

# CHEMISTRY



**A Molecular Approach**

Fourth  
Edition

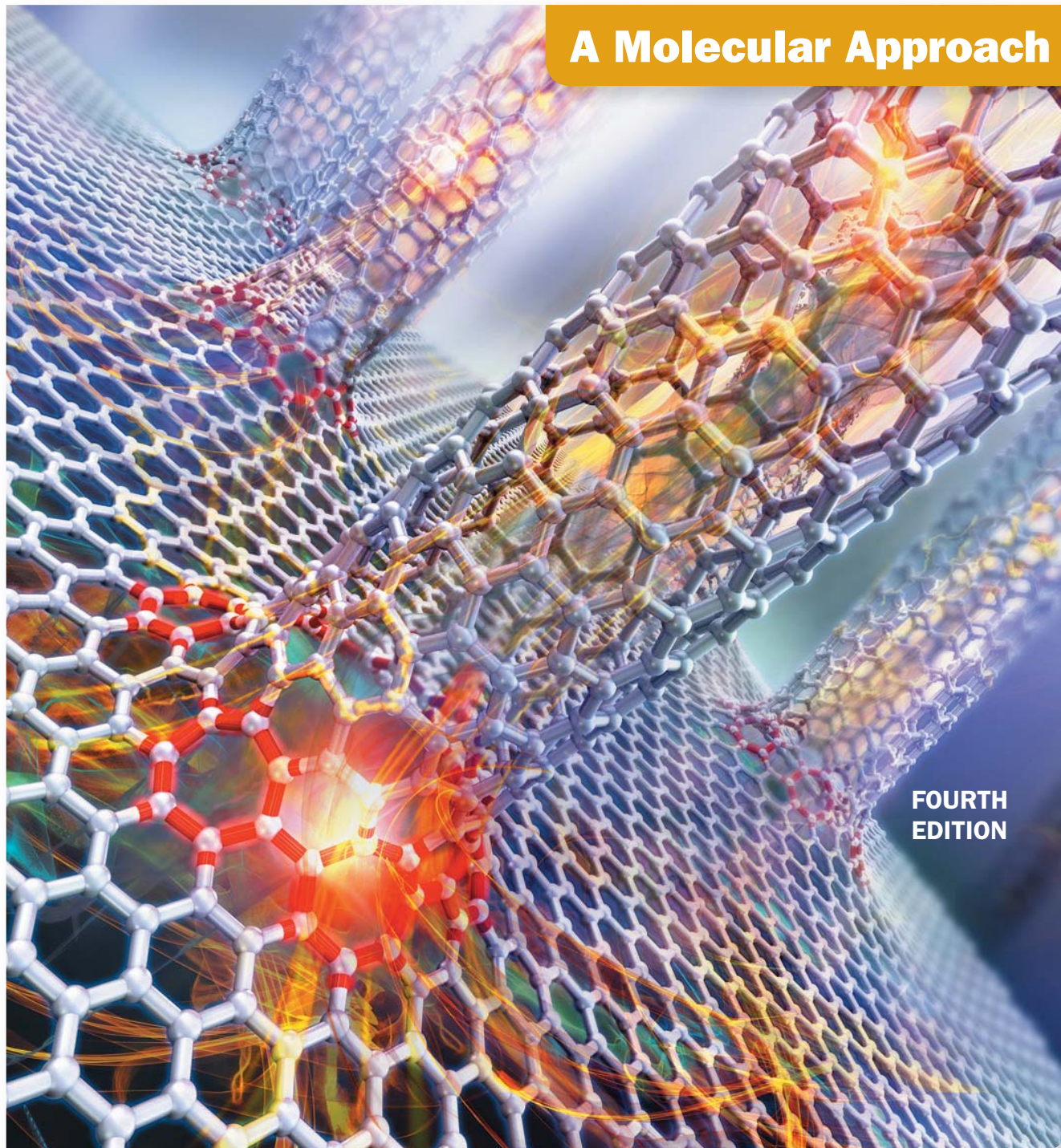
**Nivaldo J. Tro**

**CHEMISTRY**

*This page intentionally left blank*

# CHEMISTRY

A Molecular Approach



FOURTH  
EDITION

**Nivaldo J. Tro**

WESTMONT COLLEGE

PEARSON

*Editor in Chief:* Jeanne Zalesky  
*Executive Editor:* Terry Haugen  
*Director of Development:* Jennifer Hart  
*Product Marketing Manager:* Elizabeth Ellsworth  
*Executive Field Marketing Manager:* Chris Barker  
*Development Editor:* Erin Mulligan  
*Program Manager:* Sarah Shefveld  
*Project Manager:* Beth Sweeten  
*Editorial Assistant:* Lindsey Pruett  
*Content Producer:* Jackie Jacob  
*Text and Image Permissions Project Manager:*  
William Opaluch

*Program Management Team Lead:* Kristen Flatham  
*Project Management Team Lead:* David Zielonka  
*Production Management:* Francesca Monaco,  
CodeMantra  
*Compositor:* CodeMantra  
*Design Manager and Cover Designer:* Derek Bacchus  
*Interior Designer:* Elise Lansdon  
*Illustrators:* Lachina, Inc.  
*Photo Researcher:* Eric Shrader  
*Operations Specialist:* Maura Zaldivar-Garcia  
*Cover and Chapter Opening Illustrations:*  
Quade Paul

Copyright © 2017, 2014, 2011 Pearson Education, Inc. All rights reserved. Manufactured in the United States of America. This publication is protected by copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise. For information regarding permissions, request forms and the appropriate contacts within the Pearson Education Global Rights & Permissions department, please visit [www.pearsoned.com/permissions/](http://www.pearsoned.com/permissions/).

Acknowledgements of third party content appear on page C-1, which constitutes an extension of this copyright page.

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.

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

Tro, Nivaldo J.

Chemistry : a molecular approach / Tro, Nivaldo J.

Fourth edition. | Boston : Pearson, [2017] | Includes  
bibliographical references and index.

LCCN 2015040901 | ISBN 9780134112831 (0134112830 : alk. paper)

LCSH : Chemistry, Physical and theoretical--Textbooks.

LCC QD453.3. T759 2017 | DDC 540--dc23 LC record available at <http://lcn.loc.gov/2015040901>

1 2 3 4 5 6 7 8 9 10—**V357**—18 17 16 15

ISBN-10: 0-13-411283-0 / ISBN-13: 978-0-13-411283-1 (Student Edition)  
ISBN-10: 0-13-412633-5 / ISBN-13: 978-0-13-412633-3 (Instructor Review Copy)

**PEARSON**

[www.pearsonhighered.com](http://www.pearsonhighered.com)

## ABOUT THE AUTHOR

**NIVALDO TRO** is a professor of chemistry at Westmont College in Santa Barbara, California, where he has been a faculty member since 1990. He received his Ph.D. in chemistry from Stanford University for work on developing and using optical techniques to study the adsorption and desorption of molecules to and from surfaces in ultrahigh vacuum. He then went on to the University of California at Berkeley, where he did postdoctoral research on ultrafast reaction dynamics in solution. Since coming to Westmont, Professor Tro has been awarded grants from the American Chemical Society Petroleum Research Fund, from Research Corporation, and from the National Science Foundation to study the dynamics of various processes occurring in thin adlayer films adsorbed on dielectric surfaces. He has been honored as Westmont's outstanding teacher of the year three times and has also received the college's outstanding researcher of the year award. Professor Tro lives in Santa Barbara with his wife, Ann, and their four children, Michael, Ali, Kyle, and Kaden.



TO MICHAEL, ALI, KYLE, AND KADEN

# BRIEF CONTENTS

<b>1</b>	Matter, Measurement, and Problem Solving	ii
<b>2</b>	Atoms and Elements	44
<b>3</b>	Molecules, Compounds, and Chemical Equations	86
<b>4</b>	Chemical Quantities and Aqueous Reactions	138
<b>5</b>	Gases	196
<b>6</b>	Thermochemistry	248
<b>7</b>	The Quantum-Mechanical Model of the Atom	296
<b>8</b>	Periodic Properties of the Elements	336
<b>9</b>	Chemical Bonding I: The Lewis Model	382
<b>10</b>	Chemical Bonding II: Molecular Shapes, Valence Bond Theory, and Molecular Orbital Theory	426
<b>11</b>	Liquids, Solids, and Intermolecular Forces	484
<b>12</b>	Solids and Modern Materials	532
<b>13</b>	Solutions	570
<b>14</b>	Chemical Kinetics	622
<b>15</b>	Chemical Equilibrium	674
<b>16</b>	Acids and Bases	722
<b>17</b>	Aqueous Ionic Equilibrium	778
<b>18</b>	Free Energy and Thermodynamics	838
<b>19</b>	Electrochemistry	888
<b>20</b>	Radioactivity and Nuclear Chemistry	938
<b>21</b>	Organic Chemistry	978
<b>22</b>	Biochemistry	1028
<b>23</b>	Chemistry of the Nonmetals	1062
<b>24</b>	Metals and Metallurgy	1100
<b>25</b>	Transition Metals and Coordination Compounds	1126
<b>Appendix I</b>	Common Mathematical Operations in Chemistry	A-1
<b>Appendix II</b>	Useful Data	A-5
<b>Appendix III</b>	Answers to Selected Exercises	A-15
<b>Appendix IV</b>	Answers to In-Chapter Practice Problems	A-54
<b>Glossary</b>		G-1
<b>Photo and Text Credits</b>		C-1
<b>Index</b>		I-1

# INTERACTIVE MEDIA CONTENTS



**Interactive Worked Examples (IWEs)** [https://media.pearsoncmg.com/ph/esm/esm\\_tro\\_chemistry\\_4/media/index.html](https://media.pearsoncmg.com/ph/esm/esm_tro_chemistry_4/media/index.html)

- 1.5** Determining the Number of Significant Figures in a Number
- 1.6** Significant Figures in Calculations
- 1.8** Unit Conversion
- 1.9** Unit Conversions Involving Units Raised to a Power
- 1.10** Density as a Conversion Factor
- 1.12** Problems with Equations
- 2.3** Atomic Numbers, Mass Numbers, and Isotope Symbols
- 2.5** Atomic Mass
- 2.8** The Mole Concept—Converting between Mass and Number of Atoms
- 2.9** The Mole Concept
- 3.3** Writing Formulas for Ionic Compounds
- 3.11** Using the Nomenclature Flow Chart to Name Compounds
- 3.13** The Mole Concept—Converting between Mass and Number of Molecules
- 3.16** Chemical Formulas as Conversion Factors
- 3.18** Obtaining an Empirical Formula from Experimental Data
- 3.21** Determining an Empirical Formula from Combustion Analysis
- 3.23** Balancing Chemical Equations
- 4.1** Stoichiometry
- 4.3** Limiting Reactant and Theoretical Yield
- 4.5** Calculating Solution Concentration
- 4.6** Using Molarity in Calculations
- 4.8** Solution Stoichiometry
- 4.10** Writing Equations for Precipitation Reactions
- 5.5** Ideal Gas Law I
- 5.7** Density
- 5.8** Molar Mass of a Gas
- 5.12** Gases in Chemical Reactions
- 5.15** Graham's Law of Effusion
- 6.2** Temperature Changes and Heat Capacity
- 6.3** Thermal Energy Transfer
- 6.5** Measuring  $\Delta E_{\text{rxn}}$  in a Bomb Calorimeter
- 6.7** Stoichiometry Involving  $\Delta H$
- 6.8** Measuring  $\Delta H_{\text{rxn}}$  in a Coffee-Cup Calorimeter
- 6.11**  $\Delta H_{\text{rxn}}^{\circ}$  and the Standard Enthalpies of Formation
- 7.2** Photon Energy
- 7.3** Wavelength, Energy, and Frequency
- 7.5** Quantum Numbers I
- 7.7** Wavelength of Light for a Transition in the Hydrogen Atom
- 8.4** Writing Electron Configurations from the Periodic Table
- 8.5** Atomic Size
- 8.6** Electron Configurations and Magnetic Properties for Ions
- 8.8** First Ionization Energy
- 9.4** Writing Lewis Structures
- 9.6** Writing Lewis Structures for Polyatomic Ions
- 9.7** Writing Resonance Structures
- 9.8** Assigning Formal Charges
- 9.10** Writing Lewis Structures for Compounds Having Expanded Octets
- 9.11** Calculating  $\Delta H_{\text{rxn}}$  from Bond Energies
- 10.2** Predicting Molecular Geometries
- 10.4** Predicting the Shape of Larger Molecules
- 10.5** Determining Whether a Molecule Is Polar
- 10.8** Hybridization and Bonding Scheme
- 10.10** Molecular Orbital Theory
- 11.1** Dipole–Dipole Forces
- 11.2** Hydrogen Bonding
- 11.3** Using the Heat of Vaporization in Calculations
- 11.5** Using the Two-Point Form of the Clausius–Clapeyron Equation to Predict the Vapor Pressure at a Given Temperature
- 12.4** Relating Density to Crystal Structure
- 13.3** Using Parts by Mass in Calculations
- 13.4** Calculating Concentrations
- 13.5** Converting between Concentration Units
- 13.6** Calculating the Vapor Pressure of a Solution Containing a Nonelectrolyte and Nonvolatile Solute
- 13.9** Boiling Point Elevation
- 14.2** Determining the Order and Rate Constant of a Reaction
- 14.4** The First-Order Integrated Rate Law: Determining the Concentration of a Reactant at a Given Time
- 14.8** Using the Two-Point Form of the Arrhenius Equation
- 14.9** Reaction Mechanisms
- 15.1** Expressing Equilibrium Constants for Chemical Equations
- 15.5** Finding Equilibrium Constants from Experimental Concentration Measurements
- 15.8** Finding Equilibrium Concentrations When You Know the Equilibrium Constant and All but One of the Equilibrium Concentrations of the Reactants and Products
- 15.9** Finding Equilibrium Concentrations from Initial Concentrations and the Equilibrium Constant
- 15.12** Finding Equilibrium Concentrations from Initial Concentrations in Cases with a Small Equilibrium Constant
- 15.14** The Effect of a Concentration Change on Equilibrium
- 16.1** Identifying Brønsted–Lowry Acids and Bases and Their Conjugates



- 16.3** Calculating pH from  $[H_3O^+]$  or  $[OH^-]$
- 16.5** Finding the  $[H_3O^+]$  of a Weak Acid Solution
- 16.7** Finding the pH of a Weak Acid Solution in Cases Where the *x is small* Approximation Does Not Work
- 16.8** Finding the Equilibrium Constant from pH
- 16.9** Finding the Percent Ionization of a Weak Acid
- 16.12** Finding the  $[OH^-]$  and pH of a Weak Base Solution
- 16.14** Determining the pH of a Solution Containing an Anion Acting as a Base
- 17.2** Calculating the pH of a Buffer Solution as an Equilibrium Problem and with the Henderson–Hasselbalch Equation
- 17.3** Calculating the pH Change in a Buffer Solution after the Addition of a Small Amount of Strong Acid or Base
- 17.4** Using the Henderson–Hasselbalch Equation to Calculate the pH of a Buffer Solution Composed of a Weak Base and Its Conjugate Acid
- 17.6** Strong Acid–Strong Base Titration pH Curve
- 17.7** Weak Acid–Strong Base Titration pH Curve
- 17.8** Calculating Molar Solubility from  $K_{sp}$
- 18.4** Calculating Gibbs Free Energy Changes and Predicting Spontaneity from  $\Delta H$  and  $\Delta S$
- 18.5** Calculating Standard Entropy Changes ( $\Delta S_{rxn}^\circ$ )
- 18.6** Calculating the Standard Change in Free Energy for a Reaction Using  $\Delta G_{rxn}^\circ = \Delta H_{rxn}^\circ - T\Delta S_{rxn}^\circ$
- 18.10** Calculating  $\Delta G_{rxn}$  under Nonstandard Conditions
- 18.11** The Equilibrium Constant and  $\Delta G_{rxn}^\circ$
- 19.2** Half-Reaction Method of Balancing Aqueous Redox Equations in Acidic Solution
- 19.3** Balancing Redox Reactions Occurring in Basic Solution
- 19.4** Calculating Standard Potentials for Electrochemical Cells from Standard Electrode Potentials of the Half-Reactions
- 19.6** Relating  $\Delta G^\circ$  and  $E_{cell}^\circ$
- 20.1** Writing Nuclear Equations for Alpha Decay
- 20.2** Writing Nuclear Equations for Beta Decay, Positron Emission, and Electron Capture
- 20.4** Radioactive Decay Kinetics
- 20.5** Radiocarbon Dating
- 21.3** Naming Alkanes

## Key Concept Videos (KCVs) [https://media.pearsoncmg.com/ph/esm/esm\\_tro\\_chemistry\\_4/media/index.html](https://media.pearsoncmg.com/ph/esm/esm_tro_chemistry_4/media/index.html)

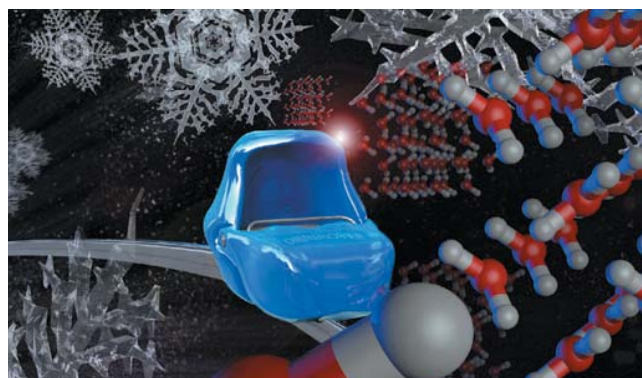
- 1.1** Atoms and Molecules
- 1.3** Classifying Matter
- 1.8** Solving Chemical Problems
- 2.3** Atomic Theory
- 2.6** Subatomic Particles and Isotope Symbols
- 2.9** The Mole Concept
- 3.5** Naming Ionic Compounds
- 3.6** Naming Molecular Compounds
- 3.11** Writing and Balancing Chemical Equations
- 4.2** Reaction Stoichiometry
- 4.3** Limiting Reactant, Theoretical Yield, and Percent Yield
- 4.6** Reactions in Solution
- 5.3** Simple Gas Laws and Ideal Gas Law
- 5.4** Simple Gas Laws and Ideal Gas Law
- 5.6** Mixtures of Gases and Partial Pressures
- 5.8** Kinetic Molecular Theory
- 6.3** The First Law of Thermodynamics
- 6.4** Heat Capacity
- 6.6** The Change in Enthalpy for a Chemical Reaction
- 7.2** The Nature of Light
- 7.4** The Wave Nature of Matter
- 7.5** Quantum Mechanics and the Atom: Orbitals and Quantum Numbers
- 8.3** Electron Configurations
- 8.4** Writing an Electron Configuration based on an Element's Position on the Periodic Table
- 8.6** Periodic Trends in the Size of Atomic Effective Nuclear Charge
- 9.5** The Lewis Model for Chemical Bonding
- 9.7** Writing Lewis Structures for Molecular Compounds
- 9.8** Resonance and Formal Charge
- 10.2** VSEPR Theory
- 10.3** VSEPR Theory: The Effect of Lone Pairs
- 10.6** Valence Bond Theory
- 10.7** Valence Bond Theory: Hybridization
- 11.3** Intermolecular Forces
- 11.5** Vaporization and Vapor Pressure
- 11.7** Heating Curve for Water
- 11.8** Phase Diagrams
- 12.3** Unit Cells: Simple Cubic, Body-Centered Cubic, and Face-Centered Cubic
- 13.4** Solution Equilibrium and the Factors Affecting Solubility
- 13.5** Solution Concentration: Molarity, Molality, Parts by Mass and Volume, Mole Fraction
- 13.6** Colligative Properties
- 14.3** The Rate Law for a Chemical Reaction
- 14.4** The Integrated Rate Law
- 14.5** The Effect of Temperature on Reaction Rate
- 15.3** The Equilibrium Constant
- 15.8** Finding Equilibrium Concentrations from Initial Concentrations
- 15.9** Le Châtelier's Principle
- 16.3** Definitions of Acids and Bases
- 16.6** Finding the  $[H_3O^+]$  and pH of Strong and Weak Acid Solutions
- 16.8** The Acid–Base Properties of Ions and Salts
- 17.2** Buffers
- 17.2** Finding pH and pH Changes in Buffer Solutions
- 17.4** The Titration of a Weak Acid and a Strong Base
- 18.3** Entropy and the Second Law of Thermodynamics
- 18.6** The Effect of  $\Delta H$ ,  $\Delta S$ , and  $T$  on Reaction Spontaneity
- 18.7** Standard Molar Entropies
- 19.4** Standard Electrode Potentials
- 19.5** Cell Potential, Free Energy, and the Equilibrium Constant
- 20.3** Types of Radioactivity

# CONTENTS

PREFACE xxii

## 1 Matter, Measurement, and Problem Solving xxxiv

- 1.1 Atoms and Molecules 1
  - 1.2 The Scientific Approach to Knowledge 3
    - The Nature of Science** Thomas S. Kuhn and Scientific Revolutions 5
  - 1.3 The Classification of Matter 5
    - The States of Matter: Solid, Liquid, and Gas 6
    - Classifying Matter according to Its Composition: Elements, Compounds, and Mixtures 7
    - Separating Mixtures 8
  - 1.4 Physical and Chemical Changes and Physical and Chemical Properties 9
  - 1.5 Energy: A Fundamental Part of Physical and Chemical Change 12
  - 1.6 The Units of Measurement 13
    - Standard Units 13 The Meter: A Measure of Length 14 The Kilogram: A Measure of Mass 14 The Second: A Measure of Time 14 The Kelvin: A Measure of Temperature 15
    - Prefix Multipliers 17 Derived Units: Volume and Density 17 Calculating Density 19
    - Chemistry and Medicine** Bone Density 20
  - 1.7 The Reliability of a Measurement 20
    - Counting Significant Figures 22 Exact Numbers 22 Significant Figures in Calculations 23 Precision and Accuracy 25
    - Chemistry in Your Day** Integrity in Data Gathering 26
  - 1.8 Solving Chemical Problems 26
    - Converting from One Unit to Another 26 General Problem-Solving Strategy 28 Units Raised to a Power 30 Order-of-Magnitude Estimations 31 Problems Involving an Equation 32
- CHAPTER IN REVIEW** Self-Assessment Quiz 33 Key Terms 34 Key Concepts 35 Key Equations and Relationships 35 Key Learning Outcomes 36
- EXERCISES** Review Questions 36 Problems by Topic 36 Cumulative Problems 40 Challenge Problems 41 Conceptual Problems 42 Questions for Group Work 42 Data Interpretation and Analysis 43 Answers to Conceptual Connections 43



## 2 Atoms and Elements 44

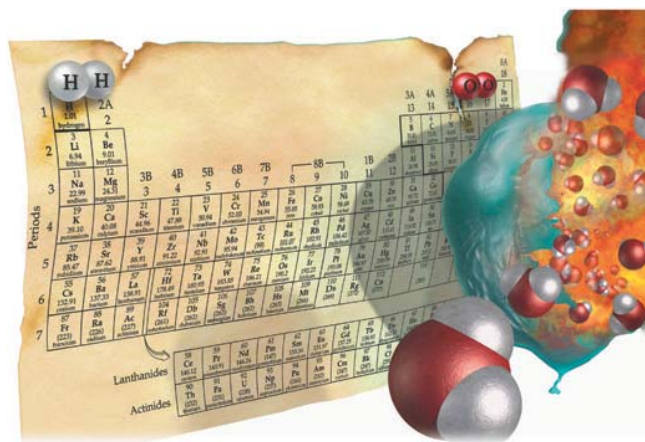


- 2.1 Brownian Motion: Atoms Confirmed 45
- 2.2 Early Ideas About the Building Blocks of Matter 47
- 2.3 Modern Atomic Theory and the Laws That Led to It 47
  - The Law of Conservation of Mass 47 The Law of Definite Proportions 48 The Law of Multiple Proportions 49 John Dalton and the Atomic Theory 50
  - Chemistry in Your Day** Atoms and Humans 50
- 2.4 The Discovery of the Electron 51
  - Cathode Rays 51 Millikan's Oil Drop Experiment: The Charge of the Electron 52
- 2.5 The Structure of the Atom 53
- 2.6 Subatomic Particles: Protons, Neutrons, and Electrons in Atoms 55
  - Elements: Defined by Their Numbers of Protons 56
  - Isotopes: When the Number of Neutrons Varies 57
  - Ions: Losing and Gaining Electrons 59
  - Chemistry in Your Day** Where Did Elements Come From? 60
- 2.7 Finding Patterns: The Periodic Law and the Periodic Table 60
  - Modern Periodic Table Organization 62 Ions and the Periodic Table 64
  - Chemistry and Medicine** The Elements of Life 65
- 2.8 Atomic Mass: The Average Mass of an Element's Atoms 65
  - Mass Spectrometry: Measuring the Mass of Atoms and Molecules 66
  - Chemistry in Your Day** Evolving Atomic Masses 68
- 2.9 Molar Mass: Counting Atoms by Weighing Them 69
  - The Mole: A Chemist's "Dozen" 69 Converting between Number of Moles and Number of Atoms 70
  - Converting between Mass and Amount (Number of Moles) 71

