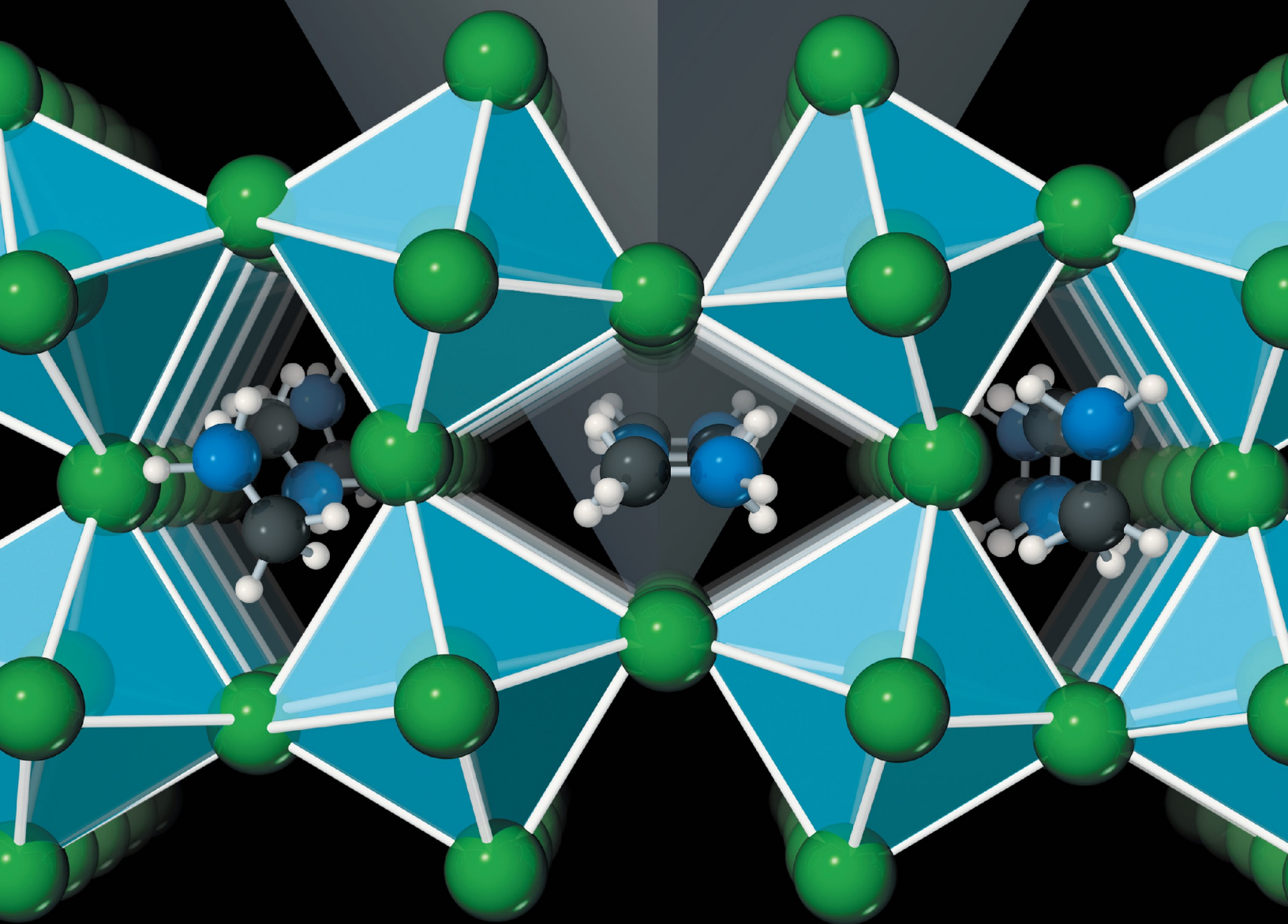


BROWN LEMAY BURSTEN MURPHY WOODWARD STOLTZFUS

# CHEMISTRY

THE CENTRAL SCIENCE

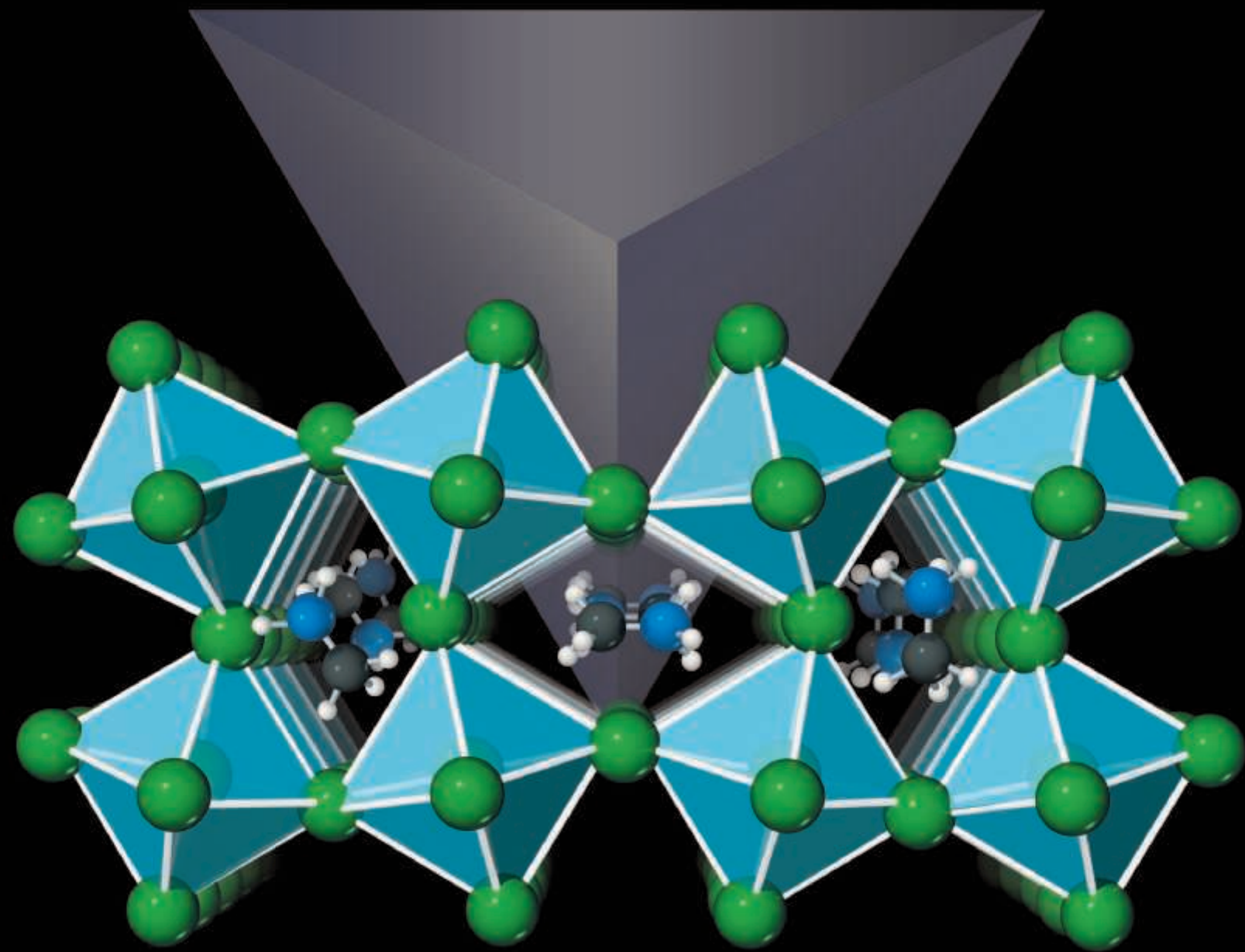


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The halide perovskites, exemplified by methylammonium lead iodide ( $\text{CH}_3\text{NH}_3\text{PbI}_3$ ), whose structure is shown on the front cover, have emerged in recent years as alternatives to conventional semiconductors like silicon, gallium arsenide, and cadmium selenide. These materials show tremendous potential for use in devices such as light-emitting diodes and radiation detectors, but no application has generated more excitement than their performance in solar cells. Scientists have been able to prepare halide perovskite-based solar cells that convert sunlight to electricity with 20% efficiency, a figure comparable to the best silicon solar cells on the market. While the high efficiencies are impressive, the truly revolutionary breakthrough is that halide perovskite solar cells can be made from solution using inexpensive, readily available laboratory equipment, whereas fabrication of solar cells from conventional semiconductors requires expensive, sophisticated facilities. Chemists are actively researching alternative perovskite materials that do not contain lead and are less prone to degradation upon exposure to moist air.

# CHEMISTRY

THE CENTRAL SCIENCE 14<sup>TH</sup> EDITION

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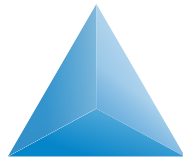
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To our students,  
whose enthusiasm and curiosity  
have often inspired us,  
and whose questions and suggestions  
have sometimes taught us.

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# BRIEF CONTENTS

## PREFACE xxiii

- 1** Introduction: Matter, Energy, and Measurement 2
- 2** Atoms, Molecules, and Ions 42
- 3** Chemical Reactions and Reaction Stoichiometry 82
- 4** Reactions in Aqueous Solution 120
- 5** Thermochemistry 162
- 6** Electronic Structure of Atoms 212
- 7** Periodic Properties of the Elements 256
- 8** Basic Concepts of Chemical Bonding 298
- 9** Molecular Geometry and Bonding Theories 338
- 10** Gases 394
- 11** Liquids and Intermolecular Forces 434
- 12** Solids and Modern Materials 472
- 13** Properties of Solutions 524
- 14** Chemical Kinetics 568
- 15** Chemical Equilibrium 622
- 16** Acid–Base Equilibria 664
- 17** Additional Aspects of Aqueous Equilibria 716
- 18** Chemistry of the Environment 766
- 19** Chemical Thermodynamics 806
- 20** Electrochemistry 848
- 21** Nuclear Chemistry 900
- 22** Chemistry of the Nonmetals 942
- 23** Transition Metals and Coordination Chemistry 986
- 24** The Chemistry of Life: Organic and Biological Chemistry 1030

## APPENDICES

- A** Mathematical Operations 1080
- B** Properties of Water 1087
- C** Thermodynamic Quantities for Selected Substances at 298.15 K (25 °C) 1088
- D** Aqueous Equilibrium Constants 1092
- E** Standard Reduction Potentials at 25 °C 1094

**ANSWERS TO SELECTED EXERCISES** A-1

**ANSWERS TO GIVE IT SOME THOUGHT** A-31

**ANSWERS TO GO FIGURE** A-37

**ANSWERS TO SELECTED PRACTICE EXERCISES** A-43

**GLOSSARY** G-1

**PHOTO AND ART CREDITS** P-1


**INDEX** I-1



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# CONTENTS

## PREFACE xxiii



# 1 Introduction: Matter, Energy, and Measurement 2

- 1.1 The Study of Chemistry 4**  
The Atomic and Molecular Perspective of Chemistry 4  
Why Study Chemistry? 5
- 1.2 Classifications of Matter 7**  
States of Matter 7 Pure Substances 7  
Elements 8 Compounds 9 Mixtures 10
- 1.3 Properties of Matter 12**  
Physical and Chemical Changes 12 Separation of  
Mixtures 13
- 1.4 The Nature of Energy 15**  
Kinetic Energy and Potential Energy 15
- 1.5 Units of Measurement 17**  
SI Units 17 Length and Mass 19  
Temperature 19 Derived SI Units 20 Volume 20  
Density 21 Units of Energy 21
- 1.6 Uncertainty in Measurement 24**  
Precision and Accuracy 24 Significant Figures 25  
Significant Figures in Calculations 26
- 1.7 Dimensional Analysis 28**  
Conversion Factors 28 Using Two or More Conversion  
Factors 30 Conversions Involving Volume 31  
**Chapter Summary and Key Terms 33**  
**Learning Outcomes 34 Key Equations 34**  
**Exercises 35 Additional Exercises 39**

**Chemistry Put to Work** Chemistry and the Chemical Industry 6

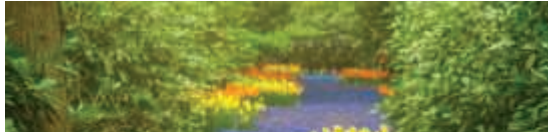
**A Closer Look** The Scientific Method 17

**Chemistry Put to Work** Chemistry in the News 23

**Strategies for Success** Estimating Answers 30

**Strategies for Success** The Importance of Practice 32

**Strategies for Success** The Features of This Book 32



# 2 Atoms, Molecules, and Ions 42

- 2.1 The Atomic Theory of Matter 44**
- 2.2 The Discovery of Atomic Structure 45**  
Cathode Rays and Electrons 45 Radioactivity 47  
The Nuclear Model of the Atom 48
- 2.3 The Modern View of Atomic Structure 49**  
Atomic Numbers, Mass Numbers, and Isotopes 51
- 2.4 Atomic Weights 53**  
The Atomic Mass Scale 53 Atomic Weight 53
- 2.5 The Periodic Table 55**
- 2.6 Molecules and Molecular Compounds 58**  
Molecules and Chemical Formulas 58 Molecular and  
Empirical Formulas 58 Picturing Molecules 59
- 2.7 Ions and Ionic Compounds 60**  
Predicting Ionic Charges 61 Ionic Compounds 62
- 2.8 Naming Inorganic Compounds 65**  
Names and Formulas of Ionic Compounds 65  
Names and Formulas of Acids 69 Names and  
Formulas of Binary Molecular Compounds 70
- 2.9 Some Simple Organic Compounds 71**  
Alkanes 71 Some Derivatives of Alkanes 72  
**Chapter Summary and Key Terms 74**  
**Learning Outcomes 74 Key Equations 75**  
**Exercises 75 Additional Exercises 80**

---

**A Closer Look** Basic Forces 51

**A Closer Look** The Mass Spectrometer 54

**A Closer Look** What Are Coins Made Of? 57

**Chemistry and Life** Elements Required by Living Organisms 64

**Strategies for Success** How to Take a Test 73



## 3 Chemical Reactions and Reaction Stoichiometry 82

### 3.1 Chemical Equations 84

Balancing Equations 84 A Step-by-Step Example of Balancing a Chemical Equation 85 Indicating the States of Reactants and Products 87

