principles of Chemical Reactivity: Energy and Chemical Reactions 254

Part Two Atoms and Molecules

- 6 The Structure of Atoms 304
- 7 The Structure of Atoms and Periodic Trends 344
- 8 Bonding and Molecular Structure 386
- 9 Bonding and Molecular Structure: Orbital Hybridization and Molecular Orbitals 458

Part Three States of Matter

- 10 Gases and Their Properties 498
- 11 Intermolecular Forces and Liquids 540
- 12 The Solid State 580
- 13 Solutions and Their Behavior 626

Part Four The Control of Chemical Reactions

- 14 Chemical Kinetics: The Rates of Chemical Reactions 672
- 15 Principles of Chemical Reactivity: Equilibria 736
- 16 Principles of Chemical Reactivity: The Chemistry of Acids and Bases 776
- 17 Principles of Chemical Reactivity: Other Aspects of Aqueous Equilibria 830
- 18 Principles of Chemical Reactivity: Entropy and Free Energy 886
- 19 Principles of Chemical Reactivity: Electron Transfer Reactions 932

Part Five The Chemistry of the Elements

- 20 Nuclear Chemistry 992
- 21 The Chemistry of the Main Group Elements 1038
- 22 The Chemistry of the Transition Elements 1104
- 23 Carbon: Not Just Another Element 1150
- 24 Biochemistry 1206
- 25 Environmental Chemistry—Earth's Environment, Energy, and Sustainability 1244

List of Appendices

- A Using Logarithms and Solving Quadratic Equations A-2
- B Some Important Physical Concepts A-6
- C Abbreviations and Useful Conversion Factors A-9
- D Physical Constants A-13
- E A Brief Guide to Naming Organic Compounds A-15
- F Values for the Ionization Energies and Electron Attachment Enthalpies of the Elements A-18
- G Vapor Pressure of Water at Various Temperatures A-19
- H Ionization Constants for Aqueous Weak Acids at 25 °C A-20
- I Ionization Constants for Aqueous Weak Bases at 25 °C A-22
- J Solubility Product Constants for Some Inorganic Compounds at 25 °C A-23
- K Formation Constants for Some Complex Ions in Aqueous Solution at 25 °C A-24
- L Selected Thermodynamic Values A-25
- M Standard Reduction Potentials in Aqueous Solution at 25 °C A-32
- N Answers to Study Questions, Check Your Understanding, and Applying Chemical Principles Questions A-36

Index of Names I-1

Index and Glossary I-4

Contents

Preface xii

Part One The Basic Tools of Chemistry

1 Basic Concepts of Chemistry 2

- 1.1 Chemistry and Its Methods 3
- 1.2 Sustainability and Green Chemistry 7
- 1.3 Classifying Matter 8
- 1.4 Elements 12
- 1.5 Compounds 13
- 1.6 Properties and Changes 15
- 1.7 Energy: Some Basic Principles 20
- Applying Chemical Principles 1.1:**
CO₂ in the Oceans 21

1R Let's Review: The Tools of Quantitative Chemistry 30

- 1R.1 Units of Measurement 31
 - A Closer Look:** The SI Base Units 34
 - A Closer Look:** Energy and Food 37
- 1R.2 Making Measurements: Precision, Accuracy, Experimental Error, and Standard Deviation 37
- 1R.3 Mathematics of Chemistry 41
- 1R.4 Problem Solving by Dimensional Analysis 47
- 1R.5 Graphs and Graphing 48
- 1R.6 Problem Solving and Chemical Arithmetic 49
 - Applying Chemical Principles 1R.1:**
Out of Gas! 51
 - Applying Chemical Principles 1R.2:**
Ties in Swimming and Significant Figures 52

2 Atoms, Molecules, and Ions 62

- 2.1 Atomic Structure, Atomic Number, and Atomic Mass 63
- 2.2 Atomic Weight 67

A Closer Look: Isotopic Abundances and Atomic Weights 70

Key Experiments: The Nature of the Atom and Its Components 72

2.3 The Periodic Table 74

A Closer Look: Mendeleev and the Periodic Table 78

A Closer Look: Marie Curie (1867–1934) 82

2.4 Molecules: Formulas, Models, and Names 84

2.5 Ions 89

2.6 Ionic Compounds: Formulas, Names, and Properties 93

A Closer Look: Hydrated Ionic Compounds 98

2.7 Atoms, Molecules, and the Mole 99

A Closer Look: Amedeo Avogadro and His Number 100

A Closer Look: The Mole, a Counting Unit 103

2.8 Chemical Analysis: Determining Compound Formulas 106

2.9 Instrumental Analysis: Determining Compound Formulas 114

Applying Chemical Principles 2.1:
Using Isotopes: Ötzi, the Iceman of the Alps 117

Applying Chemical Principles 2.2:
Arsenic, Medicine, and the Formula of Compound 606 118

Applying Chemical Principles 2.3:
Argon—An Amazing Discovery 118

3 Chemical Reactions 138

3.1 Introduction to Chemical Equations 139

A Closer Look: Antoine Laurent Lavoisier (1743–1794) 141

3.2 Balancing Chemical Equations 142

3.3 Introduction to Chemical Equilibrium 145

3.4 Aqueous Solutions 147

3.5 Precipitation Reactions 151

3.6 Acids and Bases 156

A Closer Look: Sulfuric Acid 162

- 3.7 Acid–Base Reactions 163
- 3.8 Oxidation–Reduction Reactions 167
- A Closer Look:** Are Oxidation Numbers Real? 171
- 3.9 Classifying Reactions in Aqueous Solution 173
- A Closer Look:** Alternative Organizations of Reaction Types 174
- Applying Chemical Principles 3.1:** Superconductors 177
- Applying Chemical Principles 3.2:** Sequestering Carbon Dioxide 177
- Applying Chemical Principles 3.3:** Black Smokers and Volcanoes 178

