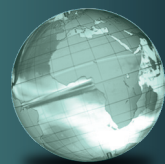


GLOBAL
EDITION



Chemistry

The Central Science

Expanded Edition

Fifteenth Global Edition in SI Units

Brown • LeMay • Bursten
Murphy • Woodward • Stoltzfus
Langford • George



Periodic Table of the Elements

| Main Group Representative Elements | | | Main Group Representative Elements | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---------------------------------------|------------------------------|-----------------------------|---------------------------------------|-------------------------------|--------------------------------|-------------------------------|------------------------------|-----------------------------|------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|---------------------------|---------------------------|-----------------------------|---------------------------|---------------------------|---------------------------|----------------------------|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|
| 1A ^a 1 | | | | | | | | | | | | | | | | | | | | | 8A 18 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 H 1.00794 | 2A 2 | 3A 13 | 4A 14 | 5A 15 | 6A 16 | 7A 17 | 8A 18 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 3 Li 6.941 | 4 Be 9.012182 | 5 B 10.811 | 6 C 12.0107 | 7 N 14.0067 | 8 O 15.9994 | 9 F 18.998403 | 10 Ne 20.1797 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 11 Na 22.989770 | 12 Mg 24.3050 | 13 Al 26.981538 | 14 Si 28.0855 | 15 P 30.973761 | 16 S 32.065 | 17 Cl 35.453 | 18 Ar 39.948 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | 19 K 39.0983 | 20 Ca 40.078 | 21 Sc 44.955910 | 22 Ti 47.867 | 23 V 50.9415 | 24 Cr 51.9961 | 25 Mn 54.938049 | 26 Fe 55.845 | 27 Co 58.933200 | 28 Ni 58.6934 | 29 Cu 63.546 | 30 Zn 65.39 | 31 Ga 69.723 | 32 Ge 72.64 | 33 As 74.92160 | 34 Se 78.96 | 35 Br 79.904 | 36 Kr 83.80 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | 37 Rb 85.4678 | 38 Sr 87.62 | 39 Y 88.90585 | 40 Zr 91.224 | 41 Nb 92.90638 | 42 Mo 95.94 | 43 Tc [98] | 44 Ru 101.07 | 45 Rh 102.90550 | 46 Pd 106.42 | 47 Ag 107.8682 | 48 Cd 112.411 | 49 In 114.818 | 50 Sn 118.710 | 51 Sb 121.760 | 52 Te 127.60 | 53 I 126.90447 | 54 Xe 131.293 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | 55 Cs 132.90545 | 56 Ba 137.327 | 57 La [262.11] | 58 Ce [261.11] | 59 Pr [262.11] | 60 Nd [266.12] | 61 Pm [269.13] | 62 Sm [268.14] | 63 Eu [281.15] | 64 Gd [272.15] | 65 Tb [285] | 66 Dy [284] | 67 Ho [289.2] | 68 Er [288] | 69 Tm [293] | 70 Yb [294] | 71 Lu [262.11] | 72 Hf [261.11] | 73 Ta [262.11] | 74 W [266.12] | 75 Re [264.12] | 76 Os [269.13] | 77 Ir [268.14] | 78 Pt [281.15] | 79 Au [272.15] | 80 Hg [285] | 81 Tl [284] | 82 Pb [289.2] | 83 Bi [294] | 84 Po [293] | 85 At [294] | 86 Rn [294] | | | | | | | | | | | | | | | | | | |
| 7 | 87 Fr [223.02] | 88 Ra [226.03] | 89 Ac [227.03] | 90 Th [232.0381] | 91 Pa [231.03588] | 92 U [238.02891] | 93 Np [237.05] | 94 Pu [244.06] | 95 Am [243.06] | 96 Cm [247.07] | 97 Bk [247.07] | 98 Cf [251.08] | 99 Es [252.08] | 100 Fm [257.10] | 101 Md [258.10] | 102 No [259.10] | 103 Lr [262.11] | 104 Rf [261.11] | 105 Db [262.11] | 106 Sg [266.12] | 107 Bh [264.12] | 108 Hs [269.13] | 109 Mt [268.14] | 110 Ds [281.15] | 111 Rg [272.15] | 112 Cn [285] | 113 Nh [284] | 114 Fl [289.2] | 115 Mc [293] | 116 Lv [294] | 117 Uu [294] | 118 Ubn [294] | | | | | | | | | | | | | | | | | | |
| | | | Lanthanide series | | | | | | | | | | | | | | | Actinide series | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | 138.9055 | 140.116 | 140.90765 | 144.24 | [145] | 150.36 | 151.964 | 157.25 | 158.92534 | 162.50 | 164.93032 | 167.259 | 168.93421 | 173.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 | 101 | 102 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | [227.03] | 232.0381 | 231.03588 | 238.02891 | [237.05] | [244.06] | [243.06] | [247.07] | [247.07] | [251.08] | [252.08] | [257.10] | [258.10] | [259.10] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

^aThe labels on top (1A, 2A, etc.) are common American usage. The labels below these (1, 2, etc.) are those recommended by the International Union of Pure and Applied Chemistry (IUPAC).
 Except for elements 114 and 116, the names and symbols for elements above 113 have not yet been decided. Atomic weights in brackets are the names of the longest-lived or most important isotope of radioactive elements. Further information is available at <http://www.webelements.com>
 ** Discovered in 2010, element 117 is currently under review by IUPAC.

List of Elements with Their Symbols and Atomic Weights

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

^aMass of longest-lived or most important isotope.

This page is intentionally left blank

CHEMISTRY

THE CENTRAL SCIENCE

EXPANDED EDITION

15TH GLOBAL EDITION IN SI UNITS



CHEMISTRY

THE CENTRAL SCIENCE

EXPANDED EDITION

15TH GLOBAL EDITION IN SI UNITS

Theodore L. Brown

University of Illinois at Urbana-Champaign

H. Eugene LeMay, Jr.

University of Nevada, Reno

Bruce E. Bursten

Worcester Polytechnic Institute

Catherine J. Murphy

University of Illinois at Urbana-Champaign

Patrick M. Woodward

The Ohio State University

Matthew W. Stoltzfus

The Ohio State University

Adrian V. George

University of Sydney

Steven J. Langford

Swinburne University of Technology

With contributions by

Michael W. Lufaso

University of North Florida



Pearson Education Limited

KAO Two
KAO Park
Hockham Way
Harlow
CM17 9SR
United Kingdom

and Associated Companies throughout the world

Visit us on the World Wide Web at: www.pearsonglobaleditions.com

© Pearson Education Limited 2022

The rights of Theodore L. Brown, H. Eugene LeMay, Bruce E. Bursten, Catherine J. Murphy, Patrick M. Woodward, Matthew W. Stoltzfus to be identified as the authors of this work have been asserted by them in accordance with the Copyright, Designs and Patents Act 1988.

Authorized adaptation from the United States edition entitled Chemistry: The Central Science, 14th Edition, ISBN 978-0-13-441423-2 by Theodore L. Brown, H. Eugene LeMay, Bruce E. Bursten, Catherine J. Murphy, Patrick M. Woodward, Matthew W. Stoltzfus, published by Pearson Education © 2018.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without either the prior written permission of the publisher or a license permitting restricted copying in the United Kingdom issued by the Copyright Licensing Agency Ltd, Saffron House, 6–10 Kirby Street, London EC1N 8TS. For information regarding permissions, request forms and the appropriate contacts within the Pearson Education Global Rights & Permissions department, please visit www.pearsoned.com/permissions/.

All trademarks used herein are the property of their respective owners. The use of any trademark in this text does not vest in the author or publisher any trademark ownership rights in such trademarks, nor does the use of such trademarks imply any affiliation with or endorsement of this book by such owners.

PEARSON, ALWAYS LEARNING, and MYLAB are exclusive trademarks in the U.S. and/or other countries owned by Pearson Education, Inc. or its affiliates.

Unless otherwise indicated herein, any third-party trademarks that may appear in this work are the property of their respective owners and any references to third-party trademarks, logos or other trade dress are for demonstrative or descriptive purposes only. Such references are not intended to imply any sponsorship, endorsement, authorization, or promotion of Pearson's products by the owners of such marks, or any relationship between the owner and Pearson Education, Inc. or its affiliates, authors, licensees or distributors.

ISBN 10: 1-292-40876-6

ISBN 13: 978-1-292-40876-7

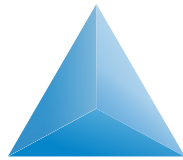
eBook ISBN 13: 978-1-292-40877-4

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

1 21

Typeset by Straive
eBook formatted by B2R Technologies Pvt. Ltd.