### 3.2 Simple Patterns of Chemical Reactivity 88

Combination and Decomposition Reactions 88 Combustion Reactions 90

### 3.3 Formula Weights 90

Formula and Molecular Weights 91 Percentage Composition from Chemical Formulas 92

### 3.4 Avogadro's Number and the Mole 93

Molar Mass 94 Interconverting Masses and Moles 96 Interconverting Masses and Numbers of Particles 97

### 3.5 Empirical Formulas from Analyses 98

Molecular Formulas from Empirical Formulas 100 Combustion Analysis 101

### 3.6 Quantitative Information from Balanced Equations 102

### 3.7 Limiting Reactants 106

Theoretical and Percent Yields 108

**Chapter Summary and Key Terms 110**  
**Learning Outcomes 110 Key Equations 110**  
**Exercises 111 Additional Exercises 117**  
**Integrative Exercises 118 Design an Experiment 119**

**Strategies for Success** Problem Solving 92

**Chemistry and Life** Glucose Monitoring 96

**Strategies for Success** Design an Experiment 109



## 4 Reactions in Aqueous Solution 120

### 4.1 General Properties of Aqueous Solutions 122

Electrolytes and Nonelectrolytes 122

How Compounds Dissolve in Water 123 Strong and Weak Electrolytes 124

### 4.2 Precipitation Reactions 126

Solubility Guidelines for Ionic Compounds 126 Exchange (Metathesis) Reactions 127 Ionic Equations and Spectator Ions 129

### 4.3 Acids, Bases, and Neutralization Reactions 130

Acids 130 Bases 131 Strong and Weak Acids and Bases 132 Identifying Strong and Weak Electrolytes 132 Neutralization Reactions and Salts 134 Neutralization Reactions with Gas Formation 136

### 4.4 Oxidation-Reduction Reactions 137

Oxidation and Reduction 137 Oxidation Numbers 138 Oxidation of Metals by Acids and Salts 140 The Activity Series 141

### 4.5 Concentrations of Solutions 144

Molarity 144 Expressing the Concentration of an Electrolyte 145 Interconverting Molarity, Moles, and Volume 146 Dilution 147

### 4.6 Solution Stoichiometry and Chemical Analysis 148

Titration 150

**Chapter Summary and Key Terms 153**

**Learning Outcomes 154 Key Equations 154**

**Exercises 154 Additional Exercises 159**

**Integrative Exercises 160 Design an Experiment 161**

**Chemistry Put to Work** Antacids 136

**Strategies for Success** Analyzing Chemical Reactions 144



## 5 Thermochemistry 162

### 5.1 The Nature of Chemical Energy 164

### 5.2 The First Law of Thermodynamics 166

System and Surroundings 166 Internal Energy 167 Relating  $\Delta E$  to Heat and Work 168 Endothermic and Exothermic Processes 170 State Functions 170

### 5.3 Enthalpy 172


Pressure-Volume Work 172 Enthalpy Change 174

### 5.4 Enthalpies of Reaction 176

### 5.5 Calorimetry 178

Heat Capacity and Specific Heat 179 Constant-Pressure Calorimetry 180 Bomb Calorimetry (Constant-Volume Calorimetry) 182

- 5.6 Hess's Law** 183
- 5.7 Enthalpies of Formation** 186  
Using Enthalpies of Formation to Calculate Enthalpies of Reaction 188
- 5.8 Bond Enthalpies** 190  
Bond Enthalpies and the Enthalpies of Reactions 192
- 5.9 Foods and Fuels** 194  
Foods 194 Fuels 196 Other Energy Sources 197
- Chapter Summary and Key Terms** 200  
**Learning Outcomes** 201 **Key Equations** 201  
**Exercises** 202 **Additional Exercises** 208  
**Integrative Exercises** 210 **Design an Experiment** 211
- 
- A Closer Look** Energy, Enthalpy, and *P-V* Work 175
- A Closer Look** Using Enthalpy as a Guide 178
- Chemistry and Life** The Regulation of Body Temperature 183
- Chemistry Put to Work** The Scientific and Political Challenges of Biofuels 198



## 6 Electronic Structure of Atoms 212

- 6.1 The Wave Nature of Light** 214
- 6.2 Quantized Energy and Photons** 216  
Hot Objects and the Quantization of Energy 216  
The Photoelectric Effect and Photons 217
- 6.3 Line Spectra and the Bohr Model** 219  
Line Spectra 219 Bohr's Model 220 The Energy States of the Hydrogen Atom 221 Limitations of the Bohr Model 224
- 6.4 The Wave Behavior of Matter** 224  
The Uncertainty Principle 226
- 6.5 Quantum Mechanics and Atomic Orbitals** 227  
Orbitals and Quantum Numbers 228
- 6.6 Representations of Orbitals** 231  
The *s* Orbitals 231 The *p* Orbitals 233 The *d* and *f* Orbitals 234
- 6.7 Many-Electron Atoms** 234  
Orbitals and Their Energies 235 Electron Spin and the Pauli Exclusion Principle 236
- 6.8 Electron Configurations** 236  
Hund's Rule 238 Condensed Electron Configurations 240 Transition Metals 240  
The Lanthanides and Actinides 241

- 6.9 Electron Configurations and the Periodic Table** 241  
Anomalous Electron Configurations 244  
**Chapter Summary and Key Terms** 246  
**Learning Outcomes** 247 **Key Equations** 248  
**Exercises** 248 **Additional Exercises** 253  
**Integrative Exercises** 255 **Design an Experiment** 255

- 
- A Closer Look** Measurement and the Uncertainty Principle 226
- A Closer Look** Thought Experiments and Schrödinger's Cat 229
- A Closer Look** Probability Density and Radial Probability Functions 233
- Chemistry and Life** Nuclear Spin and Magnetic Resonance Imaging 237



## 7 Periodic Properties of the Elements 256

- 7.1 Development of the Periodic Table** 258
- 7.2 Effective Nuclear Charge** 259
- 7.3 Sizes of Atoms and Ions** 262  
Periodic Trends in Atomic Radii 264 Periodic Trends in Ionic Radii 264
- 7.4 Ionization Energy** 268  
Variations in Successive Ionization Energies 268  
Periodic Trends in First Ionization Energies 269  
Electron Configurations of Ions 270
- 7.5 Electron Affinity** 272  
Periodic Trends in Electron Affinity 273
- 7.6 Metals, Nonmetals, and Metalloids** 273  
Metals 274 Nonmetals 276 Metalloids 278
- 7.7 Trends for Group 1A and Group 2A Metals** 278  
Group 1A: The Alkali Metals 278 Group 2A: The Alkaline Earth Metals 282
- 7.8 Trends for Selected Nonmetals** 283  
Hydrogen 283 Group 6A: The Oxygen Group 284  
Group 7A: The Halogens 285 Group 8A: The Noble Gases 287
- Chapter Summary and Key Terms** 288  
**Learning Outcomes** 289 **Key Equations** 289  
**Exercises** 290 **Additional Exercises** 294

**Integrative Exercises 296 Design an Experiment 297**

**A Closer Look** Effective Nuclear Charge 262

**Chemistry Put to Work** Ionic Size and Lithium-Ion Batteries 267

**Chemistry and Life** The Improbable Development of Lithium Drugs 281



## 8 Basic Concepts of Chemical Bonding 298

**8.1 Lewis Symbols and the Octet Rule 300**  
The Octet Rule 300

**8.2 Ionic Bonding 301**  
Energetics of Ionic Bond Formation 302 Electron Configurations of Ions of the *s*- and *p*-Block Elements 304 Transition Metal Ions 305

**8.3 Covalent Bonding 306**  
Lewis Structures 307 Multiple Bonds 308

**8.4 Bond Polarity and Electronegativity 309**  
Electronegativity 309 Electronegativity and Bond Polarity 310 Dipole Moments 311 Comparing Ionic and Covalent Bonding 314

**8.5 Drawing Lewis Structures 315**  
Formal Charge and Alternative Lewis Structures 317

**8.6 Resonance Structures 319**  
Resonance in Benzene 321

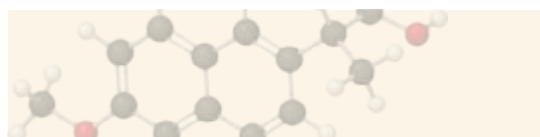
**8.7 Exceptions to the Octet Rule 322**  
Odd Number of Electrons 323 Less Than an Octet of Valence Electrons 323 More Than an Octet of Valence Electrons 324

**8.8 Strengths and Lengths of Covalent Bonds 325**

**Chapter Summary and Key Terms 328**  
**Learning Outcomes 329 Key Equations 329**  
**Exercises 329 Additional Exercises 334**  
**Integrative Exercises 335 Design an Experiment 337**

**A Closer Look** Calculation of Lattice Energies: The Born–Haber Cycle 305

**A Closer Look** Oxidation Numbers, Formal Charges, and Actual Partial Charges 319



## 9 Molecular Geometry and Bonding Theories 338

**9.1 Molecular Shapes 340**

**9.2 The VSEPR Model 342**

Applying the VSEPR Model to Determine Molecular Shapes 343 Effect of Nonbonding Electrons and Multiple Bonds on Bond Angles 347 Molecules with Expanded Valence Shells 347 Shapes of Larger Molecules 350

**9.3 Molecular Shape and Molecular Polarity 352**

**9.4 Covalent Bonding and Orbital Overlap 354**

**9.5 Hybrid Orbitals 355**

*sp* Hybrid Orbitals 355 *sp*<sup>2</sup> and *sp*<sup>3</sup> Hybrid Orbitals 357 Hypervalent Molecules 359 Hybrid Orbital Summary 359

**9.6 Multiple Bonds 361**

Resonance Structures, Delocalization, and  $\pi$  Bonding 365 General Conclusions about  $\sigma$  and  $\pi$  Bonding 367

**9.7 Molecular Orbitals 368**

Molecular Orbitals of the Hydrogen Molecule 368 Bond Order 370

**9.8 Bonding in Period 2 Diatomic Molecules 371**

Molecular Orbitals for Li<sub>2</sub> and Be<sub>2</sub> 372 Molecular Orbitals from 2*p* Atomic Orbitals 373 Electron Configurations for B<sub>2</sub> through Ne<sub>2</sub> 376 Electron Configurations and Molecular Properties 377 Heteronuclear Diatomic Molecules 380

**Chapter Summary and Key Terms 382**  
**Learning Outcomes 383 Key Equations 384**  
**Exercises 384 Additional Exercises 389**  
**Integrative Exercises 392 Design an Experiment 393**

**Chemistry and Life** The Chemistry of Vision 367

**A Closer Look** Phases in Atomic and Molecular Orbitals 374

**Chemistry Put to Work** Orbitals and Energy 381



# 10 Gases 394


- 10.1 Characteristics of Gases** 396
- 10.2 Pressure** 397  
Atmospheric Pressure and the Barometer 397
- 10.3 The Gas Laws** 400  
The Pressure–Volume Relationship: Boyle’s Law 400  
The Temperature–Volume Relationship: Charles’s Law 401 The Quantity–Volume Relationship: Avogadro’s Law 402
- 10.4 The Ideal-Gas Equation** 403  
Relating the Ideal-Gas Equation and the Gas Laws 406
- 10.5 Further Applications of the Ideal-Gas Equation** 407  
Gas Densities and Molar Mass 407 Volumes of Gases in Chemical Reactions 409
- 10.6 Gas Mixtures and Partial Pressures** 410  
Partial Pressures and Mole Fractions 411
- 10.7 The Kinetic-Molecular Theory of Gases** 412  
Distributions of Molecular Speed 413 Application of Kinetic-Molecular Theory to the Gas Laws 414
- 10.8 Molecular Effusion and Diffusion** 415  
Graham’s Law of Effusion 416 Diffusion and Mean Free Path 417
- 10.9 Real Gases: Deviations from Ideal Behavior** 419  
The van der Waals Equation 421

**Chapter Summary and Key Terms** 423  
**Learning Outcomes** 424 **Key Equations** 424  
**Exercises** 424 **Additional Exercises** 430  
**Integrative Exercises** 432 **Design an Experiment** 433

**Strategies for Success** Calculations Involving Many Variables 405

**A Closer Look** The Ideal-Gas Equation 414

**Chemistry Put to Work** Gas Separations 418




# 11 Liquids and Intermolecular Forces 434

- 11.1 A Molecular Comparison of Gases, Liquids, and Solids** 436
- 11.2 Intermolecular Forces** 438  
Dispersion Forces 439 Dipole–Dipole Interactions 440 Hydrogen Bonding 441 Ion–Dipole Forces 444 Comparing Intermolecular Forces 444
- 11.3 Select Properties of Liquids** 445  
Viscosity 446 Surface Tension 447 Capillary Action 448
- 11.4 Phase Changes** 449  
Energy Changes Accompany Phase Changes 449 Heating Curves 450 Critical Temperature and Pressure 451
- 11.5 Vapor Pressure** 453  
Volatility, Vapor Pressure, and Temperature 454 Vapor Pressure and Boiling Point 455
- 11.6 Phase Diagrams** 456  
The Phase Diagrams of H<sub>2</sub>O and CO<sub>2</sub> 457
- 11.7 Liquid Crystals** 459  
Types of Liquid Crystals 459
- Chapter Summary and Key Terms** 462 **Learning Outcomes** 463 **Exercises** 463 **Additional Exercises** 468 **Integrative Exercises** 470 **Design an Experiment** 471

**Chemistry Put to Work** Ionic Liquids 447

**A Closer Look** The Clausius–Clapeyron Equation 455



# 12 Solids and Modern Materials 472

- 12.1 Classification of Solids** 474
- 12.2 Structures of Solids** 475  
Crystalline and Amorphous Solids 475 Unit Cells and Crystal Lattices 475 Filling the Unit Cell 477