4 Stoichiometry: Quantitative Information about Chemical Reactions 190

- 4.1 Mass Relationships in Chemical Reactions: Stoichiometry 191
- 4.2 Reactions in Which One Reactant Is Present in Limited Supply 195
- 4.3 Percent Yield 200
- 4.4 Chemical Equations and Chemical Analysis 202
- A Closer Look:** Nuclear Magnetic Resonance (NMR) Spectroscopy 208
- 4.5 Measuring Concentrations of Compounds in Solution 209
- A Closer Look:** Serial Dilutions 215
- 4.6 pH, a Concentration Scale for Acids and Bases 215
- 4.7 Stoichiometry of Reactions in Aqueous Solution—Fundamentals 217
- 4.8 Stoichiometry of Reactions in Aqueous Solution—Titrations 220
- 4.9 Spectrophotometry 227
- Applying Chemical Principles 4.1:** Atom Economy 232
- Applying Chemical Principles 4.2:** Bleach 232
- Applying Chemical Principles 4.3:** How Much Salt is There in Seawater? 233
- Applying Chemical Principles 4.4:** The Martian 234

5 Principles of Chemical Reactivity: Energy and Chemical Reactions 254

- 5.1 Energy: Some Basic Principles 255
- A Closer Look:** What Is Heat? 257
- 5.2 Specific Heat Capacity: Heating and Cooling 258
- 5.3 Energy and Changes of State 262
- 5.4 The First Law of Thermodynamics 266
- A Closer Look:** P - V Work 268
- A Closer Look:** Enthalpy, Internal Energy, and Non-Expansion Work 270
- 5.5 Enthalpy Changes for Chemical Reactions 271
- 5.6 Calorimetry 274
- 5.7 Enthalpy Calculations 278
- A Closer Look:** Hess's Law and Equation 5.7 284
- 5.8 Product- or Reactant-Favored Reactions and Thermodynamics 285
- Applying Chemical Principles 5.1:** Gunpowder 286
- Applying Chemical Principles 5.2:** The Fuel Controversy—Alcohol and Gasoline 287

Part Two Atoms and Molecules

6 The Structure of Atoms 304

- 6.1 Electromagnetic Radiation 305
- 6.2 Quantization: Planck, Einstein, Energy, and Photons 308
- 6.3 Atomic Line Spectra and Niels Bohr 312
- A Closer Look:** Niels Bohr (1885–1962) 314
- 6.4 Wave–Particle Duality: Prelude to Quantum Mechanics 319
- 6.5 The Modern View of Electronic Structure: Wave or Quantum Mechanics 321
- 6.6 The Shapes of Atomic Orbitals 325
- A Closer Look:** More about H Atom Orbital Shapes and Wavefunctions 329
- 6.7 One More Electron Property: Electron Spin 330
- Applying Chemical Principles 6.1:** Sunburn, Sunscreens, and Ultraviolet Radiation 330

Applying Chemical Principles 6.2:
What Makes the Colors in Fireworks? 331

Applying Chemical Principles 6.3:
Chemistry of the Sun 332

7 The Structure of Atoms and Periodic Trends 344

- 7.1 The Pauli Exclusion Principle 345
- 7.2 Atomic Subshell Energies and Electron Assignments 347
- 7.3 Electron Configurations of Atoms 350
- A Closer Look:** Orbital Energies, Z^* , and Electron Configurations 359
- 7.4 Electron Configurations of Ions 360
- A Closer Look:** Questions about Transition Element Electron Configurations 361
- A Closer Look:** Paramagnetism and Ferromagnetism 364
- 7.5 Atomic Properties and Periodic Trends 364
- A Closer Look:** Photoelectron Spectroscopy 371
- 7.6 Periodic Trends and Chemical Properties 374
- Applying Chemical Principles 7.1:**
The Not-So-Rare Earths 375
- Applying Chemical Principles 7.2:**
Metals in Biochemistry 376

8 Bonding and Molecular Structure 386

- 8.1 Lewis Electron Dot Symbols and Chemical Bond Formation 388
- 8.2 Electronegativity and Bond Polarity 390
- 8.3 Lewis Structures of Molecules and Polyatomic Ions 393
- 8.4 Common Patterns of Bonding in Lewis Structures 399
- 8.5 Resonance 404
- A Closer Look:** Resonance 405
- 8.6 Exceptions to the Octet Rule 406
- A Closer Look:** Structure and Bonding for Hypervalent Molecules 409
- 8.7 Formal Charges in Covalent Molecules and Ions 410
- A Closer Look:** Comparing Oxidation Number and Formal Charge 411
- 8.8 Molecular Shapes 416

A Closer Look: A Scientific Controversy—Resonance, Formal Charges, and the Question of Double Bonds in Sulfate and Phosphate Ions 417

- 8.9 Molecular Polarity 424
- A Closer Look:** Measuring Molecular Polarity and Debye Units 426
- A Closer Look:** Visualizing Charge Distributions and Molecular Polarity—Electrostatic Potential Surfaces and Partial Charge 428
- 8.10 Bond Properties: Order, Length, and Dissociation Enthalpy 432
- 8.11 DNA 437
- Applying Chemical Principles 8.1:**
Ibuprofen, A Study in Green Chemistry 441
- Applying Chemical Principles 8.2:**
van Arkel Triangles and Bonding 442
- Applying Chemical Principles 8.3:**
Linus Pauling and the Origin of the Concept of Electronegativity 443

9 Bonding and Molecular Structure: Orbital Hybridization and Molecular Orbitals 458

- 9.1 Valence Bond Theory 459
- 9.2 Molecular Orbital Theory 473
- A Closer Look:** Molecular Orbitals for Molecules Formed from p -Block Elements 481
- 9.3 Theories of Chemical Bonding: A Summary 483
- A Closer Look:** Three-Center Bonds in HF_2^- , B_2H_6 , and SF_6 484
- Applying Chemical Principles 9.1:**
Probing Molecules with Photoelectron Spectroscopy 485
- Applying Chemical Principles 9.2:**
Green Chemistry, Safe Dyes, and Molecular Orbitals 486

Part Three States of Matter

10 Gases and Their Properties 498

- 10.1 Modeling a State of Matter: Gases and Gas Pressure 499
- A Closer Look:** Measuring Gas Pressure 500
- 10.2 Gas Laws: The Experimental Basis 502