**CHAPTER IN REVIEW** Self-Assessment Quiz 74  
Key Terms 75 Key Concepts 76 Key Equations and Relationships 76 Key Learning Outcomes 77

**EXERCISES** Review Questions 77 Problems by Topic 78  
Cumulative Problems 81 Challenge Problems 82  
Conceptual Problems 83 Questions for Group Work 83 Data Interpretation and Analysis 84  
Answers to Conceptual Connections 85

## 3 Molecules, Compounds, and Chemical Equations 86



**3.1 Hydrogen, Oxygen, and Water** 87

**3.2 Chemical Bonds** 89

Ionic Bonds 89 Covalent Bonds 90

**3.3 Representing Compounds: Chemical Formulas and Molecular Models** 90

Types of Chemical Formulas 90 Molecular Models 92

**3.4 An Atomic-Level View of Elements and Compounds** 92

**3.5 Ionic Compounds: Formulas and Names** 96

Writing Formulas for Ionic Compounds 96  
Naming Ionic Compounds 97 Naming Binary Ionic Compounds Containing a Metal That Forms Only One Type of Cation 98 Naming Binary Ionic Compounds Containing a Metal That Forms More Than One Kind of Cation 99 Naming Ionic Compounds Containing Polyatomic Ions 100 Hydrated Ionic Compounds 101

**3.6 Molecular Compounds: Formulas and Names** 101

Naming Molecular Compounds 102 Naming Acids 103 Naming Binary Acids 103 Naming Oxyacids 104

**Chemistry in the Environment** Acid Rain 104

**3.7 Summary of Inorganic Nomenclature** 105

**3.8 Formula Mass and the Mole Concept for Compounds** 107

Molar Mass of a Compound 107 Using Molar Mass to Count Molecules by Weighing 107

**3.9 Composition of Compounds** 109

Mass Percent Composition as a Conversion Factor 110 Conversion Factors from Chemical Formulas 112

**Chemistry and Medicine** Methylmercury in Fish 114

**3.10 Determining a Chemical Formula from Experimental Data** 114

Determining Molecular Formulas for Compounds 116 Combustion Analysis 117

**3.11 Writing and Balancing Chemical Equations** 119

**3.12 Organic Compounds** 123

Hydrocarbons 124 Functionalized Hydrocarbons 125

**CHAPTER IN REVIEW** Self-Assessment Quiz 127

Key Terms 127 Key Concepts 128 Key Equations and Relationships 128 Key Learning Outcomes 129

**EXERCISES** Review Questions 129 Problems by Topic 130  
Cumulative Problems 134 Challenge Problems 135  
Conceptual Problems 135 Questions for Group Work 135 Data Interpretation and Analysis 136  
Answers to Conceptual Connections 137

## 4 Chemical Quantities and Aqueous Reactions 138

**4.1 Climate Change and the Combustion of Fossil Fuels** 139

**4.2 Reaction Stoichiometry: How Much Carbon Dioxide?** 141

Making Pizza: The Relationships among Ingredients 141 Making Molecules: Mole-to-Mole Conversions 141 Making Molecules: Mass-to-Mass Conversions 142

**4.3 Limiting Reactant, Theoretical Yield, and Percent Yield** 145

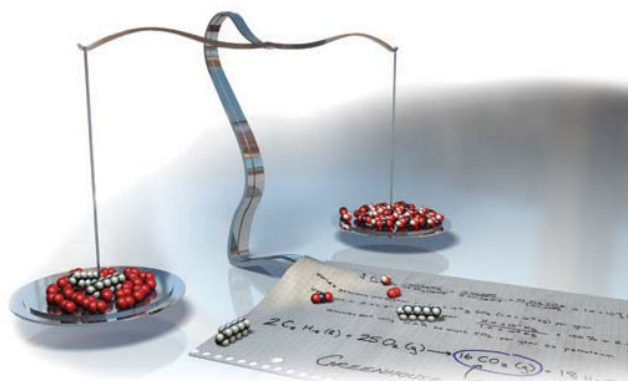
Calculating Limiting Reactant, Theoretical Yield, and Percent Yield 146 Calculating Limiting Reactant, Theoretical Yield, and Percent Yield from Initial Reactant Masses 147

**4.4 Solution Concentration and Solution Stoichiometry** 151

Solution Concentration 151 Using Molarity in Calculations 153 Solution Dilution 154 Solution Stoichiometry 156

**4.5 Types of Aqueous Solutions and Solubility** 158

Electrolyte and Nonelectrolyte Solutions 158 The Solubility of Ionic Compounds 160



- 4.6 Precipitation Reactions** 162
- 4.7 Representing Aqueous Reactions: Molecular, Ionic, and Complete Ionic Equations** 166
- 4.8 Acid–Base and Gas-Evolution Reactions** 167  
Acid–Base Reactions 168 Gas-Evolution Reactions 173
- 4.9 Oxidation–Reduction Reactions** 175  
Oxidation States 176 Identifying Redox Reactions 178  
**Chemistry in Your Day** *Bleached Blonde* 181  
Combustion Reactions 181

**CHAPTER IN REVIEW** Self-Assessment Quiz 182  
Key Terms 183 Key Concepts 184 Key Equations and Relationships 185 Key Learning Outcomes 185

**EXERCISES** Review Questions 186 Problems by Topic 186  
Cumulative Problems 190 Challenge Problems 192  
Conceptual Problems 192 Questions for Group Work 193  
Data Interpretation and Analysis 194 Answers to Conceptual Connections 195

## 5 Gases 196



- 5.1 Supersonic Skydiving and the Risk of Decompression** 197
- 5.2 Pressure: The Result of Molecular Collisions** 198  
Pressure Units 199 The Manometer: A Way to Measure Pressure in the Laboratory 200  
**Chemistry and Medicine** *Blood Pressure* 201
- 5.3 The Simple Gas Laws: Boyle's Law, Charles's Law, and Avogadro's Law** 201  
Boyle's Law: Volume and Pressure 202 Charles's Law: Volume and Temperature 204  
**Chemistry in Your Day** *Extra-Long Snorkels* 205  
Avogadro's Law: Volume and Amount (in Moles) 207
- 5.4 The Ideal Gas Law** 208
- 5.5 Applications of the Ideal Gas Law: Molar Volume, Density, and Molar Mass of a Gas** 211  
Molar Volume at Standard Temperature and Pressure 211 Density of a Gas 212 Molar Mass of a Gas 213
- 5.6 Mixtures of Gases and Partial Pressures** 214  
Deep-Sea Diving and Partial Pressures 217  
Collecting Gases over Water 219

- 5.7 Gases in Chemical Reactions: Stoichiometry Revisited** 221  
Molar Volume and Stoichiometry 222
- 5.8 Kinetic Molecular Theory: A Model for Gases** 224  
How Kinetic Molecular Theory Explains Pressure and the Simple Gas Laws 225 Kinetic Molecular Theory and the Ideal Gas Law 226 Temperature and Molecular Velocities 227
- 5.9 Mean Free Path, Diffusion, and Effusion of Gases** 230
- 5.10 Real Gases: The Effects of Size and Intermolecular Forces** 232  
The Effect of the Finite Volume of Gas Particles 233  
The Effect of Intermolecular Forces 234 Van der Waals Equation 235 Real Gases 235

**CHAPTER IN REVIEW** Self-Assessment Quiz 236  
Key Terms 237 Key Concepts 237 Key Equations and Relationships 238 Key Learning Outcomes 238

**EXERCISES** Review Questions 239 Problems by Topic 240  
Cumulative Problems 243 Challenge Problems 245  
Conceptual Problems 245 Questions for Group Work 246  
Data Interpretation and Analysis 246 Answers to Conceptual Connections 247

## 6 Thermochemistry 248

- 6.1 Chemical Hand Warmers** 249
- 6.2 The Nature of Energy: Key Definitions** 250  
Types of Energy 250 Energy Conservation and Energy Transfer 251 Units of Energy 251
- 6.3 The First Law of Thermodynamics: There Is No Free Lunch** 253  
Internal Energy 253  
**Chemistry in Your Day** *Redheffer's Perpetual Motion Machine* 253  
Heat and Work 256
- 6.4 Quantifying Heat and Work** 258  
Heat 258 Work: Pressure–Volume Work 262
- 6.5 Measuring  $\Delta E$  for Chemical Reactions: Constant-Volume Calorimetry** 264
- 6.6 Enthalpy: The Heat Evolved in a Chemical Reaction at Constant Pressure** 267  
Exothermic and Endothermic Processes: A Molecular View 269 Stoichiometry Involving  $\Delta H$ : Thermochemical Equations 269



- 6.7 Constant-Pressure Calorimetry: Measuring  $\Delta H_{\text{rxn}}$**  270
- 6.8 Relationships Involving  $\Delta H_{\text{rxn}}$**  272
- 6.9 Determining Enthalpies of Reaction from Standard Enthalpies of Formation** 275  
Standard States and Standard Enthalpy Changes 275 Calculating the Standard Enthalpy Change for a Reaction 277
- 6.10 Energy Use and the Environment** 280  
Energy Consumption 280 Environmental Problems Associated with Fossil Fuel Use 281 Air Pollution 281 Global Climate Change 282  
**Chemistry in the Environment** *Renewable Energy* 284

**CHAPTER IN REVIEW** Self-Assessment Quiz 285  
Key Terms 286 Key Concepts 286 Key Equations and Relationships 287 Key Learning Outcomes 287

**EXERCISES** Review Questions 288 Problems by Topic 289 Cumulative Problems 292 Challenge Problems 293 Conceptual Problems 293 Questions for Group Work 294 Data Interpretation and Analysis 294 Answers to Conceptual Connections 295

## 7 The Quantum-Mechanical Model of the Atom 296

- 7.1 Schrödinger's Cat** 297
- 7.2 The Nature of Light** 298  
The Wave Nature of Light 299 The Electromagnetic Spectrum 301  
**Chemistry and Medicine** *Radiation Treatment for Cancer* 303  
Interference and Diffraction 303  
The Particle Nature of Light 305
- 7.3 Atomic Spectroscopy and the Bohr Model** 308  
**Chemistry in Your Day** *Atomic Spectroscopy, a Bar Code for Atoms* 310
- 7.4 The Wave Nature of Matter: The de Broglie Wavelength, the Uncertainty Principle, and Indeterminacy** 311  
The de Broglie Wavelength 313 The Uncertainty Principle 314 Indeterminacy and Probability Distribution Maps 315

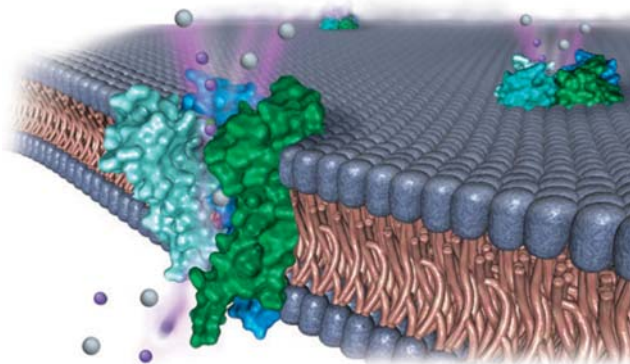


- 7.5 Quantum Mechanics and the Atom** 317  
Solutions to the Schrödinger Equation for the Hydrogen Atom 317 Atomic Spectroscopy Explained 320
- 7.6 The Shapes of Atomic Orbitals** 323  
*s* Orbitals ( $l=0$ ) 323 *p* Orbitals ( $l=1$ ) 326  
*d* Orbitals ( $l=2$ ) 326 *f* Orbitals ( $l=3$ ) 326  
The Phase of Orbitals 327 The Shape of Atoms 328

**CHAPTER IN REVIEW** Self-Assessment Quiz 328  
Key Terms 329 Key Concepts 329 Key Equations and Relationships 330 Key Learning Outcomes 330

**EXERCISES** Review Questions 330 Problems by Topic 331 Cumulative Problems 332 Challenge Problems 333 Conceptual Problems 334 Questions for Group Work 334 Data Interpretation and Analysis 334 Answers to Conceptual Connections 335

## 8 Periodic Properties of the Elements 336



- 8.1 Nerve Signal Transmission** 337
- 8.2 The Development of the Periodic Table** 338
- 8.3 Electron Configurations: How Electrons Occupy Orbitals** 339  
Electron Spin and the Pauli Exclusion Principle 340 Sublevel Energy Splitting in Multielectron Atoms 341 Electron Configurations for Multielectron Atoms 344
- 8.4 Electron Configurations, Valence Electrons, and the Periodic Table** 347  
Orbital Blocks in the Periodic Table 348 Writing an Electron Configuration for an Element from Its Position in the Periodic Table 349 The Transition and Inner Transition Elements 350
- 8.5 The Explanatory Power of the Quantum-Mechanical Model** 351
- 8.6 Periodic Trends in the Size of Atoms and Effective Nuclear Charge** 352  
Effective Nuclear Charge 353 Atomic Radii and the Transition Elements 355
- 8.7 Ions: Electron Configurations, Magnetic Properties, Ionic Radii, and Ionization Energy** 357  
Electron Configurations and Magnetic Properties of Ions 357 Ionic Radii 359 Ionization Energy 361 Trends in First Ionization Energy 361

Exceptions to Trends in First Ionization Energy 363  
Trends in Second and Successive Ionization Energies 364

### 8.8 Electron Affinities and Metallic Character 365

Electron Affinity 365 Metallic Character 366

### 8.9 Some Examples of Periodic Chemical Behavior: The Alkali Metals, the Halogens, and the Noble Gases 369

The Alkali Metals (Group 1A) 369 The Halogens (Group 7A) 370 The Noble Gases (Group 8A) 371

**CHAPTER IN REVIEW** Self-Assessment Quiz 372  
Key Terms 373 Key Concepts 374 Key Equations and Relationships 374 Key Learning Outcomes 375

**EXERCISES** Review Questions 375 Problems by Topic 376 Cumulative Problems 378 Challenge Problems 379 Conceptual Problems 379 Questions for Group Work 380 Data Interpretation and Analysis 380 Answers to Conceptual Connections 381

## 9 Chemical Bonding I: The Lewis Model 382

### 9.1 Bonding Models and AIDS Drugs 383

### 9.2 Types of Chemical Bonds 384

### 9.3 Representing Valence Electrons with Dots 386

### 9.4 Ionic Bonding: Lewis Symbols and Lattice Energies 387

Ionic Bonding and Electron Transfer 387 Lattice Energy: The Rest of the Story 388 The Born–Haber Cycle 388 Trends in Lattice Energies: Ion Size 391 Trends in Lattice Energies: Ion Charge 391 Ionic Bonding: Models and Reality 392

**Chemistry and Medicine** *Ionic Compounds in Medicine* 393

### 9.5 Covalent Bonding: Lewis Structures 394

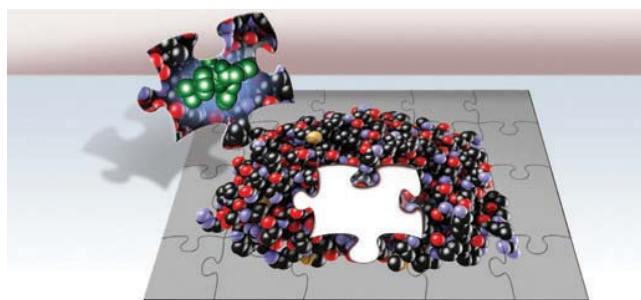
Single Covalent Bonds 394 Double and Triple Covalent Bonds 394 Covalent Bonding: Models and Reality 395

### 9.6 Electronegativity and Bond Polarity 396

Electronegativity 397 Bond Polarity, Dipole Moment, and Percent Ionic Character 398

### 9.7 Lewis Structures of Molecular Compounds and Polyatomic Ions 400

Writing Lewis Structures for Molecular Compounds 400 Writing Lewis Structures for Polyatomic Ions 402



### 9.8 Resonance and Formal Charge 402

Resonance 402 Formal Charge 404

### 9.9 Exceptions to the Octet Rule: Odd-Electron Species, Incomplete Octets, and Expanded Octets 407

Odd-Electron Species 408 Incomplete Octets 408

**Chemistry in the Environment** *Free Radicals and the Atmospheric Vacuum Cleaner* 409

Expanded Octets 410

### 9.10 Bond Energies and Bond Lengths 411

Bond Energy 412 Using Average Bond Energies to Estimate Enthalpy Changes for Reactions 413 Bond Lengths 414

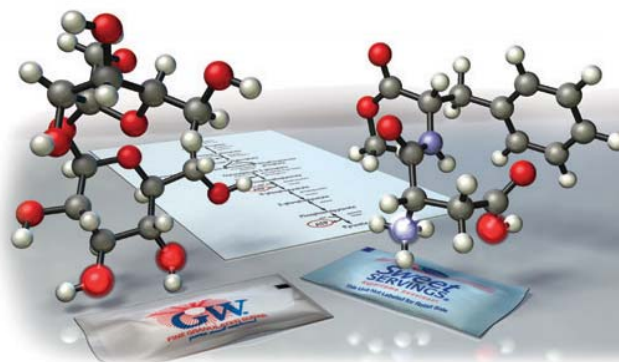
### 9.11 Bonding in Metals: The Electron Sea Model 415

**Chemistry in the Environment** *The Lewis Structure of Ozone* 416

**CHAPTER IN REVIEW** Self-Assessment Quiz 417 Key Terms 418 Key Concepts 418 Key Equations and Relationships 419 Key Learning Outcomes 419

**EXERCISES** Review Questions 420 Problems by Topic 421 Cumulative Problems 422 Challenge Problems 424 Conceptual Problems 424 Questions for Group Work 424 Data Interpretation and Analysis 425 Answers to Conceptual Connections 425

## 10 Chemical Bonding II: Molecular Shapes, Valence Bond Theory, and Molecular Orbital Theory 426



### 10.1 Artificial Sweeteners: Fooled by Molecular Shape 427

### 10.2 VSEPR Theory: The Five Basic Shapes 428

Two Electron Groups: Linear Geometry 429 Three Electron Groups: Trigonal Planar Geometry 429 Four Electron Groups: Tetrahedral Geometry 429 Five Electron Groups: Trigonal Bipyramidal Geometry 431 Six Electron Groups: Octahedral Geometry 431

### 10.3 VSEPR Theory: The Effect of Lone Pairs 432

Four Electron Groups with Lone Pairs 432 Five Electron Groups with Lone Pairs 434 Six Electron Groups with Lone Pairs 435

**10.4 VSEPR Theory: Predicting Molecular Geometries** 437

Representing Molecular Geometries on Paper 439  
 Predicting the Shapes of Larger Molecules 439

**10.5 Molecular Shape and Polarity** 440

Vector Addition 442

**Chemistry in Your Day** *How Soap Works* 444

**10.6 Valence Bond Theory: Orbital Overlap as a Chemical Bond** 445**10.7 Valence Bond Theory: Hybridization of Atomic Orbitals** 447

$sp^3$  Hybridization 448  $sp^2$  Hybridization and Double Bonds 450

**Chemistry in Your Day** *The Chemistry of Vision* 454

$sp$  Hybridization and Triple Bonds 454  $sp^3d$  and  $sp^3d^2$  Hybridization 456 Writing Hybridization and Bonding Schemes 457

**10.8 Molecular Orbital Theory: Electron Delocalization** 460

Linear Combination of Atomic Orbitals (LCAOs) 461 Period Two Homonuclear Diatomic Molecules 465 Second-Period Heteronuclear Diatomic Molecules 470 Polyatomic Molecules 472

**CHAPTER IN REVIEW** Self-Assessment Quiz 473

Key Terms 474 Key Concepts 474 Key Equations and Relationships 474 Key Learning Outcomes 475

**EXERCISES** Review Questions 475 Problems by Topic 476

Cumulative Problems 478 Challenge Problems 480 Conceptual Problems 481 Questions for Group Work 481 Data Interpretation and Analysis 482 Answers to Conceptual Connections 483

**11 Liquids, Solids, and Intermolecular Forces** 484**11.1 Water, No Gravity** 485**11.2 Solids, Liquids, and Gases: A Molecular Comparison** 486

Differences between States of Matter 486 Changes between States 488

**11.3 Intermolecular Forces: The Forces That Hold Condensed States Together** 489

Dispersion Force 490 Dipole–Dipole Force 492 Hydrogen Bonding 495 Ion–Dipole Force 497

**Chemistry and Medicine** *Hydrogen Bonding in DNA* 498

**11.4 Intermolecular Forces in Action: Surface Tension, Viscosity, and Capillary Action** 499

Surface Tension 499 Viscosity 501

**Chemistry in Your Day** *Viscosity and Motor Oil* 501

Capillary Action 501

**11.5 Vaporization and Vapor Pressure** 502

The Process of Vaporization 502 The Energetics of Vaporization 503 Vapor Pressure and Dynamic Equilibrium 505 The Critical Point: The Transition to an Unusual State of Matter 511

**11.6 Sublimation and Fusion** 512

Sublimation 512 Fusion 513 Energetics of Melting and Freezing 513

**11.7 Heating Curve for Water** 514**11.8 Phase Diagrams** 517

The Major Features of a Phase

Diagram 517 Navigation within a Phase

Diagram 518 The Phase Diagrams of Other

Substances 519

**11.9 Water: An Extraordinary Substance** 520

**Chemistry in the Environment** *Water Pollution* 521

**CHAPTER IN REVIEW** Self-Assessment Quiz 522

Key Terms 523 Key Concepts 523 Key Equations and Relationships 524 Key Learning Outcomes 524

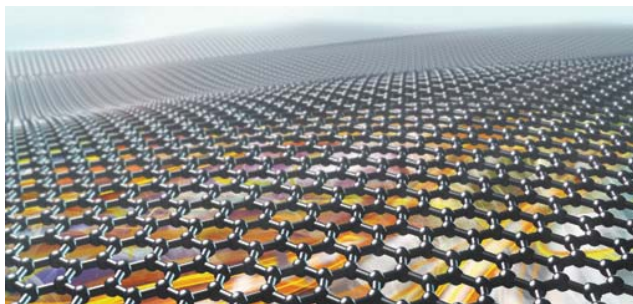
**EXERCISES** Review Questions 524 Problems by Topic 525

Cumulative Problems 528 Challenge Problems 528

Conceptual Problems 529 Questions for Group

Work 529 Data Interpretation and Analysis 530

Answers to Conceptual Connections 531

**12 Solids and Modern Materials** 532**12.1 Friday Night Experiments: The Discovery of Graphene** 533**12.2 X-Ray Crystallography** 534**12.3 Unit Cells and Basic Structures** 537

Cubic Unit Cells 537 Closest-Packed Structures 543

**12.4 The Fundamental Types of Crystalline Solids** 544

Molecular Solids 545

**Chemistry in Your Day** *Chocolate, An Edible Material* 546

Ionic Solids 547 Atomic Solids 547

**12.5 The Structures of Ionic Solids** 548**12.6 Network Covalent Atomic Solids: Carbon and Silicates** 550

Carbon 550 Silicates 553

- 12.7 Ceramics, Cement, and Glass** 553  
Ceramics 553 Cement 554 Glass 555
- 12.8 Semiconductors and Band Theory** 555  
Molecular Orbitals and Energy Bands 555 Doping:  
Controlling the Conductivity of  
Semiconductors 557
- 12.9 Polymers and Plastics** 557  
**Chemistry in Your Day** Kevlar 560
- CHAPTER IN REVIEW** Self-Assessment Quiz 560  
Key Terms 561 Key Concepts 562 Key Equations  
and Relationships 562 Key Learning Outcomes 562
- EXERCISES** Review Questions 563 Problems by Topic 563  
Cumulative Problems 566 Challenge Problems 567  
Conceptual Problems 567 Questions for Group  
Work 568 Data Interpretation and Analysis 568  
Answers to Conceptual Connections 569