- 12.3 Metallic Solids 478**  
The Structures of Metallic Solids 479 Close Packing 480 Alloys 483
- 12.4 Metallic Bonding 486**  
Electron-Sea Model 486 Molecular Orbital Model 487
- 12.5 Ionic Solids 489**  
Structures of Ionic Solids 490
- 12.6 Molecular Solids 494**
- 12.7 Covalent-Network Solids 494**  
Semiconductors 495 Semiconductor Doping 497
- 12.8 Polymers 500**  
Making Polymers 501 Structure and Physical Properties of Polymers 504
- 12.9 Nanomaterials 506**  
Semiconductors on the Nanoscale 506 Metals on the Nanoscale 507 Carbon on the Nanoscale 509
- Chapter Summary and Key Terms 512**  
**Learning Outcomes 513 Key Equations 513**  
**Exercises 514 Additional Exercises 521**  
**Integrative Exercises 522 Design an Experiment 523**

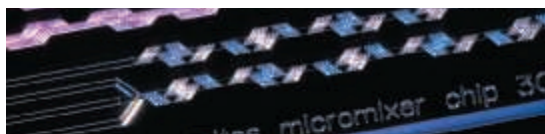
**A Closer Look** X-ray Diffraction 478

**Chemistry Put to Work** Alloys of Gold 485

**Chemistry Put to Work** Solid-State Lighting 499

**Chemistry Put to Work** Modern Materials in the Automobile 503

**Chemistry Put to Work** Microporous and Mesoporous Materials 508



## 13 Properties of Solutions 524

- 13.1 The Solution Process 526**  
The Natural Tendency toward Mixing 526 The Effect of Intermolecular Forces on Solution Formation 527 Energetics of Solution Formation 528 Solution Formation and Chemical Reactions 530
- 13.2 Saturated Solutions and Solubility 530**
- 13.3 Factors Affecting Solubility 532**  
Solute–Solvent Interactions 532 Pressure Effects 534 Temperature Effects 537
- 13.4 Expressing Solution Concentration 538**  
Mass Percentage, ppm, and ppb 538 Mole Fraction, Molarity, and Molality 539 Converting Concentration Units 540

- 13.5 Colligative Properties 542**  
Vapor–Pressure Lowering 542 Boiling-Point Elevation 544 Freezing-Point Depression 545 Osmosis 547 Determination of Molar Mass from Colligative Properties 550
- 13.6 Colloids 552**  
Hydrophilic and Hydrophobic Colloids 553 Colloidal Motion in Liquids 555
- Chapter Summary and Key Terms 556**  
**Learning Outcomes 557 Key Equations 558**  
**Exercises 558 Additional Exercises 564**  
**Integrative Exercises 565 Design an Experiment 567**

**Chemistry and Life** Fat-Soluble and Water-Soluble Vitamins 533

**Chemistry and Life** Blood Gases and Deep-Sea Diving 537

**A Closer Look** Ideal Solutions with Two or More Volatile Components 544

**A Closer Look** The van't Hoff Factor 551

**Chemistry and Life** Sickle-Cell Anemia 555



## 14 Chemical Kinetics 568

- 14.1 Factors That Affect Reaction Rates 570**
- 14.2 Reaction Rates 571**  
Change of Rate with Time 572 Instantaneous Rate 573 Reaction Rates and Stoichiometry 574
- 14.3 Concentration and Rate Laws 575**  
Reaction Orders: The Exponents in the Rate Law 577 Magnitudes and Units of Rate Constants 579 Using Initial Rates to Determine Rate Laws 580
- 14.4 The Change of Concentration with Time 581**  
First-Order Reactions 581 Second-Order Reactions 583 Zero-Order Reactions 585 Half-Life 585
- 14.5 Temperature and Rate 587**  
The Collision Model 587 The Orientation Factor 588 Activation Energy 588 The Arrhenius Equation 590 Determining the Activation Energy 591
- 14.6 Reaction Mechanisms 593**  
Elementary Reactions 593 Multistep Mechanisms 593 Rate Laws for Elementary Reactions 595 The Rate-Determining Step for a Multistep Mechanism 596 Mechanisms with a Slow Initial Step 597 Mechanisms with a Fast Initial Step 598

**14.7 Catalysis 600**

Homogeneous Catalysis 600 Heterogeneous Catalysis 602 Enzymes 603

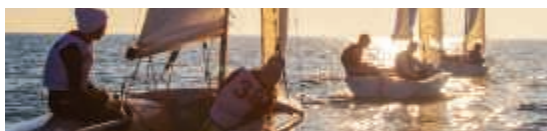
**Chapter Summary and Key Terms 608**  
**Learning Outcomes 608 Key Equations 609**  
**Exercises 609 Additional Exercises 617**  
**Integrative Exercises 620 Design an Experiment 621**

**A Closer Look** Using Spectroscopic Methods to Measure Reaction Rates: Beer's Law 576

**Chemistry Put to Work** Methyl Bromide in the Atmosphere 586

**Chemistry Put to Work** Catalytic Converters 604

**Chemistry and Life** Nitrogen Fixation and Nitrogenase 606

**15 Chemical Equilibrium 622****15.1 The Concept of Equilibrium 625****15.2 The Equilibrium Constant 627**

Evaluating  $K_c$  629 Equilibrium Constants in Terms of Pressure,  $K_p$  630 Equilibrium Constants and Units 631

**15.3 Understanding and Working with Equilibrium Constants 632**

The Magnitude of Equilibrium Constants 632  
 The Direction of the Chemical Equation and  $K$  633  
 Relating Chemical Equation Stoichiometry and Equilibrium Constants 634

**15.4 Heterogeneous Equilibria 636****15.5 Calculating Equilibrium Constants 638****15.6 Applications of Equilibrium Constants 640**

Predicting the Direction of Reaction 641 Calculating Equilibrium Concentrations 642

**15.7 Le Châtelier's Principle 644**

Change in Reactant or Product Concentration 646  
 Effects of Volume and Pressure Changes 647 Effect of Temperature Changes 649 The Effect of Catalysts 651

**Chapter Summary and Key Terms 654**  
**Learning Outcomes 655 Key Equations 655**  
**Exercises 656 Additional Exercises 661**  
**Integrative Exercises 662 Design an Experiment 663**

**Chemistry Put to Work** The Haber Process 628

**A Closer Look** Temperature Changes and Le Châtelier's Principle 651

**Chemistry Put to Work** Controlling Nitric Oxide Emissions 654

**16 Acid–Base Equilibria 664****16.1 Arrhenius Acids and Bases 666****16.2 Brønsted–Lowry Acids and Bases 667**

The  $H^+$  Ion in Water 667 Proton-Transfer Reactions 667 Conjugate Acid–Base Pairs 668 Relative Strengths of Acids and Bases 670

**16.3 The Autoionization of Water 672**

The Ion Product of Water 672

**16.4 The pH Scale 674**

pOH and Other “p” Scales 676 Measuring pH 677

**16.5 Strong Acids and Bases 678**

Strong Acids 678 Strong Bases 679

**16.6 Weak Acids 680**

Calculating  $K_a$  from pH 681 Percent Ionization 682 Using  $K_a$  to Calculate pH 683 Polyprotic Acids 687

**16.7 Weak Bases 690**

Types of Weak Bases 690

**16.8 Relationship between  $K_a$  and  $K_b$  693****16.9 Acid–Base Properties of Salt Solutions 696**

An Anion's Ability to React with Water 696  
 A Cation's Ability to React with Water 696  
 Combined Effect of Cation and Anion in Solution 697

**16.10 Acid–Base Behavior and Chemical Structure 699**

Factors That Affect Acid Strength 699 Binary Acids 700 Oxyacids 701 Carboxylic Acids 703

**16.11 Lewis Acids and Bases 704**

**Chapter Summary and Key Terms 707**  
**Learning Outcomes 707 Key Equations 708**  
**Exercises 708 Additional Exercises 713**  
**Integrative Exercises 715 Design an Experiment 715**

**A Closer Look** Polyprotic Acids 689

**Chemistry Put to Work** Amines and Amine Hydrochlorides 695

**Chemistry and Life** The Amphiprotic Behavior of Amino Acids 703





## 17 Additional Aspects of Aqueous Equilibria 716

- 17.1 The Common-Ion Effect** 718
- 17.2 Buffers** 721  
Composition and Action of Buffers 721 Calculating the pH of a Buffer 723 Buffer Capacity and pH Range 726 Addition of Strong Acids or Bases to Buffers 726
- 17.3 Acid–Base Titrations** 729  
Strong Acid–Strong Base Titrations 730 Weak Acid–Strong Base Titrations 732 Titrating with an Acid–Base Indicator 736 Titrations of Polyprotic Acids 738
- 17.4 Solubility Equilibria** 739  
The Solubility-Product Constant,  $K_{sp}$  740 Solubility and  $K_{sp}$  741
- 17.5 Factors That Affect Solubility** 743  
The Common-Ion Effect 743 Solubility and pH 744 Formation of Complex Ions 746 Amphoterism 749
- 17.6 Precipitation and Separation of Ions** 751  
Selective Precipitation of Ions 752
- 17.7 Qualitative Analysis for Metallic Elements** 753  
Chapter Summary and Key Terms 756  
Learning Outcomes 757 Key Equations 757  
Exercises 758 Additional Exercises 763  
Integrative Exercises 764 Design an Experiment 765

**Chemistry and Life** Blood as a Buffered Solution 729

**A Closer Look** Limitations of Solubility Products 743

**Chemistry and Life** Tooth Decay and Fluoridation 746

**A Closer Look** Lead Contamination in Drinking Water 750



## 18 Chemistry of the Environment 766

- 18.1 Earth's Atmosphere** 768  
Composition of the Atmosphere 769

Photochemical Reactions in the Atmosphere 770  
Ozone in the Stratosphere 773

### 18.2 Human Activities and Earth's Atmosphere 774

The Ozone Layer and Its Depletion 774 Sulfur Compounds and Acid Rain 776 Nitrogen Oxides and Photochemical Smog 779 Greenhouse Gases: Water Vapor, Carbon Dioxide, and Climate 780

### 18.3 Earth's Water 784

The Global Water Cycle 784 Salt Water: Earth's Oceans and Seas 785 Freshwater and Groundwater 786

### 18.4 Human Activities and Water Quality 787

Dissolved Oxygen and Water Quality 788 Water Purification: Desalination 788 Water Purification: Municipal Treatment 789

### 18.5 Green Chemistry 792

Supercritical Solvents 794 Greener Reagents and Processes 794

**Chapter Summary and Key Terms** 797

**Learning Outcomes** 797 **Exercises** 798

**Additional Exercises** 803 **Integrative**

**Exercises** 804 **Design an Experiment** 805

**A Closer Look** Other Greenhouse Gases 783

**A Closer Look** The Ogallala Aquifer—A Shrinking Resource 787

**A Closer Look** Fracking and Water Quality 790

**Chemistry and Life** Ocean Acidification 792



## 19 Chemical Thermodynamics 806

### 19.1 Spontaneous Processes 808

Seeking a Criterion for Spontaneity 809 Reversible and Irreversible Processes 810

### 19.2 Entropy and the Second Law of Thermodynamics 812

The Relationship between Entropy and Heat 812  $\Delta S$  for Phase Changes 813 The Second Law of Thermodynamics 814

### 19.3 The Molecular Interpretation of Entropy and the Third Law of Thermodynamics 815

Expansion of a Gas at the Molecular Level 815 Boltzmann's Equation and Microstates 816 Molecular Motions and Energy 818 Making Qualitative Predictions about  $\Delta S$  819 The Third Law of Thermodynamics 821

**19.4 Entropy Changes in Chemical Reactions 822**

Temperature Variation of Entropy 822 Standard Molar Entropies 823 Calculating the Standard Entropy Change for a Reaction 824 Entropy Changes in the Surroundings 824

**19.5 Gibbs Free Energy 825**

Standard Free Energy of Formation 828

**19.6 Free Energy and Temperature 830****19.7 Free Energy and the Equilibrium Constant 832**

Free Energy under Nonstandard Conditions 832 Relationship between  $\Delta G^\circ$  and  $K$  834

**Chapter Summary and Key Terms 836**  
**Learning Outcomes 837 Key Equations 837**  
**Exercises 838 Additional Exercises 844**  
**Integrative Exercises 846 Design an Experiment 847**

**A Closer Look** The Entropy Change When a Gas Expands Isothermally 814

**Chemistry and Life** Entropy and Human Society 822

**A Closer Look** What's "Free" About Free Energy? 829

**Chemistry and Life** Driving Nonspontaneous Reactions: Coupling Reactions 835

**20 Electrochemistry 848****20.1 Oxidation States and Oxidation–Reduction Reactions 850****20.2 Balancing Redox Equations 852**

Half-Reactions 852 Balancing Equations by the Method of Half-Reactions 852 Balancing Equations for Reactions Occurring in Basic Solution 855

**20.3 Voltaic Cells 857****20.4 Cell Potentials under Standard Conditions 860**

Standard Reduction Potentials 861 Strengths of Oxidizing and Reducing Agents 866

**20.5 Free Energy and Redox Reactions 868**

Emf, Free Energy, and the Equilibrium Constant 869

**20.6 Cell Potentials under Nonstandard Conditions 871**

The Nernst Equation 872 Concentration Cells 874

**20.7 Batteries and Fuel Cells 877**

Lead–Acid Battery 878 Alkaline Battery 878 Nickel–Cadmium and Nickel–Metal Hydride Batteries 878 Lithium-Ion Batteries 879 Hydrogen Fuel Cells 879

**20.8 Corrosion 882**

Corrosion of Iron (Rusting) 882 Preventing Corrosion of Iron 883

**20.9 Electrolysis 884**

Quantitative Aspects of Electrolysis 886

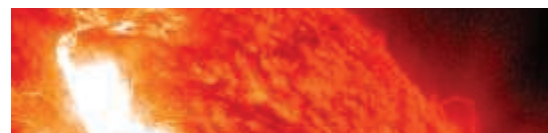
**Chapter Summary and Key Terms 889**  
**Learning Outcomes 890 Key Equations 890**  
**Exercises 890 Additional Exercises 897**  
**Integrative Exercises 898 Design an Experiment 899**