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

This page is intentionally left blank

BRIEF CONTENTS

PREFACE 25

- 1 Introduction: Matter, Energy, and Measurement 46
- 2 Atoms, Molecules, and Ions 89
- 3 Chemical Reactions and Stoichiometry 134
- 4 Reactions in Aqueous Solution 175
- 5 Thermochemistry 219
- 6 Electronic Structure of Atoms 274
- 7 Periodic Properties of the Elements 323
- 8 Basic Concepts of Chemical Bonding 369
- 9 Molecular Geometry and Bonding Theories 412
- 10 Gases 472
- 11 Liquids and Intermolecular Forces 517
- 12 Solids and Modern Materials 560
- 13 Properties of Solutions 613
- 14 Chemical Kinetics 658
- 15 Chemical Equilibrium 715
- 16 Acid–Base Equilibria 757
- 17 Additional Aspects of Aqueous Equilibria 813
- 18 Chemistry of the Environment 864
- 19 Chemical Thermodynamics 904
- 20 Electrochemistry 950
- 21 Nuclear Chemistry 1007
- 22 Chemistry of the Nonmetals 1052
- 23 Transition Metals and Coordination Chemistry 1102
- 24 The Chemistry of Organic Compounds 1149
- 25 Stereochemistry of Organic Compounds 1185
- 26 Chemistry of Alkenes and Alkynes 1210
- 27 Alcohols, Haloalkanes, and Ethers 1253
- 28 Aldehydes, Ketones, and Carbohydrates 1292
- 29 Carboxylic Acids and their Derivatives 1332
- 30 Benzene and its Derivatives 1371
- 31 Nitrogen-Containing Organic Compounds 1402
- 32 Solving Molecular Structure 1452

APPENDICES

- A Mathematical Operations 1504
- B Properties of Water 1510
- C Thermodynamic Quantities for Selected Substances at 298.15 K (25 °C) 1511
- D Aqueous Equilibrium Constants 1515
- E Standard Reduction Potentials at 25 °C 1517

ANSWERS TO SELECTED EXERCISES 1518

ANSWERS TO GO FIGURE 1573

ANSWERS TO SELECTED PRACTICE EXERCISES 1579

GLOSSARY 1589

PHOTO AND ART CREDITS 1613

INDEX 1615

CONTENTS

PREFACE 25

1 Introduction: Matter, Energy, and Measurement 46

- 1.1 The Study of Chemistry 46**
The Atomic and Molecular Perspective of Chemistry 47
Why Study Chemistry? 48
- 1.2 Classifications of Matter 50**
States of Matter 50 Pure Substances 51
Elements 52 Compounds 52 Mixtures 54
- 1.3 Properties of Matter 56**
Physical and Chemical Changes 56 Separation of
Mixtures 56
- 1.4 The Nature of Energy 60**
Kinetic Energy and Potential Energy 60
- 1.5 Units of Measurement 62**
SI Units 63 Length and Mass 65
Temperature 65 Derived SI Units 65 Volume 66
Density 67 Units of Energy 67
- 1.6 Uncertainty in Measurement 71**
Precision and Accuracy 71 Significant Figures 72
Significant Figures in Calculations 73
- 1.7 Dimensional Analysis 76**
Conversion Factors 77 Using Two or More Conversion
Factors 78 Conversions Involving Volume 79
Chapter Summary and Key Terms 81
Learning Outcomes 82 Key Equations 82
Exercises 82 Additional Exercises 86

Chemistry Put to Work Chemistry and the
Chemical Industry 49

A Closer Look The Scientific Method 63

Chemistry Put to Work Chemistry in the News 69

Strategies for Success Estimating Answers 78

Strategies for Success The Importance of Practice 80

Strategies for Success The Features of This Book 80

2 Atoms, Molecules, and Ions 89

- 2.1 The Atomic Theory of Matter 89**
- 2.2 The Discovery of Atomic Structure 92**
Cathode Rays and Electrons 92 Radioactivity 94
The Nuclear Model of the Atom 95

2.3 The Modern View of Atomic Structure 97

Atomic Numbers, Mass Numbers, and Isotopes 98

2.4 Atomic Weights 101

The Atomic Mass Scale 102 Atomic Weight 102

2.5 The Periodic Table 104

2.6 Molecules and Molecular Compounds 108

Molecules and Chemical Formulas 108 Molecular and
Empirical Formulas 109 Picturing Molecules 109

2.7 Ions and Ionic Compounds 111

Predicting Ionic Charges 112 Ionic Compounds 113

2.8 Naming Inorganic Compounds 116

Names and Formulas of Ionic Compounds 117
Names and Formulas of Acids 121 Names and
Formulas of Binary Molecular Compounds 122

2.9 Some Simple Organic Compounds 124

Alkanes 124 Some Derivatives of Alkanes 125

Chapter Summary and Key Terms 127

Learning Outcomes 128 Key Equations 128

Exercises 128 Additional Exercises 131

A Closer Look Basic Forces 99

A Closer Look The Mass Spectrometer 103

Chemistry and Life Elements Required by Living
Organisms 115

Strategies for Success How to Take a Test 126

3 Chemical Reactions and Stoichiometry 134

3.1 The Conservation of Mass, Chemical Equations, and Stoichiometry 134

How to Balance Chemical Equations 135 A Step-by-
Step Example of Balancing a Chemical Equation 136

3.2 Simple Patterns of Chemical Reactivity: Combination, Decomposition, and Combustion 139

Combination and Decomposition Reactions 140
Combustion Reactions 141

3.3 Formula Weights and Elemental Compositions of Substances 143

Formula and Molecular Weights 144 Elemental
Compositions of Substances 144

3.4 Avogadro's Number and the Mole; Molar Mass 146

The Mole and Avogadro's Number 147 Molar Mass 147 Converting Between Masses, Moles, and Atoms/Molecules/Ions 148

3.5 Formula Weights and Elemental Compositions of Substances 152

Molecular Formulas from Empirical Formulas 154 Combustion Analysis 155

3.6 Reaction Stoichiometry 158**3.7 Limiting Reactants 162**

Theoretical and Percent Yields 165

Chapter Summary and Key Terms 168

Learning Outcomes 168 Key Equations 168

Exercises 169 Additional Exercises 172

Integrative Exercises 173 Design an Experiment 174

Strategies for Success Problem Solving 145

Chemistry and Life Glucose Monitoring 149

Strategies for Success Design an Experiment 166

4 Reactions in Aqueous Solution 175**4.1 General Properties of Aqueous Solutions 175**

Electrolytes and Nonelectrolytes 176

How Compounds Dissolve in Water 177 Strong and Weak Electrolytes 178

4.2 Precipitation Reactions 180

Solubility Guidelines for Ionic Compounds 180

Exchange (Metathesis) Reactions 182 Ionic Equations and Spectator Ions 183

4.3 Acids, Bases, and Neutralization Reactions 185

Acids 186 Bases 186 Strong and Weak Acids and Bases 187 Identifying Strong and Weak Electrolytes 187 Neutralization Reactions and Salts 189 Neutralization Reactions with Gas Formation 191

4.4 Oxidation–Reduction Reactions 193

Oxidation and Reduction 193 Oxidation Numbers 194 Oxidation of Metals by Acids and Salts 196 The Activity Series 197

4.5 Concentrations of Solutions 201

Molarity 201 Expressing the Concentration of an Electrolyte 201 Interconverting Molarity, Moles, and Volume 203 Dilution 204

4.6 Solution Stoichiometry and Chemical Analysis 207

Titration 208

Chapter Summary and Key Terms 212

Learning Outcomes 213 Key Equations 213

Exercises 213 Additional Exercises 216

Integrative Exercises 218 Design an Experiment 218

Chemistry Put to Work Antacids 191

Strategies for Success Analyzing Chemical Reactions 200

5 Thermochemistry 219**5.1 The Nature of Chemical Energy 219****5.2 The First Law of Thermodynamics 223**

System and Surroundings 223 Internal Energy 224 Relating ΔE to Heat and Work 225 Endothermic and Exothermic Processes 227 State Functions 228

5.3 Enthalpy 230

Pressure–Volume Work 231 Enthalpy Change 232

5.4 Enthalpies of Reaction 234**5.5 Calorimetry 238**

Heat Capacity and Specific Heat 239

Constant-Pressure Calorimetry 240

Bomb Calorimetry (Constant-Volume Calorimetry) 242

5.6 Hess's Law 244**5.7 Enthalpies of Formation 248**

Using Enthalpies of Formation to Calculate Enthalpies of Reaction 250

5.8 Bond Enthalpies 254

Bond Enthalpies and the Enthalpies of Reactions 255

5.9 Foods and Fuels 258

Foods 259 Fuels 261 Other Energy Sources 261

Chapter Summary and Key Terms 264

Learning Outcomes 265 Key Equations 265

Exercises 266 Additional Exercises 270

Integrative Exercises 272 Design an Experiment 273

A Closer Look Energy, Enthalpy, and P - V Work 233

A Closer Look Using Enthalpy as a Guide 236

Chemistry and Life The Regulation of Body Temperature 243

Chemistry Put to Work The Scientific and Political Challenges of Biofuels 262

6 Electronic Structure of Atoms 274**6.1 The Wave Nature of Light 274****6.2 Quantized Energy and Photons 278**

Hot Objects and the Quantization of Energy 278

The Photoelectric Effect and Photons 279

6.3 Line Spectra and the Bohr Model 281

Line Spectra 281 Bohr's Model 283 The Energy States of the Hydrogen Atom 283 Limitations of the Bohr Model 286

6.4 The Wave Behavior of Matter 287

The Uncertainty Principle 289

6.5 Quantum Mechanics and Atomic Orbitals 291

Orbitals and Quantum Numbers 292

6.6 Representations of Orbitals 296

The *s* Orbitals 296 The *p* Orbitals 298 The *d* and *f* Orbitals 299

6.7 Many-Electron Atoms 300

Orbitals and Their Energies 301 Electron Spin and the Pauli Exclusion Principle 301

6.8 Electron Configurations 303

Hund's Rule 305 Condensed Electron Configurations 306 Transition Metals 307 The Lanthanides and Actinides 308

6.9 Electron Configurations and the Periodic Table 309

Anomalous Electron Configurations 312

Chapter Summary and Key Terms 314

Learning Outcomes 315 Key Equations 315

Exercises 316 Additional Exercises 319

Integrative Exercises 321 Design an Experiment 322

A Closer Look Measurement and the Uncertainty Principle 290

A Closer Look Thought Experiments and Schrödinger's Cat 293

A Closer Look Probability Density and Radial Probability Functions 298

Chemistry and Life Nuclear Spin and Magnetic Resonance Imaging 304

7 Periodic Properties of the Elements 323**7.1 Development of the Periodic Table 323****7.2 Effective Nuclear Charge 326****7.3 Sizes of Atoms and Ions 330**