## 13 Solutions 570

- 13.1 Thirsty Solutions: Why You Shouldn't Drink Seawater** 571



- 13.2 Types of Solutions and Solubility** 573  
Nature's Tendency toward Mixing: Entropy 574  
The Effect of Intermolecular Forces 574
- 13.3 Energetics of Solution Formation** 577  
Energy Changes in Solution  
Formation 578 Aqueous Solutions and Heats of  
Hydration 579
- 13.4 Solution Equilibrium and Factors Affecting Solubility** 581  
The Temperature Dependence of the Solubility of  
Solids 582 Factors Affecting the Solubility of  
Gases in Water 583
- 13.5 Expressing Solution Concentration** 585  
**Chemistry in the Environment** Lake Nyos 586  
Molarity 586 Molality 588 Parts by Mass and  
Parts by Volume 588 Using Parts by Mass (or Parts  
by Volume) in Calculations 588 Mole Fraction  
and Mole Percent 589  
**Chemistry in the Environment** The Dirty Dozen 590
- 13.6 Colligative Properties: Vapor Pressure Lowering, Freezing Point Depression, Boiling Point Elevation, and Osmotic Pressure** 593

Vapor Pressure Lowering 593 Vapor Pressures of  
Solutions Containing a Volatile (Nonelectrolyte)  
Solute 597 Freezing Point Depression and Boiling  
Point Elevation 600

**Chemistry in Your Day** Antifreeze in Frogs 603  
Osmotic Pressure 603

- 13.7 Colligative Properties of Strong Electrolyte Solutions** 605  
Strong Electrolytes and Vapor Pressure 606  
Colligative Properties and Medical Solutions 607
- 13.8 Colloids** 608

**CHAPTER IN REVIEW** Self-Assessment Quiz 611  
Key Terms 612 Key Concepts 612 Key Equations  
and Relationships 613 Key Learning Outcomes 613

**EXERCISES** Review Questions 614 Problems by Topic 614  
Cumulative Problems 618 Challenge Problems 619  
Conceptual Problems 619 Questions for Group  
Work 620 Data Interpretation and Analysis 620  
Answers to Conceptual Connections 621

## 14 Chemical Kinetics 622

- 14.1 Catching Lizards** 623
- 14.2 The Rate of a Chemical Reaction** 624  
Definition of Reaction Rate 624 Measuring  
Reaction Rates 627
- 14.3 The Rate Law: The Effect of Concentration on Reaction Rate** 629  
The Three Common Reaction Orders ( $n=0, 1,$  and  
 $2$ ) 629 Determining the Order of a Reaction 630  
Reaction Order for Multiple Reactants 632
- 14.4 The Integrated Rate Law: The Dependence of Concentration on Time** 634  
The Integrated Rate Law 634 The Half-Life of a  
Reaction 638
- 14.5 The Effect of Temperature on Reaction Rate** 642  
The Arrhenius Equation 642 The Activation  
Energy, Frequency Factor, and Exponential  
Factor 643 Arrhenius Plots: Experimental  
Measurements of the Frequency Factor and the  
Activation Energy 644 The Collision Model: A  
Closer Look at the Frequency Factor 647





**14.6 Reaction Mechanisms** 648

Rate Laws for Elementary Steps 649 Rate-Determining Steps and Overall Reaction Rate Laws 650 Mechanisms with a Fast Initial Step 651

**14.7 Catalysis** 653

Homogeneous and Heterogeneous Catalysis 655 Enzymes: Biological Catalysts 656  
**Chemistry and Medicine** *Enzyme Catalysis and the Role of Chymotrypsin in Digestion* 658

**CHAPTER IN REVIEW** Self-Assessment Quiz 659

Key Terms 661 Key Concepts 661 Key Equations and Relationships 662 Key Learning Outcomes 662

**EXERCISES** Review Questions 663 Problems by Topic 663 Cumulative Problems 668 Challenge Problems 670 Conceptual Problems 671 Questions for Group Work 672 Data Interpretation and Analysis 672 Answers to Conceptual Connections 673

**15 Chemical Equilibrium** 674**15.1 Fetal Hemoglobin and Equilibrium** 675**15.2 The Concept of Dynamic Equilibrium** 677**15.3 The Equilibrium Constant ( $K$ )** 680

Expressing Equilibrium Constants for Chemical Reactions 680 The Significance of the Equilibrium Constant 681

**Chemistry and Medicine** *Life and Equilibrium* 682 Relationships between the Equilibrium Constant and the Chemical Equation 683

**15.4 Expressing the Equilibrium Constant in Terms of Pressure** 684

Relationship Between  $K_p$  and  $K_c$  685 Units of  $K$  686

**15.5 Heterogeneous Equilibria: Reactions Involving Solids and Liquids** 687**15.6 Calculating the Equilibrium Constant from Measured Equilibrium Concentrations** 688**15.7 The Reaction Quotient: Predicting the Direction of Change** 691**15.8 Finding Equilibrium Concentrations** 693

Finding Equilibrium Concentrations from the Equilibrium Constant and All but One of the Equilibrium Concentrations of the Reactants and Products 694 Finding Equilibrium Concentrations

from the Equilibrium Constant and Initial Concentrations or Pressures 695 Simplifying Approximations in Working Equilibrium Problems 699

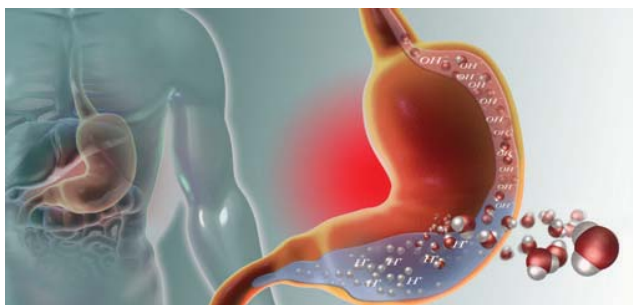
**15.9 Le Châtelier's Principle: How a System at Equilibrium Responds to Disturbances** 703

The Effect of a Concentration Change on Equilibrium 704 The Effect of a Volume (or Pressure) Change on Equilibrium 706 The Effect of a Temperature Change on Equilibrium 708

**CHAPTER IN REVIEW** Self-Assessment Quiz 710

Key Terms 711 Key Concepts 711 Key Equations and Relationships 712 Key Learning Outcomes 712

**EXERCISES** Review Questions 713 Problems by Topic 714 Cumulative Problems 717 Challenge Problems 718 Conceptual Problems 719 Questions for Group Work 719 Data Interpretation and Analysis 720 Answers to Conceptual Connections 721

**16 Acids and Bases** 722**16.1 Heartburn** 723**16.2 The Nature of Acids and Bases** 724**16.3 Definitions of Acids and Bases** 726

The Arrhenius Definition 726 The Brønsted-Lowry Definition 727

**16.4 Acid Strength and the Acid Ionization Constant ( $K_a$ )** 729

Strong Acids 729 Weak Acids 730 The Acid Ionization Constant ( $K_a$ ) 731

**16.5 Autoionization of Water and pH** 732

The pH Scale: A Way to Quantify Acidity and Basicity 734 pOH and Other p Scales 735

**Chemistry and Medicine** *Ulcers* 736

**16.6 Finding the  $[H_3O^+]$  and pH of Strong and Weak Acid Solutions** 737

Strong Acids 737 Weak Acids 737 Percent Ionization of a Weak Acid 742 Mixtures of Acids 743

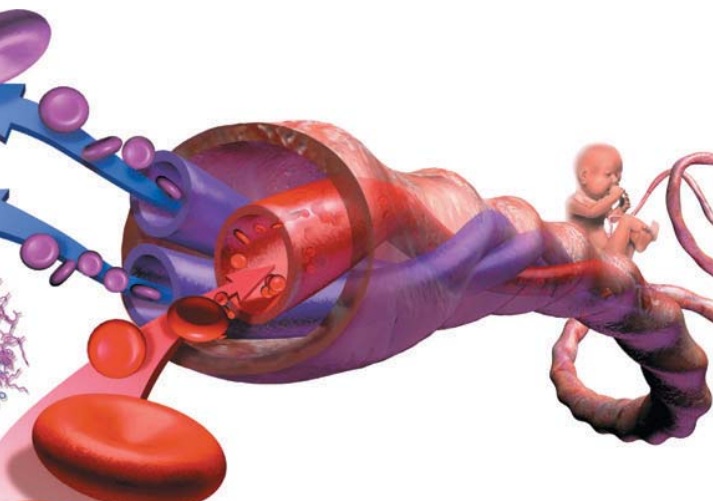
**16.7 Base Solutions** 746

Strong Bases 746 Weak Bases 746 Finding the  $[OH^-]$  and pH of Basic Solutions 748

**Chemistry and Medicine** *What's in My Antacid?* 750

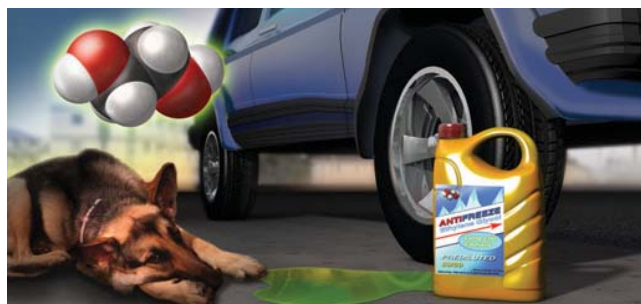
**16.8 The Acid-Base Properties of Ions and Salts** 750

Anions as Weak Bases 751 Cations as Weak Acids 754 Classifying Salt Solutions as Acidic, Basic, or Neutral 755



- 16.9 Polyprotic Acids** 757  
 Finding the pH of Polyprotic Acid Solutions 758 Finding the Concentration of the Anions for a Weak Diprotic Acid Solution 760
- 16.10 Acid Strength and Molecular Structure** 762  
 Binary Acids 762 Oxyacids 763
- 16.11 Lewis Acids and Bases** 764  
 Molecules That Act as Lewis Acids 764 Cations That Act as Lewis Acids 765
- 16.12 Acid Rain** 765  
 Effects of Acid Rain 766 Acid Rain Legislation 767
- CHAPTER IN REVIEW** Self-Assessment Quiz 767  
 Key Terms 768 Key Concepts 768 Key Equations and Relationships 769 Key Learning Outcomes 770
- EXERCISES** Review Questions 770 Problems by Topic 771 Cumulative Problems 774 Challenge Problems 775 Conceptual Problems 776 Questions for Group Work 776 Data Interpretation and Analysis 776 Answers to Conceptual Connections 777

## 17 Aqueous Ionic Equilibrium 778



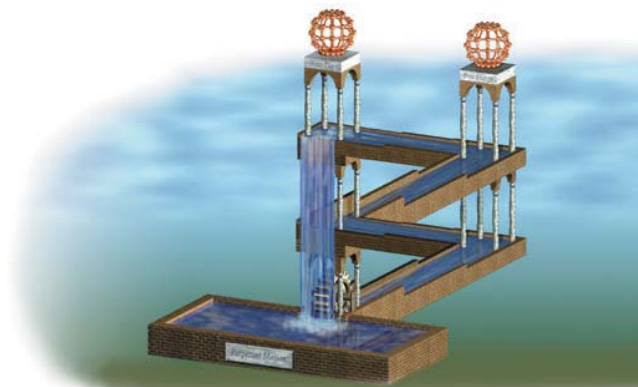
- 17.1 The Danger of Antifreeze** 779
- 17.2 Buffers: Solutions That Resist pH Change** 780  
 Calculating the pH of a Buffer Solution 782 The Henderson–Hasselbalch Equation 783 Calculating pH Changes in a Buffer Solution 786 Buffers Containing a Base and Its Conjugate Acid 790
- 17.3 Buffer Effectiveness: Buffer Range and Buffer Capacity** 791  
 Relative Amounts of Acid and Base 791 Absolute Concentrations of the Acid and Conjugate Base 792 Buffer Range 793  
**Chemistry and Medicine** Buffer Effectiveness in Human Blood 794  
 Buffer Capacity 794
- 17.4 Titrations and pH Curves** 795  
 The Titration of a Strong Acid with a Strong Base 796 The Titration of a Weak Acid with a Strong Base 800 The Titration of a Weak Base with a Strong Acid 805 The Titration of a Polyprotic Acid 805 Indicators: pH-Dependent Colors 806
- 17.5 Solubility Equilibria and the Solubility Product Constant** 809  
 $K_{sp}$  and Molar Solubility 809  
**Chemistry in Your Day** Hard Water 811

$K_{sp}$  and Relative Solubility 812 The Effect of a Common Ion on Solubility 812 The Effect of pH on Solubility 814

- 17.6 Precipitation** 815  
 Selective Precipitation 816
- 17.7 Qualitative Chemical Analysis** 818  
 Group 1: Insoluble Chlorides 819 Group 2: Acid-Insoluble Sulfides 819 Group 3: Base-Insoluble Sulfides and Hydroxides 820 Group 4: Insoluble Phosphates 820 Group 5: Alkali Metals and  $\text{NH}_4^+$  820
- 17.8 Complex Ion Equilibria** 821  
 The Effect of Complex Ion Equilibria on Solubility 823 The Solubility of Amphoteric Metal Hydroxides 824
- CHAPTER IN REVIEW** Self-Assessment Quiz 825  
 Key Terms 826 Key Concepts 826 Key Equations and Relationships 827 Key Learning Outcomes 827
- EXERCISES** Review Questions 828 Problems by Topic 829 Cumulative Problems 834 Challenge Problems 835 Conceptual Problems 835 Questions for Group Work 836 Data Interpretation and Analysis 836 Answers to Conceptual Connections 837

## 18 Free Energy and Thermodynamics 838

- 18.1 Nature's Heat Tax: You Can't Win and You Can't Break Even** 839
- 18.2 Spontaneous and Nonspontaneous Processes** 841
- 18.3 Entropy and the Second Law of Thermodynamics** 843  
 Entropy 844 The Entropy Change upon the Expansion of an Ideal Gas 846
- 18.4 Entropy Changes Associated with State Changes** 848  
 Entropy and State Change: The Concept 849 Entropy and State Changes: The Calculation 850
- 18.5 Heat Transfer and Changes in the Entropy of the Surroundings** 852  
 The Temperature Dependence of  $\Delta S_{\text{surr}}$  853 Quantifying Entropy Changes in the Surroundings 854



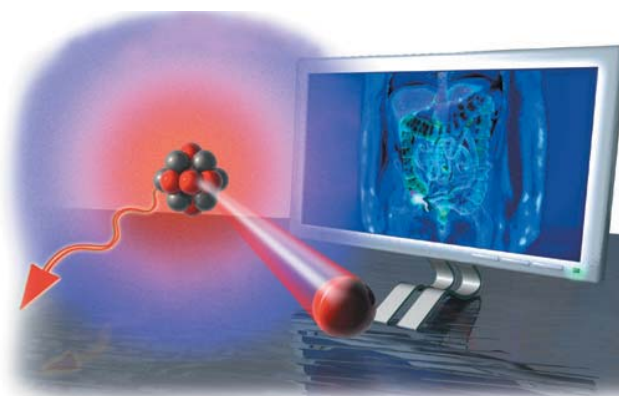
- 18.6 Gibbs Free Energy** 855  
The Effect of  $\Delta H$ ,  $\Delta S$ , and  $T$  on Spontaneity 856
- 18.7 Entropy Changes in Chemical Reactions: Calculating  $\Delta S_{\text{rxn}}^{\circ}$**  859  
Defining Standard States and Standard Entropy Changes 859 Standard Molar Entropies ( $S^{\circ}$ ) and the Third Law of Thermodynamics 859 Calculating the Standard Entropy Change ( $\Delta S_{\text{rxn}}^{\circ}$ ) for a Reaction 863
- 18.8 Free Energy Changes in Chemical Reactions: Calculating  $\Delta G_{\text{rxn}}^{\circ}$**  863  
Calculating Standard Free Energy Changes with  $\Delta G_{\text{rxn}}^{\circ} = \Delta H_{\text{rxn}}^{\circ} - T\Delta S_{\text{rxn}}^{\circ}$  864 Calculating  $\Delta G_{\text{rxn}}^{\circ}$  with Tabulated Values of Free Energies of Formation 865  
**Chemistry in Your Day** Making a Nonspontaneous Process Spontaneous 867  
Calculating  $\Delta G_{\text{rxn}}^{\circ}$  for a Stepwise Reaction from the Changes in Free Energy for Each of the Steps 867 Why Free Energy Is “Free” 868
- 18.9 Free Energy Changes for Nonstandard States: The Relationship between  $\Delta G_{\text{rxn}}^{\circ}$  and  $\Delta G_{\text{rxn}}$**  870  
Standard versus Nonstandard States 870 The Free Energy Change of a Reaction under Nonstandard Conditions 870
- 18.10 Free Energy and Equilibrium: Relating  $\Delta G_{\text{rxn}}^{\circ}$  to the Equilibrium Constant ( $K$ )** 873  
The Relationship between  $\Delta G_{\text{rxn}}^{\circ}$  and  $K$  873 The Temperature Dependence of the Equilibrium Constant 875
- CHAPTER IN REVIEW** Self-Assessment Quiz 876  
Key Terms 877 Key Concepts 877 Key Equations and Relationships 878 Key Learning Outcomes 878
- EXERCISES** Review Questions 879 Problems by Topic 880 Cumulative Problems 883 Challenge Problems 884 Conceptual Problems 885 Questions for Group Work 885 Data Interpretation and Analysis 886 Answers to Conceptual Connections 887
- 19.4 Standard Electrode Potentials** 898  
Predicting the Spontaneous Direction of an Oxidation–Reduction Reaction 902 Predicting Whether a Metal Will Dissolve in Acid 905
- 19.5 Cell Potential, Free Energy, and the Equilibrium Constant** 905  
The Relationship between  $\Delta G^{\circ}$  and  $E_{\text{cell}}^{\circ}$  906 The Relationship between  $E_{\text{cell}}^{\circ}$  and  $K$  908
- 19.6 Cell Potential and Concentration** 909  
Cell Potential under Nonstandard Conditions: The Nernst Equation 909 Concentration Cells 912  
**Chemistry and Medicine** Concentration Cells in Human Nerve Cells 914
- 19.7 Batteries: Using Chemistry to Generate Electricity** 914  
Dry-Cell Batteries 914 Lead–Acid Storage Batteries 915 Other Rechargeable Batteries 916 Fuel Cells 917  
**Chemistry in Your Day** The Fuel-Cell Breathalyzer 918
- 19.8 Electrolysis: Driving Nonspontaneous Chemical Reactions with Electricity** 918  
Predicting the Products of Electrolysis 921 Stoichiometry of Electrolysis 924
- 19.9 Corrosion: Undesirable Redox Reactions** 925  
Corrosion of Iron 926 Preventing the Corrosion of Iron 927
- CHAPTER IN REVIEW** Self-Assessment Quiz 927  
Key Terms 928 Key Concepts 929 Key Equations and Relationships 929 Key Learning Outcomes 930
- EXERCISES** Review Questions 930 Problems by Topic 931 Cumulative Problems 934 Challenge Problems 936 Conceptual Problems 936 Questions for Group Work 936 Data Interpretation and Analysis 937 Answers to Conceptual Connections 937

## 19 Electrochemistry 888

- 19.1 Pulling the Plug on the Power Grid** 889
- 19.2 Balancing Oxidation–Reduction Equations** 890
- 19.3 Voltaic (or Galvanic) Cells: Generating Electricity from Spontaneous Chemical Reactions** 893  
The Voltaic Cell 894 Current and Potential Difference 895 Anode, Cathode, and Salt Bridge 896 Electrochemical Cell Notation 897



## 20 Radioactivity and Nuclear Chemistry 938



- 20.1 Diagnosing Appendicitis** 939
- 20.2 The Discovery of Radioactivity** 940
- 20.3 Types of Radioactivity** 941  
Alpha ( $\alpha$ ) Decay 942 Beta ( $\beta$ ) Decay 943  
Gamma ( $\gamma$ ) Ray Emission 943 Positron Emission 944 Electron Capture 944

- 20.4 The Valley of Stability: Predicting the Type of Radioactivity** 946  
 Magic Numbers 947 Radioactive Decay Series 948
- 20.5 Detecting Radioactivity** 948
- 20.6 The Kinetics of Radioactive Decay and Radiometric Dating** 949  
 The Integrated Rate Law 951 Radiocarbon Dating: Using Radioactivity to Measure the Age of Fossils and Artifacts 952  
**Chemistry in Your Day** *Radiocarbon Dating and the Shroud of Turin* 954  
 Uranium/Lead Dating 954
- 20.7 The Discovery of Fission: The Atomic Bomb and Nuclear Power** 956  
 The Manhattan Project 956 Nuclear Power: Using Fission to Generate Electricity 958 Problems with Nuclear Power 959
- 20.8 Converting Mass to Energy: Mass Defect and Nuclear Binding Energy** 960  
 Mass Defect and Nuclear Binding Energy 960 The Nuclear Binding Energy Curve 962
- 20.9 Nuclear Fusion: The Power of the Sun** 962
- 20.10 Nuclear Transmutation and Transuranium Elements** 963
- 20.11 The Effects of Radiation on Life** 964  
 Acute Radiation Damage 965 Increased Cancer Risk 965 Genetic Defects 965 Measuring Radiation Exposure and Dose 965
- 20.12 Radioactivity in Medicine and Other Applications** 967  
 Diagnosis in Medicine 967 Radiotherapy in Medicine 968 Other Applications 969
- CHAPTER IN REVIEW** Self-Assessment Quiz 969  
 Key Terms 970 Key Concepts 970 Key Equations and Relationships 971 Key Learning Outcomes 972
- EXERCISES** Review Questions 972 Problems by Topic 973 Cumulative Problems 974 Challenge Problems 975 Conceptual Problems 976 Questions for Group Work 976 Data Interpretation and Analysis 977 Answers to Conceptual Connections 977

## 21 Organic Chemistry 978

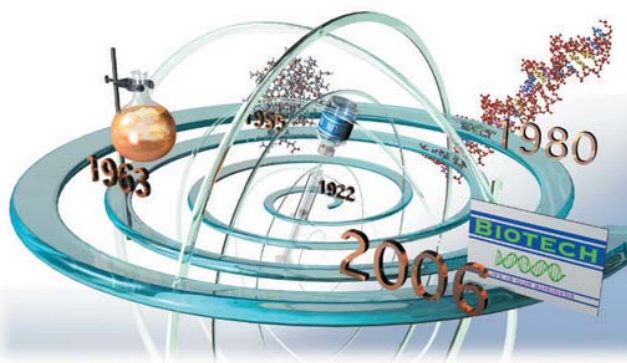
- 21.1 Fragrances and Odors** 979
- 21.2 Carbon: Why It Is Unique** 980  
**Chemistry in Your Day** *Vitalism and the Perceived Differences between Organic and Inorganic Compounds* 981
- 21.3 Hydrocarbons: Compounds Containing Only Carbon and Hydrogen** 982  
 Drawing Hydrocarbon Structures 983 Stereoisomerism and Optical Isomerism 985
- 21.4 Alkanes: Saturated Hydrocarbons** 988  
 Naming Alkanes 989
- 21.5 Alkenes and Alkynes** 992  
 Naming Alkenes and Alkynes 993 Geometric (Cis-Trans) Isomerism in Alkenes 996