**A Closer Look** Electrical Work 871

**Chemistry and Life** Heartbeats and Electrocardiography 876

**Chemistry Put to Work** Batteries for Hybrid and Electric Vehicles 880

**Chemistry Put to Work** Electrometallurgy of Aluminum 887

**21 Nuclear Chemistry 900****21.1 Radioactivity and Nuclear Equations 902**

Nuclear Equations 902 Types of Radioactive Decay 903

**21.2 Patterns of Nuclear Stability 905**

Neutron-to-Proton Ratio 905 Radioactive Decay Chains 907 Further Observations 908

**21.3 Nuclear Transmutations 909**

Accelerating Charged Particles 910 Reactions Involving Neutrons 911 Transuranium Elements 911

**21.4 Rates of Radioactive Decay 912**

Radiometric Dating 913 Calculations Based on Half-Life 915

**21.5 Detection of Radioactivity 917**

Radiotracers 917

**21.6 Energy Changes in Nuclear Reactions 919**

Nuclear Binding Energies 921

**21.7 Nuclear Power: Fission 922**

Nuclear Reactors 925 Nuclear Waste 927

**21.8 Nuclear Power: Fusion 928****21.9 Radiation in the Environment and Living Systems 930**

Radiation Doses 931

**Chapter Summary and Key Terms 933****Learning Outcomes 934 Key Equations 935****Exercises 935 Additional Exercises 939****Integrative Exercises 940 Design an Experiment 941****Chemistry and Life** Medical Applications of Radiotracers 918**A Closer Look** The Dawning of the Nuclear Age 925**A Closer Look** Nuclear Synthesis of the Elements 929**Chemistry and Life** Radiation Therapy 932

# 22

## Chemistry of the Nonmetals 942

**22.1 Periodic Trends and Chemical Reactions 944**

Chemical Reactions 945

**22.2 Hydrogen 946**

Isotopes of Hydrogen 946 Properties of Hydrogen 947 Production of Hydrogen 948 Uses of Hydrogen 949 Binary Hydrogen Compounds 949

**22.3 Group 8A: The Noble Gases 950**

Noble-Gas Compounds 951

**22.4 Group 7A: The Halogens 952**

Properties and Production of the Halogens 952 Uses of the Halogens 954 The Hydrogen Halides 954 Interhalogen Compounds 954 Oxyacids and Oxyanions 954

**22.5 Oxygen 955**

Properties of Oxygen 955 Production of Oxygen 956 Uses of Oxygen 956 Ozone 956 Oxides 956 Peroxides and Superoxides 958

**22.6 The Other Group 6A Elements: S, Se, Te, and Po 958**

Occurrence and Production of S, Se, and Te 959 Properties and Uses of Sulfur, Selenium, and Tellurium 959 Sulfides 959 Oxides, Oxyacids, and Oxyanions of Sulfur 960

**22.7 Nitrogen 962**

Properties of Nitrogen 962 Production and Uses of Nitrogen 962 Hydrogen Compounds of Nitrogen 962 Oxides and Oxyacids of Nitrogen 963

**22.8 The Other Group 5A Elements: P, As, Sb, and Bi 965**

Occurrence, Isolation, and Properties of Phosphorus 966 Phosphorus Halides 966 Oxy Compounds of Phosphorus 967

**22.9 Carbon 969**

Elemental Forms of Carbon 969 Oxides of Carbon 970 Carbonic Acid and Carbonates 971 Carbides 972

**22.10 The Other Group 4A Elements: Si, Ge, Sn, and Pb 972**

General Characteristics of the Group 4A Elements 972 Occurrence and Preparation of Silicon 973 Silicates 973 Glass 975 Silicones 976

**22.11 Boron 976****Chapter Summary and Key Terms 978 Learning Outcomes 979 Exercises 979 Additional Exercises 983 Integrative Exercises 984 Design an Experiment 985****A Closer Look** The Hydrogen Economy 948**Chemistry and Life** Nitroglycerin, Nitric Oxide, and Heart Disease 965**Chemistry and Life** Arsenic in Drinking Water 968**Chemistry Put to Work** Carbon Fibers and Composites 970

# 23

## Transition Metals and Coordination Chemistry 986

**23.1 The Transition Metals 988**

Physical Properties 989 Electron Configurations and Oxidation States 990 Magnetism 991

**23.2 Transition-Metal Complexes 992**

The Development of Coordination Chemistry: Werner's Theory 993 The Metal-Ligand Bond 995 Charges, Coordination Numbers, and Geometries 996

**23.3 Common Ligands in Coordination Chemistry 997**

Metals and Chelates in Living Systems 999

**23.4 Nomenclature and Isomerism in Coordination Chemistry 1003**

Isomerism 1005 Structural Isomerism 1005 Stereoisomerism 1006

**23.5 Color and Magnetism in Coordination Chemistry 1009**

Color 1009 Magnetism of Coordination Compounds 1011

**23.6 Crystal-Field Theory 1011**

Electron Configurations in Octahedral Complexes 1015 Tetrahedral and Square-Planar Complexes 1017

**Chapter Summary and Key Terms 1021**  
**Learning Outcomes 1021 Exercises 1022**  
**Additional Exercises 1026 Integrative Exercises 1028 Design an Experiment 1029**

**A Closer Look** Entropy and the Chelate Effect 1001

**Chemistry and Life** The Battle for Iron in Living Systems 1002

**A Closer Look** Charge-Transfer Color 1019



# 24 The Chemistry of Life: Organic and Biological Chemistry 1030

**24.1 General Characteristics of Organic Molecules 1032**

The Structures of Organic Molecules 1032  
 The Stability of Organic Compounds 1033 Solubility and Acid–Base Properties of Organic Compounds 1033

**24.2 Introduction to Hydrocarbons 1034**

Structures of Alkanes 1035 Structural Isomers 1035 Nomenclature of Alkanes 1036 Cycloalkanes 1039 Reactions of Alkanes 1039

**24.3 Alkenes, Alkynes, and Aromatic Hydrocarbons 1041**

Alkenes 1041 Alkynes 1043 Addition Reactions of Alkenes and Alkynes 1044 Aromatic Hydrocarbons 1045 Stabilization of  $\pi$  Electrons by Delocalization 1046 Substitution Reactions of Aromatic Hydrocarbons 1046

**24.4 Organic Functional Groups 1048**

Alcohols 1048 Ethers 1050 Aldehydes and Ketones 1050 Carboxylic Acids and Esters 1051 Amines and Amides 1054

**24.5 Chirality in Organic Chemistry 1055****24.6 Introduction to Biochemistry 1057****24.7 Proteins 1057**

Amino Acids 1057 Polypeptides and Proteins 1059 Protein Structure 1060

**24.8 Carbohydrates 1062**

Disaccharides 1063 Polysaccharides 1064

**24.9 Lipids 1065**

Fats 1065 Phospholipids 1066

**24.10 Nucleic Acids 1067**

**Chapter Summary and Key Terms 1071**  
**Learning Outcomes 1072 Exercises 1072**  
**Additional Exercises 1077 Integrative Exercises 1078 Design an Experiment 1079**

**Chemistry Put to Work** Gasoline 1040

**A Closer Look** Mechanism of Addition Reactions 1045

**Strategies for Success** What Now? 1070

**APPENDICES**

**A** Mathematical Operations 1080

**B** Properties of Water 1087

**C** Thermodynamic Quantities for Selected Substances at 298.15 K (25 °C) 1088

**D** Aqueous Equilibrium Constants 1092

**E** Standard Reduction Potentials at 25 °C 1094

**ANSWERS TO SELECTED EXERCISES** A-1

**ANSWERS TO GIVE IT SOME THOUGHT** A-31

**ANSWERS TO GO FIGURE** A-37

**ANSWERS TO SELECTED PRACTICE EXERCISES** A-43

**GLOSSARY** G-1

**PHOTO AND ART CREDITS** P-1

**INDEX** I-1

# CHEMICAL APPLICATIONS AND ESSAYS

## A Closer Look

- |   |   |  |
|---|---|--|
| The Scientific Method 17  | Phases in Atomic and Molecular Orbitals 374                           | Other Greenhouse Gases 783                             |
| Basic Forces 51   | The Ideal-Gas Equation 414  | The Ogallala Aquifer—A Shrinking Resource 787          |
| The Mass Spectrometer 54  | The Clausius–Clapeyron Equation 455                                   | Fracking and Water Quality 790                         |
| What Are Coins Made Of? 57  | X-ray Diffraction 478   | The Entropy Change When a Gas Expands Isothermally 814 |
| Energy, Enthalpy, and <i>P</i> - <i>V</i> Work 175                | Ideal Solutions with Two or More Volatile Components 544              | What’s “Free” About Free Energy? 829                   |
| Using Enthalpy as a Guide 178                                     | The van’t Hoff Factor 551   | Electrical Work 871                                    |
| Measurement and the Uncertainty Principle 226                     | Using Spectroscopic Methods to Measure Reaction Rates: Beer’s Law 576 | The Dawning of the Nuclear Age 925                     |
| Thought Experiments and Schrödinger’s Cat 229                     | Temperature Changes and Le Châtelier’s Principle 651                  | Nuclear Synthesis of the Elements 929                  |
| Probability Density and Radial Probability Functions 233          | Polyprotic Acids 689  | The Hydrogen Economy 948                               |
| Effective Nuclear Charge 262                                      | Limitations of Solubility Products 743                                | Entropy and the Chelate Effect 1001                    |
| Calculation of Lattice Energies: The Born–Haber Cycle 305         | Lead Contamination in Drinking Water 750                              | Charge-Transfer Color 1019                             |
| Oxidation Numbers, Formal Charges, and Actual Partial Charges 319 |   | Mechanism of Addition Reactions 1045                   |

## Chemistry Put to Work

- |   |  |  |
|---|--|--|
| Chemistry and the Chemical Industry 6                   | Ionic Liquids 447                        | The Haber Process 628                          |
| Chemistry in the News 23                                | Alloys of Gold 485                       | Controlling Nitric Oxide Emissions 654         |
| Antacids 136  | Solid-State Lighting 499                 | Amines and Amine Hydrochlorides 695            |
| The Scientific and Political Challenges of Biofuels 198 | Modern Materials in the Automobile 503   | Batteries for Hybrid and Electric Vehicles 880 |
| Ionic Size and Lithium-Ion Batteries 267                | Microporous and Mesoporous Materials 508 | Electrometallurgy of Aluminum 887              |
| Orbitals and Energy 381                                 | Methyl Bromide in the Atmosphere 586     | Carbon Fibers and Composites 970               |
| Gas Separations 418                                     | Catalytic Converters 604                 | Gasoline 1040                                  |

## Chemistry and Life

- |   |  |  |
|---|--|--|
| Elements Required by Living Organisms 64        | Blood Gases and Deep-Sea Diving 537                      | Heartbeats and Electrocardiography 876             |
| Glucose Monitoring 96                           | Sickle-Cell Anemia 555                                   | Medical Applications of Radiotracers 918           |
| The Regulation of Body Temperature 183          | Nitrogen Fixation and Nitrogenase 606                    | Radiation Therapy 932                              |
| Nuclear Spin and Magnetic Resonance Imaging 237 | The Amphiprotic Behavior of Amino Acids 703              | Nitroglycerin, Nitric Oxide, and Heart Disease 965 |
| The Improbable Development of Lithium Drugs 281 | Blood as a Buffered Solution 729                         | Arsenic in Drinking Water 968                      |
| The Chemistry of Vision 367                     | Tooth Decay and Fluoridation 746                         | The Battle for Iron in Living Systems 1002         |
| Fat-Soluble and Water-Soluble Vitamins 533      | Ocean Acidification 792                                  |  |
|   | Entropy and Human Society 822                            |  |
|   | Driving Nonspontaneous Reactions: Coupling Reactions 835 |  |

## Strategies for Success

- |                               |                                  |   |
|-------------------------------|----------------------------------|---|
| Estimating Answers 30         | Problem Solving 92               | Calculations Involving Many Variables 405 |
| The Importance of Practice 32 | Design an Experiment 109         | What Now? 1070                            |
| The Features of This Book 32  | Analyzing Chemical Reactions 144 |   |
| How to Take a Test 73         |                                  |   |

## Smart Figures

Figures 3.4 and 3.5	Methane reacts with oxygen in a Bunsen burner and balanced chemical equation for the combustion of $\text{CH}_4$	Figure 10.12	Distribution of molecular speeds for nitrogen gas
Figure 3.6	Combustion of magnesium metal in air, a combination reaction	Figure 13.2	Intermolecular interactions involved in solutions
Figure 4.4	A precipitation reaction	Figure 13.3	Dissolution of the ionic solid $\text{NaCl}$ in water
Figure 4.14	Reaction of copper metal with silver ion	Figure 13.4	Enthalpy changes accompanying the solution process
Figures 5.2 and 5.3	Electrostatic potential energy and ionic bonding	Figure 14.16	Energy profile for conversion of methyl isonitrile ( $\text{H}_3\text{CNC}$ ) to its isomer acetonitrile ( $\text{H}_3\text{CCN}$ )
Figure 5.23	Enthalpy diagram for propane combustion	Figure 15.2	Equilibrium between $\text{NO}_2$ and $\text{N}_2\text{O}_4$
Figure 5.24	Using bond enthalpies to estimate $\Delta H_{\text{rxn}}$	Figure 15.9	Predicting the direction of a reaction by comparing $Q$ and $K$ at a given temperature
Figure 6.25	General energy ordering of orbitals for a many-electron atom	Le Châtelier's box, pg 645	Le Châtelier's principle
Figure 8.5	Periodic trends in lattice energy as a function of cation or anion radius	Figure 17.7	Titration of a strong acid with a strong base
Figure 9.12	Covalent bonds in $\text{H}_2$ , $\text{HCl}$ , and $\text{Cl}_2$	Figure 17.9	Titration of a weak acid with a strong base
Figure 9.13	Formation of the $\text{H}_2$ molecule as atomic orbitals overlap	Figure 20.3	Spontaneous oxidation–reduction reaction involving zinc and copper
Figure 9.14	Formation of $sp$ hybrid orbitals	Figure 20.5	A voltaic cell that uses a salt bridge to complete the electrical circuit
Figure 9.16	Formation of $sp^2$ hybrid orbitals		
Figure 9.17	Formation of $sp^3$ hybrid orbitals		
Figure 9.22	Hybrid orbital bonding in ethylene		
Figure 9.23	Formation of $\pi$ bond in acetylene, $\text{C}_2\text{H}_2$		