- A Closer Look** Studies on Gases—Robert Boyle and Jacques Charles 508
- 10.3 The Ideal Gas Law 508
- 10.4 Gas Laws and Chemical Reactions 513
- 10.5 Gas Mixtures and Partial Pressures 514
- 10.6 The Kinetic-Molecular Theory of Gases 517
- 10.7 Diffusion and Effusion 521
- A Closer Look:** Surface Science and the Need for Ultrahigh Vacuum Systems 523
- 10.8 Nonideal Behavior of Gases 524
- Applying Chemical Principles 10.1:** The Atmosphere and Altitude Sickness 526
- Applying Chemical Principles 10.2:** The Chemistry of Airbags 527

11 Intermolecular Forces and Liquids 540

- 11.1 States of Matter and Intermolecular Forces 541
- 11.2 Interactions between Ions and Molecules with a Permanent Dipole 543
- A Closer Look:** Hydrated Salts: A Result of Ion-Dipole Bonding 545
- 11.3 Interactions between Molecules with a Permanent Dipole 546
- A Closer Look:** Hydrogen Bonding in Biochemistry 551
- 11.4 Intermolecular Forces Involving Nonpolar Molecules 552
- 11.5 A Summary of van der Waals Intermolecular Forces 555
- A Closer Look:** Geckos Can Climb Up der Waals 556
- 11.6 Properties of Liquids 557
- Applying Chemical Principles 11.1:** Chromatography 567
- Applying Chemical Principles 11.2:** A Pet Food Catastrophe 568

12 The Solid State 580

- 12.1 Crystal Lattices and Unit Cells 581
- A Closer Look:** Packing Oranges, Marbles, and Atoms 588
- 12.2 Structures and Formulas of Ionic Solids 589
- A Closer Look:** Using X-Rays to Determine Crystal Structures 593

- 12.3 Bonding in Ionic Compounds: Lattice Energy 594
- 12.4 Bonding in Metals and Semiconductors 596
- 12.5 Other Types of Solid Materials 602
- A Closer Look:** Glass 605
- 12.6 Phase Changes 609
- Applying Chemical Principles 12.1:** Lithium and Electric Vehicles 613
- Applying Chemical Principles 12.2:** Nanotubes and Graphene: Network Solids 614
- Applying Chemical Principles 12.3:** Tin Disease 615

13 Solutions and Their Behavior 626

- 13.1 Units of Concentration 627
- 13.2 The Solution Process 630
- A Closer Look:** Supersaturated Solutions 631
- 13.3 Factors Affecting Solubility: Pressure and Temperature 637
- 13.4 Colligative Properties 640
- A Closer Look:** Growing Crystals 641
- A Closer Look:** Hardening of Trees 646
- A Closer Look:** Reverse Osmosis for Pure Water 649
- A Closer Look:** Osmosis and Medicine 651
- 13.5 Colloids 655
- Applying Chemical Principles 13.1:** Distillation 659
- Applying Chemical Principles 13.2:** Henry's Law and Exploding Lakes 660
- Applying Chemical Principles 13.3:** Narcosis and the Bends 661

Part Four The Control of Chemical Reactions

14 Chemical Kinetics: The Rates of Chemical Reactions 672

- 14.1 Rates of Chemical Reactions 673
- 14.2 Reaction Conditions and Rate 678
- 14.3 Effect of Concentration on Reaction Rate 680
- 14.4 Concentration–Time Relationships: Integrated Rate Laws 686
- 14.5 A Microscopic View of Reaction Rates 694

- A Closer Look:** Rate Laws, Rate Constants, and Reaction Stoichiometry 695
- A Closer Look:** More about Molecular Orientation and Reaction Coordinate Diagrams 697
- 14.6 Catalysts 702
- A Closer Look:** Thinking about Kinetics, Catalysis, and Bond Energies 702
- 14.7 Reaction Mechanisms 706
- A Closer Look:** Organic Bimolecular Substitution Reactions 709
- Applying Chemical Principles 14.1:** Enzymes—Nature’s Catalysts 716
- Applying Chemical Principles 14.2:** Kinetics and Mechanisms: A 70-Year-Old Mystery Solved 717
- 16.7 Calculations with Equilibrium Constants 796
- 16.8 Polyprotic Acids and Bases 805
- 16.9 Molecular Structure, Bonding, and Acid–Base Behavior 807
- A Closer Look:** Acid Strengths and Molecular Structure 811
- 16.10 The Lewis Concept of Acids and Bases 812
- Applying Chemical Principles 16.1:** Would You Like Some Belladonna Juice in Your Drink? 816
- Applying Chemical Principles 16.2:** The Leveling Effect, Nonaqueous Solvents, and Superacids 817

15 Principles of Chemical Reactivity: Equilibria 736

- 15.1 Chemical Equilibrium: A Review 737
- 15.2 The Equilibrium Constant and Reaction Quotient 738
- A Closer Look:** Activities and Units of K 740
- A Closer Look:** Equilibrium Constant Expressions for Gases— K_c and K_p 742
- 15.3 Determining an Equilibrium Constant 746
- 15.4 Using Equilibrium Constants in Calculations 748
- 15.5 More about Balanced Equations and Equilibrium Constants 754
- 15.6 Disturbing a Chemical Equilibrium 757
- Applying Chemical Principles 15.1:** Applying Equilibrium Concepts—The Haber–Bosch Ammonia Process 762
- Applying Chemical Principles 15.2:** Trivalent Carbon 763

16 Principles of Chemical Reactivity: The Chemistry of Acids and Bases 776

- 16.1 The Brønsted–Lowry Concept of Acids and Bases 777
- 16.2 Water and the pH Scale 780
- 16.3 Equilibrium Constants for Acids and Bases 783
- 16.4 Acid–Base Properties of Salts 789
- 16.5 Predicting the Direction of Acid–Base Reactions 791
- 16.6 Types of Acid–Base Reactions 794

17 Principles of Chemical Reactivity: Other Aspects of Aqueous Equilibria 830

- 17.1 Buffers 831
- 17.2 Acid–Base Titrations 843
- 17.3 Solubility of Salts 853
- A Closer Look:** Minerals and Gems—The Importance of Solubility 859
- A Closer Look:** Solubility Calculations 860
- 17.4 Precipitation Reactions 863
- 17.5 Equilibria Involving Complex Ions 867
- Applying Chemical Principles 17.1:** Everything that Glitters . . . 871
- Applying Chemical Principles 17.2:** Take a Deep Breath 872