Periodic Trends in Atomic Radii 332 Periodic Trends in Ionic Radii 332

7.4 Ionization Energy 336

Variations in Successive Ionization Energies 337 Periodic Trends in First Ionization Energies 338 Electron Configurations of Ions 339

7.5 Electron Affinity 341

Periodic Trends in Electron Affinity 342

7.6 Metals, Nonmetals, and Metalloids 343

Metals 344 Nonmetals 346 Metalloids 347

7.7 Trends for Group 1 and Group 2 Metals 349

Group 1: The Alkali Metals 349 Group 2: The Alkaline Earth Metals 353

7.8 Trends for Selected Nonmetals 354

Hydrogen 354 Group 16: The Oxygen Group 355 Group 17: The Halogens 356 Group 18: The Noble Gases 358

Chapter Summary and Key Terms 360

Learning Outcomes 361 Key Equations 361

Exercises 361 Additional Exercises 365

Integrative Exercises 367 Design an Experiment 368

A Closer Look Effective Nuclear Charge 329

Chemistry Put to Work Ionic Size and Lithium-Ion Batteries 335

Chemistry and Life The Improbable Development of Lithium Drugs 352

8 Basic Concepts of Chemical Bonding 369**8.1 Lewis Symbols and the Octet Rule 369**

Lewis Symbols 370 The Octet Rule 370

8.2 Ionic Bonding 371

Energetics of Ionic Bond Formation 373 Electron Configurations of Ions of the *s*- and *p*-Block Elements 375 Transition Metal Ions 376

8.3 Covalent Bonding 378

Lewis Structures 379 Multiple Bonds 380

8.4 Bond Polarity and Electronegativity 381

Electronegativity 382 Electronegativity and Bond Polarity 382 Dipole Moments 384 Comparing Ionic and Covalent Bonding 387

8.5 Drawing Lewis Structures 388

Formal Charge and Alternative Lewis Structures 390

8.6 Resonance Structures 393

Resonance in Benzene 395

8.7 Exceptions to the Octet Rule 397

Odd Number of Electrons 397 Less Than an Octet of Valence Electrons 397 More Than an Octet of Valence Electrons 398

8.8 Strengths and Lengths of Covalent Bonds 400

Chapter Summary and Key Terms 404

Learning Outcomes 405 Key Equations 405

Exercises 406 Additional Exercises 408

Integrative Exercises 409 Design an Experiment 411

A Closer Look Calculation of Lattice Energies: The Born-Haber Cycle 376

A Closer Look Oxidation Numbers, Formal Charges, and Actual Partial Charges 392

9 Molecular Geometry and Bonding Theories 412

9.1 Molecular Shapes 412

9.2 The VSEPR Model 416

Applying the VSEPR Model to Determine Molecular Shapes 417 Effect of Nonbonding Electrons and Multiple Bonds on Bond Angles 421 Molecules with Expanded Valence Shells 421 Shapes of Larger Molecules 424

9.3 Molecular Shape and Molecular Polarity 426

9.4 Covalent Bonding and Orbital Overlap 429

9.5 Hybrid Orbitals 431

sp Hybrid Orbitals 432 sp^2 and sp^3 Hybrid Orbitals 433 Hypervalent Molecules 434 Hybrid Orbital Summary 436

9.6 Multiple Bonds 438

Resonance Structures, Delocalization, and π Bonding 442 General Conclusions about σ and π Bonding 444

9.7 Molecular Orbitals 445

Molecular Orbitals of the Hydrogen Molecule 446 Bond Order 448

9.8 Bonding in Period 2 Diatomic Molecules 450

Molecular Orbitals for Li_2 and Be_2 451
Molecular Orbitals from $2p$ Atomic Orbitals 452
Electron Configurations for B_2 through Ne_2 455
Electron Configurations and Molecular Properties 456
Heteronuclear Diatomic Molecules 459

Chapter Summary and Key Terms 462
Learning Outcomes 463 **Key Equations** 463
Exercises 463 **Additional Exercises** 467
Integrative Exercises 470 **Design an Experiment** 471

A Closer Look Phases in Atomic and Molecular Orbitals 453

Chemistry Put to Work Orbitals and Energy 460

10 Gases 472

10.1 Characteristics of Gases 472

10.2 Pressure 474

Atmospheric Pressure and the Barometer 475

10.3 The Gas Laws 479

The Pressure–Volume Relationship: Boyle’s Law 480
The Temperature–Volume Relationship: Charles’s Law 480
The Quantity–Volume Relationship: Avogadro’s Law 481

10.4 The Ideal Gas Equation 483

Relating the Ideal Gas Equation and the Gas Laws 486
Gas Densities and Molar Mass 487
Volumes of Gases in Chemical Reactions 489

10.5 Gas Mixtures and Partial Pressures 491

Partial Pressures and Mole Fractions 493

10.6 The Kinetic-Molecular Theory of Gases 494

Distributions of Molecular Speed 495 Application of Kinetic-Molecular Theory to the Gas Laws 496

10.7 Molecular Effusion and Diffusion 498

Graham’s Law of Effusion 499 Diffusion and Mean Free Path 501

10.8 Real Gases: Deviations from Ideal Behavior 503

The van der Waals Equation 506

Chapter Summary and Key Terms 508
Learning Outcomes 509 **Key Equations** 509
Exercises 509 **Additional Exercises** 514
Integrative Exercises 515 **Design an Experiment** 516

Chemistry and Life Blood Pressure 478

Strategies for Success Calculations Involving Many Variables 485

A Closer Look The Ideal Gas Equation 497

Chemistry Put to Work Gas Separations 502

11 Liquids and Intermolecular Forces 517

11.1 A Molecular Comparison of Gases, Liquids, and Solids 517

11.2 Intermolecular Forces 520

Dispersion Forces 522 Dipole–Dipole Interactions 523 Hydrogen Bonding 524
Ion–Dipole Forces 527 Comparing Intermolecular Forces 527

11.3 Select Properties of Liquids 529

Viscosity 530 Surface Tension 531 Capillary Action 532

11.4 Phase Changes 533

Energy Changes Accompany Phase Changes 534
Heating Curves 535 Critical Temperature and Pressure 536

11.5 Vapor Pressure 539

Volatility, Vapor Pressure, and Temperature 540
Vapor Pressure and Boiling Point 540

11.6 Phase Diagrams 542

The Phase Diagrams of H_2O and CO_2 544

11.7 Liquid Crystals 547

Types of Liquid Crystals 547

Chapter Summary and Key Terms 552 **Learning Outcomes** 552 **Exercises** 553 **Additional Exercises** 556 **Integrative Exercises** 558 **Design an Experiment** 559