## Interactive Sample Exercises

Sample Exercise 1.1	Distinguishing among Elements, Compounds, and Mixtures	Sample Exercise 4.13	Using Molarity to Calculate Grams of Solute
Sample Exercise 1.2	Using SI Prefixes	Sample Exercise 5.1	Relating Heat and Work to Changes of Internal Energy
Sample Exercise 1.6	Assigning Appropriate Significant Figures	Sample Exercise 5.4	Relating $\Delta H$ to Quantities of Reactants and Products
Sample Exercise 1.8	Determining the Number of Significant Figures in a Calculated Quantity	Sample Exercise 5.6	Measuring $\Delta H$ Using a Coffee-Cup Calorimeter
Sample Exercise 1.11	Converting Units Using Two or More Conversion Factors	Sample Exercise 5.7	Measuring $q_{\text{rxn}}$ Using a Bomb Calorimeter
Sample Exercise 1.13	Conversions Involving Density	Sample Exercise 5.8	Using Hess's Law to Calculate $\Delta H$
Sample Exercise 2.1	Atomic Size	Sample Exercise 5.10	Equations Associated with Enthalpy of Formation
Sample Exercise 2.3	Writing Symbols for Atoms	Sample Exercise 6.6	Subshells of the Hydrogen Atom
Sample Exercise 2.4	Calculating the Atomic Weight of an Element from Isotopic Abundance	Sample Exercise 6.7	Orbital Diagrams and Electron Configurations
Sample Exercise 2.5	Using the Periodic Table	Sample Exercise 6.8	Electron Configurations for a Group
Sample Exercise 2.9	Identifying Ionic and Molecular Compounds	Sample Exercise 7.2	Predicting Relative Sizes of Atomic Radii
Sample Exercise 3.2	Balancing Chemical Equations	Sample Exercise 8.2	Charges on Ions
Sample Exercise 3.5	Calculating Formula Weights	Sample Exercise 8.6	Drawing a Lewis Structure
Sample Exercise 3.8	Converting Moles to Number of Atoms	Sample Exercise 9.1	Using the VSEPR Model
Sample Exercise 3.18	Calculating the Amount of Product Formed from a Limiting Reactant	Sample Exercise 10.3	Evaluating the Effects of Changes in $P$ , $V$ , $n$ , and $T$ on a Gas
Sample Exercise 4.1	Relating Relative Numbers of Anions and Cations to Chemical Formulas	Sample Exercise 10.4	Using the Ideal-Gas Equation
Sample Exercise 4.3	Predicting a Metathesis Reaction	Sample Exercise 11.4	Relating Boiling Point to Vapor Pressure
Sample Exercise 4.4	Writing a Net Ionic Equation	Sample Exercise 12.4	Identifying Types of Semiconductors

Sample Exercise 13.6 Calculation of Molarity Using the  
Density of the Solution

Sample Exercise 14.3 Relating Rates at Which Products  
Appear and Reactants Disappear

Sample Exercise 15.1 Writing Equilibrium-Constant  
Expressions

Sample Exercise 16.1 Identifying Conjugate Acids and Bases

Sample Practice 17.11 Calculating  $K_{sp}$  from Solubility

Sample Exercise 18.1 Calculating Concentration from  
Partial Pressure

Sample Exercise 19.1 Identifying Spontaneous Processes

Sample Exercise 20.2 Balancing Redox Equations  
in Acidic Solution

Sample Exercise 21.1 Predicting the Product of a  
Nuclear Reaction

Sample Exercise 22.4 Predicting Chemical Reactions among  
the Halogens

Sample Exercise 23.2 Determining the Oxidation Number of  
a Metal in a Complex

Sample Exercise 24.1 Naming Alkanes

# 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. So 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.

Publishing the fourteenth 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 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? The answers 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 the Internet 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 edition incorporates a number of those new methodologies, including use of computer-based classroom tools, such as Learning Catalytics™, a cloud-based active learning analytics and assessment system, and web-based tools, particularly MasteringChemistry™, which is continually evolving to

provide more effective means of testing and evaluating student performance, while giving the student immediate and helpful feedback. MasteringChemistry™ not only provides feedback on a question by question basis, but using Knewton-enhanced adaptive follow-up assignments and Dynamic Study Modules, it now continually adapts to each student, offering a personalized learning experience.

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 have done our best to keep our writing clear and interesting and the book attractive and well illustrated. The book has numerous in-text study aids for students, including carefully placed descriptions of problem-solving strategies. We hope that our cumulative experiences as teachers is evident in our pacing, choice of examples, and the kinds 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 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 Put To Work* 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 usually performed in general chemistry. We believe that 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—on the one hand—trying to teach too much at too high a level and—on the other hand—resorting to oversimplifications. As with 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. Our approach of 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 wish to bypass it. In treating this topic and others in Chapters 7 and 9, we have materially enhanced the accompanying figures to more effectively bring home their central messages.

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. The chapter 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 come to be focused on green chemistry and the impacts of human activities on Earth's water and atmosphere.

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, but we recognize that not everyone teaches all the topics in the order we have chosen. We have therefore made sure that 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.

## New 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 fourteenth edition our revision was organized around the following points:

- Our treatment of energy and thermochemistry has been significantly revised. The concept of energy is now introduced in Chapter 1, whereas previously it did not appear until Chapter 5. This change allows instructors greater freedom in the order in which they cover the material. For example, this change would facilitate coverage of Chapters 6 and 7 immediately following Chapter 2, a sequence that is in line with an atoms-first approach to teaching general chemistry. More importantly, bond enthalpies are now integrated into Chapter 5 to emphasize the connection between macroscopic quantities, like reaction enthalpies, and the submicroscopic world of atoms and bonds. We feel this change leads to a better integration of thermochemical concepts with the surrounding chapters. Bond enthalpies are revisited in Chapter 8 after students have developed a more sophisticated view of chemical bonding.
- Considerable effort was made to provide students with a clear discussion, superior problem sets, and better real-

time feedback on their understanding of the material. The author team used an interactive e-book platform to view passages that students highlighted in their reading along with the related notes and questions that detailed what they did not understand. In response, numerous passages were revised for greater clarity.

- Extensive effort has gone into creating enhanced content for the eText version of the book. These features make the eText so much more than just an electronic copy of the physical textbook. New Smart Figures take key figures from the text and bring them to life through animation and narration. Likewise, new Smart Sample Exercises animate key sample exercises from the text, offering students a more in depth and detailed discussion than can be provided in the printed text. These interactive features will also include follow-up questions, which can be assigned in MasteringChemistry™.
- We used metadata from MasteringChemistry™ to inform our revisions. In the thirteenth edition a second *Practice Exercise* was added to accompany each *Sample Exercise*. Nearly all of the additional practice exercises were multiple choice questions with wrong answer distractors written to identify student misconceptions and common mistakes. As implemented in MasteringChemistry™, feedback was provided with each wrong answer to help students recognize their misconceptions. In this new edition we have carefully scrutinized the metadata from MasteringChemistry™ to identify practice exercises that either were not challenging the students or were not being used. Those exercises have either been modified or changed entirely. A similar effort was made to revise *Give It Some Thought* and *Go Figure* questions to make them more effective and amenable to use in MasteringChemistry™. Finally, the number of end-of-chapter exercises that have wrong answer feedback in MasteringChemistry™ has been dramatically expanded. We have also replaced outdated or little-used end-of-chapter exercises (~10 per chapter).
- Finally, subtle but important changes have been made to allow students to quickly reference important concepts and assess their knowledge of the material. Key points are now set in italic with line spaces above and below for greater emphasis. New skills-based *How To . . .* features offer step-by-step guidance for solving specific types of problems such as Drawing Lewis Structures, Balancing Redox Equations, and Naming Acids. These features, with numbered steps encased by a thin rule, are integrated into the main discussion and are easy to find. Finally, each Learning Objective is now correlated to specific end-of-chapter exercises. This allows students to test their mastery of each learning objective when preparing for quizzes and exams.

## Changes in This Edition

The **New in This Edition** section details changes made throughout this edition. Beyond a mere listing, however, it is worth dwelling on the general goals we set forth in formulating

this new edition. *Chemistry: The Central Science* has traditionally been valued for its clarity of writing, its scientific accuracy and currency, its strong end-of-chapter exercises, and its consistency in level of coverage. In making changes, we have made sure not to compromise these characteristics, and we have also continued to employ an open, clean design in the layout of the book.

The art program for the fourteenth edition continues the trajectory set in the previous two editions: to make greater and more effective use of the figures as learning tools, by drawing the reader more directly into the figure. The style of the art has been revised throughout for enhanced clarity and a cleaner more modern look. This includes: new white-background annotation boxes with crisp, thin leaders; richer and more saturated colors in the art, and expanded use of 3D renderings. An editorial review of every figure in the text resulted in numerous minor revisions to the art and its labels in order to increase clarity. The *Go Figure* questions have been carefully scrutinized. Using statistics from MasteringChemistry™, many have been modified or changed entirely to engage and challenge students to think critically about the concept(s) that underlie each figure. The *Give it Some Thought* feature has been revised in a similar vein to stimulate more thoughtful reading of the text and foster critical thinking.

We provide a valuable overview of each chapter under the *What's Ahead* banner. *Concept links* (∞∞) continue to provide easy-to-see cross-references to pertinent material covered earlier in the text. The essays titled *Strategies in Chemistry*, which provide advice to students on problem solving and “thinking like a chemist,” have been renamed *Strategies for Success* to better convey their usefulness to the student.

We have continued to emphasize conceptual exercises in the end-of-chapter problems. In each chapter we begin the exercises with the well-received *Visualizing Concepts* category. These exercises are designed to facilitate conceptual understanding through use of models, graphs, photographs, and other visual materials. They precede the regular end-of-chapter exercises and are identified in each case with the relevant chapter section number. A generous selection of *Integrative Exercises*, which give students the opportunity to solve problems that integrate concepts from the present chapter with those of previous chapters, is included at the end of each chapter. The importance of integrative problem solving is highlighted by the *Sample Integrative Exercise*, which ends each chapter beginning with Chapter 4. In general, we have included more conceptual end-of-chapter exercises and have made sure that there is a good representation of somewhat more difficult exercises to provide a better mix in terms of topic and level of difficulty. Many of the exercises have been restructured to facilitate their use in MasteringChemistry™. We have made extensive use of the metadata from student use of MasteringChemistry™ to analyze end-of-chapter exercises and make appropriate changes, as well as to develop *Learning Outcomes* for each chapter.

New essays in our well-received *Chemistry Put To Work* and *Chemistry and Life* series emphasize world events, scientific discoveries, and medical breakthroughs relevant to topics

developed in each chapter. We maintain our focus on the positive aspects of chemistry without neglecting the 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.

It is perhaps a natural tendency for chemistry textbooks to grow in length with succeeding editions, but it is one that we have resisted. There are, nonetheless, many new items in this edition, mostly ones that replace other material considered less pertinent. Here is a list of several significant changes in content:

Chapter 1, and every chapter that follows, begins with a new chapter opening photo and backstory to provide a real world context for the material that follows. A new section on the nature of energy (Section 1.4) has been added to Chapter 1. The inclusion of energy in the opening chapter provides much greater flexibility for the order in which subsequent chapters can be covered. The *Chemistry Put To Work* box, dealing with *Chemistry in the News*, has been completely rewritten, with items that describe diverse ways in which chemistry intersects with the affairs of modern society.

In Chapter 2 the figures depicting the key experiments that led to the discovery of the structure of the atom—Millikan's Oil Drop experiment and Rutherford's Gold Foil experiment—have been enhanced. This is also the first occurrence of the periodic table which has been updated throughout the text to reflect the acceptance and naming of elements 113 (Nihonium), 115 (Moscovium), 117 (Tennessine), and 118 (Oganesson).

Chapter 5 has undergone the most extensive revision in the book. Early parts of the chapter have been modified to reflect the fact that basic concepts of energy are now introduced in Chapter 1. Two new figures have been added. Figure 5.3 qualitatively relates electrostatic potential energy to changes in the bonding of an ionic solid, while Figure 5.16 provides a real-world analogy to help students understand the relationship between spontaneity and reaction enthalpy. The figure illustrating exothermic and endothermic reactions (Figure 5.8) has been modified to show before and after images of the reaction. Finally, to stress the atomistic origins of reaction enthalpies, a new section (Section 5.8) on bond enthalpies has been added, as discussed earlier.

A new Sample Exercise has been added to Chapter 6 that shows how the radii of orbits in the Bohr model of the hydrogen atom depend on the principal quantum number and how the electron behavior changes when a photon is emitted or absorbed.

Chapter 8 has seen some of its content on bond enthalpies moved to Chapter 5. The concepts there are now reinforced here.

In Chapter 11, attention has been paid to the text regarding various intermolecular forces to make clear that chemists usually think about them in units of energy, not units of force. A new checklist art piece replaces old Figure 11.14 in order to make it clear that intermolecular interaction energies are additive.

Chapter 12 has a new *A Closer Look* box entitled *Modern Materials in the Automobile* which discusses the wide range of

materials used in a hybrid automobile, including semiconductors, ionic solids, alloys, polymers, and more. A new *Chemistry Put To Work* entitled *Microporous and Mesoporous Materials* examines materials with different pore sizes and their application in ion exchange and catalytic converters.

In Chapter 15 a new *A Closer Look* box on *Temperature Changes and Le Châtelier's Principle* explains the theoretical underpinnings of the empirical rules that successfully predict how temperature changes influence the equilibrium constants of exothermic and endothermic reactions.

In Chapter 16 a new *A Closer Look* box on *Polyprotic Acids* explicitly shows the speciation of ions as a function of pH.