- 21.6 Hydrocarbon Reactions** 997  
 Reactions of Alkanes 997 Reactions of Alkenes and Alkynes 998
- 21.7 Aromatic Hydrocarbons** 1000  
 Naming Aromatic Hydrocarbons 1000 Reactions of Aromatic Compounds 1002
- 21.8 Functional Groups** 1003
- 21.9 Alcohols** 1004  
 Naming Alcohols 1004 About Alcohols 1004 Alcohol Reactions 1004
- 21.10 Aldehydes and Ketones** 1006  
 Naming Aldehydes and Ketones 1007 About Aldehydes and Ketones 1007 Aldehyde and Ketone Reactions 1008
- 21.11 Carboxylic Acids and Esters** 1009  
 Naming Carboxylic Acids and Esters 1009 About Carboxylic Acids and Esters 1009 Carboxylic Acid and Ester Reactions 1010
- 21.12 Ethers** 1011  
 Naming Ethers 1011 About Ethers 1012
- 21.13 Amines** 1012  
 Amine Reactions 1012
- CHAPTER IN REVIEW** Self-Assessment Quiz 1013 Key Terms 1014 Key Concepts 1014 Key Equations and Relationships 1015 Key Learning Outcomes 1016
- EXERCISES** Review Questions 1017 Problems by Topic 1017 Cumulative Problems 1023 Challenge Problems 1025 Conceptual Problems 1026 Questions for Group Work 1026 Data Interpretation and Analysis 1026 Answers to Conceptual Connections 1027

## 22 Biochemistry 1028

- 22.1 Diabetes and the Synthesis of Human Insulin** 1029
- 22.2 Lipids** 1030  
 Fatty Acids 1030 Fats and Oils 1032 Other Lipids 1033
- 22.3 Carbohydrates** 1035  
 Simple Carbohydrates: Monosaccharides and Disaccharides 1035 Complex Carbohydrates 1037



- 22.4 Proteins and Amino Acids** 1038  
Amino Acids: The Building Blocks of Proteins 1039 Peptide Bonding between Amino Acids 1041
- 22.5 Protein Structure** 1042  
Primary Structure 1044 Secondary Structure 1044 Tertiary Structure 1045 Quaternary Structure 1046
- 22.6 Nucleic Acids: Blueprints for Proteins** 1046  
The Basic Structure of Nucleic Acids 1046 The Genetic Code 1048
- 22.7 DNA Replication, the Double Helix, and Protein Synthesis** 1050  
DNA Replication and the Double Helix 1050 Protein Synthesis 1051  
**Chemistry and Medicine** *The Human Genome Project* 1052

**CHAPTER IN REVIEW** Self-Assessment Quiz 1053  
Key Terms 1054 Key Concepts 1054 Key Learning Outcomes 1055

**EXERCISES** Review Questions 1056 Problems by Topic 1056 Cumulative Problems 1059 Challenge Problems 1060 Conceptual Problems 1060 Questions for Group Work 1061 Data Interpretation and Analysis 1061 Answers to Conceptual Connections 1061

## 23 Chemistry of the Nonmetals 1062

- 23.1 Insulated Nanowires** 1063
- 23.2 The Main-Group Elements: Bonding and Properties** 1064
- 23.3 Silicates: The Most Abundant Matter in Earth's Crust** 1066  
Quartz 1066 Aluminosilicates 1066 Individual Silicate Units, Silicate Chains, and Silicate Sheets 1067
- 23.4 Boron and Its Remarkable Structures** 1070  
Elemental Boron 1070 Boron-Halogen Compounds: Trihalides 1070 Boron-Oxygen Compounds 1071 Boron-Hydrogen Compounds: Boranes 1071
- 23.5 Carbon, Carbides, and Carbonates** 1072  
Amorphous Carbon 1072 Carbides 1073 Carbon Oxides 1075 Carbonates 1075

### 23.6 Nitrogen and Phosphorus: Essential Elements for Life 1076

Elemental Nitrogen and Phosphorus 1076  
Nitrogen Compounds 1078 Phosphorus Compounds 1081

### 23.7 Oxygen 1083

Elemental Oxygen 1083 Uses for Oxygen 1084  
Oxides 1084 Ozone 1084

### 23.8 Sulfur: A Dangerous but Useful Element 1085

Elemental Sulfur 1085 Hydrogen Sulfide and Metal Sulfides 1087 Sulfur Dioxide 1088  
Sulfuric Acid 1088

### 23.9 Halogens: Reactive Elements with High Electronegativity 1089

Elemental Fluorine and Hydrofluoric Acid 1090  
Elemental Chlorine 1091 Halogen Compounds 1091

**CHAPTER IN REVIEW** Self-Assessment Quiz 1093  
Key Terms 1094 Key Concepts 1094 Key Learning Outcomes 1095

**EXERCISES** Review Questions 1095 Problems by Topic 1095 Cumulative Problems 1097 Challenge Problems 1098 Conceptual Problems 1098 Questions for Group Work 1098 Data Interpretation and Analysis 1099 Answers to Conceptual Connections 1099

## 24 Metals and Metallurgy 1100



### 24.1 Vanadium: A Problem and an Opportunity 1101

### 24.2 The General Properties and Natural Distribution of Metals 1102

### 24.3 Metallurgical Processes 1104

Separation 1104 Pyrometallurgy 1104  
Hydrometallurgy 1105 Electrometallurgy 1106  
Powder Metallurgy 1107

### 24.4 Metal Structures and Alloys 1108

Alloys 1108 Substitutional Alloys 1108 Alloys with Limited Solubility 1110 Interstitial Alloys 1111

### 24.5 Sources, Properties, and Products of Some of the 3d Transition Metals 1113

Titanium 1113 Chromium 1114  
Manganese 1115 Cobalt 1116 Copper 1117  
Nickel 1117 Zinc 1118

**CHAPTER IN REVIEW** Self-Assessment Quiz 1118 Key Terms 1120 Key Concepts 1120 Key Equations and Relationships 1120 Key Learning Outcomes 1121

**EXERCISES** Review Questions 1121 Problems by Topic 1121 Cumulative Problems 1123 Challenge Problems 1123 Conceptual Problems 1123 Questions for Group Work 1124 Data Interpretation and Analysis 1124 Answers to Conceptual Connections 1125

## 25 Transition Metals and Coordination Compounds 1126



**25.1 The Colors of Rubies and Emeralds** 1127

**25.2 Properties of Transition Metals** 1128  
 Electron Configurations 1128 Atomic Size 1130  
 Ionization Energy 1130 Electronegativity 1131  
 Oxidation States 1131

**25.3 Coordination Compounds** 1132  
 Naming Coordination Compounds 1135

**25.4 Structure and Isomerization** 1137  
 Structural Isomerism 1137 Stereoisomerism 1139

**25.5 Bonding in Coordination Compounds** 1142  
 Valence Bond Theory 1142 Crystal Field Theory 1143

**25.6 Applications of Coordination Compounds** 1147  
 Chelating Agents 1148 Chemical Analysis 1148  
 Coloring Agents 1148 Biomolecules 1148

**CHAPTER IN REVIEW** Self-Assessment Quiz 1151  
 Key Terms 1151 Key Concepts 1152 Key Equations and Relationships 1152 Key Learning Outcomes 1152

**EXERCISES** Review Questions 1153 Problems by Topic 1153 Cumulative Problems 1155 Challenge Problems 1155 Conceptual Problems 1156 Questions for Group Work 1156 Data Interpretation and Analysis 1156 Answers to Conceptual Connections 1157

**Appendix I** Common Mathematical Operations in Chemistry A-1

**Appendix II** Useful Data A-5

**Appendix III** Answers to Selected Exercises A-15

**Appendix IV** Answers to In-Chapter Practice Problems A-54

**Glossary** G-1

**Photo and Text Credits** C-1

**Index** I-1

# PREFACE

## To the Student

As you begin this course, I invite you to think about your reasons for enrolling in it. Why are you taking general chemistry? More generally, why are you pursuing a college education? If you are like most college students taking general chemistry, part of your answer is probably that this course is required for your major and that you are pursuing a college education so you can get a good job some day. Although these are good reasons, I would like to suggest a better one. I think the primary reason for your education is to prepare you to *live a good life*. You should understand chemistry—not for what it can *get* you—but for what it can *do* to you. Understanding chemistry, I believe, is an important source of happiness and fulfillment. Let me explain.

Understanding chemistry helps you to live life to its fullest for two basic reasons. The first is *intrinsic*: through an understanding of chemistry, you gain a powerful appreciation for just how rich and extraordinary the world really is. The second reason is *extrinsic*: understanding chemistry makes you a more informed citizen—it allows you to engage with many of the issues of our day. In other words, understanding chemistry makes *you* a deeper and richer person and makes your country and the world a better place to live. These reasons have been the foundation of education from the very beginnings of civilization.

How does chemistry help prepare you for a rich life and conscientious citizenship? Let me explain with two examples. My first one comes from the very first page of Chapter 1 of this book. There, I ask the following question: What is the most important idea in all of scientific knowledge? My answer to that question is this: **the behavior of matter is determined by the properties of molecules and atoms.** That simple statement is the reason I love chemistry. We humans have been able to study the substances that compose the world around us and explain their behavior by reference to particles so small that they can hardly be imagined. If you have never realized the remarkable sensitivity of the world we *can* see to the world we *cannot*, you have missed out on a fundamental truth about our universe. To have never encountered this truth is like never having read a play by Shakespeare or seen a sculpture by Michelangelo—or, for that matter, like never having discovered that the world is round. It robs you of an amazing and unforgettable experience of the world and the human ability to understand it.

My second example demonstrates how science literacy helps you to be a better citizen. Although I am largely sympathetic to the environmental movement, a lack of science literacy within some sectors of that movement and the resulting anti-environmental backlash create confusion that impedes

real progress and opens the door to what could be misinformed policies. For example, I have heard conservative pundits say that volcanoes emit more carbon dioxide—the most significant greenhouse gas—than does petroleum combustion. I have also heard a liberal environmentalist say that we have to stop using hairspray because it is causing holes in the ozone layer that will lead to global warming. Well, the claim about volcanoes emitting more carbon dioxide than petroleum combustion can be refuted by the basic tools you will learn to use in Chapter 4 of this book. We can easily show that volcanoes emit only 1/50th as much carbon dioxide as petroleum combustion. As for hairspray depleting the ozone layer and thereby leading to global warming, the chlorofluorocarbons that deplete ozone have been banned from hairspray since 1978, and ozone depletion has nothing to do with global warming anyway. People with special interests or axes to grind can conveniently distort the truth before an ill-informed public, which is why we all need to be knowledgeable.

So this is why I think you should take this course. Not just to satisfy the requirement for your major, and not just to get a good job some day, but to help you to lead a fuller life and to make the world a little better for everyone. I wish you the best as you embark on the journey to understand the world around you at the molecular level. The rewards are well worth the effort.

## To the Professor

First and foremost, thanks to all of you who adopted this book in its previous editions. You helped to make this book one of the most popular general chemistry textbooks in the world. I am grateful beyond words. Second, I have listened carefully to your feedback on the previous edition. The changes you see in this edition are the direct result of your input, as well as my own experience using the book in my general chemistry courses. If you have reviewed content or have contacted me directly, you will likely see your suggestions reflected in the changes I have made. Thank you.

Some of the most exciting changes in this edition are in the media associated with the book. I have added approximately 57 new Key Concept Videos and 61 new Interactive Worked examples to the media package. You can see a more detailed description of these videos in the following section entitled *What's New in This Edition*. This means that you now have a library of over 150 interactive videos to enhance your course. In my courses, I use these videos to implement a *before, during, after* strategy for my students. My goal is simple: *Engage students in active learning before class, during class, and after class*. To that end, I assign a key concept video *before* each class session.

The video introduces students to a key concept for that day and gets them thinking about it before they come to class. *During* class, I expand on the concept and use *Leaning Catalytics* to question my students. Instead of passively listening to a lecture, they are interacting with the concepts through questions that I pose. Some of these questions are answered individually; other times I have them pair up with a partner. This approach has changed my classroom. Students engage in the material in new ways. They have to think and process and interact. It is deeply satisfying for me to see my students so engaged. Finally, *after* class, I give them another assignment, often an interactive worked example with a follow-up question. At this point, they have to apply what they have learned to solve a problem.

The results have been fantastic. My students are enjoying the process because they are engaged before, during, and after class rather than only looking at material the night before a problem set is due. I have seen evidence of their improved learning through increases in their scores on the American Chemical Society Standard General Chemistry Exam, which I always administer as the final exam for my course.

Although we have added exciting new media elements and made other changes to the book, the book's goal remains the same: *to present a rigorous and accessible treatment of general chemistry in the context of relevance*. Teaching general chemistry would be much easier if all of our students had exactly the same level of preparation and ability. But alas, that is not the case. Even though I teach at a relatively selective institution, my courses are populated with students with a range of backgrounds and abilities in chemistry. The challenge of successful teaching, in my opinion, is figuring out how to instruct and challenge the best students while not losing those with lesser backgrounds and abilities. My strategy has always been to set the bar relatively high, while at the same time providing the motivation and support necessary to reach the high bar. That is exactly the philosophy of this book. We do not have to compromise away rigor in order to make chemistry accessible to our students. In this book, I have worked hard to combine rigor with accessibility—to create a book that does not dilute the content, yet can be used and understood by any student willing to put in the necessary effort.

*Chemistry: A Molecular Approach* is first and foremost a *student-oriented book*. My main goal is to motivate students and get them to achieve at the highest possible level. As we all know, many students take general chemistry because it is a requirement; they do not see the connection between chemistry and their lives or their intended careers. *Chemistry: A Molecular Approach* strives to make those connections consistently and effectively. Unlike other books, which often teach chemistry as something that happens only in the laboratory or in industry, this book teaches chemistry in the context of relevance. It shows students *why* chemistry is important to them, to their future careers, and to their world.

Second, *Chemistry: A Molecular Approach* is a *pedagogically driven book*. In seeking to develop problem-solving skills, a consistent approach (Sort, Strategize, Solve, and Check) is applied, usually in a two- or three-column format.

In the two-column format, the left column shows the student how to analyze the problem and devise a solution strategy. It also lists the steps of the solution, explaining the rationale for each one, while the right column shows the implementation of each step. In the three-column format, the left column outlines the general procedure for solving an important category of problems that is then applied to two side-by-side examples. This strategy allows students to see both the general pattern and the slightly different ways in which the procedure may be applied in differing contexts. The aim is to help students understand both the *concept of the problem* (through the formulation of an explicit conceptual plan for each problem) and the *solution to the problem*.

Third, *Chemistry: A Molecular Approach* is a *visual book*. Wherever possible, I use images to deepen the student's insight into chemistry. In developing chemical principles, multipart images help show the connection between everyday processes visible to the unaided eye and what atoms and molecules are actually doing. Many of these images have three parts: macroscopic, molecular, and symbolic. This combination helps students to see the relationships between the formulas they write down on paper (symbolic), the world they see around them (macroscopic), and the atoms and molecules that compose that world (molecular). In addition, most figures are designed to teach rather than just to illustrate. They are rich with annotations and labels intended to help the student grasp the most important processes and the principles that underlie them. The resulting images are rich with information but also uncommonly clear and quickly understood.

Fourth, *Chemistry: A Molecular Approach* is a “big picture” book. At the beginning of each chapter, a short paragraph helps students to see the key relationships between the different topics they are learning. Through a focused and concise narrative, I strive to make the basic ideas of every chapter clear to the student. Interim summaries are provided at selected spots in the narrative, making it easier to grasp (and review) the main points of important discussions. And to make sure that students never lose sight of the forest for the trees, each chapter includes several *Conceptual Connections*, which ask them to think about concepts and solve problems without doing any math. I want students to learn the concepts, not just plug numbers into equations to churn out the right answer. This philosophy is also integral to the *Key Concept Videos*, which concisely reinforce student appreciation of the core concepts in each chapter.

*Chemistry: A Molecular Approach* is lastly a book that delivers the depth of coverage faculty want. We do not have to cut corners and water down the material in order to get our students interested. We have to meet them where they are, challenge them to the highest level of achievement, and support them with enough pedagogy to allow them to succeed.

I hope that this book supports you in your vocation of teaching students chemistry. I am increasingly convinced of the importance of our task. Please feel free to email me with any questions or comments about the book.

Nivaldo J. Tro  
tro@westmont.edu



## What's New in This Edition?

The book has been extensively revised and contains more small changes than can be detailed here. The most significant changes to the book and its supplements are listed below:

- **NEW!** Chapter 12: *Solids and Modern Materials*. This chapter contains new topics and consolidates content on materials that was found in other parts of the book in previous editions into one new chapter. All chapters beyond Chapter 12 have been renumbered.
- With the help of my colleagues, Thomas Greenbowe (University of Oregon), Kristin Ziebert (Oregon State University), and Michael Everest (Westmont College), I have added two new categories of end-of-chapter questions designed to help students build what we call “twenty-first-century skills.” The first new category of questions is *Data Interpretation and Analysis*. These questions present real data in real-life situations and ask students to analyze that data. These in-depth exercises give students much needed practice in reading graphs, digesting tables, and making data-driven decisions. The second new category of questions is *Questions for Group Work*. Our group work questions give students the opportunity to work with their peers in small groups. The questions can be used in or out of the classroom, but the idea is to foster collaborative learning and to encourage students to work together as a team to solve problems.
- I have added approximately 57 new Key Concept Videos and 61 new Interactive Worked Examples to the media package that accompanies the book. (Since the previous edition had 40 Interactive worked examples, there is now a total of 158 interactive videos.) These tools are designed to help professors engage their students in active learning. Recent research has conclusively demonstrated that students learn better when they are active in the learning process, as opposed to passively listening and simply taking in content. The Key Concept Videos are brief (two to five minutes), and each introduces a key concept from a chapter. The student does not just passively listen to the video; the video stops in the middle and poses a question to the student. The student must answer the question before the video continues. Each video also includes a follow-up question that is assignable in MasteringChemistry™. The Interactive Worked Examples are similar in concept, but instead of explaining a key concept, they walk the student through one of the in-chapter worked examples from the book. Like the Key Concept Videos, Interactive Worked Examples stop in the middle and force the student to interact by completing a step in the example. The examples also have a follow-up question that is assignable in MasteringChemistry™. The power of interactivity to make connections in problem solving is immense. I did not quite realize this power until we started creating the Interactive Worked Examples and I saw how I could use the animations to make connections that are just not possible on the static page.

- There are approximately 21 new Conceptual Connection questions throughout the book.
- All the data throughout the book have been updated to reflect the most recent measurements available. These updates include *Figure 4.2 Carbon Dioxide in the Atmosphere*; *Figure 4.3 Global Temperatures*; *Figure 4.25 U.S. Energy Consumption*; the unnumbered figure in Section 6.10 of *U.S. Energy Consumption*; *Figure 6.12 Energy Consumption by Source*; *Table 6.6 Changes in National Average Pollutant Levels, 1980–2013*; *Table 14.4 Change in Pollutant Levels*; *Figure 14.19 Ozone Depletion in the Antarctic Spring*; *Figure 16.15 Sources of U.S. Energy*; *Figure 16.16 Acid Rain*; and *Figure 16.18 U.S. Sulfur Dioxide Pollutant Levels*.
- Example 4.13 *Writing Equations for Acid–Base Reactions Involving a Strong Acid* and Example 14.2 *Determining the Order and Rate Constant of a Reaction* have been expanded.
- New worked examples have been added, including Example 4.14 *Writing Equations for Acid–Base Reactions Involving a Weak Acid*; Example 18.2 *Calculating  $\Delta S$  for a Change of State*; Example 12.2 *Calculating the Packing Efficiency of a Unit Cell*; and Example 12.3 *Relating Unit Cell Volume, Edge Length, and Atomic Radius*.
- Several chapter-opening sections and (or) the corresponding art, including Sections 1.1, 2.1, 5.1, 16.1, and 17.1, have been replaced or modified.
- New information about *Thermoluminescent Dosimeters*, including new Figure 20.7, has been added.
- A definition and explanation for the heat (or enthalpy) of sublimation have been added to Section 11.6.
- A new section (Section 18.4) on the *Entropy Changes Associated with State Changes* has been added. This section also includes expanded coverage on reversible and irreversible processes.
- Several sections in Chapter 20: *Radioactivity and Nuclear Chemistry* have been modified, including Sections 20.3 and 20.5 and Tables 20.1 and 20.4.
- Approximately 40 end-of-chapter problems (in addition to over 40 new problems that have been added to new Chapter 12) have been added or modified.

## Acknowledgments

The book you hold in your hands bears my name on the cover, but I am really only one member of a large team that carefully crafted this book. Most importantly, I thank my editor, Terry Haugen. Terry is a great editor and friend. He gives me the right balance of freedom and direction and always supports me in my endeavors. Thanks, Terry, for all you have done for me and for general chemistry courses throughout the world. I am also grateful to Jennifer Hart, who has now worked with me on multiple editions of several books and in several different roles, including her role overseeing development. Jennifer, your guidance, organizational skills, and wisdom are central to the success of my projects, and I am eternally grateful. I also thank my development editor Erin

Mulligan, who has worked with me on many projects over several editions. Erin is an outstanding thinker and wordsmith who also has a great eye for detail and helps me tremendously on all aspects of my projects. Thank you, Erin. Thanks also to my media editor, Jackie Jakob. Jackie has been instrumental in helping me craft and develop the Key Concept Videos and Interactive Worked Examples that accompany this text. Her expertise, vision, and attention to detail are second to none. The quality and success of these videos are largely attributable to Jackie. Thanks, Jackie.

New to this edition is Sarah Shefeland. Although we have only worked together a short while, I am already indebted to her helpfulness. I am also grateful to Lindsey Pruett, who helped with organizing reviews, as well as numerous other tasks associated with keeping the team running smoothly. I am also grateful to Jeanne Zalesky, Editor-in-Chief for Physical Sciences. She has supported me and my projects and allowed me to succeed. I am also grateful to my team of marketing managers, Chris Barker and Elizabeth Ellsworth. Chris and I go way back, and I am excited to work with him in this new role. Elizabeth and I have only worked together for a short while, but I am already impressed by her energy and ideas for marketing this book. I continue to owe a special word of thanks to Glenn and Meg Turner of Burrston House, ideal collaborators whose contributions to the first edition of the book were extremely important and much appreciated. Quade and Emiko Paul, who make my ideas come alive with their art, have been with us from the beginning, and I owe a special debt of gratitude to them. I am also grateful to Derek Bacchus and Elise Landson for their creativity and hard work in crafting the design of this text. Finally, I would like to thank Beth Sweeten and the rest of the Pearson production team. They are a first-class operation—this text has benefited immeasurably from their talents and hard work. I also thank Francesca Monaco and her coworkers at CodeMantra. I am a picky author and Francesca is endlessly patient and a true professional. I am also greatly indebted to my copy editor, Betty Pessagno, for her dedication and professionalism, and to Eric Schrader for his exemplary photo research. And of course, I am continually grateful for Paul Corey, with whom I have now worked for over 15 years and 12 projects. Paul is a man of incredible energy and vision, and it is my great privilege to work with him. Paul told me many years ago (when he first signed me on to the Pearson team) to dream big, and then he provided the resources I needed to make those dreams come true. *Thanks, Paul.* I would also like to thank my first editor at Pearson, Kent Porter-Hamann. Kent and I spent many good years together writing books, and I continue to miss her presence in my work.

I acknowledge the help of my colleagues Allan Nishimura, Kristi Lazar, David Marten, Stephen Contakes, Michael Everest, and Carrie Hill who have supported me in my department while I worked on this book. I am also grateful to Gayle Beebe and Mark Sargent, the president and provost (respectively) of Westmont College, who have allowed me the time and space to work on my books. Thank you, Gayle and Mark, for allowing me to pursue my gifts and my vision. I am also grateful to those who have supported me personally. First on that list is my wife,

Ann. Her patience and love for me are beyond description, and without her, this book would never have been written. I am also indebted to my children, Michael, Ali, Kyle, and Kaden, whose smiling faces and love of life always inspire me. I come from a large Cuban family whose closeness and support most people would envy. Thanks to my parents, Nivaldo and Sara; my siblings, Sarita, Mary, and Jorge; my siblings-in-law, Jeff, Nachy, Karen, and John; and my nephews and nieces, Germain, Danny, Lisette, Sara, and Kenny. These are the people with whom I celebrate life.

I am especially grateful to Michael Tro, who put in many hours proofreading my manuscript, working problems and quiz questions, and organizing art codes and appendices. Michael, you are an amazing kid—it is my privilege to have you work with me on this project.

I would like to thank all of the general chemistry students who have been in my classes throughout my 25 years as a professor at Westmont College. You have taught me much about teaching that is now in this book.

Lastly, I am indebted to the many reviewers, listed on the following pages, whose ideas are embedded throughout this book. They have corrected me, inspired me, and sharpened my thinking on how best to teach this subject we call chemistry. I deeply appreciate their commitment to this project. I am particularly grateful to Thomas Greenbowe, Michael Everest, Kristin Ziebart, Michael Burand, Jeff Bryan, and Ali Sezer who played particularly important roles in many of the new features of this edition. I am also grateful to the accuracy reviewers (Michael Burand, Brian Gute, Tracy Knowles, Tom McGrath, Gary Mines, and Allison Sault) who tirelessly checked page proofs for correctness.

## Reviewers of the Fourth Edition

Donald Bellew, *The University of New Mexico*  
 Gary Buckley, *Cameron University*  
 Ferman Chavez, *Oakland University*  
 Ted Clark, *The Ohio State University*  
 Guy Crundwell, *Central Connecticut State University*  
 Bonnie Dixon, *University of Maryland*  
 Jack Eichler, *University of California, Riverside*  
 Elda Hegmann, *Kent State University*  
 Clifford LeMaster, *Boise State University*  
 Sarah Lievens, *University of California, Davis*  
 Lauren McMills, *Ohio University*  
 Behnoush Memari, *Broward College*  
 Nancy Mullins, *Florida State College at Jacksonville*  
 George Papadantonakis, *The University of Illinois at Chicago*  
 David Perdian, *Broward College*  
 Jerry Poteat, *Georgia Perimeter College*  
 Raymond Sadeghi, *The University of Texas at San Antonio*  
 Mark Schraf, *West Virginia University*  
 John Selegue, *University of Kentucky*  
 Susan Shadle, *Boise State University*  
 Clarissa Sorensen, *Central New Mexico Community College*  
 Frank Tsung, *Boston College*

## Reviewers of Previous Editions

Patricia G. Amateis, *Virginia Tech*  
 Margaret R. Asirvatham, *University of Colorado*  
 Paul Badger, *Robert Morris University*  
 Monica H. Baloga, *Florida Institute of Technology*  
 Rebecca Barlag, *Ohio University*  
 Mufeed M. Basti, *North Carolina Agricultural & Technological State University*

- Amy E. Beilstein, *Centre College*  
 Maria Benavides, *University of Houston, Downtown*  
 Kyle A. Beran, *University of Texas of the Permian Basin*  
 Thomas Bertolini, *University of Southern California*  
 Christine V. Bilicki, *Pasadena City College*  
 Silas C. Blackstock, *The University of Alabama*  
 Robert E. Blake, *Texas Tech University*  
 Angela E. Boerger, *Loyola University Chicago*  
 Robert S. Boikess, *Rutgers University*  
 Paul Brandt, *North Central College*  
 Michelle M. Brooks, *College of Charleston*  
 Joseph H. Bularzik, *Purdue University, Calumet*  
 Cindy M. Burkhardt, *Radford University*  
 Andrew E. Burns, *Kent State University at Stark*  
 Kim C. Calvo, *The University of Akron*  
 Stephen C. Carlson, *Lansing Community College*  
 David A. Carter, *Angelo State University*  
 Eric G. Chesloff, *Villanova University*  
 William M. Cleaver, *The University of Vermont*  
 Charles T. Cox, Jr., *Georgia Institute of Technology*  
 J. Ricky Cox, *Murray State University*  
 Samuel R. Cron, *Arkansas State University*  
 Darwin B. Dahl, *Western Kentucky University*  
 Robert F. Dias, *Old Dominion University*  
 Daniel S. Domin, *Tennessee State University*  
 Alan D. Earhart, *Southeast Community College*  
 Amina K. El-Ashmawy, *Collin College*  
 Joseph P. Ellison, *United States Military Academy at West Point*  
 Joseph M. Eridon, *Central New Mexico Community College*  
 Deborah B. Exton, *The University of Oregon*  
 William A. Faber, *Grand Rapids Community College*  
 Michael Ferguson, *Honolulu Community College*  
 Maria C. Fermin-Ennis, *Gordon College*  
 Oscar Navarro Fernandez, *University of Hawaii at Manoa*  
 Jan Florian, *Loyola University Chicago*  
 Andy Frazer, *University of Central Florida*  
 Candice E. Fulton, *Midwestern State University*  
 Ron Garber, *California State University at Long Beach*  
 Carlos D. Garcia, *The University of Texas at San Antonio*  
 Eric S. Goll, *Brookdale Community College*  
 Robert A. Gossage, *Acadia University*  
 Pierre Y. Goueth, *Santa Monica College*  
 Thomas J. Greenbowe, *Iowa State University*  
 Victoria Guarisco, *Middle Georgia State University*  
 Christin Gustafson, *Illinois Central College*  
 Jason A. Halfen, *University of Wisconsin-Eau Claire*  
 Nathan Hammer, *University of Mississippi*  
 Michael D. Hampton, *University of Central Florida*  
 Tamara Hanna, *Texas Tech University*  
 Lois Hansen-Polcar, *Cuyahoga Community College-Western Campus*  
 Tony Hascall, *Northern Arizona University*  
 Monte L. Helm, *Fort Lewis College*  
 David E. Henderson, *Trinity College*  
 Susan K. Henderson, *Quinnipiac University*  
 Peter M. Hierl, *The University of Kansas*  
 Paula Hjorth-Gustin, *San Diego Mesa College*  
 Angela Hoffman, *University of Portland*  
 Todd A. Hopkins, *Butler University*  
 Byron E. Howell, *Tyler Junior College*  
 Ralph Isovitsch, *Xavier University of Louisiana*  
 Kenneth C. Janda, *University of California, Irvine*  
 Milt Johnston, *University of South Florida*  
 Jason A. Kautz, *University of Nebraska-Lincoln*  
 Catherine A. Keenan, *Chaffey College*  
 Steven W. Keller, *University of Missouri*  
 Resa Kelly, *San Jose State University*  
 Chulsung Kim, *Georgia Gwinnett College*  
 Louis J. Kirschenbaum, *University of Rhode Island*  
 Mark Knecht, *University of Kentucky*  
 Bette Kreuz, *University of Michigan-Dearborn*  
 Sergiy Kryatov, *Tufts University*  
 Richard H. Langley, *Stephen F. Austin State University*  
 Clifford B. Lemaster, *Boise State University*  
 Robley Light, *Florida State University*  
 Adam List, *Vanderbilt University*  
 Christopher Lovallo, *Mount Royal University*  
 Eric Malina, *University of Nebraska-Lincoln*  
 Benjamin R. Martin, *Texas State University*  
 Lydia J. Martinez-Rivera, *University of Texas at San Antonio*  
 Marcus T. McEllistrem, *University of Wisconsin-Eau Claire*  
 Danny G. McGuire, *Cameron University*  
 Charles W. McLaughlin, *University of Nebraska, Lincoln*  
 Curt L. McLendon, *Saddleback College*  
 Robert C. McWilliams, *United States Military Academy*  
 David H. Metcalf, *University of Virginia*  
 Ray Mohseni, *East Tennessee State University*  
 Elisabeth A. Morlino, *University of the Science, Philadelphia*  
 James E. Murphy, *Santa Monica College*  
 Maria C. Nagan, *Truman State University*  
 Edward J. Neth, *University of Connecticut*  
 Aric Opdahl, *University of Wisconsin La Crosse*  
 Kenneth S. Overway, *Bates College*  
 Greg Owens, *University of Utah*  
 Naresh Pandya, *University of Hawaii*  
 Gerard Parkin, *Columbia University*  
 Jessica Parr, *University of Southern California*  
 Yasmin Patell, *Kansas State University*  
 Tom Pentecost, *Grand Valley State University*  
 Glenn A. Petrie, *Central Missouri State*  
 Norbert J. Pienta, *University of Iowa*  
 Louis H. Pignolet, *University of Minnesota*  
 Valerie Reeves, *University of New Brunswick*  
 Dawn J. Richardson, *Colin College*  
 Thomas G. Richmond, *University of Utah*  
 Dana L. Richter-Egger, *University of Nebraska*  
 Jason Ritchie, *University of Mississippi*  
 Christopher P. Roy, *Duke University*  
 A. Timothy Royappa, *University of West Florida*  
 Stephen P. Ruis, *American River College*  
 Alan E. Sadurski, *Ohio Northern University*  
 Thomas W. Schleich, *University of California, Santa Cruz*  
 Rod Schoonover, *CA Polytechnic State University*  
 Tom Selegue, *Pima Community College, West*  
 Anju H. Sharma, *Stevens Institute of Technology*  
 Sherril A. Soman, *Grand Valley State University*  
 Michael S. Sommer, *University of Wyoming*  
 Jie S. Song, *University of Michigan, Flint*  
 Mary Kay Sorenson, *University of Wisconsin, Milwaukee*  
 Stacy E. Sparks, *University of Texas, Austin*  
 Richard Spinney, *Ohio State University*  
 William H. Steel, *York College of Pennsylvania*  
 Vinodhkumar Subramaniam, *East Carolina University*  
 Jerry Suits, *University of Northern Colorado*  
 Tamar Y. Susskind, *Oakland Community College*  
 Uma Swamy, *Florida International University*  
 Ryan Sweeder, *Michigan State University*  
 Dennis Taylor, *Clemson University*  
 Jacquelyn Thomas, *Southwestern College*  
 Kathleen Thrush Shaginaw, *Villanova University*  
 Lydia Tien, *Monroe Community College*  
 David Livingstone Toppen, *California State University Northridge*  
 Marcy Towns, *Purdue University*  
 Harold Trimm, *Broome Community College*  
 Laura VanDorn, *University of Arizona*  
 Susan Varkey, *Mount Royal College*  
 Ramaiyer Venkatraman, *Jackson State University*  
 John B. Vincent, *University of Alabama, Tuscaloosa*  
 Kent S. Voelkner, *Lake Superior College*  
 Sheryl K. Wallace, *South Plains College*  
 Wayne E. Wesolowski, *University of Arizona*  
 Sarah E. West, *Notre Dame University*  
 John Wiginton, *University of Mississippi*  
 Kurt J. Winkelmann, *Florida Institute of Technology*  
 Troy D. Wood, *University of Buffalo*  
 Servet M. Yatin, *Quincy College*  
 Kazushige Yokoyama, *SUNY Geneseo*  
 Lin Zhu, *IUPUI*

## Chapter 12, Solids and Modern Materials, Advisory Board

Michael Burand, *Oregon State University*  
 Christopher Collison, *Rochester Institute of Technology*  
 Jordan Fantini, *Denison University*  
 Melissa Hines, *Cornell University*  
 Raymond Schaak, *Penn State University*  
 Jennifer Shanoski, *Merritt College*  
 Jim Zubricky, *University of Toledo*

## Focus Group Participants

We would like to thank the following professors for contributing their valuable time to meet with the author and the publishing team in order to provide a meaningful perspective on the most important challenges they face in teaching general chemistry and give us insight into creating a general chemistry text that successfully responds to those challenges.

### Focus Group 12

Corey Beck, *Ohio University*  
 Jennifer Duis, *Northern Arizona University*  
 Alton Hassell, *Baylor University*  
 Tina Huang, *University of Illinois*  
 Amy Irwin, *Monroe Community College*  
 Maria Korolev, *University of Florida*  
 Jennifer Schwartz Poehlmann, *Stanford University*  
 John Selegue, *University of Kentucky*  
 Sarah Siegel, *Gonzaga University*  
 Jeff Statler, *University of Utah*

### Focus Groups 1–11

Michael R. Abraham, *University of Oklahoma*  
 Ramesh D. Arasasingham, *University of California, Irvine*  
 James A. Armstrong, *City College of San Francisco*  
 Silas C. Blackstock, *University of Alabama*  
 Roberto A. Bogomolni, *University of California, Santa Cruz*  
 Stacey Brydges, *University of California San Diego*  
 Kenneth Capps, *Central Florida Community College*  
 Stephen C. Carlson, *Lansing Community College*  
 Charles E. Carraher, *Florida Atlantic University*  
 Kenneth Caswell, *University of South Florida*  
 Robert Craig Taylor, *Oakland University*  
 Darwin B. Dahl, *Western Kentucky University*  
 Mohammed Daoudi, *University of Central Florida*  
 Kate Deline, *College of San Mateo*  
 Stephanie Dillon, *Florida State University*  
 Ralph C. Dougherty, *Florida State University*  
 William Eck, *University of Wisconsin, Marshfield/Wood County*  
 Robert J. Eierman, *University of Wisconsin, Eau Claire*  
 Amina K. El-Ashmawy, *Collin County Community College*  
 William A. Faber, *Grand Rapids Community College*  
 Richard W. Frazee, *Rowan University*  
 Barbara A. Gage, *Prince George's Community College*  
 Simon Garrett, *California State University, Northridge*  
 Raymond F. Glienna, *Glendale Community College*  
 Eric S. Goll, *Brookdale Community College*

Pierre Y. Goueth, *Santa Monica College*  
 W. Tandy Grubbs, *Stetson University*  
 Jerome E. Haky, *Florida Atlantic University*  
 Jason A. Halfen, *University of Wisconsin, Eau Claire*  
 John A. W. Harkless, *Howard University*  
 Paul I. Higgs, *Barry University*  
 Norris W. Hoffman, *University of South Alabama*  
 Tony Holland, *Wallace Community College*  
 Todd A. Hopkins, *Butler University*  
 Moheb Ishak, *St. Petersburg College, St. Petersburg*  
 Kamal Ismail, *CUNY, Bronx Community College*  
 Greg M. Jorgensen, *American River College*  
 Sharon K. Kapica, *County College of Morris*  
 Jason Kautz, *University of Nebraska, Lincoln*  
 Mark Kearley, *Florida State University*  
 Catherine A. Keenan, *Chaffey College*  
 Steven W. Keller, *University of Missouri, Columbia*  
 Ellen Kime-Hunt, *Riverside Community College, Riverside Campus*  
 Peter J. Krieger, *Palm Beach Community College, Lake Worth*  
 Roy A. Lacey, *State University of New York, Stony Brook*  
 David P. Licata, *Coastline Community College*  
 Michael E. Lipschutz, *Purdue University*  
 Patrick M. Lloyd, *CUNY, Kingsborough Community College*  
 Boon H. Loo, *Towson University*  
 James L. Mack, *Fort Valley State University*  
 Jeanette C. Madea, *Broward Community College, North*  
 Joseph L. March, *University of Alabama, Birmingham*  
 Jack F. McKenna, *St. Cloud State University*  
 Curtis L. McLendon, *Saddleback College*  
 Dianne Meador, *American River College*  
 David Metcalf, *University of Virginia*  
 John A. Milligan, *Los Angeles Valley College*  
 Alice J. Monroe, *St. Petersburg College, Clearwater*  
 Elisabeth A. Morlino, *University of the Science, Philadelphia*  
 Heino Nitsche, *University of California at Berkeley*  
 Pedro Patino, *University of Central Florida*  
 Jeremy Perotti, *Nova Southeastern University*  
 Norbert J. Pienta, *University of Iowa*  
 Jayashree Ranga, *Salem State University*  
 Cathrine E. Reck, *Indiana University*  
 Thomas Ridgway, *University of Cincinnati*  
 Jil Robinson, *Indiana University*  
 Richard Rosso, *St. John's University*  
 Steven Rowley, *Middlesex County College*  
 Benjamin E. Rusiloski, *Delaware Valley College*  
 Karen Sanchez, *Florida Community College, Jacksonville*  
 David M. Sarno, *CUNY, Queensborough Community College*  
 Reva A. Savkar, *Northern Virginia Community College*  
 Thomas W. Schleich, *University of California, Santa Cruz*  
 Donald L. Siegel, *Rutgers University, New Brunswick*  
 Mary L. Sohn, *Florida Institute of Technology*  
 Sherril Soman-Williams, *Grand Valley State University*  
 Allison Soult, *University of Kentucky*  
 Louise S. Sowers, *Richard Stockton College of New Jersey*  
 Anne Spuches, *East Carolina University*  
 William H. Steel, *York College of Pennsylvania*  
 Uma Swamy, *Florida International University*  
 Richard E. Sykora, *University of South Alabama*  
 Galina G. Talanova, *Howard University*  
 Claire A. Tessier, *University of Akron*  
 Kathleen Thrush Shaginaw, *Villanova University*  
 John Vincent, *University of Alabama*  
 Gary L. Wood, *Valdosta State University*  
 Servet M. Yatin, *Quincy College*  
 James Zubricky, *University of Toledo*

# 21st Century Skills

Tro's approach to General Chemistry addresses 21st century skills, including the ability to analyze and interpret data and the capacity to work well in groups. Concepts are covered in a thorough and approachable manner, which ensures that every explanation is relevant and helps students see the real-world importance and applications of Chemistry. Students can learn concepts and build skills through numerous resources for use before, during, and after class.

## Data Interpretation and Analysis

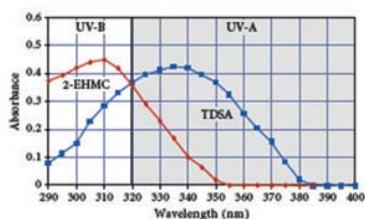
### UV Radiation and Sunscreen

114. On average sunlight shines on the surface of Earth with an intensity of  $910 \text{ Watts/m}^2$ . Some of this energy is in the form of ultraviolet (UV) radiation. The compounds in chemical sunscreens absorb ultraviolet rays and release the energy as lower-energy infrared (IR) rays, thereby preventing the skin-damaging UV rays from reaching the skin. You may have noticed

Sunscreen Compound	Chemical Formula	$M$ (g/mol)
terephthalylidenedicamphor sulfonic acid (TDSA)	$\text{C}_{28}\text{H}_{34}\text{O}_6\text{S}_2$	562.70
2-ethylhexyl <i>p</i> -methoxycinnamate (2-EHMC)	$\text{C}_{24}\text{H}_{38}\text{O}_2$	290.59

▲ FIGURE a Chemical Formula and Molar Mass ( $M$ ) of Chemicals Commonly Found in Sunscreens

Organic molecules have groups of atoms bonded together that can vibrate and rotate, making more energy states available. As a result, instead of absorbing exact wavelengths of radiation as elements do, organic molecules absorb over a broad range of wavelengths. Figure b plots absorbance versus wavelength for 2-EHMC and TDSA. Greater absorbance indicates that the compound absorbs more light.



▲ FIGURE b Sunscreen Absorption  
<http://nycps.com/critical-wavelength-broad-spectrum-uv-protection/>

references to UV-A (320–400 nm) and UV-B (280–320 nm) protection in sunscreen packaging and advertisements. Figure a lists the chemical formula and molar mass of two compounds, 2-ethylhexyl *p*-methoxycinnamate (2-EHMC), a UV-B sunscreen, and terephthalylidenedicamphor sulfonic acid (TDSA), a UV-A sunscreen.

Use the information provided in the figures to answer the following questions:

- Calculate the energy absorbed by TDSA at its maximum absorption for one photon of UV radiation.
- Calculate the energy absorbed by 2-EHMC at its maximum absorption for one photon of UV radiation.
- Which absorbs more energy, 2-EHMC or TDSA, at their respective maximum wavelengths?
- Why are these two compounds commonly included in sunscreen products?
- A person does not apply sunscreen and has  $0.42 \text{ m}^2$  of skin exposed to the sun for 1.00 hour. Calculate the total energy (in joules) absorbed by the skin. Assume there are  $3.066 \times 10^{21}$  photons/meter<sup>2</sup>/sec. Assume an average wavelength of 330 nm in order to calculate the energy of a UV photon. Assume half of the photons that strike the skin are reflected.
- In order for a sunscreen product with equal amounts of TDSA and 2-EHMC to provide adequate protection from UV-A and UV-B rays for 1.00 hour, how many molecules of TDSA and 2-EHMC must be present on the skin? Assume one molecule of TDSA and one molecule 2-EHMC can each absorb 10,000 photons per hour. Assume the photon rate is the same as in part e.
- Calculate the mass of TDSA and 2-EHMC in grams that must be present on the exposed skin referenced in parts e and f in order to protect the skin.

◀ **NEW!** Data Interpretation and Analysis questions present real data in real life situations and ask students to analyze that data. These in-depth exercises give students practice reading graphs, digesting tables, and making data-driven decisions.

## Data Interpretation and Analysis

### Heavy Metals in Recycled Paper Packages

142. Demand for recycled paper has increased as consumers have become more aware of the environmental issues surrounding waste disposal. Paper is a natural raw material made from renewable wood and plants. Recycled paper is made from waste paper and paperboard. Both new paper and recycled paper contain traces of heavy metals. However, some types of recycled paper contain more heavy metals than new paper due, in part, to the inks used for printing or adding color to the original paper. Metals can migrate from the paper packaging and containers used for food to the food itself. This metal migration is controlled and monitored to reduce the exposure of humans to heavy metals.

Food agencies in each country determine the limit of cadmium, zinc, nickel, and copper in packaging materials. Most countries impose a limit of heavy metals in recycled paper not to exceed 100.0 ppm or 100.0 mg/kg. The limit for lead in eggs, fruit, or vegetable packaging is lower—not to exceed—20.0 mg/kg. The table in Figure a lists the results of the analysis of samples of recycled paper produced by a manufacturer during a three-month period.

	Zn	Pb	Cd	Ni	Cu
March	2.7	3.5	0.129	1.7	22.3
April	3.2	2.8	0.092	1.6	29.2
May	3.7	2.4	0.096	1.5	19.8

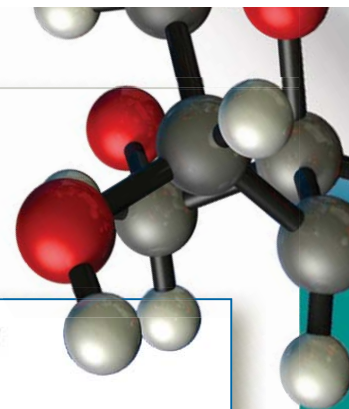
▲ FIGURE a Heavy Metal Values in Three Samples of Recycled Paper (mg/kg  $\pm$  0.1)

The goal of the manufacturer is to reduce the amount of heavy metals—especially lead—in the recycled paper it produces and sells. From March to May, the manufacturer varied the methods of production each month to determine which method would produce paper with the lowest metal content. Each month, lab technicians cut small samples of recycled paper with an area of  $1.000 \text{ dm}^2$  and a thickness of  $0.0500 \text{ cm}$ . The technicians then prepared the samples for analysis. The average density of the samples is  $800.0 \pm 0.0245 \text{ kg/m}^3$ .

Use the information provided in the figure to answer the following questions:

- Did the company reduce the amount of lead in its product between March and May?
- Which metal was not reduced?
- Each month's sample represents a different manufacturing process. Which process would you recommend the manufacturer choose to continue to use over the next year while additional processes are tested? Why?
- What is the total amount of the five metals for the April sample (in mg/kg)?
- What is the total mass (in mg) of the five metals for the April sample found in the  $1.000 \text{ dm}^2 \times 0.0500 \text{ cm}$  sample?
- Lead has four stable isotopes:  $^{204}\text{Pb}$ ,  $^{206}\text{Pb}$ ,  $^{207}\text{Pb}$ ,  $^{208}\text{Pb}$  with % abundances of 1.40, 24.10, 22.10, and 52.40, respectively. Determine the mass (in mg) of  $^{206}\text{Pb}$  in the April sample.
- Sketch the mass spectrum for lead.

# 21st Century Skills



## Active Classroom Learning

### Questions for Group Work

Discuss these questions with the group and record your consensus answer.

148. Assign one of the three simple gas laws to each member of your group. For the assigned gas law, have each member write two equations, draw a graph, and describe it in a complete sentence. Have each group member present his or her law to the group.
  149. Review the ideal gas law. Without referring back to the text, use algebra to write the ideal gas law and solve for each of the individual variables it contains. Have each group member solve for a different variable and present answers to the group.
  150. Hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) decomposes in the presence of a catalyst to form water and oxygen. The catalyst is added to 5.00 mL of a hydrogen peroxide solution at 25.0 °C, and 49.5 mL of gas is collected over water at a total pressure of 763.8 mmHg.
    - a. Write and balance the chemical reaction (note: catalysts do not appear in balanced chemical equations).
    - b. Look up the vapor pressure of water under these conditions.
    - c. What is the partial pressure of oxygen collected over the water?
    - d. How many moles of oxygen are collected?
  - e. How many grams of hydrogen peroxide were in the original sample?
  - f. What is the concentration (in mol/L) of the hydrogen peroxide solution?
  - g. Which part of this process is conceptually most difficult for your group?
151. A box contains equal amounts of helium, argon, and krypton (all gases) at 25 °C. Using complete sentences, describe the temperatures, masses, average velocities, and average kinetic energy of the three kinds of gas in the mixture. What do they have in common? What are the differences? How are these properties related?
  152. Calculate the pressure exerted by 1 mol of an ideal gas in a box that is 0.500 L and 298 K. Have each group member calculate the pressure of 1 mol of the following gases in the same box at the same temperature: He, Ne,  $\text{H}_2$ ,  $\text{CH}_4$ , and  $\text{CO}_2$ . Compare group members' answers as well as all answers with the pressure of an ideal gas. Assuming that the van der Waals equation predictions are accurate, account for why the pressure of each gas is higher or lower than that predicted for an ideal gas.