Chemistry Put to Work Ionic Liquids 531

A Closer Look The Clausius–Clapeyron Equation 541

Chemistry and Life Liquid Crystal Displays 549

12 Solids and Modern Materials 560

12.1 Classification of Solids 560

Crystalline and Amorphous Solids 562

Unit Cells and Crystal Lattices 562

Filling the Unit Cell 564

12.2 Metallic Solids 567

The Structures of Metallic Solids 568 Close

Packing 568 Alloys 572 Metallic Bonding 574

Electron-Sea Model 575 Molecular Orbital Model 575

12.3 Ionic Solids 579

Structures of Ionic Solids 580

12.4 Covalent Solids 584

Molecular Solids 585 Covalent-Network

Solids 586 Semiconductors 586 Semiconductor

Doping 589

12.5 Polymers 591

Making Polymers 593 Structure and Physical

Properties of Polymers 596

12.6 Nanomaterials 598

Semiconductors on the Nanoscale 599 Metals on the

Nanoscale 599 Carbon on the Nanoscale 601

Chapter Summary and Key Terms 604

Learning Outcomes 605 **Key Equations** 606

Exercises 606 **Additional Exercises** 610

Integrative Exercises 612 **Design an Experiment** 612

A Closer Look X-ray Diffraction 565

Chemistry Put to Work Alloys of Gold 574

Chemistry Put to Work Solid-State Lighting 590

Chemistry Put to Work Modern Materials in the Automobile 595

Chemistry Put to Work Microporous and Mesoporous Materials 600

13 Properties of Solutions 613

13.1 The Solution Process 613

The Natural Tendency toward Mixing 614 The Effect

of Intermolecular Forces on Solution Formation 615

Energetics of Solution Formation 616 Solution

Formation and Chemical Reactions 617

13.2 Saturated Solutions and Solubility 619

13.3 Factors Affecting Solubility 621

Solute–Solvent Interactions 621 Pressure

Effects 623 Temperature Effects 626

13.4 Expressing Solution Concentration 628

Mass Percentage, ppm, and ppb 628 Mole Fraction,

Molarity, and Molality 629 Converting Concentration

Units 631

13.5 Colligative Properties 633

Vapor–Pressure Lowering 633 Boiling-Point

Elevation 636 Freezing-Point Depression 637

Osmosis 639 Determination of Molar Mass from

Colligative Properties 640

13.6 Colloids 644

Hydrophilic and Hydrophobic Colloids 645

Colloidal Motion in Liquids 647

Chapter Summary and Key Terms 649

Learning Outcomes 650 **Key Equations** 650

Exercises 651 **Additional Exercises** 655

Integrative Exercises 656 **Design an Experiment** 657

Chemistry and Life Fat-Soluble and Water-Soluble Vitamins 623

Chemistry and Life Blood Gases and Deep-Sea Diving 627

A Closer Look Ideal Solutions with Two or More Volatile Components 635

A Closer Look The van't Hoff Factor 642

Chemistry and Life Sickle-Cell Anemia 647

14 Chemical Kinetics 658

14.1 Factors That Affect Reaction Rates 658

14.2 Reaction Rates 660

Change of Rate with Time 662 Instantaneous

Rate 663 Reaction Rates and Stoichiometry 664

14.3 Concentration and Rate Laws 666

Reaction Orders: The Exponents in the Rate Law 669

Magnitudes and Units of Rate Constants 670

Using Initial Rates to Determine Rate Laws 671

14.4 The Change of Concentration with Time 673

First-Order Reactions 674 Second-Order

Reactions 676 Zero-Order Reactions 677

Half-Life 678

14.5 Temperature and Rate 680

The Collision Model 681 The Orientation Factor 681

Activation Energy 681 The Arrhenius Equation 684

Determining the Activation Energy 685

14.6 Reaction Mechanisms 687

Elementary Reactions 688 Multistep

Mechanisms 688 Rate Laws for Elementary

Reactions 689 The Rate-Determining Step for a

Multistep Mechanism 690 Mechanisms with a Slow

Initial Step 691 Mechanisms with a Fast Initial

Step 693

14.7 Catalysis 695

Homogeneous Catalysis 696 Heterogeneous Catalysis 697 Enzymes 699

Chapter Summary and Key Terms 703
Learning Outcomes 704 Key Equations 704
Exercises 705 Additional Exercises 710
Integrative Exercises 713 Design an Experiment 714

A Closer Look Using Spectroscopic Methods to Measure Reaction Rates: Beer's Law 667

Chemistry Put to Work Bromomethane in the Atmosphere 679

Chemistry Put to Work Catalytic Converters 699

Chemistry and Life Nitrogen Fixation and Nitrogenase 701

15 Chemical Equilibrium 715**15.1 The Concept of Equilibrium 715****15.2 The Equilibrium Constant 718**

Evaluating K_c 721 Equilibrium Constants in Terms of Pressure, K_p 722 Equilibrium Constants and Units 723

15.3 Understanding and Working with Equilibrium Constants 724

The Magnitude of Equilibrium Constants 725
 The Direction of the Chemical Equation and K 726
 Relating Chemical Equation Stoichiometry and Equilibrium Constants 726
 Heterogeneous Equilibria 728

15.4 Calculating Equilibrium Constants 731

Applications of Equilibrium Constants 734
 Predicting the Direction of Reaction 734
 Calculating Equilibrium Concentrations 735

15.5 Le Châtelier's Principle 738

Change in Reactant or Product Concentration 740
 Effects of Volume and Pressure Changes 742
 Effect of Temperature Changes 743 The Effect of Catalysts 745

Chapter Summary and Key Terms 749
Learning Outcomes 749 Key Equations 750
Exercises 750 Additional Exercises 754
Integrative Exercises 755 Design an Experiment 756

Chemistry Put to Work The Haber Process 720

A Closer Look Temperature Changes and Le Châtelier's Principle 745

Chemistry Put to Work Controlling Nitric Oxide Emissions 748

16 Acid–Base Equilibria 757**16.1 Acid–Base Equilibria 757**

Arrhenius Acids and Bases 758 Brønsted–Lowry Acids and Bases 758 The H^+ Ion in Water 758 Proton-Transfer Reactions 759 Conjugate Acid–Base Pairs 760 Relative Strengths of Acids and Bases 761

16.2 The Autoionization of Water 764

The Ion Product of Water 765

16.3 The pH Scale 767

pOH and Other “p” Scales 769 Measuring pH 769

16.4 Strong Acids and Bases 772

Strong Acids 773 Strong Bases 773

16.5 Weak Acids 775

Calculating K_a from pH 776 Percent Ionization 777 Using K_a to Calculate pH 778 Polyprotic Acids 782

16.6 Weak Bases 786

Types of Weak Bases 788 Relationship Between K_a and K_b 789

16.7 Acid–Base Properties of Salt Solutions 792

An Anion's Ability to React with Water 793
 A Cation's Ability to React with Water 793
 Combined Effect of Cation and Anion in Solution 795

16.8 Acid–Base Behavior and Chemical Structure 797

Factors That Affect Acid Strength 797 Binary Acids 798 Oxyacids 798 Carboxylic Acids 801 Lewis Acids and Bases 802

Chapter Summary and Key Terms 805
Learning Outcomes 806 Key Equations 806
Exercises 807 Additional Exercises 810
Integrative Exercises 812 Design an Experiment 812

A Closer Look Polyprotic Acids 784

Chemistry Put to Work Amines and Amine Hydrochlorides 791

Chemistry and Life The Amphiprotic Behavior of Amino Acids 801

17 Additional Aspects of Aqueous Equilibria 813**17.1 The Common-Ion Effect 813****17.2 Buffers 817**

Composition and Action of Buffers 818 Calculating the pH of a Buffer 819 Buffer Capacity and pH Range 823 Addition of Strong Acids or Bases to Buffers 823

17.3 Acid–Base Titrations 826

Strong Acid–Strong Base Titrations 827 Weak Acid–Strong Base Titrations 829 Titrating with an Acid–Base Indicator 833 Titrations of Polyprotic Acids 835

- 17.4 Solubility Equilibria 837**
The Solubility-Product Constant, K_{sp} 838 Solubility and K_{sp} 839
- 17.5 Factors That Affect Solubility 841**
The Common-Ion Effect 842 Solubility and pH 843 Formation of Complex Ions 845 Amphoterism 848
- 17.6 Precipitation and Separation of Ions 850**
Selective Precipitation of Ions 852 Qualitative Analysis for Metallic Elements 852
- Chapter Summary and Key Terms 856**
Learning Outcomes 857 Key Equations 857
Exercises 858 Additional Exercises 861
Integrative Exercises 862 Design an Experiment 863
-
- Chemistry and Life** Blood as a Buffered Solution 825
A Closer Look Limitations of Solubility Products 841
Chemistry and Life Tooth Decay and Fluoridation 845
A Closer Look Lead Contamination in Drinking Water 849

18 Chemistry of the Environment 864

- 18.1 Earth's Atmosphere 864**
Composition of the Atmosphere 865
Photochemical Reactions in the Atmosphere 868
Ozone in the Stratosphere 870
- 18.2 Human Activities and Earth's Atmosphere 872**
The Ozone Layer and Its Depletion 873 Sulfur Compounds and Acid Rain 874 Nitrogen Oxides and Photochemical Smog 875 Greenhouse Gases: Water Vapor, Carbon Dioxide, and Climate 877
- 18.3 Earth's Water 881**
The Global Water Cycle 882 Salt Water: Earth's Oceans and Seas 882 Freshwater and Groundwater 884
- 18.4 Human Activities and Water Quality 885**
Dissolved Oxygen and Water Quality 885 Water Purification: Desalination 886 Water Purification: Municipal Treatment 887
- 18.5 Green Chemistry 891**
Supercritical Solvents 893 Greener Reagents and Processes 893
- Chapter Summary and Key Terms 896**
Learning Outcomes 897 Exercises 897
Additional Exercises 901 Integrative Exercises 902 Design an Experiment 903
-
- A Closer Look** Other Greenhouse Gases 880
A Closer Look Fracking and Water Quality 888
Chemistry and Life Ocean Acidification 890

19 Chemical Thermodynamics 904

- 19.1 Spontaneous Processes 904**
Seeking a Criterion for Spontaneity 907 Reversible and Irreversible Processes 907
- 19.2 Entropy and the Second Law of Thermodynamics 910**
The Relationship between Entropy and Heat 910 ΔS for Phase Changes 911 The Second Law of Thermodynamics 912
- 19.3 The Molecular Interpretation of Entropy and the Third Law of Thermodynamics 914**
Expansion of a Gas at the Molecular Level 914 Boltzmann's Equation and Microstates 916 Molecular Motions and Energy 917 Making Qualitative Predictions about ΔS 918 The Third Law of Thermodynamics 920
- 19.4 Entropy Changes in Chemical Reactions 922**
Temperature Variation of Entropy 923 Standard Molar Entropies 923 Calculating the Standard Entropy Change for a Reaction 924 Entropy Changes in the Surroundings 924
- 19.5 Gibbs Free Energy 926**
Standard Free Energy of Formation 929
- 19.6 Free Energy and Temperature 932**
- 19.7 Free Energy and the Equilibrium Constant 935**
Free Energy under Nonstandard Conditions 935 Relationship between ΔG° and K 938
- Chapter Summary and Key Terms 941**
Learning Outcomes 942 Key Equations 942
Exercises 943 Additional Exercises 946
Integrative Exercises 948 Design an Experiment 949
-
- A Closer Look** The Entropy Change When a Gas Expands Isothermally 912
Chemistry and Life Entropy and Human Society 921
A Closer Look What's "Free" About Free Energy? 931
Chemistry and Life Driving Nonspontaneous Reactions: Coupling Reactions 939

20 Electrochemistry 950

- 20.1 Oxidation States and Oxidation-Reduction Reactions 950**
- 20.2 Balancing Redox Equations 953**
Half-Reactions 954 Balancing Equations by the Method of Half-Reactions 954 Balancing Equations for Reactions Occurring in Basic Solution 957