In Chapter 17 a new *A Closer Look* box entitled *Lead Contamination in Drinking Water* explores the chemistry behind the water quality crisis in Flint, Michigan.

Chapter 18 has been revised to reflect the most up-to-date data on atmospheric CO<sub>2</sub> levels and the ozone hole. Figure 18.4, showing the UV absorption spectrum of ozone, has been added so students can understand its role in filtering out harmful UV radiation from the sun. A new Sample Exercise (18.3) walks students through the steps needed to calculate the amount of CO<sub>2</sub> produced from combustion of a hydrocarbon.

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.

## To the Student

*Chemistry: The Central Science*, Fourteenth 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 that we will know where we have helped you most. Also, we would like to learn of any shortcomings so we may further 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 in 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. So now you know. How important to you, in this competitive world, is a good grade in chemistry?

**Focus your study.** The amount of information you will be expected to learn may seem overwhelming. 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 *Give It Some Thought* and *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 *Learning Outcomes* and *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.

**You need to 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 MasteringChemistry™ 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.

## 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.

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 Nancy Peterson, *North Central College*  
 Robert C. Pfaff, *Saint Joseph's College*  
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 Bernard Powell, *University of Texas*  
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 Steve Rathbone, *Blinn College*  
 Scott Reeve, *Arkansas State University*  
 John Reissner Helen Richter Thomas  
 Ridgway, *University of North Carolina,*  
*University of Akron, University of*  
*Cincinnati*  
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 Mark G. Rockley, *Oklahoma State University*  
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 Amy L. Rogers, *College of Charleston*  
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*Arlington*  
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We would also like to express our gratitude to our many team members at Pearson whose hard work, imagination, and commitment have contributed so greatly to the final form of this edition: Chris Hess, our chemistry editor, for many fresh ideas and his unflagging enthusiasm, continuous encouragement, and support; Jennifer Hart, Director of Development, who has brought her experience and insight to oversight of the entire project; Matt Walker, our development editor, whose depth of experience, good judgment, and careful attention to detail were invaluable to this revision, especially in keeping us on task in

terms of consistency and student understanding. The Pearson team is a first-class operation.

There are many others who also deserve special recognition, including the following: Mary Tindle, our production editor, who skillfully kept the process moving and us authors on track; 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 fourteenth edition to completion.

- |   |  |   |  |  |   |
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# 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 fourteenth edition and accompanying MasteringChemistry™ 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, and the Morley Medal of the Cleveland Section of the American Chemical Society in 2005. 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. In addition to his teaching and service activities, Professor Bursten's research program focuses on 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 enjoyed visiting professorships at the University of Bordeaux in France and the University of Sydney in Australia. Professor Woodward has been an Alfred P. Sloan Foundation Research Fellow and a National Science Foundation CAREER Award winner. 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. He is currently the Vice President of the Neutron Scattering Society of America. 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 Chemistry Lecturer. In addition to lecturing general chemistry, Stoltzfus 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 200,000 students from all over the world. The iTunes U course, along with the videos at [www.drufus.com](http://www.drufus.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.



**Michael W. Lufaso** received his B.S. degree in Chemistry from Youngstown State University in 1998 and his Ph.D. in Chemistry from the Ohio State University in 2002. He was a National Research Council Postdoctoral Fellow at the National Institute for Standards and Technology and a postdoctoral fellow at the University of

South Carolina. In 2006 he joined the University of North Florida where he currently holds the rank of Associate Professor in the Department of Chemistry. He was a Brian Andreen Cottrell College Science Award winner from Research Corporation. He was named a Munoz Presidential Professor in 2011 and received an Outstanding Faculty Scholarship award in 2014. He has authored laboratory manuals and taught ten different undergraduate courses primarily in the areas of general, inorganic, and solid state chemistry. His undergraduate research program focuses on structure prediction, synthesis, and characterization of the structure and properties of solid state materials.

# New Levels of Student Interaction for Improved Conceptual Understanding

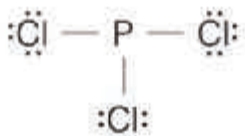
Embedded in eText 2.0, as well as assignable in MasteringChemistry™, new features engage students through interactivity to enhance the reading experience and help them learn challenging chemistry concepts.

**Interactive Sample Exercise** Drawing a Lewis Structure

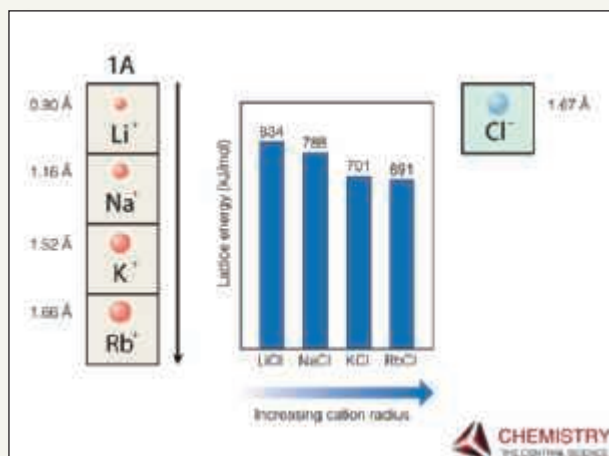
Draw the Lewis Structure for phosphorus trichloride,  $\text{PCl}_3$ .

**SOLVE**

3. Complete the octets around all the atoms bonded to the central atom.

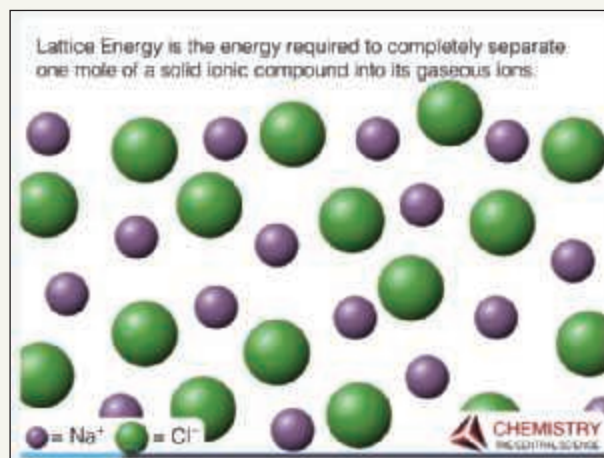


ClP(Cl)Cl



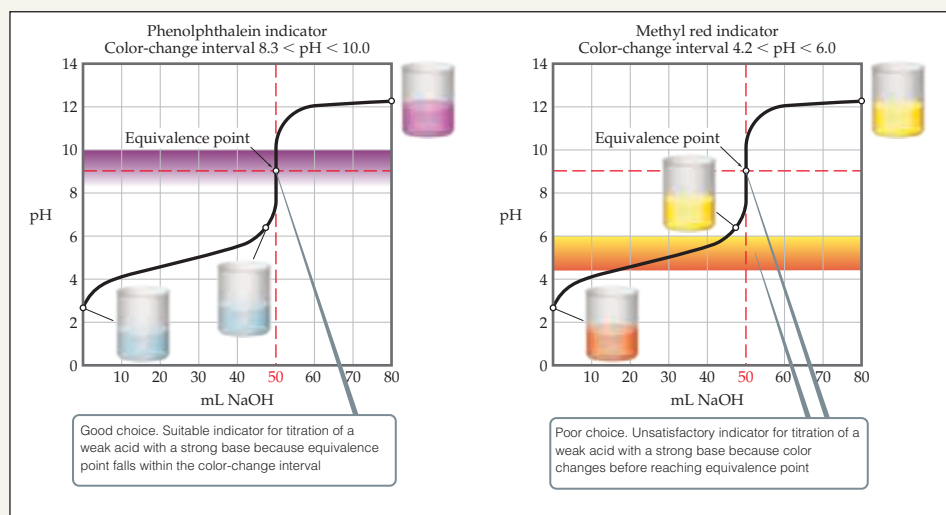
**NEW!** 50 Interactive Sample Exercises bring key *Sample Exercises* in the text to life through animation and narration. Author Matt Stoltzfus uses the text's *Analyze/Plan/Solve/Check* technique to guide students through the problem-solving process. Play icons within the text identify each Interactive Sample Exercise. Clicking the icon in the eText launches a visual and conceptual presentation which goes beyond the static page. The *Practice Exercises* within each *Sample Exercise* can also be assigned in MasteringChemistry™ where students will receive answer-specific feedback.

**NEW!** 27 Smart Figures walk students through complex visual representations, dispelling common misconceptions before they take root. Each *Smart Figure* converts a static in-text figure into a dynamic process narrated by author Matt Stoltzfus. Play icons within the text identify each *Smart Figure*. Clicking the icon in the eText launches the animation. Smart Figures are assignable in MasteringChemistry™ where they are accompanied by a multiple-choice question with answer-specific video feedback. Selecting the correct answer launches a brief wrap-up video that highlights the key concepts behind the answer.



# Visually Revised to Better Help Students Build General Chemistry

The visual program has been revised for enhanced clarity and to create a clean, modern look. Style changes include: expanded use of 3D renderings, new white annotation boxes with crisp leader lines, and a more saturated art palette.



**REVISED!** Annotations offer expanded explanations; additional new leaders emphasize key relationships and key points in figures.

**NEW!** Before and after photos clearly show characteristics of endothermic and exothermic reactions. Added reaction equations connect the chemistry to what's happening in the photos.

System =  $\text{NH}_4\text{SCN} + \text{Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O}$

Heat flows from surroundings into system, temperature of beaker and surrounding air drops.

$60 \text{ Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O} + 2 \text{NH}_4\text{SCN} \longrightarrow \text{Ba}(\text{SCN})_2 + 2 \text{NH}_3 + 10 \text{H}_2\text{O}$   
An endothermic reaction

System =  $\text{K} + \text{H}_2\text{O}$

Heat flows (violently) from system into surroundings, temperature of the water and surrounding air increases.

$(b) 2 \text{K} + 2 \text{H}_2\text{O} \longrightarrow 2 \text{KOH} + \text{H}_2$   
An exothermic reaction

**Figure 5.8** Endothermic and exothermic reactions. In both instances, the system is defined as the reactants and products, while surroundings are the containers and everything else in the universe.

# Knowledge and Understanding

The authors used the wealth of student data in MasteringChemistry™ to identify the areas where students struggle most, revising discussions, figures, and exercises throughout the text to address misconceptions and encourage thinking about the real-world use of chemistry.

**Go Figure**

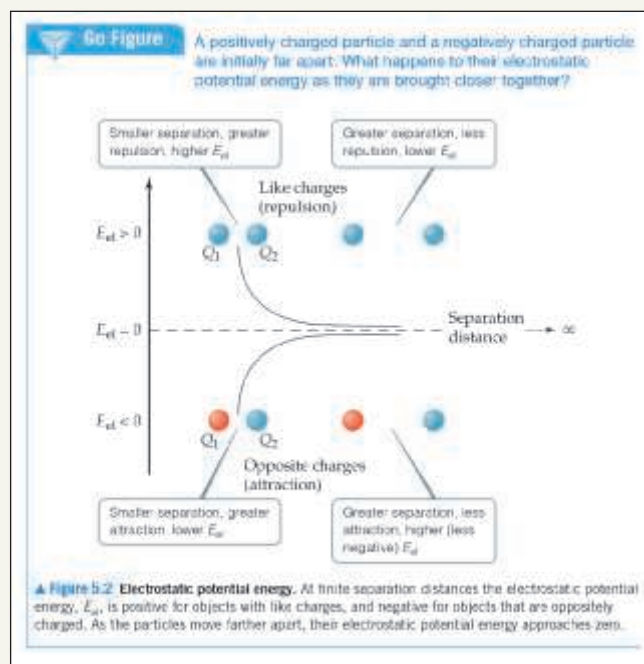
If the white powder were sugar,  $C_{12}H_{22}O_{11}$ , how would we have to change this picture?

**Metallic**  
Atoms held together by a "sea of electrons" surrounding nuclei

**Ionic**  
Ions held together by local electrostatic attractions

**Covalent**  
Atoms held together by sharing electrons in localized bonds

**Figure 8.1** Ionic, covalent, and metallic bonds. The three different substances shown here are held together by different types of chemical bonds.



**NEW!** The author team utilized Mastering metadata to edit and clarify in-chapter *Go Figure* and *Give It Some Thought* questions, as well as end-of-chapter problems. User data helped them to identify problematic questions and then modify, replace, or delete—resulting in a more diverse and polished set of problems.

**UPDATED!** A Closer Look features have been updated to reflect recent news and discoveries in the field of chemistry, providing relevance and applications for students. End-of-chapter questions give students the chance to test whether they understood the concept or not.

**A Closer Look** Lead Contamination in Drinking Water

There is often a strong urge to something new people on the Internet and social media. Unfortunately, there are some instances in which the news is not as clear as it should be. An example is the story by CNN about lead in the water supply in Flint, Michigan.

Lead is a toxic metal that is found in the human body but the amount of lead in the body is usually very low. It is important to know that lead is a toxic metal and that it can cause health problems. The amount of lead in the body is usually very low, but it can cause health problems if the amount of lead in the body is too high.

The regulatory limit set by the U.S. Environmental Protection Agency (EPA) for lead in drinking water is 15 parts per billion (ppb). According to EPA regulations, if the average lead concentration in a public water system exceeds 15 ppb, the system must take corrective action to reduce the lead concentration to 15 ppb or lower. This is the maximum lead concentration allowed in public water systems.

The Flint water crisis began in 2014 when the city of Flint, Michigan, switched its water source from Lake St. Clair to the Flint River. The Flint River water is known to contain high levels of lead. The city of Flint did not properly treat the water from the Flint River, which caused lead to leach into the water supply. This led to a public health crisis as lead levels in the water supply rose significantly above the EPA limit.

While water is properly treated, a potential level of lead in the water supply is 15 ppb. This is the maximum lead concentration allowed in public water systems. If the lead concentration in the water supply is higher than 15 ppb, the water is considered to be contaminated and the public health officials should take corrective action to reduce the lead concentration to 15 ppb or lower.