## Active Classroom Learning

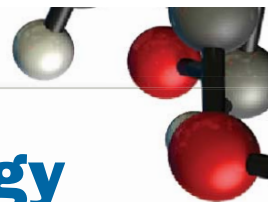
### Questions for Group Work

Discuss these questions with the group and record your consensus answer.

130. Have each member of your group represent an atom of a metal or an atom of a nonmetal. Each group member holds a coin to represent an electron. Which group members are most reluctant to give up their electrons? Which group members are most willing to give up their electrons? Determine which kind of bond could form between each pair of group members. Tabulate your results.
131. Spend a few minutes reviewing the Lewis dot symbols for the atoms H through Ne. Form a circle and have each group member ask the group member on his or her right to draw the Lewis symbol for a specific atom. Keep going around until each group member can write all the Lewis dot symbols for the atoms H through Ne. Determine the formal charge for each symbol. In a complete sentence or two, describe why they are all the same.
132. Draw the Lewis dot symbols for the atoms Al and O. Use the Lewis model to determine the formula for the compound formed from these two atoms.
133. Draft a list of step-by-step instructions for writing the correct Lewis dot structure for any molecule or polyatomic ion.
134. Pass a piece of paper around the group and ask each group member in turn to perform the next step in the process of determining a correct Lewis structure (including formal charges on all atoms and resonance structures, if appropriate) for the following molecules and ions:  $\text{N}_2\text{H}_4$ ,  $\text{CCl}_4$ ,  $\text{CO}_3^{2-}$ , and  $\text{NH}_4^+$ .



**NEW!** Questions for Group Work give students the opportunity to work with their peers in small groups. The questions can be used in or out of the classroom, and the goal is to foster collaborative learning and encourage students to work together as a team to solve problems.



# Interactive Problem-Solving Strategy

A unique and consistent step-by-step format encourages logical thinking throughout the problem-solving process, driving students to think through problems critically, rather than to simply memorize formulas.

**Example 17.6** Strong Acid–Strong Base Titration pH Curve

A 50.0-mL sample of 0.200 M sodium hydroxide is titrated with 0.200 M nitric acid. Calculate pH:

(a) after adding 30.00 mL of  $\text{HNO}_3$       (b) at the equivalence point

**SOLUTION**

(a) Begin by calculating the initial amount of NaOH (in moles) from the volume and molarity of the NaOH solution. Because NaOH is a strong base, it dissociates completely, so the amount of  $\text{OH}^-$  is equal to the amount of NaOH.

$$\text{moles NaOH} = 0.0500 \text{ L} \times \frac{0.200 \text{ mol}}{1 \text{ L}} = 0.0100 \text{ mol}$$

$$\text{moles OH}^- = 0.0100 \text{ mol}$$

Calculate the amount of  $\text{HNO}_3$  (in moles) added at 30.0 mL from the molarity of the  $\text{HNO}_3$  solution.

As  $\text{HNO}_3$  is added to the solution, it neutralizes some of the  $\text{OH}^-$ . Calculate the number of moles of  $\text{OH}^-$  remaining by setting up a table based on the neutralization reaction that shows the amount of  $\text{OH}^-$  before the addition, the amount of  $\text{H}_3\text{O}^+$  added, and the amounts left after the addition.

	$\text{OH}^-(\text{aq})$	+	$\text{H}_3\text{O}^+(\text{aq})$	$\longrightarrow$	$2 \text{H}_2\text{O}(\text{l})$
Before addition	0.0100 mol		$\approx 0.00$ mol		
Addition	—		0.00600 mol		
After addition	0.0040 mol		0.00 mol		

Calculate the  $\text{OH}^-$  concentration by dividing the amount of  $\text{OH}^-$  remaining by the total volume (initial volume plus added volume).

$$[\text{OH}^-] = \frac{0.0040 \text{ mol}}{0.0500 \text{ L} + 0.0300 \text{ L}} = 0.0500 \text{ M}$$

Calculate the pOH from  $[\text{OH}^-]$ .

$$\text{pOH} = -\log(0.0500) = 1.30$$

Calculate the pH from the pOH using the equation  $\text{pH} + \text{pOH} = 14$ .

$$\text{pH} = 14 - \text{pOH} = 14 - 1.30 = 12.70$$

(b) At the equivalence point, the strong base has completely neutralized the strong acid. The  $[\text{H}_3\text{O}^+]$  at 25°C from the ionization of water is  $1.00 \times 10^{-7} \text{ M}$  and the pH is therefore 7.00.

**FOR PRACTICE 17.6** Calculate the pH in the titration in Example 17.6 after the addition of 60.0 mL of 0.200 M  $\text{HNO}_3$ .

Icons appear next to examples indicating an **Interactive Worked Example** digital version is available in the eText and on mobile devices via a QR code located here, and on the back cover of your textbook.



## NEW! 61 Interactive Worked Examples

make Tro's unique problem-solving strategies interactive, bringing his award-winning teaching directly to all students using his text. In these digital, mobile versions, students are shown how to break down problems using Tro's proven "Sort, Strategize, Solve, and Check" technique, helping to learn how to consistently solve chemical problems. These examples can be utilized as an after class activity.

Strong Acid–Strong Base Titration pH Curve

A 50.0-mL sample of 0.200 M sodium hydroxide is titrated with 0.200 M nitric acid. Calculate: (a) the pH after adding 30.00 mL of  $\text{HNO}_3$

	$\text{OH}^-(\text{aq})$	+	$\text{H}_3\text{O}^+(\text{aq})$	$\longrightarrow$	$2 \text{H}_2\text{O}(\text{l})$
Before addition	0.0100 mol		$\approx 0.00$ mol		
Addition	—		0.00600 mol		
After addition	0.0040 mol		$\approx 0.00$ mol		

What is the pH of the solution at this point?

a) 0.0500  
b) 1.30  
c) 12.70

$$\text{moles NaOH} = 0.0500 \text{ L} \times \frac{0.200 \text{ mol}}{1 \text{ L}} = 0.0100 \text{ mol}$$

$$\text{moles OH}^- = 0.0100 \text{ mol}$$

$$\text{moles HNO}_3 \text{ added} = 0.0300 \text{ L} \times \frac{0.200 \text{ mol}}{1 \text{ L}} = 0.00600 \text{ mol HNO}_3$$

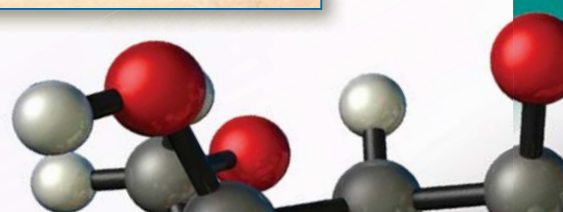
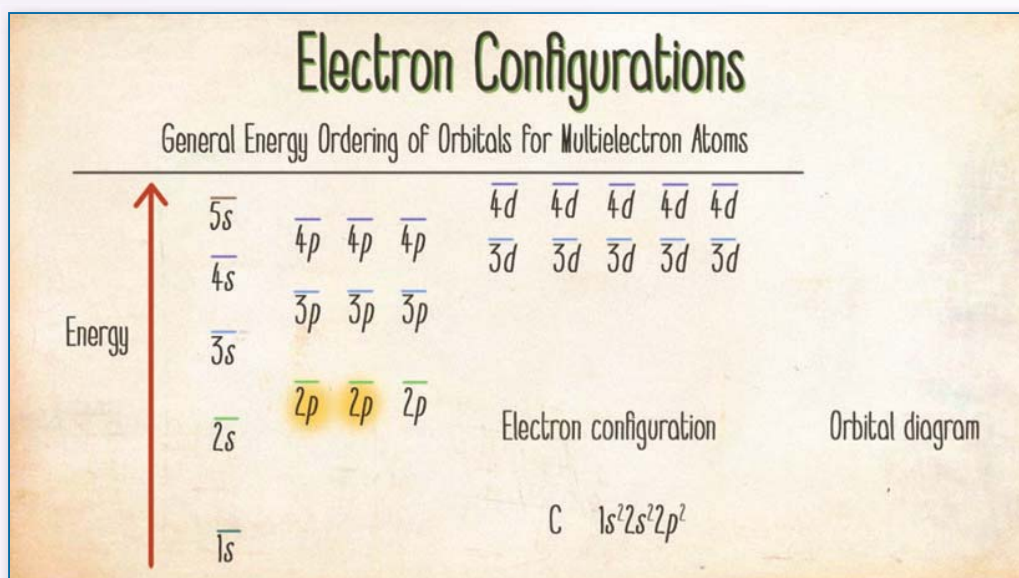
$$[\text{OH}^-] = \frac{0.0040 \text{ mol}}{0.0500 \text{ L} + 0.0300 \text{ L}} = 0.0500 \text{ M}$$

# A Focus on Conceptual Understanding



**NEW! 57 Key Concept Videos** combine artwork from the textbook with both 2D and 3D animations to create a dynamic on-screen viewing and learning experience. These short videos include narration and brief live-action clips of author Niva Tro explaining the key concepts of each chapter. These videos can be utilized as a before class activity.

**KCV** Electron Configurations





**NEW!**

## Chapter 12—Solids and Modern Materials

This chapter contains new topics and consolidates content on materials that was found in other parts of the book in previous editions into one new chapter. New and consolidated topics include unit cells, carbon and silicates, ceramics, cement, glass, polymorphs, polyethylene, and the band gap in Group 4A elements.

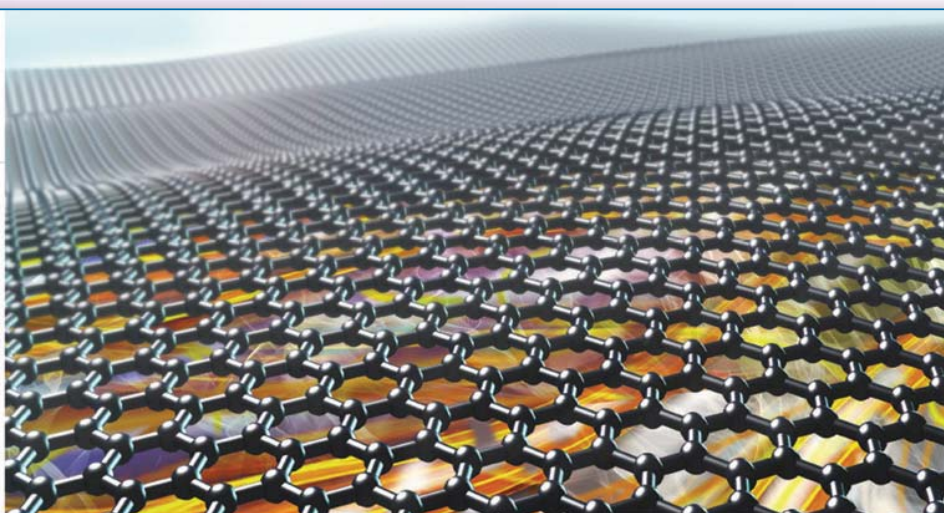
CHAPTER

# 12

## Solids and Modern Materials

Should we not suppose that in the formation of a crystal, the particles are not only established in rows and columns set in regular figures, but also by means of some polar property have turned identical sides in identical directions?

—ISAAC NEWTON (1642–1727)

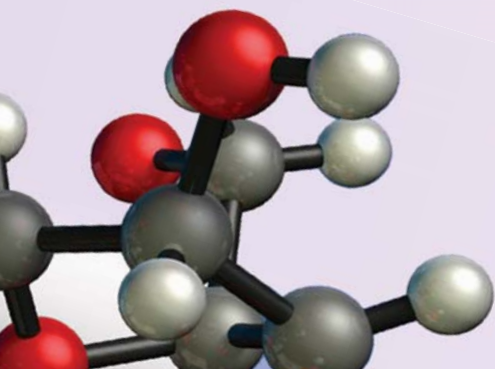


- |  |   |
|--|---|
| 12.1 Friday Night Experiments: The Discovery of Graphene 000 | 12.6 Network Covalent Atomic Solids: Carbon and Silicates 000 |
| 12.2 X-Ray Crystallography 000                               | 12.7 Ceramics, Cement, and Glass 000                          |
| 12.3 Unit Cells and Basic Structures 000                     | 12.8 Semiconductors and Band Theory 000                       |
| 12.4 The Fundamental Types of Crystalline Solids 000         | 12.9 Polymers and Plastics 000                                |
| 12.5 The Structures of Ionic Solids 000                      | KEY LEARNING OUTCOMES 000                                     |

In this chapter, we focus on the solid state of matter. We first examine the structures of solids, keeping in mind that these structures determine the properties of solids. For example, the repeating hexagonal pattern of water molecules in crystalline ice determines the hexagonal shape of a snowflake, and the repeating cubic pattern of sodium and chloride ions in sodium chloride determines the cubic shape of salt grains. We then turn our attention to the study and development of solids with unique and useful properties, a field known as *materials science*. The ceramics that compose your coffee cups, the semiconductors in your electronic devices, and the plastics that are most likely all around you even at this moment are materials developed to have specific properties that serve specific purposes. In this chapter, we take a brief look at each of these kinds of materials.

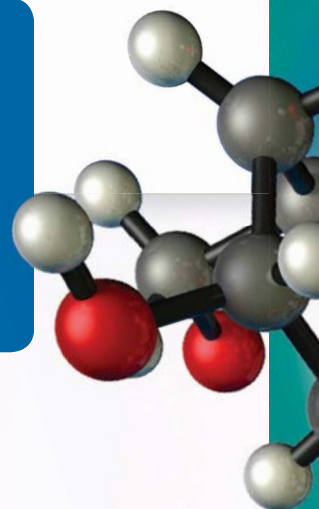
### 12.1 Friday Night Experiments: The Discovery of graphene

In 2010, Andre Geim (1958–) and Konstantin Novoselov (1974–) were awarded the Nobel Prize in Physics for the discovery of a new material—graphene. Graphene is the thinnest known material (only one atom thick); it is also the strongest. It conducts heat and electricity, it is transparent, and it is completely impermeable to all substances, including helium. Although its many possible applications are yet to be realized, graphene may one day be used to make faster computers, foldable touchscreens, ultrathin light panels,

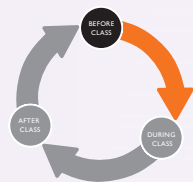


# Active and Adaptive

MasteringChemistry is the leading online homework, tutorial, and assessment system, designed to improve results by engaging students before, during, and after class with powerful content. Instructors can ensure students arrive ready to learn by assigning educationally effective content before class, and encourage critical thinking and retention with in-class resources. Students can further master concepts after class through traditional and adaptive homework assignments that provide hints and answer-specific feedback.



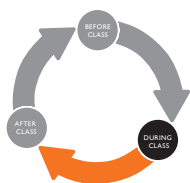
**NEW! Ready-to-Go Teaching Modules** in the Instructor Resources section help instructors efficiently make use of the available teaching tools for each chapter. Pre-built before class assignments, in-class activities, and after-class assignments are provided for ease of use. Instructors can incorporate active learning into their course with the suggested activity ideas, Learning Catalytics questions, and clicker questions.



## BEFORE CLASS

**Dynamic Study Modules** help students study effectively on their own by continuously assessing their activity and performance in real time. In this edition, 66 topics include key math skills, general chemistry skills such as nuclear chemistry, phases of matter, redox reactions, acids and bases, and organic and biochemistry skills.

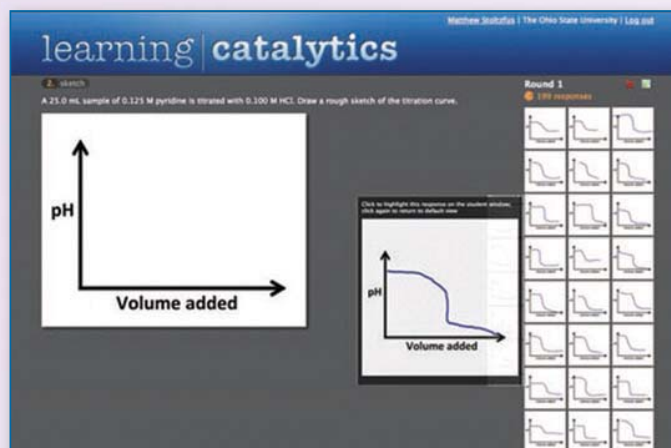
**NEW! The Chemistry Primer** is a series of tutorials focused on remedying students in preparation for their first college chemistry course. The primer is offered as a pre-built assignment automatically generated as a default assignment with every newly created General Chemistry Course.



## DURING CLASS

**Learning Catalytics™** generates class discussion, guides lecture, and promotes peer-to-peer learning with real-time analytics. MasteringChemistry with eText now provides Learning Catalytics—an interactive student response tool that uses students' smartphones, tablets, or laptops to engage them in more sophisticated tasks and thinking. Instructors can:

- Pose a variety of open-ended questions that help students develop critical thinking skills
- Monitor responses to find out where students are struggling
- Use real-time data to adjust instructional strategy and try other ways of engaging students during class
- Manage student interactions by automatically grouping students for discussion, teamwork, and peer-to-peer learning



### Questions for Group Work

Tools for active learning have been enhanced throughout the book, allowing students to dive into material in an engaging and effective way.

### Questions for Group Work

Discuss these questions with the group and record your consensus answer.

**140.** Have each group member write a problem involving the transfer of heat from one material in Table 6.4 to another material in the table. Working as a group, solve each problem. The group member who wrote each problem may act as the group facilitator when the group is working on his or her problem. What do all of your problems have in common? How do they differ?

**141.** Classify each process as endothermic or exothermic. What is the sign of  $\Delta H$  for each process? Explain your answers.

- gasoline burning in an engine
- steam condensing on a mirror
- water boiling in a pot

Provide at least two additional examples of exothermic processes and two additional examples of endothermic processes. Have each member of your group provide an example.

**142.** A propane tank on a home barbecue contains  $10.4 \times 10^3$  g of propane.

- Write the balanced chemical reaction for the combustion of gaseous propane ( $C_3H_8$ ) to form water vapor and gaseous carbon dioxide.
- Use the value for  $\Delta H_{\text{rxn}}$  provided in the text to calculate the total amount of heat produced when the entire contents of the tank of propane is burned.

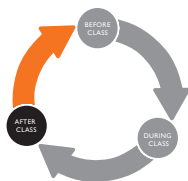
### Active Classroom Learning

**c.** What mass of water could be warmed from  $25^\circ\text{C}$  to  $100^\circ\text{C}$  with this much heat?

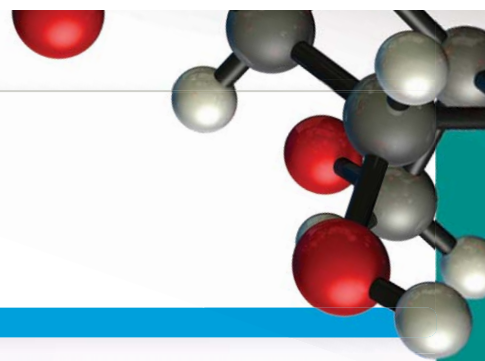
Solid carbon,  $C(s, \text{graphite})$ , gaseous hydrogen,  $H_2(g)$ , and the sugar glucose,  $C_6H_{12}O_6(s)$  are all burned with oxygen in a calorimeter, and the amount of heat given off is determined for each process. How can these data be used to determine the heat of formation of glucose? Your answer should include both chemical reactions and complete sentences.

**143.** Consider the decomposition of liquid hydrogen peroxide ( $H_2O_2$ ) to form water and oxygen.

- What is the heat of formation for hydrogen peroxide?
- What is the heat of formation for liquid water?
- What is the heat of formation for gaseous oxygen? Why?
- Write the balanced chemical equations that correspond to the  $\Delta H$  values you looked up for parts a, b, and c.
- Write the balanced chemical equation for the decomposition of hydrogen peroxide to form water and oxygen. (Write the equation such that the coefficient on oxygen is 1.)
- What is the heat of reaction for the process in part e?
- Draw a scale diagram of this reaction ( $1 \text{ cm} = 100 \text{ kJ}$ ) that shows the relative energies of reactants (on the left), products (on the right), and the elements in their most stable states (in the middle). Label all the energies you know.



# AFTER CLASS



4. Chemical Quantities and Aqueous re... Exercise 4.34 with feedback

Item Type: End-of-Chapter | Difficulty: 1 | Time: 14m | Learning Outcomes | Contact the Publisher | Manage this Item: Standard View Randomized

**Exercise 4.34 with feedback**

For each of the reactions, calculate the mass (in grams) of the product formed when 15.83 g of the underlined reactant completely reacts. Assume that there is more than enough of the other reactant.

You may want to reference [Pages 140–140](#) Section 4.2 while completing this problem.

**Part A**

$$2 \text{K(s)} + \text{Cl}_2(\text{g}) \rightarrow 2 \text{KCl(s)}$$

Express your answer using four significant figures.

m =

**Incorrect; Try Again**

Check the coefficients of the balanced reaction. There are 2 moles of KCl formed for every mole of Cl<sub>2</sub> that reacts.

**Part B**

$$2 \text{K(s)} + \text{Br}_2(\text{l}) \rightarrow 2 \text{KBr(s)}$$

Express your answer using four significant figures.

m =

◀ **NEW!** In this edition, 200 more end of chapter problems now contain wrong answer specific feedback with links to the eText.

► **Self-Assessment Quizzes** now contain wrong-answer feedback links to the eText, and an additional 10–15 multiple-choice questions authored in the ACS-exams and MCAT style in each chapter. These improvements help students optimize the use of quizzing to improve their understanding and class performance.

**Self-Assessment Quiz**

Q1. Which wavelength of light has the highest frequency?  
a) 10 nm b) 10 mm c) 1 nm d) 1 mm

Q2. Which kind of electromagnetic radiation consists of the greatest energy per photon?  
a) microwaves b) gamma rays  
c) X-rays d) visible light

Q3. How much energy (in J) is contained in 1.00 mole of 552-nm photons?  
a)  $3.60 \times 10^{19}$  J b)  $2.17 \times 10^2$  J  
c)  $3.60 \times 10^{18}$  J d)  $5.98 \times 10^{-43}$  J

Q4. Light from three different lasers (A, B, and C), each with a different wavelength, was shined onto the same metal surface. Laser A produced no photoelectrons. Lasers B and C both produced photoelectrons, but the photoelectrons produced by laser B had a greater velocity than those produced by laser C. Arrange the lasers in order of increasing wavelength.  
a) A < B < C b) B < C < A  
c) C < B < A d) A < C < B




Q5. Calculate the wavelength of an electron traveling at  $1.85 \times 10^7$  m/s.  
a)  $2.54 \times 10^{17}$  m  
b)  $3.93 \times 10^{-14}$  m  
c)  $2.54 \times 10^{19}$  m  
d)  $3.93 \times 10^{-13}$  m

Q6. Which set of three quantum numbers does not specify an orbital in the hydrogen atom?  
a)  $n = 2, l = 1, m_l = -1$  b)  $n = 2, l = 3, m_l = -2$   
c)  $n = 2, l = 0, m_l = 0$  d)  $n = 3, l = 2, m_l = 2$

Q7. Calculate the wavelength of light emitted when an electron in the hydrogen atom makes a transition from an orbital with  $n = 5$  to an orbital with  $n = 3$ .  
a)  $1.28 \times 10^{-7}$  m b)  $6.04 \times 10^{-7}$  m  
c)  $2.28 \times 10^{-6}$  m d)  $1.55 \times 10^{-13}$  m

Q8. Which electron transition produces light of the highest frequency in the hydrogen atom?  
a)  $5p \rightarrow 1s$  b)  $4p \rightarrow 1s$   
c)  $3p \rightarrow 1s$  d)  $2p \rightarrow 1s$

Q9. How much time (in seconds) does it take light in a vacuum to travel 1.00 billion km?  
a)  $3.00 \times 10^9$  s b) 3.33 s  
c)  $3.33 \times 10^3$  s d)  $3.00 \times 10^{20}$  s

Q10. Which orbital is a d orbital?  
a)   
b)   
c)   
d) None of the above

**Interactive Simulation—Density**  
Determination of a Metal

The density of a substance is an intrinsic property and a characteristic of the amount of substance present. It is often used to identify a substance. Click here to view the simulation, which automatically identifies calculations for metals using water displacement to calculate volume and a scale to calculate mass. You may need to click and hold some of the buttons to complete the specified step.