- 20.3 Voltaic Cells 959**
- 20.4 Cell Potentials under Standard Conditions 963**
Standard Reduction Potentials 965 Strengths of Oxidizing and Reducing Agents 968
- 20.5 Free Energy and Redox Reactions 972**
Emf, Free Energy, and the Equilibrium Constant 974
- 20.6 Cell Potentials under Nonstandard Conditions 977**
The Nernst Equation 977 Concentration Cells 980
- 20.7 Batteries and Fuel Cells 984**
Lead–Acid Battery 985 Alkaline Battery 985
Nickel–Cadmium and Nickel–Metal Hydride Batteries 985 Lithium–Ion Batteries 986 Hydrogen Fuel Cells 986
- 20.8 Corrosion 990**
Corrosion of Iron (Rusting) 991 Preventing Corrosion of Iron 992
- 20.9 Electrolysis 993**
Quantitative Aspects of Electrolysis 995
Chapter Summary and Key Terms 999
Learning Outcomes 1000 Key Equations 1000
Exercises 1000 Additional Exercises 1004
Integrative Exercises 1005 Design an Experiment 1006
-
- A Closer Look** Electrical Work 976
Chemistry and Life Heartbeats and Electrocardiography 981
Chemistry Put to Work Batteries for Hybrid and Electric Vehicles 987
Chemistry Put to Work Electrometallurgy of Aluminum 996

21 Nuclear Chemistry 1007

- 21.1 Radioactivity and Nuclear Equations 1007**
Nuclear Equations 1009 Types of Radioactive Decay 1009
- 21.2 Patterns of Nuclear Stability 1012**
Neutron-to-Proton Ratio 1013 Radioactive Decay Chains 1014 Further Observations 1015 Nuclear Transmutations 1016 Accelerating Charged Particles 1017 Reactions Involving Neutrons 1018 Transuranium Elements 1018
- 21.3 Rates of Radioactive Decay 1020**
Radiometric Dating 1021 Calculations Based on Half-Life 1023
- 21.4 Detection of Radioactivity 1026**
Radiotracers 1027
- 21.5 Energy Changes in Nuclear Reactions 1029**
Nuclear Binding Energies 1031 Nuclear Power: Fission 1033 Nuclear Reactors 1036 Nuclear Waste 1037 Nuclear Power: Fusion 1038

- 21.6 Radiation in the Environment and Living Systems 1041**
Radiation Doses 1042
Chapter Summary and Key Terms 1045
Learning Outcomes 1046 Key Equations 1047
Exercises 1047 Additional Exercises 1049
Integrative Exercises 1051 Design an Experiment 1051

Chemistry and Life Medical Applications of Radiotracers 1028
A Closer Look The Dawning of the Nuclear Age 1035
A Closer Look Nuclear Synthesis of the Elements 1039
Chemistry and Life Radiation Therapy 1044

22 Chemistry of the Nonmetals 1052

- 22.1 Periodic Trends and Chemical Reactions 1052**
Chemical Reactions 1055
- 22.2 Hydrogen 1056**
Isotopes of Hydrogen 1057 Properties of Hydrogen 1057 Production of Hydrogen 1058 Uses of Hydrogen 1059 Binary Hydrogen Compounds 1059
- 22.3 Group 18: The Noble Gases 1061**
Noble Gas Compounds 1062
- 22.4 Group 17: The Halogens 1064**
Properties and Production of the Halogens 1064
Uses of the Halogens 1066 The Hydrogen Halides 1066 Interhalogen Compounds 1066
Oxyacids and Oxyanions 1066
- 22.5 Oxygen 1068**
Properties of Oxygen 1068 Production of Oxygen 1069 Uses of Oxygen 1069
Ozone 1069 Oxides 1069 Peroxides and Superoxides 1070
- 22.6 The Other Group 16 Elements: S, Se, Te, and Po 1072**
Occurrence and Production of S, Se, and Te 1073
Properties and Uses of Sulfur, Selenium, and Tellurium 1073
Sulfides 1074 Oxides, Oxyacids, and Oxyanions of Sulfur 1074
- 22.7 Nitrogen 1076**
Properties of Nitrogen 1077 Production and Uses of Nitrogen 1077
Hydrogen Compounds of Nitrogen 1078 Oxides and Oxyacids of Nitrogen 1078
- 22.8 The Other Group 15 Elements: P, As, Sb, and Bi 1081**
Occurrence, Isolation, and Properties of Phosphorus 1082
Phosphorus Halides 1082 Oxy Compounds of Phosphorus 1083
- 22.9 Carbon 1085**
Elemental Forms of Carbon 1086 Oxides of Carbon 1086
Carbonic Acid and Carbonates 1088 Carbides 1088

- 22.10 The Other Group 14 Elements: Si, Ge, Sn, and Pb 1089**
 General Characteristics of the Group 14 Elements 1090
 Occurrence and Preparation of Silicon 1090
 Silicates 1091 Glass 1092 Silicones 1092

- 22.11 Boron 1093**
 Chapter Summary and Key Terms 1096 Learning Outcomes 1097 Exercises 1097 Additional Exercises 1100 Integrative Exercises 1100 Design an Experiment 1101

A Closer Look The Hydrogen Economy 1058

Chemistry and Life Nitroglycerin, Nitric Oxide, and Heart Disease 1080

Chemistry and Life Arsenic in Drinking Water 1084

Chemistry Put to Work Carbon Fibers and Composites 1087

23 Transition Metals and Coordination Chemistry 1102

- 23.1 The Transition Metals 1102**
 Physical Properties 1104 Electron Configurations and Oxidation States 1105 Magnetism 1106
- 23.2 Transition-Metal Complexes 1108**
 The Development of Coordination Chemistry: Werner's Theory 1109 The Metal–Ligand Bond 1111 Charges, Coordination Numbers, and Geometries 1112
- 23.3 Common Ligands in Coordination Chemistry 1114**
 Metals and Chelates in Living Systems 1116
- 23.4 Nomenclature and Isomerism in Coordination Chemistry 1121**
 Isomerism 1123 Constitutional Isomerism 1124 Stereoisomerism 1124
- 23.5 Color and Magnetism in Coordination Chemistry 1128**
 Color 1128 Magnetism of Coordination Compounds 1129
- 23.6 Crystal-Field Theory 1131**
 Electron Configurations in Octahedral Complexes 1134 Tetrahedral and Square-Planar Complexes 1136
 Chapter Summary and Key Terms 1141 Learning Outcomes 1141 Exercises 1142 Additional Exercises 1145 Integrative Exercises 1147 Design an Experiment 1148

A Closer Look Entropy and the Chelate Effect 1118

Chemistry and Life The Battle for Iron in Living Systems 1119

A Closer Look Charge-Transfer Color 1138

24 The Chemistry of Organic Compounds 1149

- 24.1 General Characteristics of Organic Molecules 1149**
 The Structure of Organic Molecules 1150
 The Stabilities of Organic Molecules 1150
- 24.2 An Introduction to Hydrocarbons 1151**
 Alkanes 1153 Applications and Physical Properties of Alkanes 1154 Homologous Series 1154
- 24.3 Structures of Alkanes 1155**
 Alkane Shape and Conformations 1158
 Constitutional/Structural Isomers 1159
- 24.4 Alkane Nomenclature 1162**
- 24.5 Cycloalkanes 1165**
- 24.6 Organic Functional Groups 1169**
- 24.7 Reactions of Alkanes 1172**
 Combustion 1173 Classification of C and H 1174
 Free-Radical Reactions and Electron Movement 1175
 Chapter Summary and Key Terms 1178
 Key Skills 1179 Key Equations 1179
 Exercises 1179 Additional Exercises 1183
 Integrative Exercises 1183 Design an Experiment 1184

Chemistry and Life Petroleum Products 1156

Chemistry and Life Structure–Activity Relationships 1171

A Closer Look Reactivity by Carbon Classification 1176

25 Stereochemistry of Organic Compounds 1185

- 25.1 Stereochemistry in Organic Chemistry 1185**
- 25.2 Cis–Trans Isomerism in Cycloalkanes 1188**
- 25.3 Chirality in Organic Compounds 1190**
- 25.4 Measuring Optical Activity 1194**
- 25.5 Absolute Stereochemistry 1197**
 Using Priority Rules to Find a Stereocenter's Absolute Configuration 1197
- 25.6 Molecules with More than One Stereocenter 1201**
 Resolution: Separating Enantiomers 1202
 Chapter Summary and Key Terms 1205
 Key Skills 1206 Key Equations 1206
 Exercises 1206 Additional Exercises 1208
 Integrative Exercises 1208 Design an Experiment 1209

Chemistry and Life Chiral Drugs 1199

26 Chemistry of Alkenes and Alkynes 1210

- 26.1 The Structure of Unsaturated Hydrocarbons 1210**
The π -bond 1211 Bonding in Alkenes 1212
Bonding in Alkynes 1214
- 26.2 Isomerism and Nomenclature 1217**
Isomerism in Alkenes—The *E*, *Z* System 1219
Alkynes 1220
- 26.3 Arrow Notation and Resonance Structures: Electron Counting 1222**
- 26.4 Electrophilic Addition Reactions 1226**
Addition Reactions Involving HX (X = Cl, Br, I) 1226 Addition Reactions Involving H₂O 1230 Halogenation: Addition of Br₂ and Cl₂ 1231 Halohydrin Formation 1232
- 26.5 Alkanes from Alkenes: Catalytic Hydrogenation 1237**
- 26.6 Addition Polymerization 1240**
Making Polymers 1241 Structure and Physical Properties of Addition Polymers 1243
Chapter Summary and Key Terms 1248
Key Skills 1249 Key Equations 1249
Exercises 1249 Integrative Exercises 1251
Design an Experiment 1252

Chemistry and Life Terpenes and Isoprene 1216
Chemistry and Life The Chemistry of Vision 1223
A Closer Look Describing Charge 1224
A Closer Look Stereochemistry in Halohydrin Formation 1235
A Closer Look Hydrogenation 1238
Chemistry and Life Recycling Plastics 1244
Chemistry and Life The Accidental Discovery of Teflon® 1246
Chemistry and Life Vulcanization 1246

27 Alcohols, Haloalkanes, and Ethers 1253

- 27.1 Alcohols: Structure, Properties, and Nomenclature 1253**
Common Alcohols 1257 Naming Alcohols 1257 Classifying Alcohols 1261
- 27.2 Haloalkanes 1262**
- 27.3 Ethers: Structure, Properties, and Nomenclature 1264**
Naming Ethers 1266
- 27.4 Reactions of Alcohols 1268**
Alkoxides 1269 Basicity of Alcohols 1269 Alcohols to Haloalkanes 1269 Dehydration of Alcohols 1270
- 27.5 Nucleophilic Substitution Reactions of Haloalkanes 1272**

- 27.6 Haloalkanes to Alkenes: β -Elimination 1276**
- 27.7 Substitution versus Elimination 1280**
E1 and S_N1 Reactions 1281
Chapter Summary and Key Terms 1286
Key Skills 1286 Key Equations 1286
Exercises 1287 Additional Exercises 1290
Integrative Exercises 1290 Design an Experiment 1291

Chemistry and Life Vitamin D 1256
Chemistry and Life The Solubility Nexus 1258
A Closer Look Crown Ethers 1267
A Closer Look Molecularity 1274
A Closer Look Nucleophile or Lewis Base? 1281
Chemistry and Life Polymerization versus Macrocyclization 1285

28 Aldehydes, Ketones, and Carbohydrates 1292

- 28.1 Aldehydes, Ketones, and the Carbonyl Group 1292**
- 28.2 Preparation of Aldehydes and Ketones 1297**
Oxidation of 1° and 2° Alcohols 1298 Ozonolysis 1299
- 28.3 Reactions of Aldehydes and Ketones 1300**
Addition of Carbon Nucleophiles—Grignard Reactions 1301 Addition of Nitrogen and Oxygen Nucleophiles: Formation of Imines and Acetals 1304
Reduction Reactions 1306 Cyanohydrins 1307
Tautomerism in Aldehydes and Ketones 1309
Halogenation of Aldehydes and Ketones 1310
- 28.4 Carbohydrates 1313**
Monosaccharides 1314 Cyclic versus Open-Chain Structures 1317 Oligosaccharides and Polysaccharides 1320
Chapter Summary and Key Terms 1327
Key Skills 1327 Key Equations 1328
Exercises 1328 Integrative Exercises 1331
Design an Experiment 1331

Chemistry and Life Glucosamine 1318
Chemistry and Life Cyclodextrins 1321
Chemistry and Life Vitamin C 1324

29 Carboxylic Acids and Their Derivatives 1332

- 29.1 Carboxylic Acids 1332**
Structure, Properties, and Nomenclature 1333
Acidity 1335
- 29.2 Preparation of Carboxylic Acids 1338**
- 29.3 Esters and Esterification 1342**

- 29.4 Fats, Oils, and Waxes** 1347
Soaps and Detergents 1350
- 29.5 Acid Chlorides, Anhydrides, and Nucleophilic Acyl Substitution** 1353
Nucleophilic Acyl Substitution 1356
- 29.6 Condensation Polymerization** 1359
Polymers for Medicine 1362
Chapter Summary and Key Terms 1365
Key Skills 1366 **Key Equations** 1366
Exercises 1367 **Integrative Exercises** 1369
Design an Experiment 1370
-
- Chemistry and Life** Steroids 1354
Chemistry and Life Towards the Plastic Car 1361
Chemistry and Life Biodegradable Sutures 1363

30 Benzene and its Derivatives 1371

- 30.1 The Structure of Benzene** 1371
Bonding in Benzene 1372
- 30.2 Isomerism and Nomenclature in Aromatic Compounds** 1375
Phenols 1378
- 30.3 Aromaticity** 1380
- 30.4 Acidity of Phenols** 1382
- 30.5 Electrophilic Aromatic Substitution (EAS) Reactions** 1386
Directing Groups and Substitution Effects 1389
Chapter Summary and Key Terms 1397
Key Skills 1397 **Key Equations** 1398
Exercises 1398 **Integrative Exercises** 1400
Design an Experiment 1401
-
- Chemistry and Life** The Discovery of Liquid Crystals 1376
A Closer Look Organic Dyes 1388

31 Nitrogen-Containing Organic Compounds 1402

- 31.1 Amines and the Amide Bond** 1402
Amines 1403 Reactivity of Amines 1408
Synthesis of Amines 1410 Amides 1412
- 31.2 Amino Acids** 1416
Acid–Base Properties 1419 Reactions Involving Amino Acids 1424
- 31.3 Proteins, Peptides, and Enzymes** 1426
Coding Peptides 1428 Protein Structure 1430 Enzymes 1432 Sequencing of Peptides and Proteins 1434

- 31.4 Nucleic Acids and DNA** 1438
Chapter Summary and Key Terms 1446
Key Skills 1446 **Key Equations** 1446
Exercises 1447 **Integrative Exercises** 1450
Design an Experiment 1451
-
- Chemistry and Life** Amines and Amine Hydrochlorides 1406
A Closer Look Sickle-Cell Anemia 1420
Chemistry and Life B Group Vitamins 1436

32 Solving Molecular Structure 1452

- 32.1 The Electromagnetic Spectrum** 1452
- 32.2 Infrared (IR) Spectroscopy** 1455
The Spring Model 1456 Measuring IR Spectra 1458
- 32.3 Nuclear Magnetic Resonance (NMR) Spectroscopy** 1463
Nuclear Magnetic Resonance Frequencies 1466
The Chemical Shift 1467 Sample Preparation 1468
Interpreting NMR Spectra 1469 Integration 1472
Spin–Spin Coupling 1474 ¹³C NMR Spectra 1476
- 32.4 Mass Spectrometry** 1480
Electron Impact Ionization Mass Spectrometry 1481
Interpreting Mass Spectra 1483
- 32.5 Compound Identification Using Spectra** 1487
Deducing the Molecular Formula of an Organic Compound 1487 Chemical Wet Testing: Tests for Functional Groups 1489 Using Analysis from Instrumental Techniques 1490
Chapter Summary and Key Terms 1495
Key Skills 1496 **Key Equations** 1496
Exercises 1496 **Integrative Exercises** 1499
Design an Experiment 1502
-
- A Closer Look** Using Spectroscopic Methods to Measure Reaction Rates 1454

APPENDICES

- A** Mathematical Operations 1503
B Properties of Water 1510
C Thermodynamic Quantities for Selected Substances at 298.15 K (25 °C) 1511
D Aqueous Equilibrium Constants 1515
E Standard Reduction Potentials at 25 °C 1517

ANSWERS TO SELECTED EXERCISES 1518

ANSWERS TO GO FIGURE 1573

ANSWERS TO SELECTED PRACTICE EXERCISES 1579

GLOSSARY 1589

PHOTO AND ART CREDITS 1613

INDEX 1615

CHEMICAL APPLICATIONS AND ESSAYS

A Closer Look

- The Scientific Method 63
Basic Forces 99
The Mass Spectrometer 103
Energy, Enthalpy, and *P-V* Work 233
Using Enthalpy as a Guide 236
Measurement and the Uncertainty Principle 290
Thought Experiments and Schrödinger's Cat 293
Probability Density and Radial Probability Functions 298
Effective Nuclear Charge 329
Calculation of Lattice Energies:
The Born-Haber Cycle 376
Oxidation Numbers, Formal Charges, and Actual Partial Charges 392
Phases in Atomic and Molecular Orbitals 453
The Ideal Gas Equation 497
- The Clausius-Clapeyron Equation 541
X-ray Diffraction 565
Ideal Solutions with Two or More Volatile Components 635
The van't Hoff Factor 642
Using Spectroscopic Methods to Measure Reaction Rates: Beer's Law 667
Temperature Changes and Le Châtelier's Principle 745
Polyprotic Acids 784
Limitations of Solubility Products 841
Lead Contamination in Drinking Water 849
Other Greenhouse Gases 880
Fracking and Water Quality 888
The Entropy Change When a Gas Expands Isothermally 912
What's "Free" About Free Energy? 931
Electrical Work 976
- The Dawning of the Nuclear Age 1035
Nuclear Synthesis of the Elements 1039
The Hydrogen Economy 1058
Entropy and the Chelate Effect 1118
Charge-Transfer Color 1138
Reactivity by Carbon Classification 1176
Describing charge 1224
Stereochemistry in Halohydrin Formation 1235
Hydrogenation 1238
Crown Ethers 1267
Molecularity 1274
Nucleophile or Lewis Base? 1281
Organic Dyes 1388
Sickle-Cell Anemia 1420
Using Spectroscopic Methods to Measure Reaction Rates 1454

Chemistry Put to Work

- Chemistry and the Chemical Industry 49
Chemistry in the News 69
Antacids 191
The Scientific and Political Challenges of Biofuels 262
Ionic Size and Lithium-Ion Batteries 335
Orbitals and Energy 460
Gas Separations 502
- Ionic Liquids 531
Alloys of Gold 574
Solid-State Lighting 590
Modern Materials in the Automobile 595
Microporous and Mesoporous Materials 600
Bromomethane in the Atmosphere 679
Catalytic Converters 699
- The Haber Process 720
Controlling Nitric Oxide Emissions 748
Amines and Amine Hydrochlorides 791
Batteries for Hybrid and Electric Vehicles 987
Electrometallurgy of Aluminum 996
Carbon Fibers and Composites 1087

Chemistry and Life

- Elements Required by Living Organisms 115
Glucose Monitoring 149
The Regulation of Body Temperature 243
Nuclear Spin and Magnetic Resonance Imaging 304
The Improbable Development of Lithium Drugs 352
Blood Pressure 478
Liquid Crystal Displays 549
Fat-Soluble and Water-Soluble Vitamins 623
Blood Gases and Deep-Sea Diving 627
Sickle-Cell Anemia 647
Nitrogen Fixation and Nitrogenase 701
The Amphiprotic Behavior of Amino Acids 801
Blood as a Buffered Solution 825
- Tooth Decay and Fluoridation 845
Ocean Acidification 890
Entropy and Human Society 921
Driving Nonspontaneous Reactions: Coupling Reactions 939
Heartbeats and Electrocardiography 981
Medical Applications of Radiotracers 1028
Radiation Therapy 1044
Nitroglycerin, Nitric Oxide, and Heart Disease 1080
Arsenic in Drinking Water 1084
The Battle for Iron in Living Systems 1119
Petroleum Products 1156
Structure-Activity Relationships 1171
Chiral Drugs 1199
Terpenes and Isoprene 1216
The Chemistry of Vision 1223
- Recycling Plastics 1244
The Accidental Discovery of Teflon® 1246
Vulcanisation 1246
Vitamin D 1256
The Solubility Nexus 1258
Polymerization versus Macrocyclization 1285
Glucosamine 1318
Cyclodextrins 1321
Vitamin C 1324
Steroids 1354
Towards the Plastic Car 1361
Biodegradable Sutures 1363
The Discovery of Liquid Crystals 1376
Amines and Amine Hydrochlorides 1406
B Group Vitamins 1436

Strategies for Success

- Estimating Answers 78
The Importance of Practice 80
The Features of This Book 80
- How to Take a Test 126
Problem Solving 145
Design an Experiment 166
- Analyzing Chemical Reactions 200
Calculations Involving Many Variables 485

Smart Figures

| | | | |
|---------------------|--|--------------|---|
| Figures 3.3 and 3.4 | Methane reacts with oxygen in a Bunsen burner and balanced chemical equation for the combustion of CH_4 | Figure 13.2 | Intermolecular interactions involved in solutions |
| Figure 3.5 | Combustion of magnesium metal in air, a combination reaction | Figure 13.3 | Dissolution of the ionic solid NaCl in water |
| Figure 4.3 | A precipitation reaction | Figure 13.4 | Enthalpy changes accompanying the solution process |
| Figure 4.12 | Reaction of copper metal with silver ion | Figure 14.16 | Energy profile for conversion of methyl isonitrile (H_3CNC) to its isomer acetonitrile (H_3CCN) |
| Figures 5.2 and 5.3 | Electrostatic potential energy and ionic bonding | Figure 15.1 | Equilibrium between NO_2 and N_2O_4 |
| Figure 5.23 | Enthalpy diagram for propane combustion | Figure 15.8 | Predicting the direction of a reaction by comparing Q and K at a given temperature |
| Figure 5.24 | Using bond enthalpies to estimate ΔH_{rxn} | Box feature | Le Châtelier's principle (p. 739) |
| Figure 6.24 | General energy ordering of orbitals for a many-electron atom | Figure 17.7 | Titration of a strong acid with a strong base |
| Figure 8.5 | Periodic trends in lattice energy as a function of cation or anion radius | Figure 17.9 | Titration of a weak acid with a strong base |
| Figure 9.12 | Covalent bonds in H_2 , HCl , and Cl_2 | Figure 20.3 | Spontaneous oxidation–reduction reaction involving zinc and copper |
| Figure 9.13 | Formation of the H_2 molecule as atomic orbitals overlap | Figure 20.5 | A voltaic cell that uses a salt bridge to complete the electrical circuit |
| Figure 9.14 | Formation of sp hybrid orbitals | Figure 25.12 | (<i>S</i>)-Ibuprofen |
| Figure 9.16 | Formation of sp^2 hybrid orbitals | Figure 27.17 | Substituted alkenes in which R is a non-hydrogen atom, typically being carbon. |
| Figure 9.17 | Formation of sp^3 hybrid orbitals | Figure 31.6 | Rationalizing the basicity of 4-nitroaniline. |
| Figure 9.22 | Hybrid orbital bonding in ethene | | |
| Figure 9.23 | Formation of π bond in ethyne, C_2H_2 | | |
| Figure 10.13 | Distribution of molecular speeds for nitrogen gas | | |

Interactive Sample Exercises

| | | | |
|----------------------|--|----------------------|---|
| Sample Exercise 1.1 | Distinguishing among Elements, Compounds, and Mixtures | Sample Exercise 4.3 | Predicting a Metathesis Reaction |
| Sample Exercise 1.2 | Using SI Prefixes | Sample Exercise 4.4 | Writing a Net Ionic Equation |
| Sample Exercise 1.6 | Assigning Appropriate Significant Figures | Sample Exercise 4.13 | Using Molarity to Calculate Grams of Solute |
| Sample Exercise 1.8 | Determining the Number of Significant Figures in a Calculated Quantity | Sample Exercise 5.1 | Relating Heat and Work to Changes of Internal Energy |
| Sample Exercise 1.11 | Converting Units Using Two or More Conversion Factors | Sample Exercise 5.4 | Relating ΔH to Quantities of Reactants and Products |
| Sample Exercise 2.1 | Atomic Size | Sample Exercise 5.6 | Measuring ΔH Using a Coffee-Cup Calorimeter |
| Sample Exercise 2.3 | Writing Symbols for Atoms | Sample Exercise 5.7 | Measuring q_{rxn} Using a Bomb Calorimeter |
| Sample Exercise 2.4 | Calculating the Atomic Weight of an Element from Isotopic Abundances | Sample Exercise 5.8 | Using Hess's Law to Calculate ΔH |
| Sample Exercise 2.5 | Using the Periodic Table | Sample Exercise 5.10 | Equations Associated with Enthalpies of Formation |
| Sample Exercise 2.9 | Identifying Ionic and Molecular Compounds | Sample Exercise 6.6 | Subshells of the Hydrogen Atom |
| Sample Exercise 3.2 | Balancing Chemical Equations | Sample Exercise 6.7 | Orbital Diagrams and Electron Configurations |
| Sample Exercise 3.5 | Calculating Formula Weights | Sample Exercise 6.8 | Electron Configurations for a Group |
| Sample Exercise 3.16 | Calculating the Amount of Product Formed from a Limiting Reactant | Sample Exercise 7.2 | Predicting Relative Sizes of Atomic Radii |
| Sample Exercise 4.1 | Relating Relative Numbers of Anions and Cations to Chemical Formulas | Sample Exercise 8.2 | Charges on Ions |

Sample Exercise 8.6 Drawing a Lewis Structure

Sample Exercise 9.1 Using the VSEPR Model

Sample Exercise 10.3 Evaluating the Effects of Changes in P ,
 V , n , and T on a Gas

Sample Exercise 10.4 Using the Ideal Gas Equation

Sample Exercise 11.4 Relating Boiling Point to Vapor Pressure

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 Expressions

Sample Exercise 16.1 Identifying Conjugate Acids and Bases

Sample Exercise 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 24.2 Writing condensed structural
formulas

Sample Exercise 25.4 R and S notation

Sample Exercise 26.3 Drawing isomers

Sample Exercise 27.5 β -Elimination in haloalkanes

Sample Exercise 28.6 Fischer projections

Sample Exercise 29.5 Soap structure

Sample Exercise 30.2 Electrophilic aromatic substitution

Sample Exercise 31.7 Drawing the structural formula of a
tripeptide

Sample Exercise 32.3 Differentiating between products of a
reaction

PREFACE

To the Instructor

Philosophy

We the authors of *Chemistry: The Central Science* are delighted and honored that you have chosen us as your instructional partners for your chemistry class. Collectively we have taught 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 fifteenth edition of this text bespeaks an exceptionally long record of successful textbook writing. We are appreciative of the loyalty and support the book has received over the years, and 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 continues to incorporate 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 Pearson Mastering Chemistry, which is continually evolving

to provide more effective means of testing and evaluating student performance, while giving the student immediate and helpful feedback. Pearson Mastering Chemistry not only provides feedback on a question by question basis but, using Knewton-enhanced adaptive follow-up assignments, 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 resource for students 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 online 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 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. As before, we discuss bond enthalpies in the Thermochemistry chapter to emphasize the connection between the macroscopic properties of substances and the sub-microscopic world of atoms and bonds. We believe this enables an effective, balanced approach to teaching thermodynamics in general chemistry, as well as provides 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 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 instructors to tailor coverage to focus on the materials (semiconductors, polymers, nanomaterials, and so forth) that are most relevant to students and instructors alike. 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 has two survey chapters. Chapter 22 deals with

nonmetals, and Chapter 23 with the chemistry of transition metals, including coordination compounds. These last three chapters are developed in an independent, modular fashion and can be covered in any order.

Organic chemistry is central to all living things and Chapters 24–32 lead us on a journey from elementary hydrocarbons to elaborate bio-organic molecules. Much of what we discuss is treated from a fundamental level so students' transition to tertiary studies in organic chemistry is smooth and rapid. We place emphasis on the core reactions observed in organic chemistry and treat many cases mechanistically. This fosters a deep understanding of why organic molecules react in the way they do, thereby giving students an opportunity to understand much more chemistry than is discussed.

Chapter 24 provides a foundation to our examination of organic chemistry by using hydrocarbons to illustrate how we represent and name organic molecules. It goes on to provide an overview of the functional groups—the reactive parts of the molecule—on which we build our understanding of organic chemistry. The shape of a molecule may be pivotal in determining its reactivity, particularly in a biological context, and Chapter 25 leads to an in-depth discussion of stereochemistry. The next six chapters cover the fundamental reactions encountered in organic chemistry, at each step building to the application of these reactions in a modern world (for example, polymerisation in Chapters 26 and 29) and their essential role in the chemistry of life (for example, carbohydrates in Chapter 28, fats in Chapter 29, proteins and nucleic acids in Chapter 31). Chapter 30 investigates aromatic compounds as a separate class. Here, it is important for the student to note the differences in reactivity to the alkenes studied in Chapter 26.

Finally, Chapter 32 stands alone as a reference guide to mass spectrometry, NMR spectroscopy, and IR spectroscopy. Whether these topics are taught with much emphasis on the technology is up to the instructor. What we believe is most important is students' development at complex problem-solving, bringing two or more concepts together to draw a logical conclusion. The approach to solving molecular structure also confirms their knowledge of the basic principles of organic chemistry, bonding, functional groups and drawing structural formulas. Our coverage of organic chemistry gives students a unique perspective and challenges the very 'standard format' often seen in a first-year text.

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.

We have brought students into greater contact with descriptive organic and inorganic chemistry by integrating examples throughout the text. Students 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, 22, and 23. We also incorporate descriptive organic and inorganic chemistry in the exercises found throughout each chapter.

New to This Edition

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 updates to features to serve students and instructors better in the classroom. *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. The book was updated in a way that did not 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 fifteenth 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 enhances clarity with a clean and modern look. This includes white-background annotation boxes with crisp, thin leaders; rich and saturated colors in the art, and use of 3D renderings. Using statistics from Pearson Mastering Chemistry, we have shifted some Exercises to the ends of sections, where students are more likely to attempt them before moving on to more complex questions. Also in the ends of sections are new Self-Assessment Exercises that provide immediate assessment and feedback content in the form of multiple-choice questions meant to test the concepts learnt in the section. In the Pearson eText, these exercises provide specific wrong-answer feedback.

Updates to subject matter in chapter text, Sample Exercises, and assessment content reflect current trends in teaching chemistry.

Each section now opens with new section-opening text and images that enhance students’ understanding of the concepts introduced in that section as well as explicate the historical contexts around key inventions and discoveries in chemistry.

This edition features eight detailed chapters on organic chemistry for instructors and students who have more in-depth course discussions on organic chemistry than those covered in the shorter, 24-chapter variant of this book. An additional chapter on spectrometry is also available. All these additional chapters come with the wealth of Sample Exercises, essay features, assessment content, and updated art that has made the title a favorite with students and instructors the world over.

- 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.

Key Features in This Edition

Chemistry: The Central Science, continues to provide relevant, up-to-date content—be it art or assessment material—that enhances the clarity and effectiveness of the text. Key features for this edition include the following:

- The treatment of energy and thermochemistry draws on significant revisions to previous editions. The introduction of the concept of energy in Chapter 1 allows instructors greater freedom in the order in which they cover the material. For example, this arrangement facilitates 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. The discussion of bond enthalpies in Chapter 5 emphasizes the connection between macroscopic quantities, like reaction enthalpies, and the submicroscopic world of atoms and bonds. We feel this 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.
- The text continues to provide students with a clear discussion, superior problem sets, and better real-time feedback on students’ understanding of the material. This is based on the authors’ insight into student usage of the interactive e-book platform, such as the most frequently highlighted passages and the accompanying notes and questions.
- Extensive effort has gone into creating enhanced content for the Pearson eText for the book. These features make the eText so much more than just an electronic copy of the physical textbook. Self-Assessment Exercises at the end of each section are enhanced with specific wrong-answer feedback in the Pearson eText. New Smart Figures take key figures from the text and bring them to life through animation and narration. 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 also include follow-up questions, which can be assigned in Pearson Mastering Chemistry.
- 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 set in italic with line spaces above and below for greater emphasis. The 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.

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 are structured in a way that makes it easy to use them in Pearson Mastering Chemistry. We have made extensive use of the metadata from student use of Pearson Mastering Chemistry to analyze end-of-chapter exercises and make appropriate changes, as well as to develop *Learning Outcomes* for each chapter.

The 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.

To the Student

Chemistry: The Central Science, Fifteenth Edition, has been written to introduce you to modern chemistry. As authors, we have, in effect, been engaged by your instructor to help you learn chemistry. Based on the comments of students and instructors who have used this book in its previous editions, we believe that we have done that job well. Of course, we expect the text to continue to evolve through future editions. We invite you to write to tell us what you like about the book so 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. A single reading of a chapter will generally not be enough for successful learning of chapter concepts and problem-solving skills. You will often need to go over assigned materials more than once. Don't skip the *Go Figure* features, *Sample Exercises*, and *Practice Exercises*. These are your guides to whether you are learning the material. They are also good preparation for test-taking. The *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 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. 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 Pearson Mastering Chemistry with your book, take advantage of the unique tools it provides to get the most out of your time in chemistry.

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

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.

Fourteenth Edition Reviewers

Carribeth Bliem, *University of North Carolina, Chapel Hill*

Stephen Block, *University of Wisconsin, Madison*

William Butler, *Rochester Institute of Technology*

Rachel Campbell, *Florida Gulf Coast University*

Ted Clark, *The Ohio State University*

Michelle Dean, *Kennesaw State University*

John Gorden, *Auburn University*

Tom Greenbowe, *University of Oregon*

Nathan Grove, *University of North Carolina, Wilmington*

Brian Gute, *University of Minnesota, Duluth*

Amanda Howell, *Appalachian State University*

Angela King, *Wake Forest University*

Russ Larsen, *University of Iowa*

Joe Lazafame, *Rochester Institute of Technology*

Rosemary Loza, *The Ohio State University*

Kresimir Rupnik, *Louisiana State University*

Stacy Sandler, *Arizona State University*

Jerry Suits, *University Northern Colorado*

Troy Wood, *State University of New York, Buffalo*

Bob Zelmer, *The Ohio State University*

Fourteenth Edition Accuracy Reviewers

Ted Clark, *The Ohio State University*

Jordan Fantini, *Denison University*

Amanda Howell, *Appalachian State University*

Fourteenth Edition Focus Group Participants

Christine Barnes, *University of Tennessee, Knoxville*

Marian DeWane, *University California Irvine*

Emmanue Ewane, *Houston Community College*

Tom Greenbowe, *University of Oregon*

Jeffrey Rahn, *Eastern Washington University*

Pearson Mastering Chemistry Summit Participants

Phil Bennett, *Santa Fe Community College*

Jo Blackburn, *Richland College*

John Bookstaver, *St. Charles Community College*

David Carter, *Angelo State University*

Doug Cody, *Nassau Community College*

Tom Dowd, *Harper College*

Palmer Graves, *Florida International University*

Margie Haak, *Oregon State University*

Brad Herrick, *Colorado School of Mines*

Jeff Jenson, *University of Findlay*

Jeff McVey, *Texas State University at San Marcos*

Gary Michels, *Creighton University*

Bob Pribush, *Butler University*

Al Rives, *Wake Forest University*

Joel Russell, *Oakland University*

Greg Szulczewski, *University of Alabama, Tuscaloosa*

Bhavna Rawal, *Houston Community College*

Jerry Suits, *University of Northern Colorado*

Matt Tarr, *University of New Orleans*

Dennis Taylor, *Clemson University*

Harold Trimm, *Broome Community College*

Emanuel Waddell, *University of Alabama, Huntsville*

Kurt Winklemann, *Florida Institute of Technology*

Klaus Woelk, *University of Missouri, Rolla*

Steve Wood, *Brigham Young University*

Reviewers of Previous Editions of Chemistry: The Central Science

S.K. Airee, *University of Tennessee*

John J. Alexander, *University of Cincinnati*

Robert Allendoerfer, *SUNY Buffalo*

Patricia Amateis, *Virginia Polytechnic Institute and State University*

Sandra Anderson, *University of Wisconsin*

John Arnold, *University of California*

Socorro Arteaga, *El Paso Community College*

Margaret Asirvatham, *University of Colorado*

Todd L. Austell, *University of North Carolina, Chapel Hill*

Yiyang Bai, *Houston Community College*

Melita Balch, *University of Illinois at Chicago*

Rebecca Barlag, *Ohio University*

Rosemary Bartoszek-Loza, *The Ohio State University*

Hafed Bascal, *University of Findlay*

Boyd Beck, *Snow College*

Kelly Beefus, *Anoka-Ramsey Community College*

Amy Beilstein, *Centre College*

Donald Bellew, *University of New Mexico*

Victor Berner, *New Mexico Junior College*

Narayan Bhat, *University of Texas, Pan American*

Merrill Blackman, *United States Military Academy*

Salah M. Blaih, *Kent State University*

James A. Boiani, *SUNY Genesee*

Leon Borowski, *Diablo Valley College*

Simon Bott, *University of Houston*

Kevin L. Bray, *Washington State University*

Daeg Scott Brenner, *Clark University*

Gregory Alan Brewer, *Catholic University of America*

Karen Brewer, *Virginia Polytechnic Institute and State University*

Ron Briggs, *Arizona State University*

Edward Brown, *Lee University*

Gary Buckley, *Cameron University*

Scott Bunge, *Kent State University*

Carmela Byrnes, *Texas A&M University*

B. Edward Cain, *Rochester Institute of Technology*

Kim Calvo, *University of Akron*

Donald L. Campbell, *University of Wisconsin*

Gene O. Carlisle, *Texas A&M University*

Elaine Carter, *Los Angeles City College*