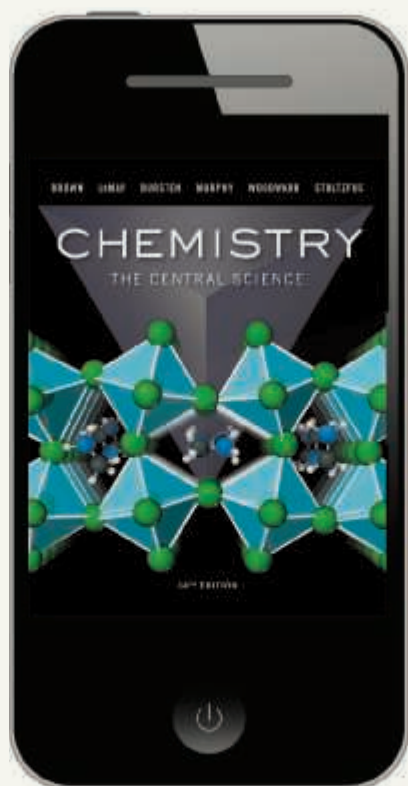
**Related Resources** 15.05, 15.06

**Figure 15.2** Predicted and unexpected lead pipe corrosion. In fact, lead that has a protective oxide layer, and that is not able to form a protective oxide layer, is more likely to corrode and release lead into the water supply.

# Continuous Learning Before, During, and After Class

## NEW! eText 2.0

- **Full eReader functionality** includes page navigation, search, glossary, highlighting, note taking, annotations, and more.
- **A responsive design** allows the eText to reflow and resize to your device or screen. eText 2.0 now works on supported smartphones, tablets, and laptop/desktop computers.
- **In-context glossary** offers students instant access to definitions by simply hovering over key terms.
- **Seamlessly integrated** elinteractives engage students through interactivity to further enhance their learning experience.
  - \* **New!** 50 Interactive Sample Exercises bring key Sample Exercises in the text to life through animation and narration.
  - \* **New!** 27 SmartFigures walk students through complex visual representations, dispelling common misconceptions before they take root.
- **Accessible** (screen-reader ready).
- **Configurable reading settings**, including resizable type and night reading mode.



## BEFORE CLASS

**NEW! 66 Dynamic Study Modules** help students study effectively on their own by continuously assessing their activity and performance in real time. Students complete a set of questions with a unique answer format that also asks them to indicate their confidence level. Questions repeat until the student can answer them all correctly and confidently. Once completed, Dynamic Study Modules explain the concept using materials from the text. These are available as graded assignments prior to class, and accessible on smartphones, tablets, and computers.

**NEW! The Chemistry Primer** helps students remediate their chemistry math skills and prepare for their first college chemistry course.

- **Pre-built Assignments** get students up to speed at the beginning of the course.
- **Math is covered** in the context of chemistry, basic chemical literacy, balancing chemical equations, mole theory, and stoichiometry.
- **Scaled to students' needs**, remediation is only suggested to students that perform poorly on initial assessment.
- **Remediation** includes tutorials, wrong-answer specific feedback, video instruction, and step-wise scaffolding to build students' abilities.



# MasteringChemistry™

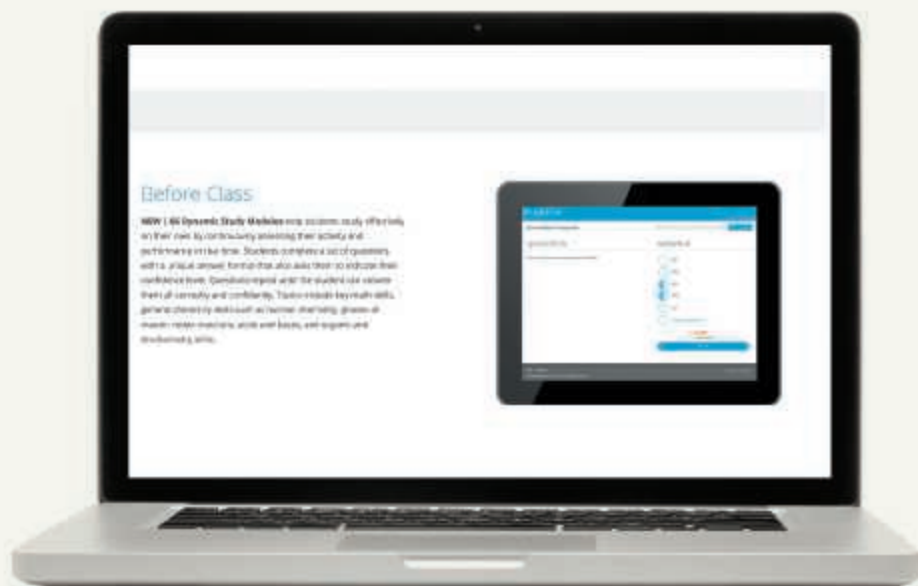
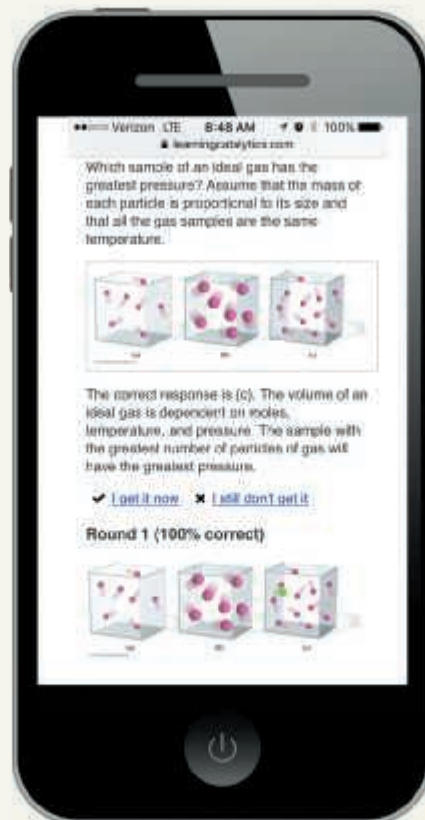
MasteringChemistry™ delivers engaging, dynamic learning opportunities—focusing on course objectives and responsive to each student's progress—that are proven to help students absorb course material and understand challenging chemistry processes and concepts.

## DURING CLASS

### Learning Catalytics™

With questions specific to *Chemistry: The Central Science 14e*, Learning Catalytics generates class discussion, guides your lecture, and promotes peer-to-peer learning with real-time analytics. MasteringChemistry™ with eText now provides Learning Catalytics—an interactive student response tool that uses students' smartphones, tablets, or laptops to engage them in more sophisticated tasks and individual and group problem-solving. Instructors can:

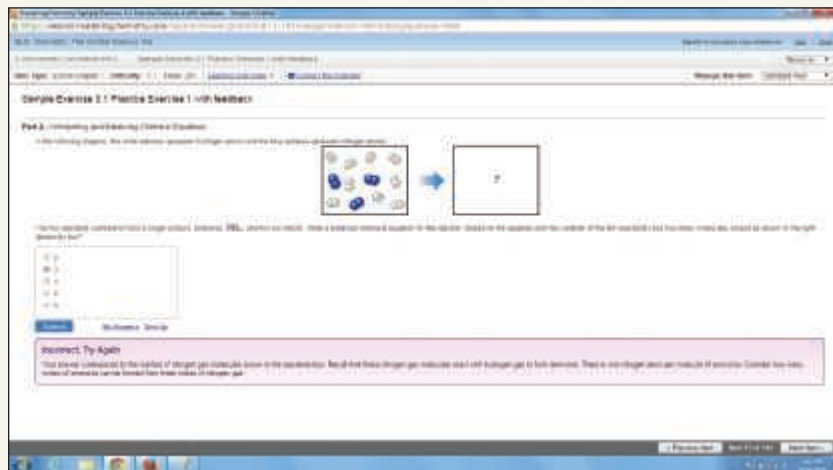
- Upload a full PowerPoint® deck for easy creation of slide questions.
- Help your students develop critical thinking skills.
- Monitor responses to find out where your students are struggling.
- Rely on real-time data to adjust your teaching strategy.
- Automatically group students for discussion, teamwork, and peer-to-peer learning.



Book-specific questions embedded in library

## AFTER CLASS

Hundreds of new Enhanced EOC questions with wrong-answer-response feedback



**Design An Experiment** feature provides a departure from the usual kinds of end-of-chapter exercises with an inquiry-based, open-ended approach that tries to stimulate the student to "think like a scientist." Designed to foster critical thinking, each exercise presents the student with a scenario in which various unknowns require investigation. The student is called upon to ponder how experiments might be set up to provide answers to particular questions about observations.



**Adaptive Follow-Up Assignments** allow instructors to deliver content to students—automatically personalized for each individual based on the strengths and weaknesses identified by his or her performance on initial Mastering assignments.



# Instructor and Student Resources

Resource	Available in Print	Available Online	Instructor or Student Resource	Description
<b>TestGen Test Bank</b> 0134554620		√	Instructor	TestGen® is a computerized test generator that lets teachers view and edit Test Bank questions, transfer questions to tests, and print tests in a variety of customized formats. This Test Bank includes over 3000 multiple choice, true/false, and answer/essay questions. Questions are rated by difficulty and are correlated to the book's Learning Outcomes.
<b>Instructor Manual</b> 0134554604		√	Instructor	Organized by chapter, this useful guide includes objectives, lecture outlines, references to figures and solved problems, as well as teaching tips.
<b>Instructor Resource Materials</b> 0134557220		√	Instructor	The material available for download includes: <ul style="list-style-type: none"> <li>• All illustrations, tables, and photos from the text in JPEG format</li> <li>• Pre-built PowerPoint™ Presentations (lecture, worked examples, images)</li> <li>• TestGen computerized software with the TestGen version of the Testbank</li> <li>• Word.doc files of the Test Item File</li> </ul>
<b>Student Guide</b> 0134554078	√		Student	This book assists students through the text material with chapter overviews, learning objectives, a review of key terms, as well as self tests with answers and explanations. This student guide also features MCAT practice questions.
<b>Solutions Manual</b> 0134552245	√		Instructor/ Student	Full solutions to all of the exercises (both red and black) in the text are provided.
<b>Solutions Manual to Red Exercises</b> 0134552237	√		Student	Full solutions to all of the red-numbered exercises in the text are provided.
<b>Solutions Manual to Black Exercises</b> 0134580095	√		Student	Full solutions to all of the black-numbered exercises in the text are provided.
<b>Laboratory Experiments</b> 0134566203	√		Student	This manual contains 43 finely-tuned experiments chosen to introduce students to basic lab techniques and to illustrate core chemical principles.
<b>Annotated Instructor's Edition to Laboratory Experiments</b> 013470150X	√		Instructor	Instructor's companion to the Laboratory Experiments.

# CHEMISTRY

THE CENTRAL SCIENCE 14<sup>TH</sup> EDITION



# INTRODUCTION: MATTER, ENERGY, AND MEASUREMENT

The title of this book—*Chemistry: The Central Science*—reflects the fact that much of what goes on in the world around us involves chemistry. Everyday chemical processes include the changes that produce brilliant fall colors in leaves, the ways our bodies process the food we eat, and the electrical energy that powers our cell phones.

**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 lives, from everyday activities like food preparation to more complex processes such as those that operate in the environment. We will also learn how the properties of substances can be tailored for specific applications by controlling their composition and structure. For example, the synthetic pigments chemists developed in the nineteenth century were used extensively by impressionist artists like van Gogh and Monet.

This first chapter provides an overview of what chemistry is about and what chemists do. The “What’s Ahead” list gives an overview of the chapter organization and of some of the ideas we will consider.

## WHAT’S AHEAD

- 1.1 ▶ **The Study of Chemistry** Learn what chemistry is, what chemists do, 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** 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 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 Cypress and Star*.

## 1.1 | The Study of Chemistry

Chemistry is at the heart of many changes we see in the world around us, and it accounts for the myriad 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

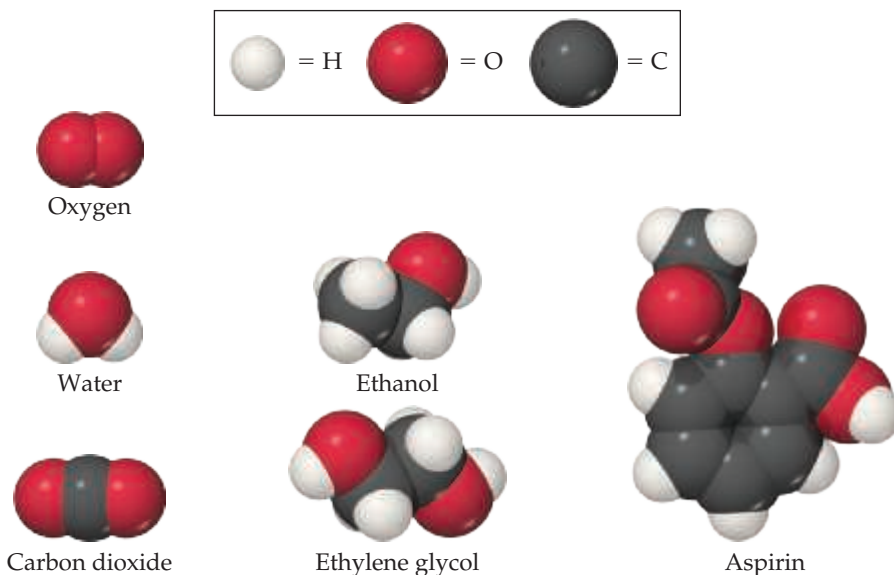
Chemistry is the study of the properties and behavior of matter. **Matter** is the physical material of the universe; it is anything that has mass and occupies space. A **property** is any characteristic that allows us to recognize a particular type of matter and to distinguish it from other types. This 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 comprised of combinations of only about 100 substances called **elements**. One of our major goals will be to relate the properties of matter to its composition, that is, to the particular elements it contains.

Chemistry also provides a background for understanding the properties of matter in terms of **atoms**, the almost infinitesimally 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 **molecules**, two or more atoms are joined in specific shapes. Throughout this text you will see molecules represented using colored spheres to show how the atoms are connected (Figure 1.1). The color provides a convenient way to distinguish between

#### 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.

atoms of different elements. For example, notice that the molecules of ethanol and ethylene glycol in Figure 1.1 have different compositions and structures. Ethanol contains one oxygen atom, depicted by one red sphere. In contrast, 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, let's compare ethanol and ethylene glycol, which appear in Figure 1.1 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 you should *never* consume ethylene glycol because it 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, shown in 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* = 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.