Calculation of density of a metal using water displacement

Water displacement can be used to find the volume of a solid by placing the solid in a known volume of water. When the object is added to water, the water level rises. The volume of the water that is displaced by the object is equal to the volume of the object. Using a scale to measure the mass of the object, you can now calculate the density of the object to be mass divided by its volume.

For example, if you add 13.7 g of silver to 25.0 mL of water, the final volume observed in the measuring cylinder is 27.3 mL. The change in volume is 23.3 mL - 20.0 mL = 3.3 mL. The density of silver is then:

$$\text{Density} = \frac{13.7 \text{ g}}{3.3 \text{ mL}} = 4.15 \text{ g/mL}$$

13.7 g / 3.3 mL = 4.15 g/mL

13.7 g / 3.3 mL = 4.15 g/mL

13.7 g / 3.3 mL = 4.15 g/mL

**Part A**

Follow the steps provided in the simulation to add water to the graduated cylinder and determine the density of the metal.

- Add water by clicking and holding **Prepare a known volume of water**.
- Click and hold the **Prepare a known volume of water** button. Note the initial volume. Select a metal. Prepare a known quantity of metal by clicking and holding the **Weigh out metal** button. Release the button to stop the addition of metal to the balance pan. Note the mass of the metal sample.
- Transfer the metal sample to the graduated cylinder. Note the change in total volume. Note the change in total volume.

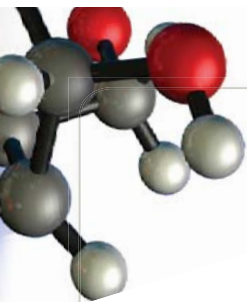
Use the following activity to collect the data needed to determine the density of different metals.

- Click and hold the **Prepare a known volume of water** button. Note the initial volume.
- Select a metal.
- Prepare a known quantity of metal by clicking and holding the **Weigh out metal** button. Release the button to stop the addition of metal to the balance pan. Note the mass of the metal sample.
- Transfer the metal sample to the graduated cylinder.
- Note the change in total volume.
- Select **Calculate density** to use the data to determine the density of the metal.
- Repeat with metals samples of different masses and compositions or with different initial volumes of water.

Buttons: Prepare a known volume of water, Calculate density, Copper, Weigh out metal, Transfer metal to graduated cylinder, Reset.

Initial volume: 21.6 mL

◀ **Multimedia-rich Tutorials** feature specific wrong-answer feedback, hints, and a wide variety of educationally effective content to guide your students through the toughest topics in chemistry. The hallmark Hints and Feedback offer instruction similar to what students would experience in an office hours visit, allowing them to learn from their mistakes without being given the answer.



# MasteringChemistry™ for Instructors

www.masteringchemistry.com

The Mastering platform was developed by scientists for science students and instructors. Mastering has been refined from data-driven insights derived from over a decade of real-world use by faculty and students.

NAME	Introductory	Ch. 2	Ch. 3	Lab 2	Ch. 4	Ch. 5	Ch. 6	Ch. 7a	Chapter 7b	Lab 4	Ch. 8	Ch. 9	Ch. 12	TOTAL
Class Average	76.4	66.0	62.6	88.1	89.5	86.7	91.6	83.7	90.0	88.4	77.7			24.5
Last01, First...	84.4	73.3	83.3	102	99.9	0.0	95.9	101	100	0.0	87.4			46.9
Last02, First...	70.3	64.9	92.9	98.0	49.5	86.2	72.9	47.5	80.0	86.9	66.3			26.2
Last03, First...	73.6	48.0	61.9	104	102	94.9	85.0	100	95.0	99.7	67.3			27.8
Last04, First...	72.5	53.8	0.0	34.3	86.3	65.3	80.0	83.4	90.0	99.2	67.0			30.3
Last05, First...	78.9	69.3	78.8	99.0	97.8	85.2	82.5	34.8	85.0	88.3	87.7			31.9
Last07, First...	77.9	66.7	51.8	101	96.1	95.9	90.0	76.7	95.0	84.8	70.6			23.2
Last08, First...	84.4	70.7	92.9	85.3	99.0	100	95.0	100	100	102	89.8			36.7
Last09, First...	66.2	70.0	76.8	104	100	90.8	78.3	78.8	95.0	94.3	82.2			31.9
Last10, First...	76.1	70.0	78.6	105	94.6	94.9	92.1	91.9	100	88.9	87.8			19.8

◀ **Gradebook**  
Every assignment is automatically graded. Shades of red highlight struggling students and challenging assignments.

## Gradebook Diagnostics

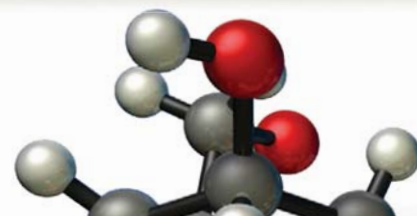
This screen provides you with your favorite diagnostics. With a single click, charts summarize the most difficult problems, vulnerable students, grade distribution, and even score improvement over the course.



**Adaptive Follow-Ups** are personalized assignments pairing MasteringChemistry's powerful content with Knewton's adaptive learning engine to provide personalized help to students before misconceptions take hold. These assignments address topics students struggle with on assigned homework, including core prerequisite topics.

# Instructor and Student Resources

Resource	Available in Print	Available Online	Instructor or Student Resource	Description
<b>Selected Solutions Manual</b> 0134066286 / 9780134066288	✓		Student	Prepared by Kathy Shaginaw, the selected solutions manual for students contains complete, step-by-step solutions to selected odd-numbered, end-of-chapter problems.
<b>Laboratory Manual</b> 013406626X / 9780134066264	✓		Student	Prepared by John B. Vincent and Erica Livingston, this manual contains experiments with a focus on real-world applications. Each experiment covers one or more topics discussed within a chapter of the textbook.
<b>Study Guide</b> 0134066278 / 9780134066271	✓		Student	This Study Guide, prepared by Jennifer Shanoski, presents the major concepts, theories, and applications discussed in the text in a comprehensive and accessible manner.
<b>Instructor's Resource Materials</b> 0134074998 / 9780134074993		✓	Instructor	This resource contains the following: <ul style="list-style-type: none"> <li>• All illustrations, tables, and photos from the text in JPEG format.</li> <li>• Three pre-built PowerPoint Presentations (lecture, worked examples, and images)</li> </ul>
<b>Instructor's Resource Manual</b> 0134125770 / 9780134125770		✓	Instructor	Organized by chapter, this useful guide includes objectives, lecture outlines, references to figures and solved problems, as well as teaching tips. Prepared by Michael Ferguson.
<b>Test Bank</b> 0134126327 / 9780134126326		✓	Instructor	The Test Bank, prepared by Christine Hermann, contains more than 3,000 multiple choice, matching, and short-answer questions.
<b>Solutions Manual</b> 0134066251 / 9780134066257	✓		Instructor	Prepared by Kathy Shaginaw, this manual contains step-by-step solutions to all end-of-chapter exercises. With instructor permission, this manual may be made available to students.
<b>Instructor's Manual for Laboratory Manual</b> 0134143485 / 9780134143484		✓	Instructor	This manual provides solutions to the questions asked before each experiment in the accompanying Laboratory Manual, and provides background and suggestions for the instructor directing the lab.



C H A P T E R

# 1

## Matter, Measurement, and Problem Solving

The most incomprehensible thing about  
the universe is that it is comprehensible.

—ALBERT EINSTEIN (1879–1955)



**1.1** Atoms and Molecules 1

**1.2** The Scientific Approach to  
Knowledge 3

**1.3** The Classification of Matter 5

**1.4** Physical and Chemical Changes  
and Physical and Chemical  
Properties 9

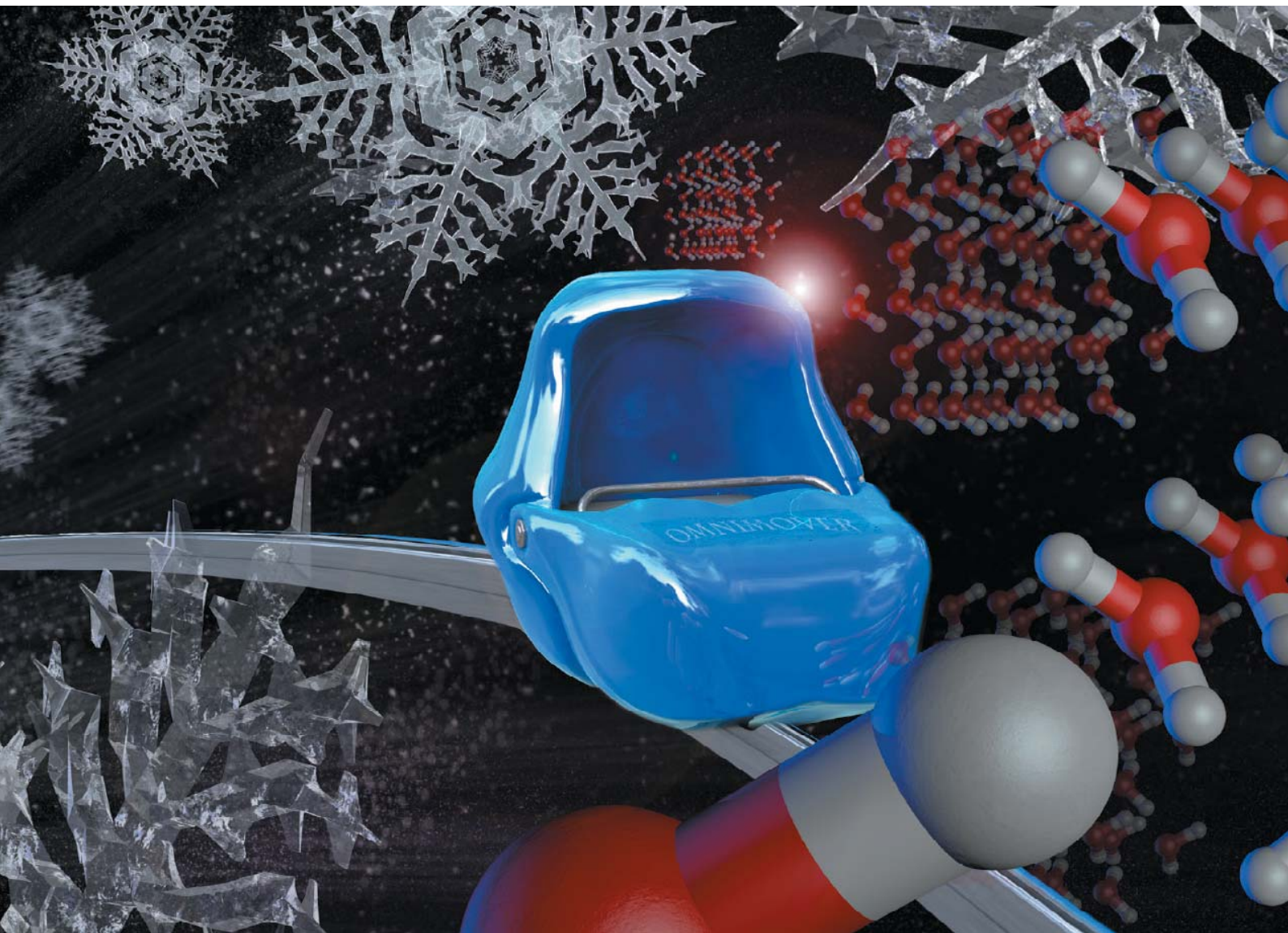
**1.5** Energy: A Fundamental Part of  
Physical and Chemical Change 12

**1.6** The Units of Measurement 13

**1.7** The Reliability of a  
Measurement 20

**1.8** Solving Chemical Problems 26

**KEY LEARNING OUTCOMES 36**



**W**hat do you think is the most important idea in all of human knowledge? There are, of course, many possible answers to this question—some practical, some philosophical, and some scientific. If we limit ourselves only to scientific answers, mine would be this: **the properties of matter are determined by the properties of atoms and molecules.** Atoms and molecules determine how matter behaves—if they were different, matter would be different. The properties of water molecules determine how water behaves, the properties of sugar molecules determine how sugar behaves, and the properties of the molecules that compose our bodies determine how our bodies behave. The understanding of matter at the molecular level gives us unprecedented control over that matter. For example, our understanding of the details of the molecules that compose living organisms has revolutionized biology over the last 50 years.

## 1.1 Atoms and Molecules

As I sat in the “omnimover” and listened to the narrator’s voice telling me that I was shrinking down to the size of an atom, I grew apprehensive but curious. Just minutes before, while waiting in line, I witnessed what appeared to be full-sized humans entering a microscope and emerging from the other end many times smaller. I was seven years old, and I was about to ride *Adventure Thru Inner Space*, a Disneyland ride

▲ This image portrays the Disneyland ride, *Adventure Thru Inner Space*. The premise of the ride is that you enter a microscope and get shrunk down to the size of an atom. The red and white spheres shown here depict oxygen and hydrogen atoms bound together to form water molecules.

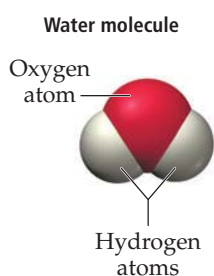


Atoms and Molecules

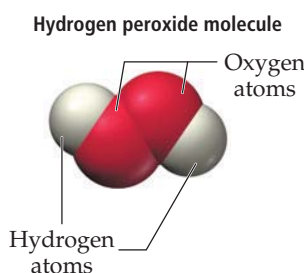


(in Tomorrowland) that simulated the process of shrinking down to the size of an atom. The ride began with darkness and shaking, but then the shaking stopped and giant snowflakes appeared. The narrator explained that you were in the process of shrinking to an ever-smaller size (which explains why the snowflakes grew larger and larger). Soon, you entered the wall of the snowflake itself and began to see water molecules all around you. These also grew larger as you continued your journey into inner space and eventually ended up within the atom itself. Although this Disneyland ride bordered on being corny, and although it has since been shut down, it was my favorite ride as a young child.

That ride sparked my interest in the world of atoms and molecules, an interest that has continued and grown to this day. I am a chemist because I am obsessed with the connection between the “stuff” around us and the atoms and molecules that compose that stuff. More specifically, I love the idea that we humans have been able to figure out the connection between the *properties of the stuff* around us and the *properties of atoms and molecules*. **Atoms** are sub-microscopic particles that are the fundamental building blocks of ordinary matter. Free atoms are rare in nature; instead they bind together in specific geometrical arrangements to form **molecules**. A good example of a molecule is the water molecule, which I remember so well from the Disneyland ride.



A water molecule is composed of one oxygen atom bound to two hydrogen atoms in the shape shown at left. The exact properties of the water molecule—the atoms that compose it, the distances between those atoms, and the geometry of how the atoms are bound together—determine the properties of water. If the molecule were different, water would be different. For example, if water contained two oxygen atoms instead of just one, it would be a molecule like this:



This molecule is hydrogen peroxide, which you may have encountered if you have ever bleached your hair. A hydrogen peroxide molecule is composed of *two* oxygen atoms and two hydrogen atoms. This seemingly small molecular difference results in a huge difference in the properties of water and hydrogen peroxide. Water is the familiar and stable liquid we all drink and bathe in. Hydrogen peroxide, in contrast, is an unstable liquid that, in its pure form, burns the skin on contact and is used in rocket fuel. When you pour water onto your hair, your hair simply becomes wet. However, if you put diluted hydrogen peroxide on your hair, a chemical reaction occurs that strips your hair of its color.

The details of how specific atoms bond to form a molecule—in a straight line, at a particular angle, in a ring, or in some other pattern—as well as the type of atoms in the molecule, determine everything about the substance that the molecule composes. If we want to understand the substances around us, we must understand the atoms and molecules that compose them—this is the central goal of chemistry. A good simple definition of **chemistry** is

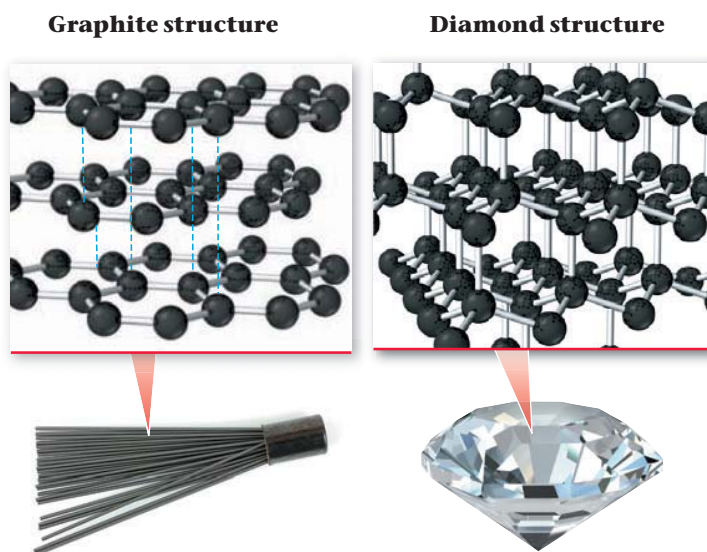
**Chemistry—the science that seeks to understand the behavior of matter by studying the behavior of atoms and molecules.**

Throughout this book, we explore the connection between atoms and molecules and the matter they compose. We seek to understand how differences on the atomic or molecular level affect the properties on the macroscopic level. Before we move on, let’s examine one more example that demonstrates this principle. Consider the structures of graphite and diamond shown on the next page.

The hydrogen peroxide we use as an antiseptic or bleaching agent is considerably diluted.

The term *atoms* in this definition can be interpreted loosely to include atoms that have lost or gained electrons.

Graphite is the slippery black substance (often called pencil lead) that you have probably used in a mechanical pencil. Diamond is the brilliant gemstone found in jewelry. Graphite and diamond are both composed of exactly the same atoms—carbon atoms. The striking differences between the substances are a result of how those atoms are arranged. In graphite, the atoms are arranged in sheets. The atoms within each sheet are tightly bound to each other, but the sheets are *not* tightly bound to other sheets. Therefore the sheets can slide past each other, which is why the graphite in a pencil leaves a trail as you write. In diamond, by contrast, the carbon atoms are all bound together in a three-dimensional structure where layers are strongly bound to other layers, resulting in the strong, nearly unbreakable substance. This example illustrates how even the same atoms can compose vastly different substances when they are bound together in different patterns. Such is the atomic and molecular world—small differences in atoms and molecules can result in large differences in the substances that they compose.



## 1.2 The Scientific Approach to Knowledge

Throughout history, humans have approached knowledge about the physical world in different ways. For example, the Greek philosopher Plato (427–347 B.C.E.) thought that the best way to learn about reality was not through the senses but through reason. He believed that the physical world was an imperfect representation of a perfect and transcendent world (a world beyond space and time). For him, true knowledge came not through observing the real physical world, but through reasoning and thinking about the ideal one.

The *scientific* approach to knowledge, however, is exactly the opposite of Plato's. Scientific knowledge is empirical—it is based on *observation* and *experiment*. Scientists observe and perform experiments on the physical world to learn about it. Some observations and experiments are qualitative (noting or describing how a process happens), but many are quantitative (measuring or quantifying something about the process). For example, Antoine Lavoisier (1743–1794), a French chemist who studied combustion (burning), made careful measurements of the mass of objects before and after burning them in closed containers. He noticed that there was no change in the total mass of material within the container during combustion. In doing so, Lavoisier made an important *observation* about the physical world.

Observations often lead scientists to formulate a **hypothesis**, a tentative interpretation or explanation of the observations. For example, Lavoisier explained his observations on combustion by hypothesizing that when a substance burns, it combines with a component of air. A good hypothesis is *falsifiable*, which means that it makes predictions that can be confirmed or refuted by further observations. Scientists test hypotheses by **experiments**, highly controlled procedures designed to generate observations that confirm or refute a hypothesis. The results of an experiment may support a hypothesis or prove it wrong—in which case the scientist must modify or discard the hypothesis.

In some cases, a series of similar observations leads to the development of a **scientific law**, a brief statement that summarizes past observations and predicts future ones. Lavoisier summarized his observations on combustion with the **law of conservation of mass**, which states, “In a chemical reaction, matter is neither created nor destroyed.” This statement summarized his observations on chemical reactions and predicted the

Although some Greek philosophers, such as Aristotle, did use observation to attain knowledge, they did not emphasize experiment and measurement to the extent that modern science does.



▲ French chemist Antoine Lavoisier with his wife, Marie, who helped him in his work by illustrating his experiments and translating scientific articles from English. Lavoisier, who also made significant contributions to agriculture, industry, education, and government administration, was executed during the French Revolution. (The Metropolitan Museum of Art)

outcome of future observations on reactions. Laws, like hypotheses, are also subject to experiments, which can support them or prove them wrong.

Scientific laws are not *laws* in the same sense as civil or governmental laws. Nature does not follow laws in the way that we obey the laws against speeding or running a stop sign. Rather, scientific laws *describe* how nature behaves—they are generalizations about what nature does. For that reason, some people find it more appropriate to refer to them as *principles* rather than *laws*.

One or more well-established hypotheses may form the basis for a scientific **theory**. A scientific theory is a model for the way nature is and tries to explain not merely what nature does but why. As such, well-established theories are the pinnacle of scientific knowledge, often predicting behavior far beyond the observations or laws from which they were developed. A good example of a theory is the **atomic theory** proposed by English chemist John Dalton (1766–1844). Dalton explained the law of conservation of mass, as well as other laws and observations of the time, by proposing that matter is composed of small, indestructible particles called atoms. Since these particles are merely rearranged in chemical changes (and not created or destroyed), the total amount of mass remains the same. Dalton’s theory is a model for the physical world—it gives us insight into how nature works and, therefore, *explains* our laws and observations.

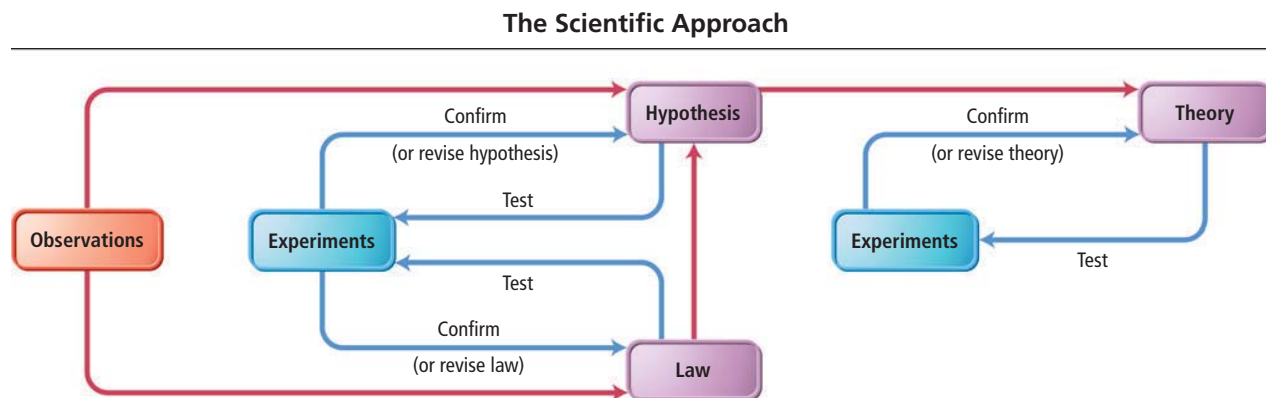
Finally, the scientific approach returns to observation to test theories. For example, scientists can test the atomic theory by trying to isolate single atoms or by trying to image them (both of which, by the way, have already been accomplished). Theories are validated by experiments; however, theories can never be conclusively proven because some new observation or experiment always has the potential to reveal a flaw. Notice that the scientific approach to knowledge begins with observation and ends with observation. An experiment is in essence a highly controlled procedure for generating critical observations designed to test a theory or hypothesis. Each new set of observations has the potential to refine the original model. Figure 1.1 summarizes one way to map the scientific approach to knowledge. Scientific laws, hypotheses, and theories are all subject to continued experimentation. If a law, hypothesis, or theory is proved wrong by an experiment, it must be revised and tested with new experiments. Over time, the scientific community eliminates or corrects poor theories and laws, and valid theories and laws—those consistent with experimental results—remain.

Established theories with strong experimental support are the most powerful pieces of scientific knowledge. You may have heard the phrase “That is just a theory,” as if theories are easily dismissible. Such a statement reveals a deep misunderstanding of the nature of a scientific theory. Well-established theories are as close to truth as we get in science. The idea that all matter is made of atoms is “just a theory,” but it has over 200 years of experimental evidence to support it. It is a powerful piece of scientific knowledge on which many other scientific ideas are based.

One last word about the scientific approach to knowledge: some people wrongly imagine science to be a strict set of rules and procedures that automatically leads to inarguable, objective facts. This is not the case. Even our diagram of the scientific approach to knowledge is only an idealization of real science, useful to help us see the

In Dalton’s time, people thought atoms were indestructible. Today, because of nuclear reactions, we know that atoms can be broken apart into their smaller components.

▼ FIGURE 1.1 The Scientific Approach to Knowledge



key distinctions of science. Real science requires hard work, care, creativity, and even a bit of luck. Scientific theories do not just arise out of data—men and women of genius and creativity craft theories. A great theory is not unlike a master painting, and many see a similar kind of beauty in both. (For more on this aspect of science, see the box below entitled *Thomas S. Kuhn and Scientific Revolutions*.)



## CONCEPTUAL CONNECTION 1.1

**Laws and Theories** Which statement best explains the difference between a law and a theory?

- (a) A law is truth; a theory is mere speculation.
- (b) A law summarizes a series of related observations; a theory gives the underlying reasons for them.
- (c) A theory describes *what* nature does; a law describes *why* nature does it.

## The Nature OF Science

### Thomas S. Kuhn and Scientific Revolutions

**W**hen scientists talk about science, they often talk in ways that imply that theories are “true.” Further, they talk as if they arrive at theories in logical and unbiased ways. For example, a theory central to chemistry that we have discussed in this chapter is John Dalton’s atomic theory—the idea that all matter is composed of atoms. Is this theory “true”? Was it reached in logical, unbiased ways? Will this theory still be around in 200 years?

The answers to these questions depend on how we view science and its development. One way to view science—let’s call it the *traditional view*—is as the continual accumulation of knowledge and the building of increasingly precise theories. In this view, a scientific theory is a model of the world that reflects what is *actually in* nature. New observations and experiments result in gradual adjustments to theories. Over time, theories get better, giving us a more accurate picture of the physical world.

In the twentieth century, a different view of scientific knowledge began to develop. A book by Thomas Kuhn (1922–1996), published in 1962 and entitled *The Structure of Scientific Revolutions*, challenged the traditional view. Kuhn’s ideas came from his study of the history of science, which, he argued, does not support the idea that science progresses in a smooth cumulative way. According to Kuhn, science goes through fairly quiet periods that he called *normal science*. In these periods, scientists make their data fit the reigning theory, or paradigm. Small inconsistencies are swept aside during periods of normal science. However, when too many inconsistencies and anomalies develop, a crisis

emerges. The crisis brings about a *revolution* and a new reigning theory. According to Kuhn, the new theory is usually quite different from the old one; it not only helps us to make sense of new or anomalous information, but it also enables us to see accumulated data from the past in a dramatically new way.

Kuhn further contended that theories are held for reasons that are not always logical or unbiased, and that theories are not *true* models—in the sense of a one-to-one mapping—of the physical world. Because new theories are often so different from the ones they replace, he argued, and because old theories always make good sense to those holding them, they must not be “True” with a capital T; otherwise “truth” would be constantly changing.

Kuhn’s ideas created a controversy among scientists and science historians that continues to this day. Some, especially postmodern philosophers of science, have taken Kuhn’s ideas one step further. They argue that scientific knowledge is *completely* biased and lacks any objectivity. Most scientists, including Kuhn, would disagree. Although Kuhn pointed out that scientific knowledge has *arbitrary elements*, he also said, “*Observation . . . can and must drastically restrict the range of admissible scientific belief, else there would be no science.*” In other words, saying that science contains arbitrary elements is quite different from saying that science itself is arbitrary.

#### QUESTION

*In his book, Kuhn stated, “A new theory . . . is seldom or never just an increment to what is already known.” From your knowledge of the history of science, can you think of any examples that support Kuhn’s statement? Do you know of any instances in which a new theory or model was drastically different from the one it replaced?*

## 1.3 The Classification of Matter



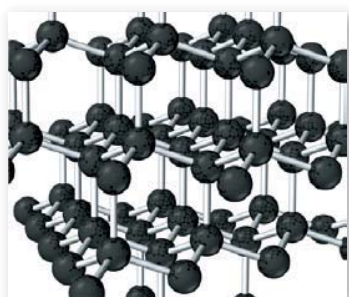
### Classifying Matter

**Matter** is anything that occupies space and has mass. Your desk, your chair, and even your body are all composed of matter. Less obviously, the air around you is also matter—it too occupies space and has mass. We call a specific instance of matter—such as air, water, or sand—a **substance**. We classify matter according to its **state** (its physical form) and its **composition** (the basic components that make it up).

The state of matter changes from solid to liquid to gas with increasing temperature.

Glass and other amorphous solids can be thought of, from one point of view, as intermediate between solids and liquids. Their atoms are fixed in position at room temperature, but they have no long-range structure and do not have distinct melting points.

**Crystalline Solid:**  
Regular  
three-dimensional pattern

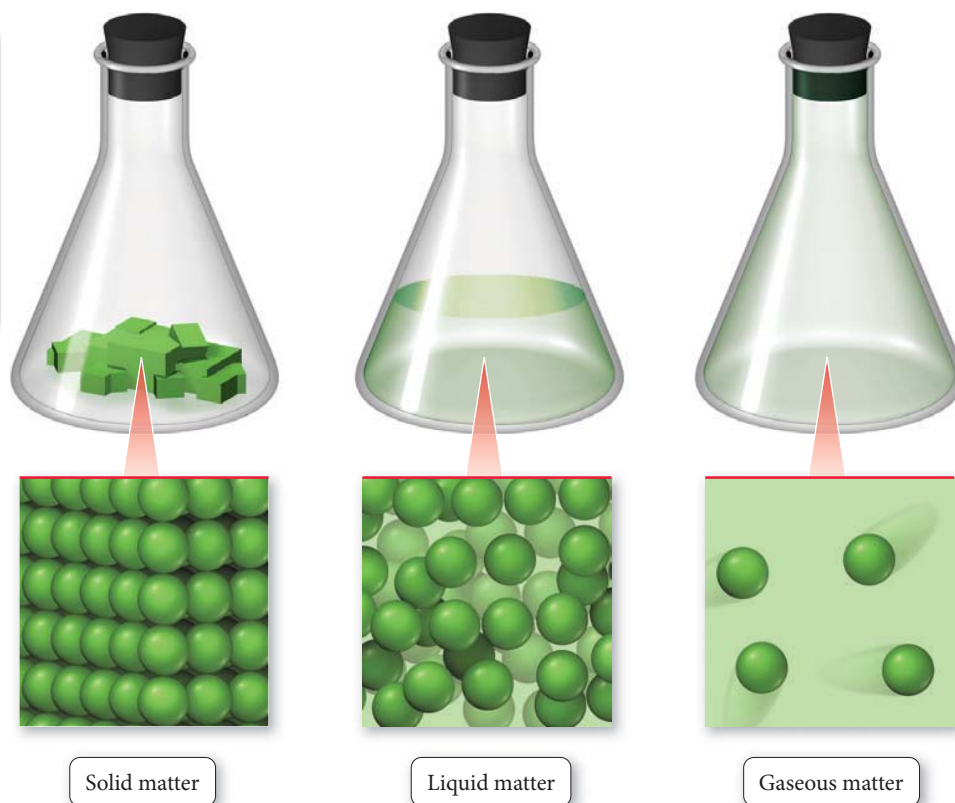


**Diamond**  
C (s, diamond)

▲ **FIGURE 1.2 Crystalline Solid** Diamond (first discussed in Section 1.1) is a crystalline solid composed of carbon atoms arranged in a regular, repeating pattern.

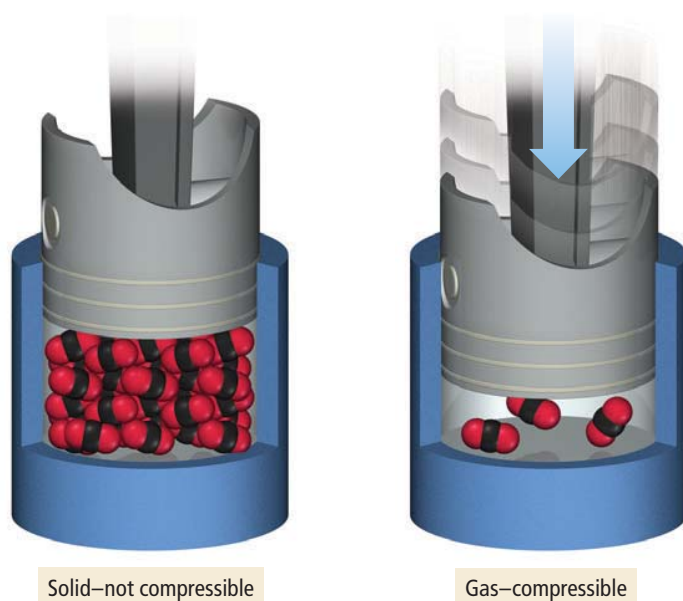
## The States of Matter: Solid, Liquid, and Gas

Matter exists in three different states: **solid**, **liquid**, and **gas**. In *solid matter*, atoms or molecules pack closely to each other in fixed locations. Although the atoms and molecules in a solid vibrate, they do not move around or past each other. Consequently, a solid has a fixed volume and rigid shape. Ice, aluminum, and diamond are examples of solids. Solid matter may be **crystalline**, in which case its atoms or molecules are in patterns with long-range, repeating order (Figure 1.2◀), or it may be **amorphous**, in which case its atoms or molecules do not have any long-range order. Table salt and diamond are examples of *crystalline* solids; the well-ordered geometric shapes of salt and diamond crystals reflect the well-ordered arrangement of their atoms (although this is not the case for *all* crystalline solids). Examples of *amorphous* solids include glass and plastic. In *liquid matter*, atoms or molecules pack about as closely as they do in solid matter, but they are free to move relative to each other, giving liquids a fixed volume but not a fixed shape. Liquids assume the shape of their containers. Water, alcohol, and gasoline are all substances that are liquids at room temperature.



▲ In a solid, the atoms or molecules are fixed in place and can only vibrate. In a liquid, although the atoms or molecules are closely packed, they can move past one another, allowing the liquid to flow and assume the shape of its container. In a gas, the atoms or molecules are widely spaced, making gases compressible as well as fluid (able to flow).

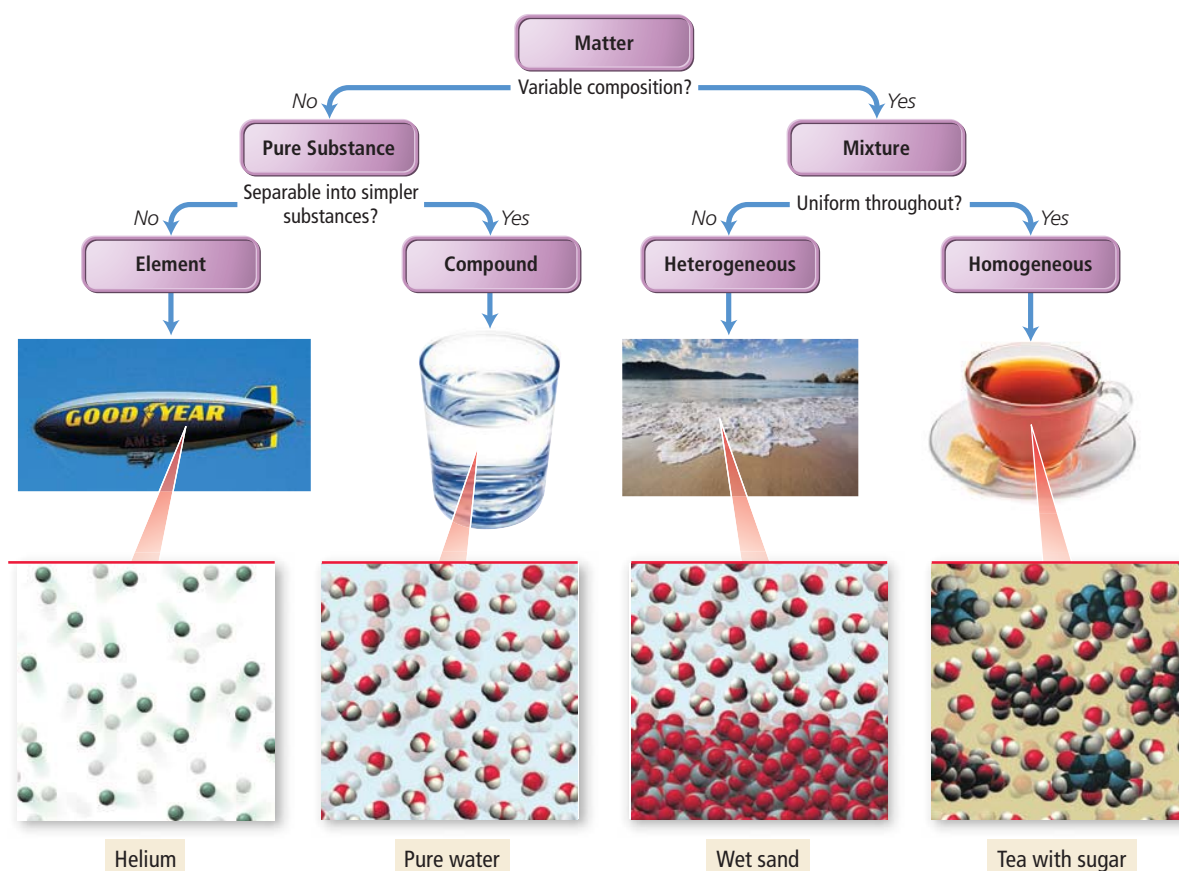
In *gaseous matter*, atoms or molecules have a lot of space between them and are free to move relative to one another, making gases *compressible* (Figure 1.3▶). When you squeeze a balloon or sit down on an air mattress, you force the atoms and molecules into a smaller space so that they are closer together. Gases always assume the shape *and* volume of their containers. Substances that are gases at room temperature include helium, nitrogen (the main component of air), and carbon dioxide.



**FIGURE 1.3 The Compressibility of Gases** Gases can be compressed—squeezed into a smaller volume—because there is so much empty space between atoms or molecules in the gaseous state.

## Classifying Matter according to Its Composition: Elements, Compounds, and Mixtures

In addition to classifying matter according to its state, we classify it according to its composition, as shown in the following chart:



The first division in the classification of matter is between a *pure substance* and a *mixture*. A **pure substance** is made up of only one component, and its composition is invariant (it does not vary from one sample to another). The *components* of a pure substance can be individual atoms or groups of atoms joined together. For example, helium, water, and table salt (sodium chloride) are all pure substances. Each of these substances is made up of only one component: helium is made up of helium atoms, water is made up of water molecules, and sodium chloride is made up of sodium chloride units. The composition of a pure sample of any one of these substances is always exactly the same (because you can't vary the composition of a substance made up of only one component).

A **mixture**, by contrast, is composed of two or more components in proportions that can vary from one sample to another. For example, sweetened tea, composed primarily of water molecules and sugar molecules (with a few other substances mixed in), is a mixture. We can make tea slightly sweet (a small proportion of sugar to water) or very sweet (a large proportion of sugar to water) or any level of sweetness in between.

We categorize pure substances themselves into two types—*elements* and *compounds*—depending on whether or not they can be broken down (or decomposed) into simpler substances. Helium, which we just noted is a pure substance, is also a good example of an **element**, a substance that cannot be chemically broken down into simpler substances. Water, also a pure substance, is a good example of a **compound**, a substance composed of two or more elements (in this case hydrogen and oxygen) in a fixed, definite proportion. On Earth, compounds are more common than pure elements because most elements combine with other elements to form compounds.

We also categorize mixtures into two types—heterogeneous and homogeneous—depending on how *uniformly* the substances within them mix. Wet sand is a **heterogeneous mixture**, one in which the composition varies from one region of the mixture to another. Sweetened tea is a **homogeneous mixture**, one with the same composition throughout. Homogeneous mixtures have uniform compositions because the atoms or molecules that compose them mix uniformly. Heterogeneous mixtures are made up of distinct regions because the atoms or molecules that compose them separate. Here again we see that the properties of matter are determined by the atoms or molecules that compose it.

Classifying a substance according to its composition is not always obvious and requires that we either know the true composition of the substance or are able to test it in a laboratory. For now, we focus on relatively common substances that you are likely to have encountered. Throughout this course, you will gain the knowledge to understand the composition of a larger variety of substances.

All known elements are listed in the periodic table in the inside front cover of this book.

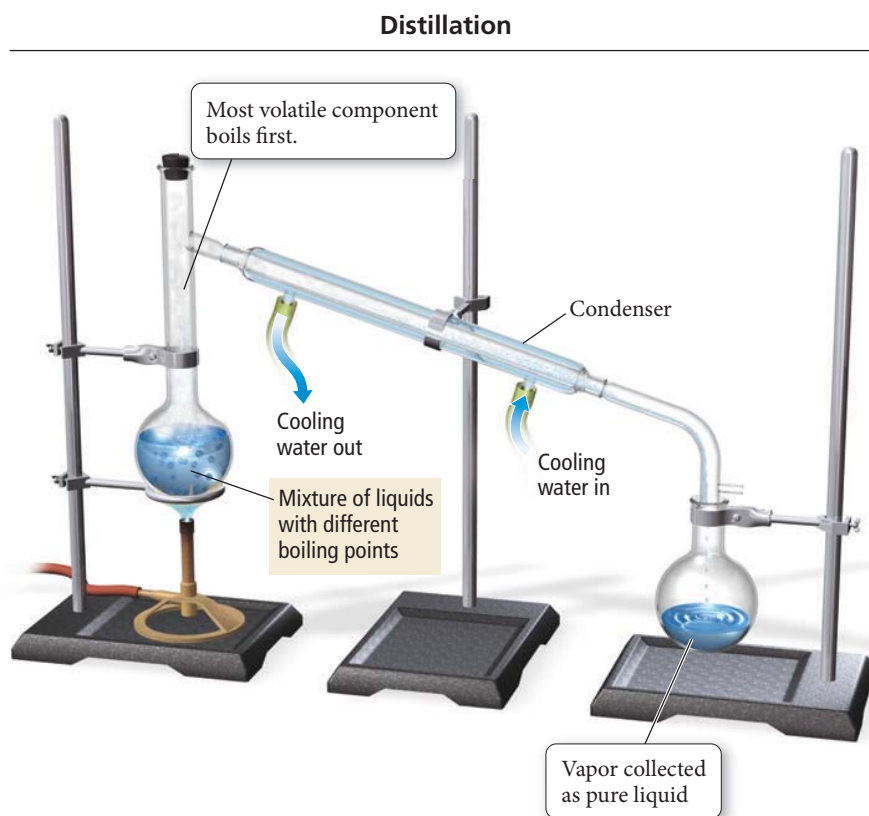


## CONCEPTUAL CONNECTION 1.2

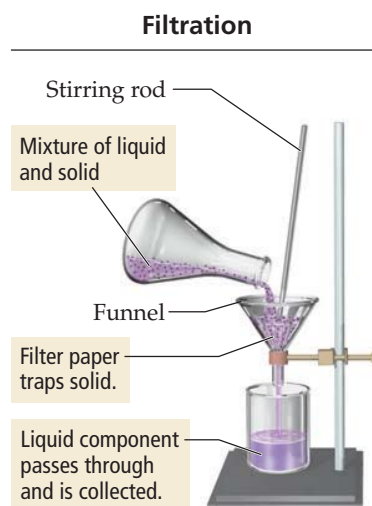
**Pure Substances and Mixtures** Let a small circle represent an atom of one type of element and a small square represent an atom of a second type of element. Make a drawing of (a) a pure substance (a compound) composed of the two elements (in a one-to-one ratio), (b) a homogeneous mixture composed of the two elements, and (c) a heterogeneous mixture composed of the two elements.

## Separating Mixtures

Chemists often want to separate a mixture into its components. Such separations can be easy or difficult, depending on the components in the mixture. In general, mixtures are separable because the different components have different physical or chemical properties. We can use various techniques that exploit these differences to achieve separation. For example, we can separate a mixture of sand and water by **decanting**—carefully pouring off—the water into another container. A homogeneous mixture of liquids can usually be separated by **distillation**, a process in which the mixture is heated to boil off the more **volatile** (easily vaporizable) liquid. The volatile liquid is then recondensed in a condenser and collected in a separate flask (Figure 1.4▶). If a mixture is composed of an insoluble solid and a liquid, we can separate the two by **filtration**, in which the mixture is poured through filter paper in a funnel (Figure 1.5▶).



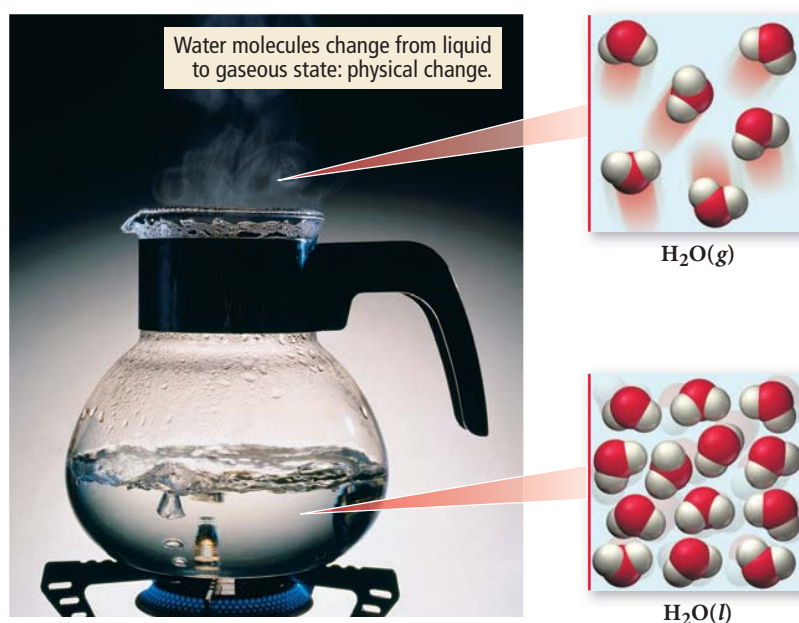
▲ **FIGURE 1.4** Separating Substances by Distillation When a liquid mixture is heated, the component with the lowest boiling point vaporizes first, leaving behind less volatile liquids or dissolved solids. The vapor is then cooled, condensing it back to a liquid, and collected.



▲ **FIGURE 1.5** Separating Substances by Filtration A solid and liquid mixture can be separated by pouring the mixture through a funnel containing filter paper designed to allow only the liquid to pass.

## 1.4 Physical and Chemical Changes and Physical and Chemical Properties

Every day we witness changes in matter: ice melts, iron rusts, gasoline burns, fruit ripens, and water evaporates. What happens to the molecules or atoms that compose these substances during such changes? The answer depends on the type of change. Changes that alter only state or appearance, but not composition, are **physical changes**. The atoms or molecules that compose a substance *do not change* their identity during a physical change. For example, when water boils, it changes its state from a liquid to a gas, but the gas remains composed of water molecules, so this is a physical change (Figure 1.6▶).



▶ **FIGURE 1.6** Boiling, a Physical Change When water boils, it turns into a gas but does not alter its chemical identity—the water molecules are the same in both the liquid and gaseous states. Boiling is a physical change, and the boiling point of water is a physical property.