18 Principles of Chemical Reactivity: Entropy and Free Energy 886

- 18.1 Spontaneity and Dispersal of Energy: Entropy 887
- 18.2 Entropy: A Microscopic Understanding 889
- A Closer Look:** Reversible and Irreversible Processes 890
- 18.3 Entropy Measurement and Values 894
- 18.4 Entropy Changes and Spontaneity 898
- A Closer Look:** Entropy and Spontaneity? 899
- 18.5 Gibbs Free Energy 902
- 18.6 Calculating and Using Standard Free Energies, $\Delta_r G^\circ$ 906
- 18.7 The Interplay of Kinetics and Thermodynamics 914

- Applying Chemical Principles 18.1:**
Thermodynamics and Living Things 916
- Applying Chemical Principles 18.2:**
Are Diamonds Forever? 917

19 Principles of Chemical Reactivity: Electron Transfer Reactions 932

- 19.1 Oxidation–Reduction Reactions 933
- 19.2 Voltaic Cells 940
- 19.3 Commercial Voltaic Cells 946
- 19.4 Standard Electrochemical Potentials 951
A Closer Look: EMF, Cell Potential, and Voltage 952
- 19.5 Electrochemical Cells Under Nonstandard Conditions 960
- 19.6 Electrochemistry and Thermodynamics 964
- 19.7 Electrolysis: Chemical Change Using Electrical Energy 968
A Closer Look: Electrochemistry and Michael Faraday 970
- 19.8 Counting Electrons 973
- 19.9 Corrosion: Redox Reactions in the Environment 975
Applying Chemical Principles 19.1:
Electric Batteries versus Gasoline 978
Applying Chemical Principles 19.2:
Sacrifice! 978

Part Five The Chemistry of the Elements

20 Nuclear Chemistry 992

- 20.1 Natural Radioactivity 994
- 20.2 Nuclear Reactions and Radioactive Decay 995
A Closer Look: Radioactive Decay Series 997
- 20.3 Stability of Atomic Nuclei 1000
- 20.4 Origin of the Elements: Nucleosynthesis 1006
- 20.5 Rates of Nuclear Decay 1008
- 20.6 Artificial Nuclear Reactions 1014
- 20.7 Nuclear Fission and Nuclear Fusion 1018
A Closer Look: Lise Meitner (1878–1968) 1020
- 20.8 Radiation Health and Safety 1021
- 20.9 Applications of Nuclear Chemistry 1023
Applying Chemical Principles 20.1:
A Primordial Nuclear Reactor 1027

- Applying Chemical Principles 20.2:**
Technetium-99m and Medical Imaging 1028
- Applying Chemical Principles 20.3:**
The Age of Meteorites 1029

21 The Chemistry of the Main Group Elements 1038

- 21.1 Abundance of the Elements 1039
- 21.2 The Periodic Table: A Guide to the Elements 1040
- 21.3 Hydrogen 1046
A Closer Look: Hydrogen in Transportation 1049
- 21.4 The Alkali Metals, Group 1A (1) 1049
A Closer Look: The Reactivity of the Alkali Metals 1054
- 21.5 The Alkaline Earth Elements, Group 2A (2) 1054
A Closer Look: Alkaline Earth Metals and Biology 1057
A Closer Look: Cement—The Second Most Used Substance 1058
- 21.6 Boron, Aluminum, and the Group 3A (13) Elements 1059
A Closer Look: Complexity in Boron Chemistry 1064
- 21.7 Silicon and the Group 4A (14) Elements 1065
- 21.8 Nitrogen, Phosphorus, and the Group 5A (15) Elements 1070
A Closer Look: Alchemists Making Phosphorus 1072
A Closer Look: Ammonium Nitrate—A Mixed Blessing 1075
- 21.9 Oxygen, Sulfur, and the Group 6A (16) Elements 1079
- 21.10 The Halogens, Group 7A (17) 1082
A Closer Look: Iodine and Your Thyroid Gland 1084
A Closer Look: The Many Uses of Fluorine-Containing Compounds 1085
- 21.11 The Noble Gases, Group 8A (18) 1087
A Closer Look: The Noble Gases—Not So Inert 1088
Applying Chemical Principles 21.1:
Lead in the Environment 1089
Applying Chemical Principles 21.2:
Hydrogen Storage 1090

22 The Chemistry of the Transition Elements 1104

- 22.1 Overview of the Transition Elements 1105
- 22.2 Periodic Properties of the Transition Elements 1107
- 22.3 Metallurgy 1111
- 22.4 Coordination Compounds 1114
 - A Closer Look:** Hemoglobin: A Molecule with a Tetradentate Ligand 1118
- 22.5 Structures of Coordination Compounds 1122
- 22.6 Bonding in Coordination Compounds 1128
- 22.7 Colors of Coordination Compounds 1133
 - Applying Chemical Principles 22.1:** *Blue!* 1137
 - Applying Chemical Principles 22.2:** *Cisplatin:* Accidental Discovery of a Chemotherapy Agent 1138
 - Applying Chemical Principles 22.3:** The Rare Earth Elements 1139

23 Carbon: Not Just Another Element 1150

- 23.1 Why Carbon? 1151
 - A Closer Look:** Writing Formulas and Drawing Structures 1153
- 23.2 Hydrocarbons 1155
 - A Closer Look:** Flexible Molecules 1161
- 23.3 Alcohols, Ethers, and Amines 1170
- 23.4 Compounds with a Carbonyl Group 1176
 - A Closer Look:** Omega-3 Fatty Acids 1180
- 23.5 Polymers 1184
 - A Closer Look:** Green Chemistry: Recycling PET 1190
 - Applying Chemical Principles 23.1:** An Awakening with L-DOPA 1192
 - Applying Chemical Principles 23.2:** Green Adhesives 1193
 - Applying Chemical Principles 23.3:** Bisphenol A (BPA) 1193

24 Biochemistry 1206

- 24.1 Proteins 1208
- 24.2 Carbohydrates 1216

- 24.3 Nucleic Acids 1219
 - A Closer Look:** Genetic Engineering with CRISPR-Cas9 1222
- 24.4 Lipids and Cell Membranes 1225
 - A Closer Look:** mRNA Vaccines 1228
- 24.5 Metabolism 1230
 - Applying Chemical Principles 24.1:** Polymerase Chain Reaction 1236

25 Environmental Chemistry—Earth's Environment, Energy, and Sustainability 1244

- 25.1 The Atmosphere 1246
 - A Closer Look:** The Earth's Atmosphere 1247
 - A Closer Look:** Methane Hydrates 1256
- 25.2 The Aqua Sphere (Water) 1256
 - A Closer Look:** Perfluoroalkyl Substances (PFAS) 1263
- 25.3 Energy 1263
 - A Closer Look:** Fracking 1266
- 25.4 Fossil Fuels 1267
 - A Closer Look:** Petroleum Chemistry 1271
- 25.5 Environmental Impact of Fossil Fuels 1271
- 25.6 Alternative Sources of Energy 1277
- 25.7 Green Chemistry and Sustainability 1281
 - Applying Chemical Principles 25.1:** Chlorination of Water Supplies 1282
 - Applying Chemical Principles 25.2:** Hard Water 1283

List of Appendices A-1

- A Using Logarithms and Solving Quadratic Equations A-2
- B Some Important Physical Concepts A-6
- C Abbreviations and Useful Conversion Factors A-9
- D Physical Constants A-13
- E A Brief Guide to Naming Organic Compounds A-15
- F Values for the Ionization Energies and Electron Attachment Enthalpies of the Elements A-18
- G Vapor Pressure of Water at Various Temperatures A-19
- H Ionization Constants for Aqueous Weak Acids at 25 °C A-20

- I Ionization Constants for Aqueous Weak Bases at 25 °C A-22
- J Solubility Product Constants for Some Inorganic Compounds at 25 °C A-23
- K Formation Constants for Some Complex Ions in Aqueous Solution at 25 °C A-24
- L Selected Thermodynamic Values A-25

- M Standard Reduction Potentials in Aqueous Solution at 25 °C A-32
- N Answers to Study Questions, Check Your Understanding, and Applying Chemical Principles Questions A-36

Index of Names I-1

Index and Glossary I-4

Preface

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

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

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



Fireworks. See Chapter 6 for the chemistry of fireworks.

problems as a scientist. We have tried to provide the tools to help you become a chemically and scientifically literate citizen.

Audience for *Chemistry & Chemical Reactivity*

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

Philosophy and Approach of *Chemistry & Chemical Reactivity*

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

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

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

General Organization

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

Flexibility of Chapter Organization

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

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

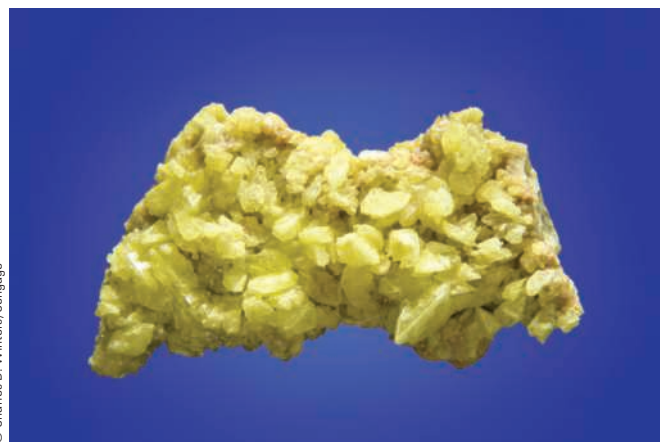
The order of topics in the text was also devised to introduce as early as possible the background required for the laboratory experiments that are usually performed in introductory chemistry courses. For this reason, chapters on chemical and physical properties, common reaction types, and stoichiometry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

units are introduced in Chapter 1, and thermochemistry is introduced in Chapter 5.

Sections of the Book — Organization and Purpose

Part One: The Basic Tools of Chemistry

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



© Charles D. Winters/Cengage
Elemental sulfur.

Part Two: Atoms and Molecules

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



© Charles D. Winters/Cengage

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

Part Three: States of Matter

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



John C. Katz

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

Part Four: The Control of Chemical Reactions

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



© Charles D. Winters/Cengage

The explosive reaction of hydrogen and oxygen.

Part Five: The Chemistry of the Elements

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

concepts in earlier chapters into a discussion of “Environmental Chemistry—Earth’s Environment, Energy, and Sustainability.”



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

What’s New to this Edition?

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

Think–Pair–Share Questions

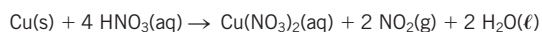
Many instructors have experimented with moving beyond simply lecturing in general chemistry. One approach that has worked especially well has been to take class time for students to work together on questions that help them learn course topics. This is the purpose of the *Think–Pair–Share* questions.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

Think–Pair–Share

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

- Outline the steps for an experimental procedure to determine the specific heat capacity of the metal using the available equipment and supplies.
- Identify possible sources of error in your experimental procedure that might cause an inaccurate result. (Assume the graduated cylinder and thermometer are both accurate and precise, and that human error is not a source of error.)
- Suggest some ideas for how to correct for some of these error sources.

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



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

- Define the system and the surroundings for this experiment.
 - Does energy as heat (q) flow into the system or out of the system? What is the sign of q ?
 - Is work (w) done in this experiment? If so, is work done by the system on the surroundings, or by the surroundings on the system? What is the sign of w ?
- The following table shows the enthalpy of combustion for some fuels in units of kJ/mol , kJ/L , and kJ/g . The enthalpy of combustion per volume assumes a temperature of $25\text{ }^\circ\text{C}$ and atmospheric pressure (1 atm). Note that although gasoline is a mixture of many hydrocarbons, it is often represented as octane.

Fuel	ΔH° (kJ/mol)	ΔH° (kJ/L)	ΔH° (kJ/g)
Hydrogen, $\text{H}_2(\text{g})$	−285.8	−11.7	−141.8
Methane, $\text{CH}_4(\text{g})$	−890.2	−36.4	−55.5
Ethane, $\text{C}_2\text{H}_6(\text{g})$	−1560.6	−63.8	−51.9
Ethanol, $\text{C}_2\text{H}_5\text{O}(\ell)$	−1376.5	−23,590	−29.9
Octane, $\text{C}_8\text{H}_{18}(\ell)$	−5490	−33,814	−48.1

- When determining which fuel provides the most energy in a car engine, is it best to compare the enthalpy change in a combustion reaction by moles, volume, or mass? Explain your reasoning? Based on your decision, which fuel provides the most energy (at the given temperature and pressure)?
- Gasoline sold in the United States is often a blend of 10%, 15%, or even up to 85% ethanol by volume. Identify at least one advantage and one disadvantage of using gasoline blended with ethanol versus ethanol-free gasoline?
- Why are the enthalpies of combustion per liter of hydrogen, methane, and ethane much lower than those of ethanol and octane?
- The enthalpy of combustion of hydrogen per gram is nearly three times that of a hydrocarbon. And unlike a hydrocarbon, which produces the greenhouse gas CO_2 upon combustion, the combustion of hydrogen produces only water. Unfortunately, there are multiple issues in replacing gasoline with hydrogen as a fuel. What are some of the problems that must be overcome if hydrogen is to compete with, or possibly replace, gasoline as a fuel in vehicles?

Chemistry in Your Career

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

students that they have a place in chemistry and STEM courses.

Redesigned Strategy Maps

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

Example 4.1

Strategy Map

Problem

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

Data/Information

Formulas for reactants and products and the mass of one reactant (glucose)

Mass Relations in Chemical Reactions

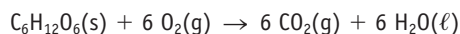
Problem Glucose, $C_6H_{12}O_6$, reacts with oxygen to give CO_2 and H_2O . What mass of oxygen (in grams) is required to completely react with 25.0 g of glucose? What masses of carbon dioxide and water (in grams) are formed?

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

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

Solution

Step 1 Write the balanced equation.



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

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

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

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

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

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

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

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

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

Some of the Other Changes for This Edition

- Recent changes to the definitions of the SI Base Units are explained in a new *Closer Look* box (page 34).
- The atomic weights of the elements on the periodic tables and other tables have been updated based on values from the International Union of Pure and Applied Chemistry (IUPAC) and the National Institute of Standards and Technology (NIST).
- The issue of ranges being recommended by IUPAC for the atomic weights of some elements is discussed in a new *Closer Look* box (page 70).
- References to element groups in the periodic table are now given in both the traditional system used in the United States (Group 5A, for example) and the 1–18 system recommended by IUPAC.
- Biographies of some important scientists and their discoveries have been prepared (Marie Curie [page 82]; Antoine and Marie-Anne Lavoisier [page 141]; Niels Bohr [page 314]; James Watson, Francis Crick, and Rosalind Franklin [page 439]; and Lise Meitner [page 1020]).
- A new subsection “Naming Common Acids” (page 157) was added.
- The classification scheme for acid–base and gas-forming acid–base reactions (Sections 3.6–3.7) has been revised as well as the overall classification scheme of reactions in aqueous solution (Section 3.9).
- A *Closer Look* box (page 208) on nuclear magnetic resonance spectroscopy has been added.
- A greater distinction between heat capacity and specific heat capacity was made in Chapter 5.
- A new *Closer Look* box “Enthalpy, Internal Energy and Non-Expansion Work” (page 270) was added.
- A new *Problem-Solving Tip* (page 355) was included about the different methods used for writing the electron configuration of an atom.
- Chapter 8, “Bonding and Molecular Structure,” was restructured.
- The story of the unraveling of the structure of DNA was expanded in Chapter 8.
- Two *Closer Look* boxes were added in Chapter 12, one on using X-rays to determine crystal structure and the other about glass.
- The positions of the chapters about nuclear chemistry (Chapter 20 in the current edition) and environmental chemistry (Chapter 25) were swapped so that information about nuclear chemistry can inform the content of later chapters and so that the chapter on

environmental chemistry can serve as an overarching conclusion to the book.

- A new *Closer Look* box about radioactive decay series (page 997) was added to Chapter 20.
- The section on the origin of the elements (in Chapter 20, “Nuclear Chemistry”) was expanded and revised.
- In Chapter 24, “Biochemistry,” new material has been added on mRNA vaccines, electron carriers in biochemical oxidation–reduction reactions, and the metabolism of glucose in respiration.
- Chapter 25, “Environmental Chemistry—Earth’s Environment, Energy, and Sustainability” has been updated and reorganized.
- All *Examples* have been reviewed, some have been revised to make the steps of the strategy clearer, and nine new *Examples* were written (*Example R.3* “Precision and Standard Deviation;” *Example 2.5* “Binary Molecular Compounds;” *Example 2.8* “Naming Ionic Compounds;” *Example 3.5* “Separating a Mixture by Selective Precipitation;” *Example 3.9* “Recognizing Oxidation–Reduction Reactions;” *Example 4.3* “Calculating Percent Yield;” *Example 4.8* “Relating Amount and Molarity;” *Example 4.12* “Acid–Base Titration;” and *Example 6.6* “Orbitals and Quantum Numbers”).
- There are now over 2650 *Study Questions* in the book. Of these, over 360 are either new or revised in this edition.
- All appendices have been updated to ensure they contain the latest information.
- Appendix N, “Answers to Study Questions, Check Your Understanding, and Applying Chemical Principles Questions,” has been accuracy checked by the book authors and the author of the *Student Solutions Manual*, Professor Charles Atwood.
- An *Index of Names* has been added so readers can find the contributions of generations of chemists.

Features of the Book

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

Problem-Solving Approach: Organization and Strategy Maps

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

Problem: A statement of the problem.

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

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

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

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

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

Chapter Goals Revisited

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

End-of-Chapter Study Questions

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

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

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

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

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

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

A Closer Look Essays and Problem-Solving Tips

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

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

Applying Chemical Principles

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

Online Learning

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

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

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

Acknowledgments

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

Cengage

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

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

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

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

Art, Design, and Photography

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

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

Other Collaborators

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

Eleventh Edition Reviewers

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

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

About the Authors

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

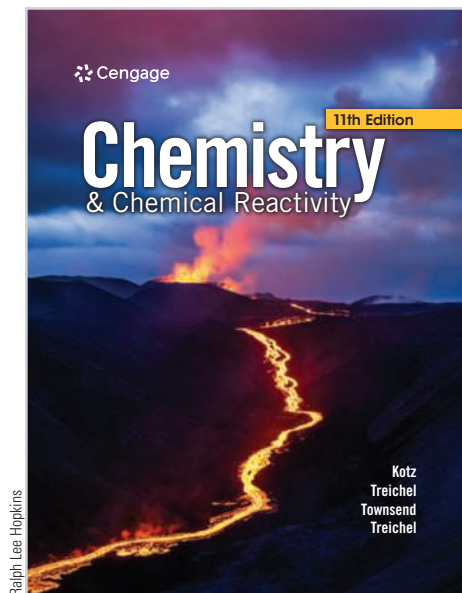
Paul M. Treichel received his B.S. degree from the University of Wisconsin in 1958 and a Ph.D. from Harvard University in 1962. After a year of postdoctoral study in London, he assumed a faculty position at the University of Wisconsin–Madison. He served as department chair from 1986 through 1995 and was awarded a Helfaer Professorship in 1996. He has held visiting faculty positions in South Africa (1975) and in Japan (1995). Retiring after 44 years as a faculty member in 2007, he is currently

Emeritus Professor of Chemistry. During his faculty career he taught courses in general chemistry, inorganic chemistry, organometallic chemistry, and scientific ethics. Professor Treichel's research in organometallic and metal-cluster chemistry and in mass spectrometry, aided by 75 graduate and undergraduate students, has led to more than 170 papers in scientific journals. He may be contacted by email at treichelpaul@me.com.

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

David A. Treichel, Professor of Chemistry at Nebraska Wesleyan University, received a B.A. degree from Carleton College. He earned a M.S. and a Ph.D. in analytical chemistry at Northwestern University. After postdoctoral research at the University of Texas in Austin, he joined the faculty at Nebraska Wesleyan University. His research interests are in the fields of electrochemistry and surface laser spectroscopy. He may be contacted by email at dat@nebrwesleyan.edu.

About the Cover



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

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

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

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

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

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

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

Dedication

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

1

Basic Concepts of Chemistry



Dnsphotography/iStock/Getty Images

Chapter Outline

- 1.1 Chemistry and Its Methods
- 1.2 Sustainability and Green Chemistry
- 1.3 Classifying Matter
- 1.4 Elements
- 1.5 Compounds
- 1.6 Properties and Changes
- 1.7 Energy: Some Basic Principles

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

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

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

1.1 Chemistry and Its Methods

Goal for Section 1.1

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

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

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

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

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

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

Perhaps most importantly, scientists across multiple disciplines are studying ways to slow climate change. Increasing levels of carbon dioxide, methane, and other greenhouse gases are changing the conditions on earth, both on land and in the oceans (“Applying Chemical Principles 1.1: CO₂ in the Oceans,” page 21). It is accepted by the scientific community that significant changes to the environment will continue to occur if greenhouse gas emissions are not reduced. Some hope comes from sequestering greenhouse gases (“Applying Chemical Principles 3.2: Sequestering Carbon Dioxide,” page 177) and reducing our reliance on fossil fuels (“Applying Chemical Principles 5.2: The Fuel Controversy—Alcohol and Gasoline,” page 287). The environment is so important that an entire chapter (Chapter 25) is devoted to the subject.

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

Chemistry and Change

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

Methods of Science

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

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

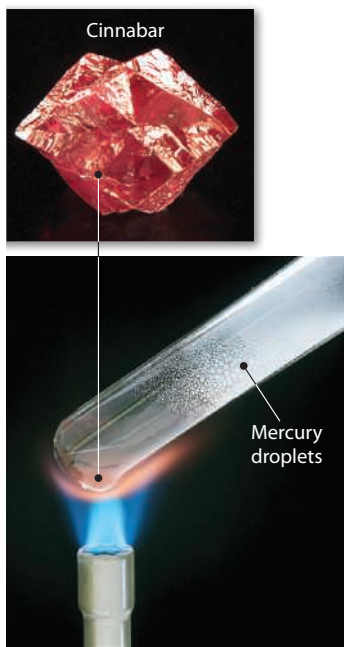
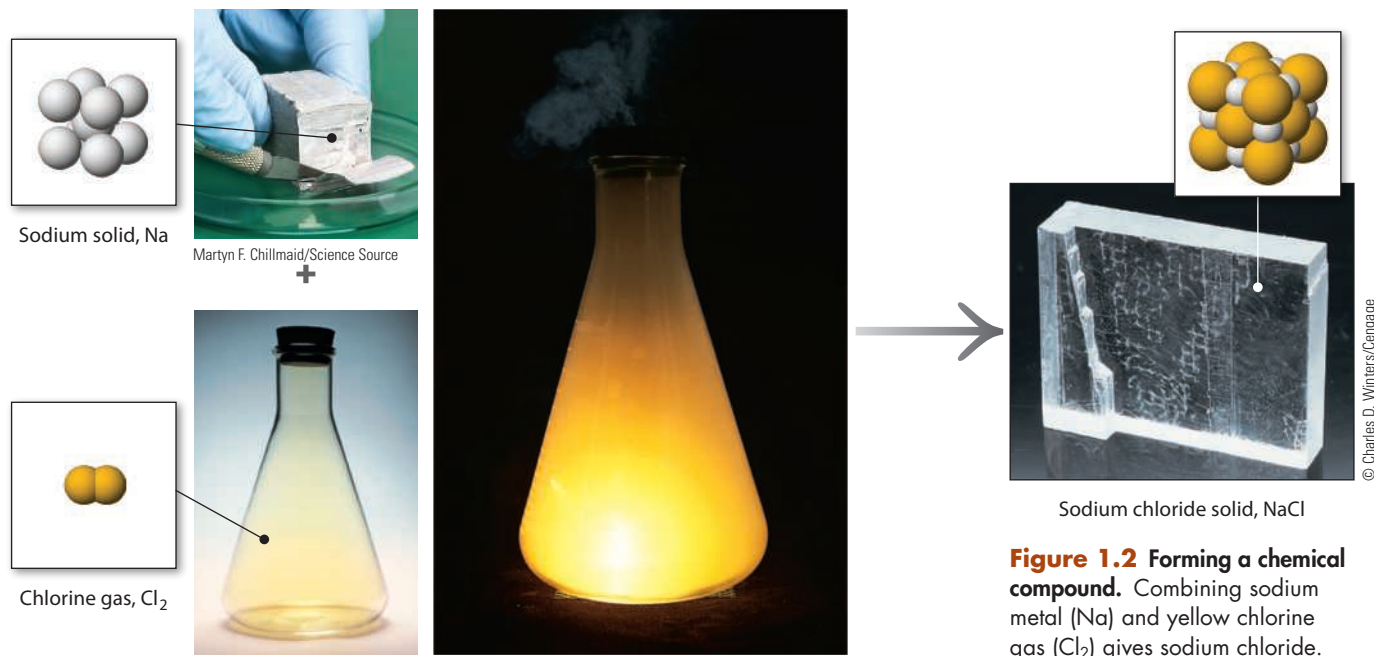


Figure 1.1 Cinnabar and mercury. Heating cinnabar (mercury(II) sulfide) in air changes it into orange mercury(III) oxide, which, upon further heating, decomposes into the elements mercury and oxygen gas.



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

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

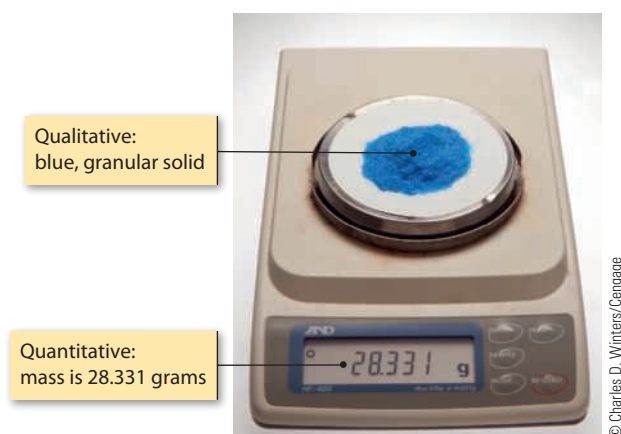


Figure 1.3 Qualitative and quantitative observations. Weighing a compound on a laboratory balance.



© Charles D. Winters/Cengage

Figure 1.4 The metallic element sodium reacts with water.

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

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

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

Goals of Science

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

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

Dilemmas and Integrity in Science

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

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

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



Darius Z. Brown

Darius Z. Brown

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

Missing something in his industry work, Brown returned to school to become a high school chemistry teacher. “Having a solid educational background in chemistry, along with

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

1.2 Sustainability and Green Chemistry

Goal for Section 1.2

- Understand the principles of green chemistry.

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

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

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

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

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



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

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

1.3 Classifying Matter

Goals for Section 1.3

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

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

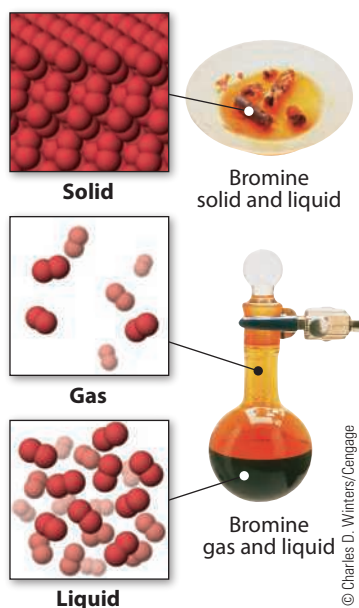


Figure 1.5 States of matter—solid, liquid, and gas. Elemental bromine exists in all three states near room temperature.

States of Matter and Kinetic-Molecular Theory

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

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

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

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

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

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

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

Matter at the Macroscopic and Particulate Levels

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

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

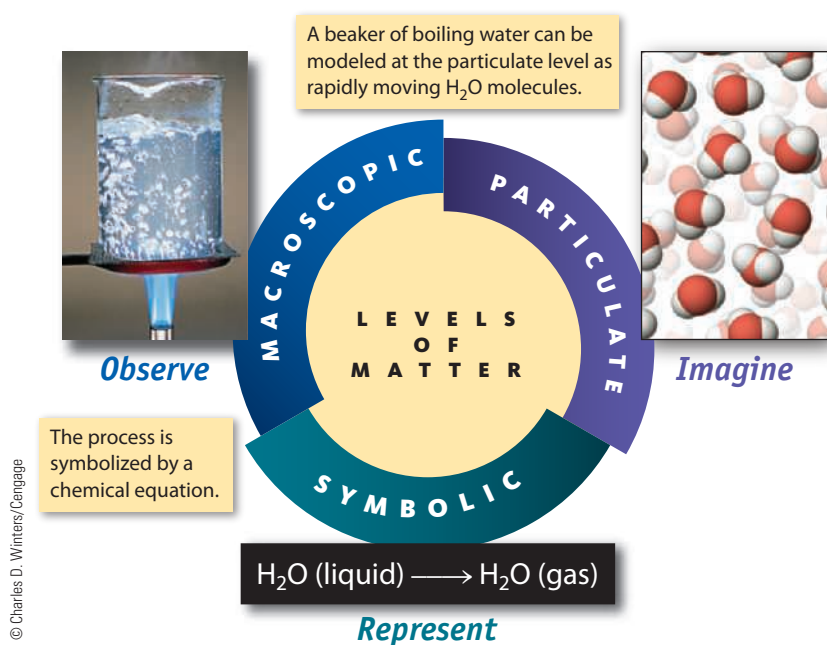


Figure 1.6 Levels of matter. Chemical and physical processes are observed at the macroscopic level. To understand or illustrate these processes, scientists often imagine what has occurred at the particulate atomic and molecular levels and write symbols to represent these observations.