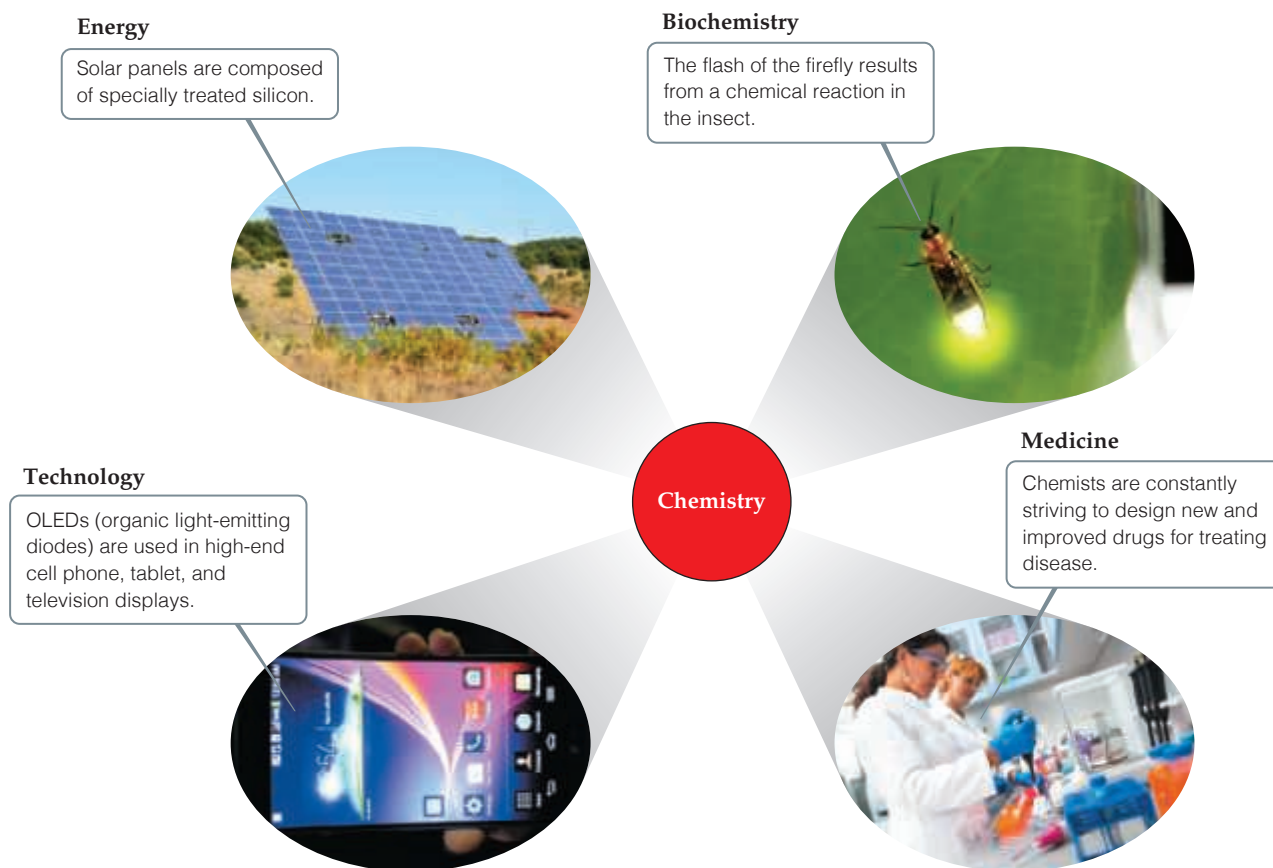
### Give It Some Thought

- (a) Approximately how many elements are there?
- (b) What submicroscopic particles are the building blocks of matter?

## Why Study Chemistry?

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, in order to arrive at 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. [Figure 1.2](#) illustrates how chemistry is central to several different realms of modern life.



▲ **Figure 1.2** Chemistry is central to our understanding of the world around us.

## CHEMISTRY PUT TO WORK Chemistry and the Chemical Industry

Chemistry is all around us. We are all familiar with household chemicals, particularly those used for cleaning as shown in **Figure 1.3**. However, few realize the size and importance of the chemical industry. The chemical industry in the United States is estimated to be an \$800 billion enterprise that employs over 800,000 people and accounts for 14% of all U.S. exports.

**Who are chemists, and what do they do?** People who have degrees in chemistry hold a variety of positions in industry, government, and academia. Those in industry work as laboratory chemists, developing new products (research and development); analyzing materials (quality control); or assisting customers in using products (sales and service). Those with more experience or training may work as managers or company directors. Chemists are important members of the scientific workforce in government (the National Institutes of Health, Department of Energy, and Environmental Protection Agency all employ chemists) and at universities. A chemistry degree is also good preparation for careers in teaching, medicine, biomedical research, information science, environmental work, technical sales, government regulatory agencies, and patent law.

Fundamentally, chemists do three things: They (1) make new types of matter: materials, substances, or combinations of substances with desired properties; (2) measure the properties of matter; and (3) develop models that explain and/or predict the properties of matter. One chemist, for example, may work in the laboratory to discover new drugs. Another may concentrate on the development of new instrumentation to measure properties of matter at the atomic level. Other chemists may use existing

materials and methods to understand how pollutants are transported in the environment or how drugs are processed in the body. Yet another chemist will develop theory, write computer code, and run computer simulations to understand how molecules move and react. The collective chemical enterprise is a rich mix of all of these activities.



▲ **Figure 1.3** Common chemicals used for household cleaning.

## 1.2 | Classifications of Matter

Let's begin our study of chemistry by examining two fundamental ways in which matter is classified. Matter is typically characterized by (1) its physical state (gas, liquid, or solid) and (2) its composition (whether it is an element, a *compound*, or a *mixture*).

### States of Matter

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 compressible to any appreciable extent.
- A **solid** has both a definite shape and a definite volume and is not compressible to any appreciable extent.

The properties of the states of matter can be understood on the molecular level (Figure 1.4). 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 lead to conversion from one state of matter to another, illustrated by such familiar processes as ice melting or water vapor condensing.

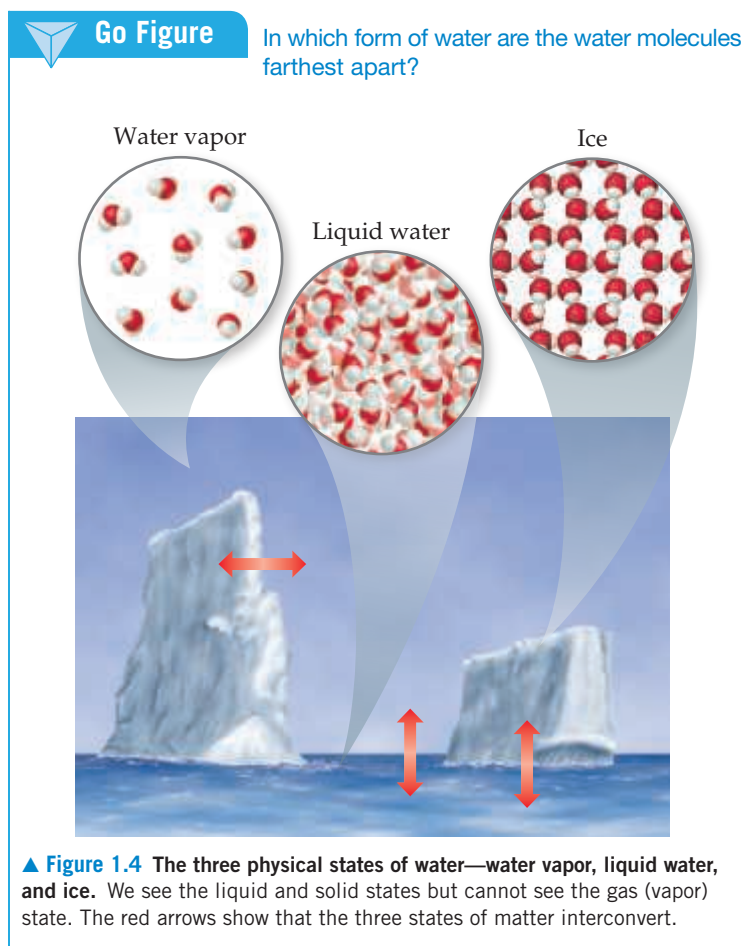
### Pure Substances

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 1.5(a and b)].
- **Compounds** are substances composed of two or more elements; they contain two or more kinds of atoms [Figure 1.5(c)]. Water, for example, is a compound composed of two elements: hydrogen and oxygen.

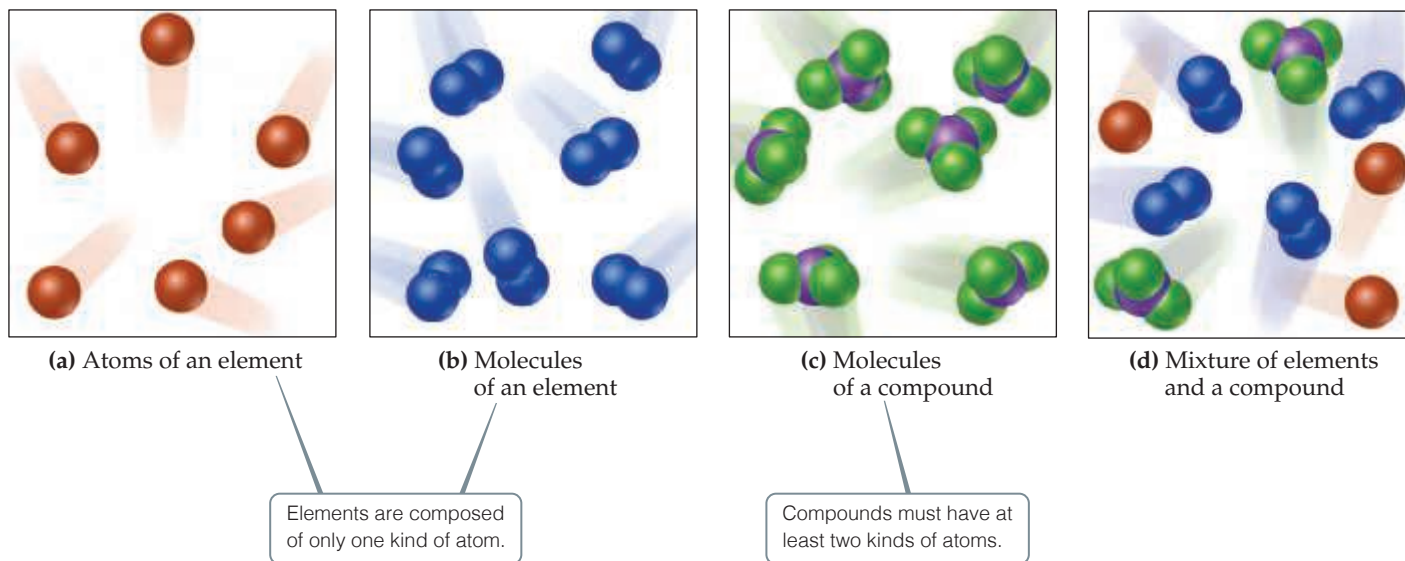
Figure 1.5(d) shows a mixture of substances. **Mixtures** are combinations of two or more substances in which each substance retains its chemical identity.





### Go Figure

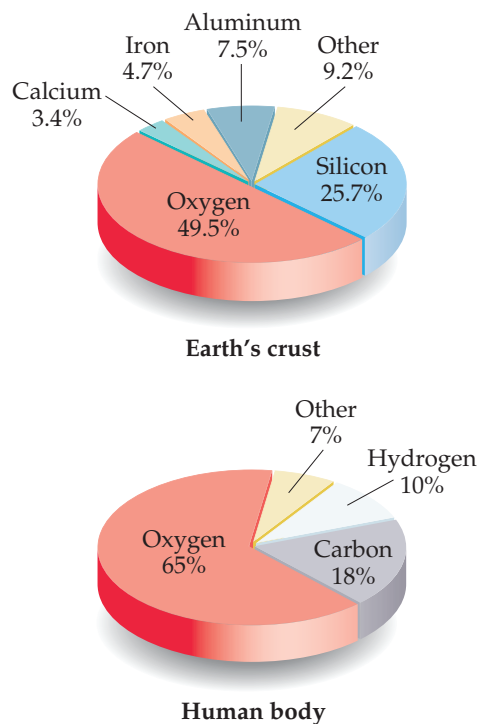
How do the molecules of a compound differ from the molecules of an element?



▲ Figure 1.5 Molecular comparison of elements, compounds, and mixtures.

### Go Figure

If the lower pie chart was 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 1.6 Relative abundances of elements.\* Elements in percent by mass in Earth's crust (including oceans and atmosphere) and the human body.

## 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 Earth's crust (including oceans and atmosphere), and only three—oxygen, carbon, and hydrogen—account for over 90% of the mass of the human body (Figure 1.6).

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 (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

TABLE 1.1 Some Common Elements and Their Symbols

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

\*U.S. Geological Survey Circular 285, U.S. Department of the Interior.

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. Conversely, water can be decomposed into its elements by passing an electrical current through it (Figure 1.7).

**Go Figure** Is the volume of  $\text{H}_2$  produced larger than the volume of  $\text{O}_2$  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?

Water,  $\text{H}_2\text{O}$

Oxygen gas,  $\text{O}_2$

Hydrogen gas,  $\text{H}_2$

**▲ Figure 1.7 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.

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 has the same number of hydrogen and oxygen atoms. While the mass percentages make it seem that water is mostly oxygen, there are actually two hydrogen atoms and only one oxygen atom per molecule. The explanation for this apparent discrepancy comes from the fact that hydrogen atoms are much lighter than oxygen atoms. This macroscopic composition corresponds to the molecular composition, which consists of two hydrogen atoms combined with one oxygen atom:

