



EIGHTH EDITION

CHEMISTRY

ROBINSON | MCMURRY | FAY



List of the Elements with Their Atomic Symbols and Atomic Weights

Name	Symbol	Atomic Number	Atomic Weight	Name	Symbol	Atomic Number	Atomic Weight
Actinium	Ac	89	(227)*	Mendelevium	Md	101	(258)
Aluminum	Al	13	26.981538	Mercury	Hg	80	200.59
Americium	Am	95	(243)	Molybdenum	Mo	42	95.96
Antimony	Sb	51	121.760	Moscovium	Mc	115	(288)
Argon	Ar	18	39.948	Neodymium	Nd	60	144.242
Arsenic	As	33	74.92160	Neon	Ne	10	20.1797
Astatine	At	85	(210)	Neptunium	Np	93	(237)
Barium	Ba	56	137.327	Nickel	Ni	28	58.6934
Berkelium	Bk	97	(247)	Nihonium	Nh	113	(284)
Beryllium	Be	4	9.012182	Niobium	Nb	41	92.90638
Bismuth	Bi	83	208.98040	Nitrogen	N	7	14.0067
Bohrium	Bh	107	(272)	Nobelium	No	102	(259)
Boron	B	5	10.811	Oganesson	Og	118	(294)
Bromine	Br	35	79.904	Osmium	Os	76	190.23
Cadmium	Cd	48	112.411	Oxygen	O	8	15.9994
Calcium	Ca	20	40.078	Palladium	Pd	46	106.42
Californium	Cf	98	(251)	Phosphorus	P	15	30.973762
Carbon	C	6	12.0107	Platinum	Pt	78	195.094
Cerium	Ce	58	140.116	Plutonium	Pu	94	(244)
Cesium	Cs	55	132.90545	Polonium	Po	84	(209)
Chlorine	Cl	17	35.453	Potassium	K	19	39.0983
Chromium	Cr	24	51.9961	Praseodymium	Pr	59	140.90765
Cobalt	Co	27	58.933195	Promethium	Pm	61	(145)
Copernicium	Cn	112	(285)	Protactinium	Pa	91	231.03588
Copper	Cu	29	63.546	Radium	Ra	88	(226)
Curium	Cm	96	(247)	Radon	Rn	86	(222)
Darmstadtium	Ds	110	(281)	Rhenium	Re	75	186.207
Dubnium	Db	105	(268)	Rhodium	Rh	45	102.90550
Dysprosium	Dy	66	162.500	Roentgenium	Rg	111	(280)
Einsteinium	Es	99	(252)	Rubidium	Rb	37	85.4678
Erbium	Er	68	167.259	Ruthenium	Ru	44	101.07
Europium	Eu	63	151.964	Rutherfordium	Rf	104	(265)
Fermium	Fm	100	(257)	Samarium	Sm	62	150.36
Flerovium	Fl	114	(289)	Scandium	Sc	21	44.955912
Fluorine	F	9	18.998403	Seaborgium	Sg	106	(271)
Francium	Fr	87	(223)	Selenium	Se	34	78.96
Gadolinium	Gd	64	157.25	Silicon	Si	14	28.0855
Gallium	Ga	31	69.723	Silver	Ag	47	107.8682
Germanium	Ge	32	72.64	Sodium	Na	11	22.989769
Gold	Au	79	196.96657	Strontium	Sr	38	87.62
Hafnium	Hf	72	178.49	Sulfur	S	16	32.065
Hassium	Hs	108	(270)	Tantalum	Ta	73	180.9479
Helium	He	2	4.002602	Technetium	Tc	43	(98)
Holmium	Ho	67	164.93032	Tellurium	Te	52	127.60
Hydrogen	H	1	1.00794	Tennessine	Ts	117	(292)
Indium	In	49	114.818	Terbium	Tb	65	158.92535
Iodine	I	53	126.90447	Thallium	Tl	81	204.3833
Iridium	Ir	77	192.217	Thorium	Th	90	232.0381
Iron	Fe	26	55.845	Thulium	Tm	69	168.93421
Krypton	Kr	36	83.798	Tin	Sn	50	118.710
Lanthanum	La	57	138.9055	Titanium	Ti	22	47.867
Lawrencium	Lr	103	(262)	Tungsten	W	74	183.84
Lead	Pb	82	207.2	Uranium	U	92	238.02891
Lithium	Li	3	6.941	Vanadium	V	23	50.9415
Livermorium	Lv	116	(293)	Xenon	Xe	54	131.293
Lutetium	Lu	71	174.9668	Ytterbium	Yb	70	173.054
Magnesium	Mg	12	24.3050	Yttrium	Y	39	88.90585
Manganese	Mn	25	54.938045	Zinc	Zn	30	65.38
Meitnerium	Mt	109	(276)	Zirconium	Zr	40	91.224

*Values in parentheses are the mass numbers of the most common or longest lived isotopes of radioactive elements.

CHEMISTRY

E I G H T H E D I T I O N

JILL K. ROBINSON

Indiana University

JOHN E. MCMURRY

Cornell University

ROBERT C. FAY

Cornell University



Director of Portfolio Management: Jeanne Zalesky
Executive Courseware Portfolio Manager: Terry Haugen
Content Producer: Shercian Kinoshian
Managing Producer: Kristen Flathman
Courseware Director, Content Development: Barbara Yien
Courseware Analysts: Cathy Murphy, Coleen Morrison, Jay McElroy
Courseware Editorial Assistant: Harry Misthos
Rich Media Content Producers: Jenny Moryan, Ziki Dekel
Director MasteringChemistry Content Development: Amir Said
MasteringChemistry Senior Content Producer: Margaret Trombley
MasteringChemistry Content Producers: Meaghan Fallano, Kaitlin Smith
Full-Service Vendor, Project Manager: Pearson CSC, Kelly Murphy
Copyeditor: Pearson CSC
Compositor: Pearson CSC
Art House, Coordinator: Lachina, Rebecca Marshall
Design Manager: Maria Guglielmo Walsh
Interior & Cover Designer: Gary Hespeneide
Rights & Permissions Manager: Ben Ferrini
Rights & Permissions Project Manager: Pearson CSC, Eric Schrader
Rights & Permissions Specialist/Photo Researcher: Pearson CSC, Angelica Aranas
Manufacturing Buyer: Stacey Weinberger
VP, Director of Field Marketing: Tim Galligan
Director of Product Marketing: Allison Rona
Executive Field Marketing Manager: Christopher Barker
Senior Product Marketing Manager: Elizabeth Bell
Cover Photo Credit: Beauty of Science/Science Source

Copyright © 2020, 2016, 2012 by Pearson Education, Inc. 221 River Street, Hoboken, NJ 07030. All Rights Reserved. Printed 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.

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

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

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

Library of Congress Cataloging-in-Publication Data

Names: Robinson, Jill K. | McMurry, John. | Fay, Robert C., 1936-
Title: Chemistry / Jill K. Robinson (Indiana University), John E. McMurry
(Cornell University), Robert C. Fay (Cornell University).
Description: Eighth edition. | Hoboken, NJ : Pearson Education, Inc., [2020]
Identifiers: LCCN 2018053050 | ISBN 9780134856230 (casebound)
Subjects: LCSH: Chemistry--Textbooks.
Classification: LCC QD33.2 .M36 2020 | DDC 540--dc23
LC record available at <https://lccn.loc.gov/2018053050>

Brief Contents

Preface xiii

For Instructors xvi

- 1** Chemical Tools: Experimentation and Measurement 1
- 2** Atoms, Molecules, and Ions 33
- 3** Mass Relationships in Chemical Reactions 83
- 4** Reactions in Aqueous Solution 116
- 5** Periodicity and the Electronic Structure of Atoms 161
- 6** Ionic Compounds: Periodic Trends and Bonding Theory 208
- 7** Covalent Bonding and Electron-Dot Structures 238
- 8** Covalent Compounds: Bonding Theories and Molecular Structure 278
- 9** Thermochemistry: Chemical Energy 327
- 10** Gases: Their Properties and Behavior 374
- 11** Liquids and Phase Changes 422
- 12** Solids and Solid-State Materials 450
- 13** Solutions and Their Properties 494
- 14** Chemical Kinetics 538
- 15** Chemical Equilibrium 601
- 16** Aqueous Equilibria: Acids and Bases 654
- 17** Applications of Aqueous Equilibria 708
- 18** Thermodynamics: Entropy, Free Energy, and Spontaneity 768
- 19** Electrochemistry 813
- 20** Nuclear Chemistry 870
- 21** Transition Elements and Coordination Chemistry 904
- 22** The Main-Group Elements 954
- 23** Organic and Biological Chemistry 1003

Contents

Preface xiii

For Instructors xvi

1 Chemical Tools: Experimentation and Measurement 1

- 1.1 The Scientific Method: Nanoparticle Catalysts for Fuel Cells 2
- 1.2 Measurements: SI Units and Scientific Notation 5
- 1.3 Mass and Its Measurement 7
- 1.4 Length and Its Measurement 8
- 1.5 Temperature and Its Measurement 9
- 1.6 Derived Units: Volume and Its Measurement 11
- 1.7 Derived Units: Density and Its Measurement 13
- 1.8 Derived Units: Energy and Its Measurement 14
- 1.9 Accuracy, Precision, and Significant Figures in Measurement 16
- 1.10 Significant Figures in Calculations 18
- 1.11 Converting from One Unit to Another 20

INQUIRY ? What are the unique properties of nanoscale materials? 23

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

2 Atoms, Molecules, and Ions 33

- 2.1 Chemistry and the Elements 34
- 2.2 Elements and the Periodic Table 36
- 2.3 Some Common Groups of Elements and Their Properties 38
- 2.4 Observations Supporting Atomic Theory: The Conservation of Mass and the Law of Definite Proportions 41
- 2.5 The Law of Multiple Proportions and Dalton's Atomic Theory 43
- 2.6 Atomic Structure: Electrons 45
- 2.7 Atomic Structure: Protons and Neutrons 47
- 2.8 Atomic Numbers 49
- 2.9 Atomic Weights and the Mole 51
- 2.10 Measuring Atomic Weight: Mass Spectrometry 55
- 2.11 Mixtures and Chemical Compounds; Molecules and Covalent Bonds 57

- 2.12 Ions and Ionic Bonds 61
- 2.13 Naming Chemical Compounds 63

INQUIRY ? How can measurements of oxygen and hydrogen isotopes in ice cores determine past climates? 69

Study Guide • Key Terms • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

3 Mass Relationships in Chemical Reactions 83

- 3.1 Representing Chemistry on Different Levels 84
- 3.2 Balancing Chemical Equations 85
- 3.3 Molecular Weight and Molar Mass 88
- 3.4 Stoichiometry: Relating Amounts of Reactants and Products 90
- 3.5 Yields of Chemical Reactions 92
- 3.6 Reactions with Limiting Amounts of Reactants 94
- 3.7 Percent Composition and Empirical Formulas 97
- 3.8 Determining Empirical Formulas: Elemental Analysis 100
- 3.9 Determining Molecular Weights: Mass Spectrometry 103

INQUIRY ? How is the principle of atom economy used to minimize waste in a chemical synthesis? 105

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

4 Reactions in Aqueous Solution 116

- 4.1 Solution Concentration: Molarity 117
- 4.2 Diluting Concentrated Solutions 119
- 4.3 Electrolytes in Aqueous Solution 121
- 4.4 Types of Chemical Reactions in Aqueous Solution 123
- 4.5 Aqueous Reactions and Net Ionic Equations 124
- 4.6 Precipitation Reactions and Solubility Guidelines 125
- 4.7 Acids, Bases, and Neutralization Reactions 128
- 4.8 Solution Stoichiometry 132
- 4.9 Measuring the Concentration of a Solution: Titration 133

- 4.10 Oxidation–Reduction (Redox) Reactions 135
- 4.11 Identifying Redox Reactions 138
- 4.12 The Activity Series of the Elements 141
- 4.13 Redox Titrations 144
- 4.14 Some Applications of Redox Reactions 146

INQUIRY ? How do sports drinks replenish the substances lost in sweat? 148

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

5 Periodicity and the Electronic Structure of Atoms 161

- 5.1 Wave Properties of Radiant Energy and the Electromagnetic Spectrum 162
- 5.2 Particlelike Properties of Radiant Energy: The Photoelectric Effect and Planck's Postulate 166
- 5.3 Atomic Line Spectra and Quantized Energy 169
- 5.4 Wavelike Properties of Matter: de Broglie's Hypothesis 173
- 5.5 The Quantum Mechanical Model of the Atom: Heisenberg's Uncertainty Principle 175
- 5.6 The Quantum Mechanical Model of the Atom: Orbitals and Quantum Numbers 176
- 5.7 The Shapes of Orbitals 179
- 5.8 Electron Spin and the Pauli Exclusion Principle 184
- 5.9 Orbital Energy Levels in Multielectron Atoms 185
- 5.10 Electron Configurations of Multielectron Atoms 187
- 5.11 Anomalous Electron Configurations 189
- 5.12 Electron Configurations and the Periodic Table 189
- 5.13 Electron Configurations and Periodic Properties: Atomic Radii 192

INQUIRY ? How does knowledge of atomic emission spectra help us build more efficient light bulbs? 195

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

6 Ionic Compounds: Periodic Trends and Bonding Theory 208

- 6.1 Electron Configurations of Ions 209
- 6.2 Ionic Radii 212
- 6.3 Ionization Energy 214
- 6.4 Higher Ionization Energies 216

- 6.5 Electron Affinity 218
- 6.6 The Octet Rule 220
- 6.7 Ionic Bonds and the Formation of Ionic Solids 222
- 6.8 Lattice Energies in Ionic Solids 226

INQUIRY ? How do ionic liquids lead to more environmentally friendly processes? 228

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

7 Covalent Bonding and Electron-Dot Structures 238

- 7.1 Covalent Bonding in Molecules 239
- 7.2 Strengths of Covalent Bonds 240
- 7.3 Polar Covalent Bonds: Electronegativity 242
- 7.4 A Comparison of Ionic and Covalent Compounds 246
- 7.5 Electron-Dot Structures: The Octet Rule 247
- 7.6 Procedure for Drawing Electron-Dot Structures 250
- 7.7 Drawing Electron-Dot Structures for Radicals 254
- 7.8 Electron-Dot Structures of Compounds Containing Only Hydrogen and Second-Row Elements 255
- 7.9 Electron-Dot Structures and Resonance 257
- 7.10 Formal Charges 261

INQUIRY ? How does bond polarity affect the toxicity of organophosphate insecticides? 265

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

8 Covalent Compounds: Bonding Theories and Molecular Structure 278

- 8.1 Molecular Shapes: The VSEPR Model 279
- 8.2 Valence Bond Theory 286
- 8.3 Hybridization and sp^3 Hybrid Orbitals 287
- 8.4 Other Kinds of Hybrid Orbitals 290
- 8.5 Polar Covalent Bonds and Dipole Moments 295
- 8.6 Intermolecular Forces 298
- 8.7 Molecular Orbital Theory: The Hydrogen Molecule 306
- 8.8 Molecular Orbital Theory: Other Diatomic Molecules 308
- 8.9 Combining Valence Bond Theory and Molecular Orbital Theory 312

INQUIRY ? Which is better for human health, natural or synthetic vitamins? 314

Study Guide • Key Terms • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

9 Thermochemistry: Chemical Energy 327

- 9.1 Energy and Its Conservation 328
- 9.2 Internal Energy and State Functions 330
- 9.3 Expansion Work 332
- 9.4 Energy and Enthalpy 334
- 9.5 Thermochemical Equations and the Thermodynamic Standard State 336
- 9.6 Enthalpies of Chemical and Physical Changes 338
- 9.7 Calorimetry and Heat Capacity 341
- 9.8 Hess's Law 345
- 9.9 Standard Heats of Formation 348
- 9.10 Bond Dissociation Energies 350
- 9.11 An Introduction to Entropy 352
- 9.12 An Introduction to Free Energy 355

INQUIRY ? How do we determine the energy content of biofuels? 359

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

10 Gases: Their Properties and Behavior 374

- 10.1 Gases and Gas Pressure 375
- 10.2 The Gas Laws 380
- 10.3 The Ideal Gas Law 385
- 10.4 Stoichiometric Relationships with Gases 387
- 10.5 Mixtures of Gases: Partial Pressure and Dalton's Law 390
- 10.6 The Kinetic–Molecular Theory of Gases 393
- 10.7 Gas Diffusion and Effusion: Graham's Law 395
- 10.8 The Behavior of Real Gases 397
- 10.9 The Earth's Atmosphere and the Greenhouse Effect 398
- 10.10 Greenhouse Gases 401
- 10.11 Climate Change 403

INQUIRY ? How do inhaled anesthetics work? 407

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

11 Liquids and Phase Changes 422

- 11.1 Properties of Liquids 423
- 11.2 Vapor Pressure and Boiling Point 424
- 11.3 Phase Changes between Solids, Liquids, and Gases 428

- 11.4 Energy Changes during Phase Transitions 431
- 11.5 Phase Diagrams 433
- 11.6 Liquid Crystals 436

INQUIRY ? How is caffeine removed from coffee? 439

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

12 Solids and Solid-State Materials 450

- 12.1 Types of Solids 451
- 12.2 Probing the Structure of Solids: X-Ray Crystallography 453
- 12.3 The Packing of Spheres in Crystalline Solids: Unit Cells 455
- 12.4 Structures of Some Ionic Solids 459
- 12.5 Structures of Some Covalent Network Solids 462
- 12.6 Bonding in Metals 464
- 12.7 Semiconductors 468
- 12.8 Semiconductor Applications 471
- 12.9 Superconductors 475
- 12.10 Ceramics and Composites 477

INQUIRY ? What are quantum dots, and what controls their color? 482

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

13 Solutions and Their Properties 494

- 13.1 Solutions 495
- 13.2 Enthalpy Changes and the Solution Process 496
- 13.3 Predicting Solubility 498
- 13.4 Concentration Units for Solutions 501
- 13.5 Some Factors That Affect Solubility 506
- 13.6 Physical Behavior of Solutions: Colligative Properties 510
- 13.7 Vapor-Pressure Lowering of Solutions: Raoult's Law 511
- 13.8 Boiling-Point Elevation and Freezing-Point Depression of Solutions 517
- 13.9 Osmosis and Osmotic Pressure 521

INQUIRY ? How does hemodialysis cleanse the blood of patients with kidney failure? 525

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

14 Chemical Kinetics 538

- 14.1 Reaction Rates 539
- 14.2 Rate Laws and Reaction Order 544
- 14.3 Method of Initial Rates: Experimental Determination of a Rate Law 546
- 14.4 Integrated Rate Law: Zeroth-Order Reactions 550
- 14.5 Integrated Rate Law: First-Order Reactions 552
- 14.6 Integrated Rate Law: Second-Order Reactions 557
- 14.7 Reaction Rates and Temperature: The Arrhenius Equation 560
- 14.8 Using the Arrhenius Equation 564
- 14.9 Reaction Mechanisms 567
- 14.10 Rate Laws for Elementary Reactions 570
- 14.11 Rate Laws for Overall Reactions 573
- 14.12 Catalysis 577
- 14.13 Homogeneous and Heterogeneous Catalysts 580

INQUIRY ? How do enzymes work? 583

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

15 Chemical Equilibrium 601

- 15.1 The Equilibrium State 603
- 15.2 The Equilibrium Constant K_c 605
- 15.3 The Equilibrium Constant K_p 610
- 15.4 Heterogeneous Equilibria 612
- 15.5 Using the Equilibrium Constant 614
- 15.6 Factors That Alter the Composition of an Equilibrium Mixture: Le Châtelier's Principle 624
- 15.7 Altering an Equilibrium Mixture: Changes in Concentration 625
- 15.8 Altering an Equilibrium Mixture: Changes in Pressure and Volume 629
- 15.9 Altering an Equilibrium Mixture: Changes in Temperature 631
- 15.10 The Link between Chemical Equilibrium and Chemical Kinetics 634

INQUIRY ? How does high altitude affect oxygen transport in the body? 637

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

16 Aqueous Equilibria: Acids and Bases 654

- 16.1 Acid–Base Concepts: The Brønsted–Lowry Theory 655
- 16.2 Acid Strength and Base Strength 658
- 16.3 Factors That Affect Acid Strength 661

- 16.4 Dissociation of Water 664
- 16.5 The pH Scale 666
- 16.6 Measuring pH 668
- 16.7 The pH in Solutions of Strong Acids and Strong Bases 669
- 16.8 Equilibria in Solutions of Weak Acids 671
- 16.9 Calculating Equilibrium Concentrations in Solutions of Weak Acids 673
- 16.10 Percent Dissociation in Solutions of Weak Acids 677
- 16.11 Polyprotic Acids 678
- 16.12 Equilibria in Solutions of Weak Bases 682
- 16.13 Relation Between K_a and K_b 684
- 16.14 Acid–Base Properties of Salts 686
- 16.15 Lewis Acids and Bases 691

INQUIRY ? Has the problem of acid rain been solved? 694

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

17 Applications of Aqueous Equilibria 708

- 17.1 Neutralization Reactions 709
- 17.2 The Common-Ion Effect 712
- 17.3 Buffer Solutions 716
- 17.4 The Henderson–Hasselbalch Equation 720
- 17.5 pH Titration Curves 723
- 17.6 Strong Acid–Strong Base Titrations 724
- 17.7 Weak Acid–Strong Base Titrations 727
- 17.8 Weak Base–Strong Acid Titrations 732
- 17.9 Polyprotic Acid–Strong Base Titrations 733
- 17.10 Solubility Equilibria for Ionic Compounds 738
- 17.11 Measuring K_{sp} and Calculating Solubility from K_{sp} 739
- 17.12 Factors That Affect Solubility 742
- 17.13 Precipitation of Ionic Compounds 750
- 17.14 Separation of Ions by Selective Precipitation 751
- 17.15 Qualitative Analysis 752

INQUIRY ? What is causing ocean acidification? 754

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

18 Thermodynamics: Entropy, Free Energy, and Spontaneity 768

- 18.1 Spontaneous Processes 769
- 18.2 Enthalpy, Entropy, and Spontaneous Processes 770
- 18.3 Entropy and Probability 773

- 18.4** Entropy and Temperature 777
18.5 Standard Molar Entropies and Standard Entropies of Reaction 779
18.6 Entropy and the Second Law of Thermodynamics 781
18.7 Free Energy and the Spontaneity of Chemical Reactions 784
18.8 Standard Free-Energy Changes for Reactions 787
18.9 Standard Free Energies of Formation 789
18.10 Free-Energy Changes for Reactions under Nonstandard-State Conditions 792
18.11 Free Energy and Chemical Equilibrium 794

INQUIRY ? Does the formation of highly ordered molecules violate the second law of thermodynamics? 798

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

19 Electrochemistry 813

- 19.1** Balancing Redox Reactions by the Half-Reaction Method 814
19.2 Galvanic Cells 819
19.3 Shorthand Notation for Galvanic Cells 824
19.4 Cell Potentials and Free-Energy Changes for Cell Reactions 825
19.5 Standard Reduction Potentials 827
19.6 Using Standard Reduction Potentials 830
19.7 Cell Potentials under Nonstandard-State Conditions: The Nernst Equation 833
19.8 Electrochemical Determination of pH 836
19.9 Standard Cell Potentials and Equilibrium Constants 838
19.10 Batteries 840
19.11 Corrosion 843
19.12 Electrolysis and Electrolytic Cells 846
19.13 Commercial Applications of Electrolysis 849
19.14 Quantitative Aspects of Electrolysis 852

INQUIRY ? How do hydrogen fuel cells work? 854

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

20 Nuclear Chemistry 870

- 20.1** Nuclear Reactions and Their Characteristics 871
20.2 Radioactivity 872
20.3 Nuclear Stability 875
20.4 Radioactive Decay Rates 877
20.5 Dating with Radioisotopes 881

- 20.6** Energy Changes during Nuclear Reactions 882
20.7 Nuclear Fission and Fusion 886
20.8 Nuclear Transmutation 890
20.9 Detecting and Measuring Radioactivity 891

INQUIRY ? How are radioisotopes used in medicine? 894

Study Guide • Key Terms • Key Equations • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

21 Transition Elements and Coordination Chemistry 904

- 21.1** Electron Configurations 906
21.2 Properties of Transition Elements 908
21.3 Oxidation States of Transition Elements 912
21.4 Coordination Compounds 913
21.5 Ligands 915
21.6 Naming Coordination Compounds 918
21.7 Isomers 921
21.8 Enantiomers and Molecular Handedness 926
21.9 Color of Transition Metal Complexes 929
21.10 Crystal Field Theory 930
21.11 Bonding in Complexes: Valence Bond Theory 936

INQUIRY ? How does cisplatin kill cancer cells? 940

Study Guide • Key Terms • Key Equation • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

22 The Main-Group Elements 954


- 22.1** A Review of General Properties and Periodic Trends 955
22.2 Distinctive Properties of the Second-Row Elements 957
22.3 Group 1A: Hydrogen 959
22.4 Group 1A: Alkali Metals and Group 2A: Alkaline Earth Metals 962
22.5 Group 3A Elements 965
22.6 Group 4A Elements 967
22.7 Group 5A Elements 974
22.8 Group 6A Elements 980
22.9 Group 7A: The Halogens 987
22.10 Group 8A: Noble Gases 989

INQUIRY ? What are the barriers to a hydrogen economy? 990

Study Guide • Key Terms • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

23 Organic and Biological Chemistry 1003

- 23.1 Organic Molecules and Their Structures: Constitutional Isomers 1004
- 23.2 Stereoisomers: Chiral Molecules 1008
- 23.3 Families of Organic Compounds: Functional Groups 1011
- 23.4 Carbohydrates: A Biological Example of Isomers 1014
- 23.5 Valence Bond Theory and Orbital Overlap Pictures 1017
- 23.6 Lipids: A Biological Example of Cis–Trans Isomerism 1021
- 23.7 Formal Charge and Resonance in Organic Compounds 1025
- 23.8 Conjugated Systems 1030
- 23.9 Proteins: A Biological Example of Conjugation 1034
- 23.10 Aromatic Compounds and Molecular Orbital Theory 1038
- 23.11 Nucleic Acids: A Biological Example of Aromaticity 1041

INQUIRY  Why do enantiomers have different biological responses? 1045

Study Guide • Key Terms • Practice Test • Conceptual Problems • Section Problems • Multiconcept Problems

Appendix A: Mathematical Operations A-1

- A.1 Scientific Notation A-1
- A.2 Logarithms A-4
- A.3 Straight-Line Graphs and Linear Equations A-6
- A.4 Quadratic Equations A-7
- A.5 Calculus Derivations of Integrated Rate Laws A-7

Appendix B: Thermodynamic Properties at 25 °C A-9

Appendix C: Equilibrium Constants at 25 °C A-14

Appendix D: Standard Reduction Potentials at 25 °C A-18

Appendix E: Properties of Water A-20

Answers to Selected Problems A-21

Glossary G-1

Index I-1

Photo/Text Credits C-1

List of Interactive Videos

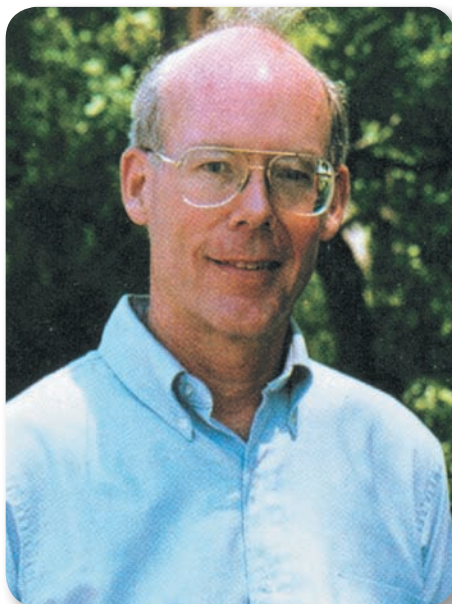
- 1 WORKED EXAMPLE 1.8** Unit conversions using significant figures 21
WORKED EXAMPLE 1.9 Unit conversions with squared and cubed units 22
- 2 WORKED EXAMPLE 2.5** Calculating an atomic weight 52
WORKED EXAMPLE 2.6 Converting between mass and numbers of moles and atoms 54
- 3 WORKED EXAMPLE 3.5** Relating the masses of reactants and products 91
WORKED EXAMPLE 3.6 Calculating percent yield 93
WORKED EXAMPLE 3.8 Calculating the amount of product or excess reactant when one reactant is limiting 96
- 4 WORKED EXAMPLE 4.2** Calculating the number of moles of solute in a solution 119
WORKED EXAMPLE 4.11 Determining the concentration of a solution using a titration procedure 134
- 5 WORKED EXAMPLE 5.4** Relating the Bohr model and the Balmer–Rydberg equation 173
WORKED EXAMPLE 5.6 Assigning quantum numbers to an orbital 179
WORKED EXAMPLE 5.8 Assigning a ground-state electron configuration to an atom 192
- 6 WORKED EXAMPLE 6.4** Higher ionization energies 218
WORKED EXAMPLE 6.7 Calculating the energy change in the formation of an ionic compound 225
WORKED EXAMPLE 6.8 Lattice energies 227
- 7 WORKED EXAMPLE 7.5** Drawing electron-dot structures for molecules with one central atom and multiple bonds 253
WORKED EXAMPLE 7.10 Drawing resonance structures in organic compounds 260
WORKED EXAMPLE 7.11 Calculating formal charges 263
- 8 WORKED EXAMPLE 8.4** Identifying hybridization and orbital overlap in single and double bonds 292
WORKED EXAMPLE 8.6 Predicting the presence of a dipole moment 297
- 9 WORKED EXAMPLE 9.6** Calculating ΔH in a constant-pressure calorimetry experiment 343
WORKED EXAMPLE 9.7 Calculating ΔE in constant-volume calorimetry 344
WORKED EXAMPLE 9.12 Predicting the signs of ΔH , ΔS , and ΔG for a reaction 357
- 10 WORKED EXAMPLE 10.3** Visual representations of gas laws 383
WORKED EXAMPLE 10.5 Using the ideal gas law when variables change 387

- WORKED EXAMPLE 10.8** Calculating partial pressure 392
- 11 WORKED EXAMPLE 11.3** Calculating the amount of heat of a temperature change 433
- 12 WORKED EXAMPLE 12.2** Using unit-cell dimensions to calculate the density of a metal 459
- WORKED EXAMPLE 12.4** Using band theory to account for melting points 467
- 13 WORKED EXAMPLE 13.5** Using density to convert molarity to other measures of concentration 505
- WORKED EXAMPLE 13.7** Calculating the vapor pressure of an electrolyte solution 514
- 14 WORKED EXAMPLE 14.3** Determining a rate law from initial rates 548
- WORKED EXAMPLE 14.6** Using the integrated rate law for a first-order reaction 553
- 15 WORKED EXAMPLE 15.9** Calculating equilibrium concentrations (solving the equilibrium equation by taking the square root of both sides of the equation) 619
- WORKED EXAMPLE 15.12** Calculating equilibrium partial pressures from initial partial pressures 623
- 16 WORKED EXAMPLE 16.10** Calculating the pH and the equilibrium concentrations in a solution of a weak acid 675
- WORKED EXAMPLE 16.12** Calculating the pH and the equilibrium concentrations in a solution of a weak base 683
- 17 WORKED EXAMPLE 17.4** Calculating the pH of a buffer after addition of OH^- or H_3O^+ 718
- WORKED EXAMPLE 17.8** Calculating the pH at the equivalence point in the titration of a weak acid with a strong base 731
- 18 WORKED EXAMPLE 18.1** Predicting the sign of ΔS 773
- WORKED EXAMPLE 18.8** Calculating ΔG for a reaction under nonstandard-state conditions 792
- 19 WORKED EXAMPLE 19.1** Balancing a redox equation for a reaction in acidic solution 816
- WORKED EXAMPLE 19.8** Calculating the voltage of a galvanic cell under standard-state conditions 832
- WORKED EXAMPLE 19.13** Calculating the amount of product produced by electrolysis 853
- 20 WORKED EXAMPLE 20.3** Using half-life to calculate an amount remaining 879
- WORKED EXAMPLE 20.6** Calculating a mass defect and a binding energy 885
- 21 WORKED EXAMPLE 21.7** Drawing diastereoisomers and enantiomers 928
- WORKED EXAMPLE 21.8** Drawing crystal field energy-level diagrams for octahedral complexes 934
- 22 WORKED EXAMPLE 22.4** Interpreting representations of silicate anions 973
- 23 WORKED EXAMPLE 23.3** Identifying chiral molecules 1010
- WORKED EXAMPLE 23.13** Predicting if an organic compound is aromatic 1040

About the Authors



Jill K. Robinson received her Ph.D. in analytical and atmospheric chemistry from the University of Colorado at Boulder. She is a senior lecturer at Indiana University and teaches general, analytical, and environmental chemistry courses. Her clear and relatable teaching style has been honored with several awards including the President's Award for Distinguished Teaching at Indiana University and the J. Calvin Giddings Award for Excellence in Education from the American Chemical Society Division of Analytical Chemistry. She leads workshops to help faculty transition from lecture-based instruction to student-centered pedagogies.



John McMurry, educated at Harvard and Columbia, has taught more than 20,000 students in general and organic chemistry over a 40-year period. An emeritus professor of chemistry at Cornell University, Dr. McMurry previously spent 13 years on the faculty at the University of California at Santa Cruz. He has received numerous awards, including the Alfred P. Sloan Fellowship (1969–71), the National Institute of Health Career Development Award (1975–80), the Alexander von Humboldt Senior Scientist Award (1986–87), and the Max Planck Research Award (1991).



Robert C. Fay, professor emeritus at Cornell University, taught general and inorganic chemistry at Cornell for 45 years beginning in 1962. Known for his clear, well-organized lectures, Dr. Fay was the 1980 recipient of the Clark Distinguished Teaching Award. He has also taught as a visiting professor at Harvard University and the University of Bologna (Italy). A Phi Beta Kappa graduate of Oberlin College, Dr. Fay received his Ph.D. from the University of Illinois. He has been an NSF Science Faculty Fellow at the University of East Anglia and the University of Sussex (England) and a NATO/Heineman Senior Fellow at Oxford University.

Preface

FOR THE STUDENT

Francie came away from her first chemistry lecture in a glow. In one hour she found out that everything was made up of atoms which were in continual motion. She grasped the idea that nothing was ever lost or destroyed. Even if something was burned up or rotted away, it did not disappear from the face of the earth; it changed into something else—gases, liquids, and powders. Everything, decided Francie after that first lecture, was vibrant with life and there was no death in chemistry. She was puzzled as to why learned people didn't adopt chemistry as a religion.

—Betty Smith, *A Tree Grows in Brooklyn*

We know that not everyone has such a breathless response to their chemistry lectures, and few would mistake chemistry as a religion, yet chemistry *is* a subject with great logical beauty. We love chemistry because it explains the “why” behind many observations of the world around us and we use it every day to help us make informed choices about our health, lifestyle, and politics. Moreover, chemistry is the fundamental, enabling science that underlies many of the great advances of the last century that have so lengthened and enriched our lives. Chemistry provides a strong understanding of the physical world and will give you the foundation you need to go on and make important contributions to science and humanity.

HOW TO USE THIS BOOK

You no doubt have experience using textbooks and know they are not meant to read like a novel. We have written this book to provide you with a clear, cohesive introduction to chemistry in a way that will help you, as a new student of chemistry, understand and relate to the subject. While you *could* curl up with this book, you will greatly benefit from continually formulating questions and checking your understanding as you *work* through each section. The way this book is designed and written will help you keep your mind active, thus allowing you to digest important concepts as you learn some of the many principles of chemistry.

The 8th edition was revised to create an **interactive** study cycle based on research of effective learning methods. Many common study habits such as highlighting, rereading, and long study sessions create the illusion of fast progress, but these gains fade quickly. More deep and durable learning occurs from self-testing, difficulty in practice, and spaced practice of different skills. Let's see how specific steps in the study cycle use proven strategies to maximize your learning.

Step 1. Learning New Material

The 8th edition eText contains many new interactive features (Big Idea Questions, Interactive Worked Examples, Practice problems, and Figure It Out Questions) that should be used to quiz yourself and receive feedback as you work through the material in each chapter.

- **Narrative:** As you read through the text, always challenge yourself to understand the “why” behind the concept. For example, you will learn that carbon forms four bonds, and the narrative will give the reason why. By gaining a conceptual understanding, you will *not need to memorize* a large collection of facts, making learning and retaining important principles much easier! **Big Idea Questions** were written to help you digest and apply the most important concepts. In the printed book, these

questions appear in the margins, and in the eText, they are multiple choice questions with feedback to help you identify common mistakes.

- **Figures:** Figures are not optional! Most summarize and convey important points. *Figure It Out Questions* draw your attention to a key principle and provide guidance in interpreting graphs. Answer the question by examining the figure and perhaps rereading the related narrative. We've provided answers to Figure It Out Questions near the figure in the printed book and use an interactive hide-and-reveal feature in the eText.
- **Worked Examples:** Numerous worked examples throughout the text show the approach for solving a certain type of problem. Each worked example uses a step-by-step procedure.
 - **Identify**—The first step in problem solving is to identify key information and classify it as a known or unknown quantity. This step also involves translating between words and chemical symbols. Listing knowns on one side and unknowns on the other organizes the information and makes the process of identifying the correct strategy more visual. The *Identify* step is used in numerical problems.
 - **Strategy**—The strategy describes how to solve the problem without actually solving it. Failing to articulate the needed strategy is a common pitfall; too often students start manipulating numbers and variables without first identifying key equations or making a plan. Articulating a strategy will develop conceptual understanding and is highly preferable to simply memorizing the steps involved in solving a certain type of problem.
 - **Solution**—Once the plan is outlined, the key information is used to answer the question.
 - **Check**—A problem is not completed until you have thought about whether the answer makes sense. Use both your practical knowledge of the world and knowledge of chemistry to evaluate your answer. For example, if heat is added to a sample of liquid water and you are asked to calculate the final temperature, you should critically consider your answer: Is the final temperature lower than the original? Shouldn't adding heat raise the temperature? Is the new temperature above 100 °C, the boiling point of water? The *Check* step is used in problems when the magnitude and sign of a number can be estimated or the physical meaning of the answer verified based on familiar observations.

To test your mastery of the concept explored in Worked Examples, two problems will follow. **PRACTICE** problems are similar in style and complexity to the Worked Example and will test your basic understanding. Interactive Practice Problems are available in the eText and have answer-specific feedback to help you identify common mistakes.

Once you have correctly completed this problem, tackle the **APPLY** problem, in which the concept is used in a new situation to assess a deeper understanding of the topic. Answers to Apply Problems can be found at the end of the book or by using the hide-and-reveal feature in the eText.

- **Interactive Worked Examples:** Each chapter has two video tutorials for challenging problems that model the process of expert thinking. The videos are interactive and ask you to make predictions before moving forward to the complete solution.
- **Conceptual Problems:** Conceptual understanding is a primary focus of this book. Conceptual problems are intended to help you with the critical skill of visualizing the structure and interactions of atoms and molecules while probing your understanding of key principles rather than your ability to correctly use numbers in an equation. The time you spend mastering these problems will provide high long-term returns by solidifying main ideas.

Step 2. Problem-Solving Practice

We achieve more complex and long-lasting learning by practicing problems that require more effort and slow down the pace of learning.

- **End-of-Chapter Problem Sets:** Working problems is essential for success in chemistry! The number and variety of problems at the end of chapter will give you the practice needed to gain mastery of specific concepts. Answers to every other problem are given in the “Answers” section at the back of the book so that you can assess your understanding. Your instructor may assign problems in an online format using the Mastering™ Chemistry platform, which comes with the added benefit of tutorials, feedback, and links to relevant content in the eText.

Step 3. Mastery

Once you have read the chapter and completed the end-of-chapter problems, you will need to review for the exam and assess which topics you have mastered and which still need to be solidified. Inquiry sections and practice tests are chapter capstones that strengthen mental representations by replaying learning and giving it meaning.

- **Inquiries:** Inquiry sections connect chemistry to the world around you by highlighting useful links in the future careers of many science students. Typical themes are materials, medicine, and the environment. The goal of these sections is to deepen your understanding and aid in retention by tying concepts to memorable applications. These sections can be considered as a capstone for each chapter because *Inquiry* problems review several main concepts and calculations. These sections will also help you prepare for professional exams because they were written in the same style as new versions of these exams: a passage of text describing an application followed by a set of questions probing your ability to apply basic scientific concepts to the situation.
- **End-of-Chapter Practice Test and Study Guide:** The end-of-chapter practice test and study guide are useful tools for exam preparation. Each practice test question is linked to a learning objective in the study guide. If you answer a question incorrectly or want more practice on that skill, refer to the study guide, which matches the learning objective to a concept summary, key skills for solving the problem, Worked Examples for assistance, and end-of-chapter problems so that you can practice your mastery of that skill.

NEW TO THIS EDITION

A primary change in the 8th edition is the development of an interactive learning environment. We designed interactive features for the text and classroom based on educational research and strategies proven to help students succeed. Features that help students read a science text and prepare for exams are available for self-assessment in the printed text but are most effectively implemented in the eText. Big Idea Questions, Interactive Worked Examples, and Practice problems have multiple-choice options with answer-specific feedback targeting common mistakes and misconceptions. The eText includes more than 1,000 new interactive features, and students can assess their understanding by answering a question with feedback every one to two pages. In addition to an interactive eText, questions have been developed to help instructors engage students during class using Learning Catalytics, a personal response system used with smart devices. A large body of educational literature has clearly demonstrated increased learning gains, higher attendance, and lower failure rates in classrooms that employ active learning. New interactive features include:

- 1. Interactive Big Idea Questions:** Efficient and skilled reading requires students to parse out main ideas and important details and relate new information to prior knowledge. Big Idea Questions probe understanding of important concepts from a text passage. These questions teach students how to actively read a science text by modeling the kinds of questions they should ask themselves and stimulate them to make connections between concepts and mathematical problems. These questions can be found in the margin in the printed text and are multiple-choice questions with specific wrong-answer feedback in the eText.
- 2. Interactive Figure It Out Questions:** These questions test knowledge of key principles shown in a figure and the ability to read and interpret graphs. Answers to Figure It Out Questions are provided near the figure in the printed book and use a hide-and-reveal feature in the eText with answer-specific feedback.
- 3. Interactive Worked Examples:** Each chapter has two video tutorials featuring lead author Jill Robinson as she models the process of expert problem solving. The videos require students to pause and digest information and then predict how to proceed at key points before moving forward to the complete solution.
- 4. Interactive PRACTICE Problems:** These problems follow a Worked Example and test basic understanding. Answers to Practice Problems are provided at the end of the printed book and are multiple-choice questions with specific wrong-answer feedback in the eText. For example, the feedback for Practice problems in the eText provides an opportunity to give remediation in the mathematical operations including the quadratic equation. All steps in solving the algebraic expressions are shown to help students who may need a review.
- 5. Interactive APPLY Problems:** These problems follow the Practice Problems and discourage a plug-and-chug approach to problem solving by providing an example of how the same principle can be used in different types of problems with different levels of complexity. Answers to Apply problems are provided at the end of the printed book and use a hide-and-reveal feature in the eText.
- 6. Interactive Practice Test Linked to Study Guide:** A useful way for students to review each chapter is by taking the Practice Test, which assesses mastery of chapter learning objectives. The Study Guide provides a targeted follow-up to the Practice Test through the linking of learning objectives to the main lessons in each chapter, associated worked examples, and end-of-chapter problems for more practice. When a

student answers incorrectly in Mastering Chemistry or the eText, the Practice Test automatically links to worked examples and additional practice problems.

7. **Interactive Learning Catalytics Questions:** The Learning Catalytics questions developed for each chapter promote strong conceptual understanding and advanced problem-solving skills. Learning Catalytics includes prebuilt questions for every key topic in chemistry written by lead author Jill Robinson.

Inquiry Sections have been updated and integrated conceptually into each chapter.

Inquiry sections highlight the importance of chemistry, promote student interest, and deepen students' understanding of the content. The Inquiry sections include problems that revisit several chapter concepts and can be covered in class or recitation sections or assigned as homework in Mastering Chemistry. In the 8th edition, the delivery of Inquiry problems in Mastering Chemistry has been improved and new topics have been developed. New Inquiries for the 8th edition are:

- Chapter 2: How can measurements of oxygen and hydrogen isotopes determine past climates?
- Chapter 3: How is the principle of atom economy used to minimize waste in a chemical synthesis?
- Chapter 8: Which is better for human health, natural or synthetic vitamins?
- Chapter 10: How do inhaled anesthetics work?
- Chapter 12: What are quantum dots, and what controls their color?
- Chapter 14: How do enzymes work?
- Chapter 15: How does high altitude affect oxygen transport in the blood?
- Chapter 20: How are radioisotopes used in medicine?

NEW! End-of-chapter problems continually build on concepts and skills from earlier in the chapter.

Educational research shows that interleaved and varied practice with different concepts and skills produces higher learning gains than drilling on a single topic. Section Problems at the end of the chapter now include questions that build on concepts taught earlier in the chapter. In previous editions, Section Problems focused only on learning objectives from that specific section in the text. New questions and questions from the Chapter Problems sections in previous editions that integrate multiple chapter concepts have been incorporated into Section Problems to revisit key ideas on a regular basis and apply them in different situations.

Here is a list of some of the key chemistry content changes made in each chapter:

Chapter 1 Chemical Tools: Experimentation and Measurement

- The scientific method is described in the context of a new case study in the field of nanoscience to help students see the utility of chemistry in solving important world problems.
- Nanotechnology Inquiry problems were updated to promote better understanding of the unique properties of matter on the nanoscale and the size of nanoparticles.
- Figure 1.8 was updated to show the most commonly used laboratory glassware.

Chapter 2 Atoms, Molecules, and Ions

- Several updates to terminology and the periodic table were made. The names of recently discovered elements 113, 115,

117, and 118 were officially assigned in 2016 and listed in Section 2.1 Chemistry and the Elements. A clarification about the definition and common use of the term *atomic mass unit* was added. The atomic mass unit (*amu*) is an obsolete unit, but it is commonly used interchangeably with the correct unit, unified atomic mass unit (*u*). Since 2011, the Union of Pure and Applied Chemistry gives the atomic weights for some elements as a range of values instead of a single value due to isotopic abundances that vary with the source of the sample.

- Section 2.10 Measuring Atomic Weight: Mass Spectrometry was added to describe how atomic weights are experimentally measured. The process of using a mass spectrum to calculate an atomic weight is described in a Worked Example, and follow-up problems and new end-of-chapter problems were written. The description of a mass spectrometer from Chapter 3 was moved into Chapter 2 because it is the instrument used to measure atomic weight.

- In Section 2.12 Ions and Ionic Bonds, additional details on writing formulas for ionic compounds were added for clarification.
- A new Inquiry on isotopes and the climate record provides a strong connection with the Chapter 2 topics of isotopes, atomic weight, and the mole concept.

Chapter 3 Mass Relationships in Chemical Reactions

- Chemical Arithmetic: Stoichiometry was a very long section and contained many concepts. It has been divided into two sections: Section 3.3 Molecular Weight and Molar Mass and Section 3.4 Stoichiometry: Relating Amounts of Reactants and Products.
- A new Inquiry on atom economy concisely summarizes the important concept of relating amounts of reactants and products and introduces green chemistry.
- The section on measuring molecular weight was revised because the mass spectrometer was previously described in Chapter 2 in the section on atomic weight.

Chapter 4 Reactions in Aqueous Solution

- Added a Remember note in the margin at the beginning of Section 4.3 Electrolytes in Aqueous Solution to remind students about the differences between molecules and ions.
- Section 4.7 Acids, Bases, and Neutralization Reactions: Added a Looking Ahead note regarding acids/bases coverage in Chapter 16. Also, added the dissociation reaction for sodium hydroxide and barium hydroxide when discussing strong and weak bases.
- More explanation added to Worked Example 4.12 to help students assign oxidation numbers.
- Section 4.11 Identifying Redox Reactions: New figure shows that silver-colored powdered iron is oxidized by oxygen to produce iron(III)oxide, which is red in color.

Chapter 5 Periodicity and Electronic Structure of Atoms

Chapter 5 contains abstract ideas such as particles behaving as waves and the notion of wave functions of electrons. Eight new figures and descriptive text were added to help students grasp these difficult concepts.

- In Section 5.1 Wave Properties of Radiant Energy and the Electromagnetic Spectrum, the double-slit experiment was described to show that both light and matter have wave properties. New Figure 5.4: Diffraction and interference are phenomena exhibited by waves. New Figure 5.5: Radiant energy exhibits wave properties in a double-slit experiment.
- Section 5.3 Atomic Line Spectra and Quantized Energy: The connection between quantized energy and atomic line spectra was strengthened by condensing content and placing both concepts into the same section. Also, radial distribution plots were added to help visualize the meaning of an orbital and explain electron shielding and the ordering of orbital energies.

- Section 5.4 Wavelike Properties of Matter: de Broglie's Hypothesis: New Figure 5.11: Wave properties of electrons illustrate the different behaviors of particles and waves in a double-slit experiment. Figure also shows that electrons have wave properties, which is a key idea for understanding orbitals.
- Added an electron microscope image that shows individual DNA molecules to illustrate the utility of the wave properties of an electron in Worked Example 5.5 and Apply problem 5.10.
- Section 5.7 The Shapes of Orbitals: New Figure 5.14: Representations of a 1s orbital. New Figure 5.15: Concert hall analogy for radial probability. A figure was added to help explain the concept of radial probability in a familiar way.
- New Figure 5.18: Radial probability plots for the 1s, 2s, and 3s orbitals in a hydrogen atom. Radial probability plots are a useful way to explain the differences in size, energy, and number of nodes for the different s orbitals.
- Section 5.9 Orbital Energy Levels in Multielectron Atoms: New Figure 5.23: Radial distribution plots for 3s, 3p, and 3d orbitals. The penetration of the different orbitals determines the ordering of orbital energies ($3s < 3p < 3d$).
- Section 5.10 Electron Configurations of Multielectron Atoms: New Figure 5.24: Energy levels of orbitals in multielectron atoms was placed in the margin for easy reference when writing electron configurations.

Chapter 6 Ionic Compounds: Periodic Trends and Bonding Theory

- Section 6.1 Electron Configurations of Ions: Added text and a figure to make it more clear why ns electrons are lost before $(n - 1)d$ electrons when forming transition metal ions. A relatively recent article in the *Journal of Chemical Education* describes how many textbooks contain incomplete or inaccurate discussions of this topic. The d orbital collapse for transition metals was described as concisely as possible. (Reference: The Full Story of the Electron Configurations of the Transition Elements, J. Chem Ed., Vol 87, No. 4, April 2010)
- Modified Figure 6.6 so negative electron affinities appear below zero on the graph.
- In the reactions in the Born-Haber cycle, the energy of the reaction is written in units of kJ, not kJ/mol. Figures 6.7 and 6.8 were updated to reflect the change.
- Updated Inquiry questions on ionic liquids.

Chapter 7 Covalent Bonding and Electron-Dot Structures

- Electronegativity was defined earlier in the section to more clearly explain the existence of polar covalent bonds. Electrostatic potential maps of Cl₂, HCl, and NaCl were combined into one figure for comparison and to relate the extent of electron transfer to differences in electronegativity between the elements in the bond.

- Added the topics of dipole moment and percent ionic character to illustrate the extent of electron transfer as a continuum instead of as a sharp cutoff between a polar covalent bond and an ionic bond. A new Worked Example and new Practice and Apply problems were added. End-of-chapter problems were added as well. The content on percent ionic character was moved from Chapter 8 to Chapter 7 because it is much more relevant in this section.
- New Looking Ahead note about intermolecular forces in Section 7.4 A Comparison of Ionic and Covalent Compounds.
- Revised Inquiry Questions.

Chapter 8 Covalent Compounds: Bonding Theories and Molecular Structure

- Developed a new style for representing orbitals in all figures to more clearly show orbital overlap to form chemical bonds in valence bond theory.
- Clarified answer key for orbital overlap diagrams. Terminal atoms that have multiple bonds use the hybrid orbital model.
- References added to help students/instructors learn more about the vague statement “main-group compounds with five and six charge clouds use a more complex bonding pattern that is not easily explained by valence bond theory.” The reference appears as a footnote. Some books report that main-group atoms that expand their octets use sp^3d or sp^3d^2 hybrid orbitals, which is not considered an accurate representation based on density functional theory calculations.
- The quantitative aspects of dipole moments were moved to Chapter 7 to help students better understand the differences between a nonpolar covalent bond, polar covalent bond, and ionic bond. A qualitative discussion of dipole moments of molecules is sufficient for Chapter 8 and is aligned with how instructors cover this topic.
- Changed the order of presentation of the different types of intermolecular forces. We now start with London dispersion forces because all molecules have these types of forces. We then get more restrictive and describe polar molecules with dipole-dipole forces, followed by hydrogen bonding, which is more restrictive and a special case of dipole-dipole forces. Finally, ion-dipole is described. The ordering of presentation of forces is from weakest to strongest.
- New Inquiry topic on the difference between natural and synthetic compounds such as vitamins.

Chapter 9 Thermochemistry: Chemical Energy

- A new chapter introduction was written to better connect chapter topics to examples familiar to students.
- Improved the strategy for solving constant-pressure calorimetry problems in Worked Example 9.6.
- Changed the way constant-volume calorimetry was presented to more accurately reflect the way this type of experiment was carried out in the laboratory. A new Worked Example (9.7)

and follow-up problems were written. End-of-chapter problems were revised to fit with this pedagogy.

- Section 9.11 on fossil fuels was removed. This section did not teach any new chemistry content, and the Inquiry on biofuels serves to connect thermochemistry concepts to fuels.

Chapter 10 Gases: Their Properties and Behavior

- Changed formulas for Graham’s Law in Section 10.7 Gas Diffusion and Effusion: Graham’s Law to replace mass (m) with molar mass (M).
- Removed the section on pollution to shorten the chapter. Most instructors do want to cover some relevant topic about the atmosphere, and the climate change section was improved. Figures on greenhouse gases and climate change were updated to include data from years since the last revision.
- New Inquiry on inhaled anesthetics.

Chapter 11 Liquids and Phase Changes

- The focus of Chapter 11 is on liquids, their properties, and phase changes. The topics of solids and unit cells have been moved to Chapter 12 on solids and solid-state materials.
- A new section on liquid crystals and end-of-chapter problems have been added.

Chapter 12 Solids and Solid-State Materials

- The topics of unit cells of solids and solid-state materials are closely related and are now contained in one chapter. (Chapters 11 and 21 content from the 7th edition is combined to make one coherent unit on solids.)
- Revised Inquiry on quantum dots.

Chapter 13 Solutions and Their Properties

- Added a new figure to show the difference between a solution and colloid using light-scattering properties.
- Divided Section 12.2 from the 7th edition into two new sections to improve the description of the solution-making process.
- Section 13.2 Enthalpy Changes and the Solution Process focuses on describing the intermolecular forces involved in solution formation and the overall effect on the heat of solution.
- New Figure 13.1: A molecular view of the solution making process.
- Section 13.3 Predicting Solubility relates the thermodynamic value of ΔG to the simple rule for solubility “like dissolves like.”
- Added a paragraph to Section 13.5 Some Factors That Affect Solubility to explain why increasing temperature increases the solubility of solids but decreases the solubility of gases. A new Big Idea Question highlights this concept.

- Added a figure and description in Section 13.7 Vapor-Pressure Lowering of Solutions: Raoult's Law to illustrate ion pairing and explain why the dissociation of ionic compounds is not complete.
- Section 12.9 from the 7th edition on the fractional distillation of mixtures was deleted. There is already a lot of difficult material in this chapter, and this topic is not covered in most general chemistry courses.

Chapter 14 Chemical Kinetics

- Revised Figure 14.2 and text description to more clearly show how the instantaneous rate is determined from experimental data.
- Worked Example 14.8 (to replace 13.8) was revised to focus on the main idea of calculating half-life and not have students get lost in the details by referring to previous graphs.
- New analogy for rate-limiting step in Section 14.11 Rate Laws for Overall Reactions.
- New Inquiry on enzyme kinetics.
- Data in numerous end-of-chapter problems involving graphing were revised.

Chapter 15 Chemical Equilibrium

- Figure 15.1 was revised to show a macroscale and molecular scale representation of the $\text{N}_2\text{O}_4/\text{NO}_2$ equilibrium. This figure provides a picture of the data in the concentration versus time graphs in Figures 15.2 and 15.3.
- The feedback for practice problems in the eText provides an opportunity to give remediation in the mathematical operations including the quadratic equation. All steps in solving the algebraic expressions are shown to help students who may need a review.
- Inquiry focus was changed from the general concept of the equilibrium reaction of oxygen and hemoglobin to the more specific focus of the effect of altitude on oxygen supply in muscles.

Chapter 16 Aqueous Equilibria: Acids and Bases

- The procedure for solving acid-base equilibrium problems was reduced from eight steps to five steps, which are simpler to understand. All subsequent worked examples in Chapters 16 and 17 were modified using the new procedure. Figure 16.7 and the description of solving acid-base problems were revised to eliminate wording that was unusual and confusing. Examples are "big" concentrations and "small" concentrations.
- A photo sequence showing the pH change when CO_2 dissolves to produce carbonic acid was added to Worked Example 16.11.
- The Inquiry section was updated to discuss current problems related to acid rain.

Chapter 17 Applications of Aqueous Equilibria

- Section 17.2 The Common-Ion Effect was revised in three ways. The concept of the common-ion effect was presented before mathematical calculations to give students an understanding of the main idea first. Calculating the pH of a weak acid and conjugate base mixture was modified to follow the new simplified approach to solving equilibrium problems given in Figure 16.7. Two example calculations that were repetitive were combined into one example in Worked Example 17.2.
- Section 17.3 Buffer Solutions was rearranged to present the concept of a buffer before showing the calculation of pH change of a buffer upon addition of a strong acid or base. Figure 17.3 describes a buffer by showing pH change after adding a strong base to two different solutions: a strong acid and a buffer. The color change of an acid-base indicator shows that the buffer resists changes in pH. A conceptual Big Idea Question was created on the definition of a buffer.
- The Inquiry section on ocean acidification was updated with recent CO_2 and pH measurements. The problems were revised to promote understanding of the problem and for clarity.

Chapter 18 Thermodynamics: Entropy, Free Energy, and Spontaneity

- The introductory paragraph was revised to include familiar examples to students and review the concepts of reaction direction and extent of reaction.
- Two new figures were created to clarify the question in Worked Example 18.2 on calculating entropy.
- A more realistic example of a process that represents the standard free-energy change was described in Section 18.8 Standard Free-Energy Changes for Reactions.

Chapter 19 Electrochemistry

- In Section 19.1 Balancing Redox Reactions by the Half-Reaction Method, a brief review of oxidation numbers was added that includes a Remember note, a new figure showing oxidation numbers in redox reaction, and a Big Idea Question for students to assess themselves on this important concept from Chapter 4.
- Figure 19.1 showing the steps needed for balancing redox reactions by the half-reaction method was revised to make the individual steps clearer.
- New Worked Example 19.1 (Balancing a Redox Reaction in Acidic Solution): From the previous edition more detail was included so students can more easily follow the steps and canceling process when adding half-reactions.
- Revised Worked Example 19.2 (Balancing a Redox Reaction in Basic Solution): Added more detail so students can more easily follow the steps and canceling process when adding half-reactions.
- It is a convention in electrochemistry to put the anode half-cell on the left and cathode half-cell on the right. Several figures were changed to reflect this common convention.

- Worked Example 19.6 was revised to more clearly show the thought process for determining strengths of reducing agents.
- New Worked Example 19.8 was added on the very important concept of calculating voltage of a galvanic cell (a battery).
- The Inquiry was updated with recent status of commercialization of fuel-cell vehicles.

Chapter 20 Nuclear Chemistry

- In Section 20.3 Nuclear Stability, superheavy elements 113, 115, 117, and 118 were added to the periodic table. The discovery of these elements was connected to nuclear theory and the island of stability.
- In Section 20.3 Nuclear Stability, real examples of nuclear equations were provided instead of general equations to more clearly show how radioactive decay processes affect the neutron to proton ratio.
- Section 20.5 Dating with Radioisotopes was given its own section. The age of artifacts such as the Dead Sea Scrolls were updated based on improved methods of radiocarbon dating. The method of reporting artifact age using the term “Before Present (BP)” with the reference year 1950 was removed because it adds an extra step and is potentially confusing. The age of the object is now reported in the more conventional method of the time frame when the artifact was living. End-of-chapter problems were revised to match this change.
- In Section 20.7 Nuclear Fission and Fusion, Figure 20.9, which provides information on the number of nuclear reactors and nuclear power output worldwide, was updated.
- In Section 20.8 Nuclear Transmutation, information about the nuclear transformation reactions used in the synthesis of new elements $Z = 113-118$ was added, and new problems were written on this topic.
- New Inquiry topic: How are radioisotopes used in medicine? The previous text section was updated and expanded with some recent advances in nuclear medicine such as boron neutron capture therapy.

Chapter 21 Transition Elements and Coordination Chemistry

- Section 20.4 Chemistry of Selected Transition Elements was removed because it did not cover any new chemistry concepts and involved memorization of specific reactions that would not be retained easily. This content in this section is not needed to understand the main concepts of transition metal chemistry such as the color and magnetic properties of complexes.
- Modified Figure 21.9 to label the chelate ring discussed in the text description and added a Figure It Out Question in order to identify a chelate ring.
- Figure 21.24 showing colors of nickel complexes was moved next to text describing the accompanying crystal field diagrams. A description of the connection between the crystal field energy diagrams and the observed color of the complexes was added.
- The section Valence Bond Theory of Coordination Complexes is now placed at the end of the chapter to strengthen the connection between the color of coordination compounds and crystal field theory. The key terms *high-spin* and *low-spin complex* are now defined based on crystal field theory instead of valence bond theory.
- Also, crystal field theory was developed before valence bond theory. The text was modified to reiterate how crystal field theory is different from bonding theories based on quantum mechanics. (Also, many books do not cover valence bond theory of coordination complexes, so placing it last gives instructors the option to omit it.)

Chapter 22 The Main-Group Elements

- The chemistry of each main group was merged into its own section and the content trimmed to avoid excessive memorization.
- Continued emphasis on relating main-group chemistry to previous topics in the book such as periodic trends, bonding, structure, equilibrium, and acid-base chemistry. New end-of-chapter problems were written with emphasis on reviewing important chemical principles.

Chapter 23 Organic and Biological Chemistry

- Section 23.3 Naming Organic Compounds, was removed because the focus of the chapter is on bonding and structure, and naming is not needed to address these topics.
- In Section 23.1 Organic Molecules and Their Structures: Constitutional Isomers on organic molecules and their structures, the concept of constitutional isomers (instead of simply isomers) was stressed. This allows other important types of isomers such as enantiomers and cis-trans isomers to be distinguished and addressed in later sections.
- Unnumbered figure of 2-methylbutane was revised to more clearly show the zigzag structure of the carbon chain, which serves as the basis for organic line drawings.
- New Section 23.2 Stereoisomers: Chiral Molecules. Chirality is an extremely important concept with organic molecules, and the topic warrants its own section. Worked Examples and a set of end-of-chapter problems were developed.
- New Worked Example 23.4: Interpreting Line Drawings for Molecules with Functional Groups.
- New Inquiry on chiral molecules and their biological response to connect with new Section 23.2 Stereoisomers: Chiral Molecules on chiral molecules.

ACKNOWLEDGMENTS

Our thanks go to our families and to the many talented people who helped bring this new edition into being. We are grateful to Terry Haugen, Executive Courseware Portfolio Manager, for his insight and suggestions that improved the book; to Cathy Murphy, Coleen Morrison, and Jay McElroy for their critical review that made the manuscript and art program more understandable for students; to Elizabeth Bell, Senior Product Marketing Manager, who brought new energy to describing features of the 8th edition; and to Shercian Kinosian and Kelly Murphy for their production and editorial efforts. Thank you to Rebecca Marshall for coordinating art production and to Angelica D. Aranas for her photo research efforts.

We are particularly pleased to acknowledge the outstanding contributions of several colleagues who created the many important supplements that turn a textbook into a complete package:

- The author who updated the accompanying Test Bank.
- Joseph Topich, *Virginia Commonwealth University*, who prepared both the full and partial solutions manuals.
- Mark Benvenuto, *University of Detroit Mercy*, who contributed valuable content for the Instructor Resources.
- Kristi Mock, *University of Toledo*, who prepared the Student Study Guide to accompany this 8th edition.
- Dennis Taylor, *Clemson University*, who prepared the Instructor Resource Manual.
- Sandra Chimon-Rogers, *Calumet College of St. Joseph*, who updated the Laboratory Manual.

Finally, we want to thank all accuracy reviewers, text reviewers, and our colleagues at so many other institutions who read, criticized, and improved our work.

Jill K. Robinson
John McMurry
Robert C. Fay

REVIEWERS FOR THE EIGHTH EDITION

Stanley Bajue, Medger Evers College
 Joe Casalnuovo, Cal Poly, Pomona
 Kathryn Davis, Manchester University
 Sarah Edwards, Western Kentucky University
 Stacy O'Reilly, Butler University

Gabriela Smeureanu, Hunter College
 Lucinda Spryn, Thomas Nelson Community College
 Joe Topich, Virginia Commonwealth University
 Ken Tyrrell, Connors State College
 Zachary Varpness, Chadron State College

REVIEWERS OF THE PREVIOUS EDITIONS OF CHEMISTRY

James Almy, Golden West College
 Laura Andersson, Big Bend Community College
 David Atwood, University of Kentucky
 James Ayers, Colorado Mesa University
 Mufeed Basti, North Carolina A&T State University
 David S. Ballantine, Northern Illinois University
 Debbie Beard, Mississippi State University
 Robert Blake, Glendale Community College
 Ronald Bost, North Central Texas University
 Danielle Brabazon, Loyola College
 Gary Buckley, Cameron University
 Robert Burk, Carleton University
 Ken Capps, Central FL Community College
 Joe Casalnuovo, Cal Poly Pomona
 Myron Cherry, Northeastern State University
 Sandra Chimon-Rogers, Calumet College of St. Joseph
 Allen Clabo, Francis Marion University
 Claire Cohen, University of Toledo
 Paul Cohen, University of New Jersey
 Katherine Covert, West Virginia University
 David De Haan, University of San Diego
 Nordulf W. G. Debye, Towson University
 Dean Dickerhoof, Colorado School of Mines
 David Dobberpuhl, Creighton University
 Kenneth Dorris, Lamar University
 Jon A. Draeger, University of Pittsburgh at Bradford
 Brian Earle, Cedar Valley College
 Amina El- Ashmawy, Collin County Community College
 Joseph W. Ellison, United States Military Academy at West Point
 Erik Eriksson, College of the Canyons
 Peter M. Fichte, Coker College
 Kathy Flynn, College of the Canyons
 Joanne Follweiler, Lafayette College
 Ted Foster, Folsom Lake College
 Cheryl Frech, University of Central Oklahoma
 Mark Freilich, University of Memphis
 Mark Freitag, Creighton University
 Travis Fridgen, Memorial University of Newfoundland
 Chammi Gamage-Miller, Blinn College–Bryan Campus
 Rachel Garcia, San Jacinto College
 Katherine Geiser-Bush, Durham Technical Community College
 Jack Goldsmith, University of South Carolina Aiken
 Carolyn Griffin, Grand Canyon University
 Nathaniel Grove, UNC Wilmington
 Thomas Grow, Pensacola Junior College
 Mildred Hall, Clark State University

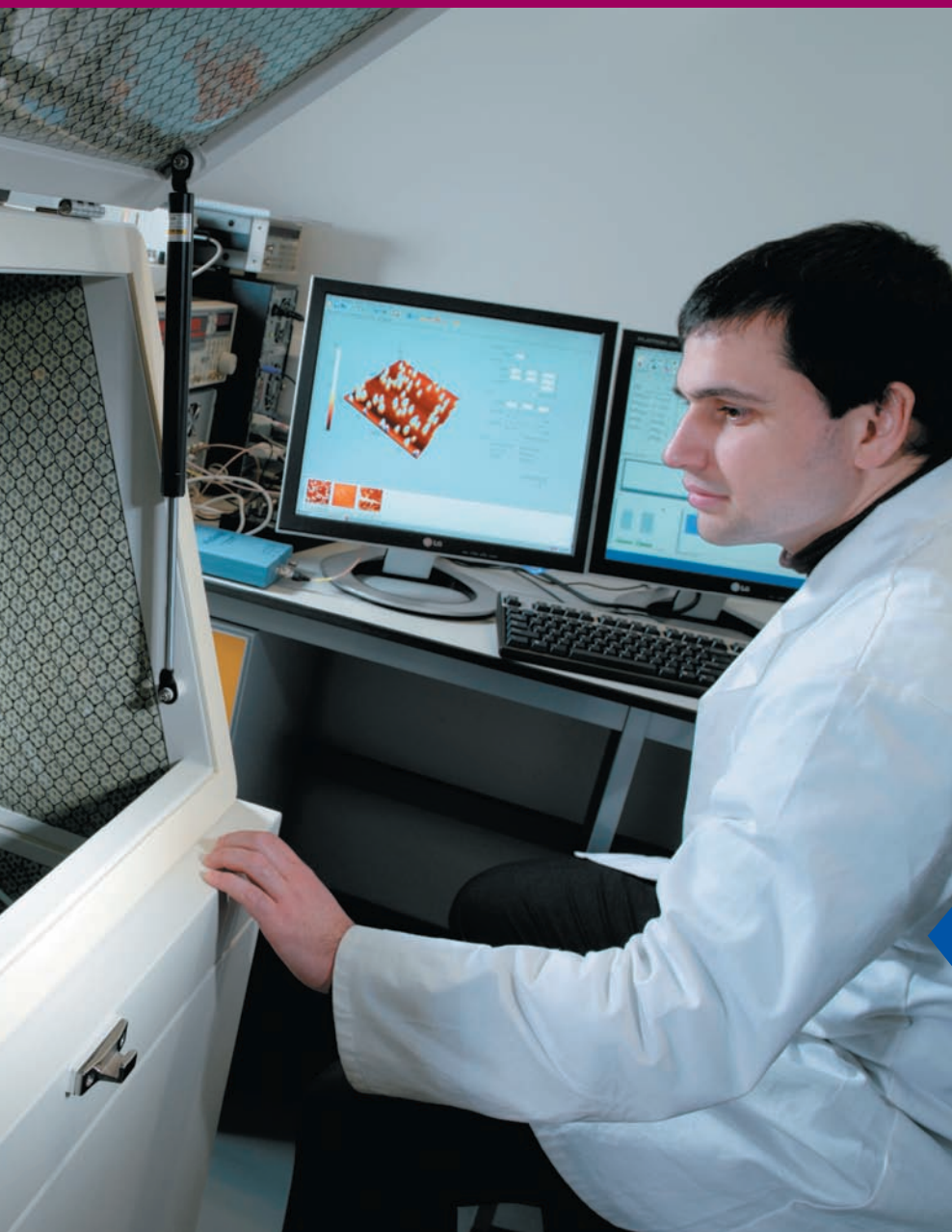
Tracy A. Halmi, Pennsylvania State University Erie
 Keith Hansen, Lamar University
 Lois Hansen-Polcar, Cuyahoga Community College
 Wesley Hanson, John Brown University
 Alton Hassell, Baylor University
 Michael Hauser, St. Louis Community College–Meramec
 M. Dale Hawley, Kansas State University
 Patricia Heiden, Michigan Tech University
 Sherman Henzel, Monroe Community College
 Thomas Hermann, University of California–San Diego
 Thomas Herrington, University of San Diego
 Margaret E. Holzer, California State University–Northridge
 Geoff Hoops, Butler University
 Todd Hopkins, Baylor University
 Narayan S. Hosmane, Northern Illinois University
 Jeff Joens, Florida International University
 Andy Jorgensen, University of Toledo
 Jerry Keister, University of Buffalo
 Chulsung Kim, University of Dubuque
 Angela King, Wake Forest University
 Regis Komperda, Wright State University
 Ranjit Koodali, University of South Dakota
 Peter Kuhlman, Denison University
 Valerie Land, University of Arkansas Community College
 John Landrum, Florida International University
 Leroy Laverman, University of California–Santa Barbara
 Celestia Lau, Lorain County Community College
 Stephen S. Lawrence, Saginaw Valley State University
 David Leddy, Michigan Technological University
 Shannon Lieb, Butler University
 Don Linn, IUPU Fort Wayne
 Karen Linscott, Tri-County Technical College
 Irving Lipschitz, University of Massachusetts–Lowell
 Rosemary Loza, Ohio State University
 Rudy Luck, Michigan Technological University
 Rod Macrae, Marian University
 Riham Mahfouz, Thomas Nelson Community College
 Ashley Mahoney, Bethel College
 Jack F. McKenna, St. Cloud State University
 Craig McLauchlan, Illinois State University
 Iain McNab, University of Toronto
 Christina Mewhinney, Eastfield College
 David Miller, California State University–Northridge
 Rebecca S. Miller, Texas Tech University
 Abdul Mohammed, North Carolina A&T State University
 Linda Mona, United States Naval Academy

Edward Mottell, Rose-Hulman Institute
Ed Navarre, Southern Illinois University Edwardsville
Christopher Nichols, California State University–Chico
Gayle Nicoll, Texas Technological University
Mya Norman, University of Arkansas
Allyn Ontko, University of Wyoming
Robert H. Paine, Rochester Institute of Technology
Cynthia N. Peck, Delta College
Eileen Pérez, University of South Florida
Kris Quinlan, University of Toronto
Betsy Ratcliffe, West Virginia University
Al Rives, Wake Forest University
Richard Roberts, Des Moines Area Community College–Ankeny
Michael R. Ross, College of St. Benedict/St. John’s University
Lev Ryzhkov, Towson University
Svein Saebo, Mississippi State University
Mark Schraf, West Virginia University
John Schreifels, George Mason University
Patricia Schroeder, Johnson County Community College
David Shoop, John Brown University
Penny Snetsinger, Sacred Heart University

Robert L. Snipp, Creighton University
Steven M. Socol, McHenry County College
Thomas E. Sorensen, University of Wisconsin–Milwaukee
L. Sreerama, St. Cloud State University
Keith Stein, University of Missouri–St. Louis
Beth Steiner, University of Akron
Kelly Sullivan, Creighton University
Susan Sutheimer, Green Mountain College
Andrew Sykes, University of South Dakota
Erach Talaty, Wichita State University
Edwin Thall, Florida Community College at Jacksonville
Lydia Tien, Monroe Community College
Donald Van Derveer, Georgia Institute of Technology
John B. Vincent, University of Alabama
Erik Wasinger, California State University–Chico
Steve Watton, Virginia Commonwealth University
Marcy Whitney, University of Alabama
James Wu, Tarrant County Community College
Mingming Xu, West Virginia University
Crystal Lin Yau, Towson University
James Zubricky, University of Toledo

chapter 1

Chemical Tools: Experimentation and Measurement



Contents

- 1.1 The Scientific Method: Nanoparticle Catalysts for Fuel Cells
- 1.2 Measurements: SI Units and Scientific Notation
- 1.3 Mass and Its Measurement
- 1.4 Length and Its Measurement
- 1.5 Temperature and Its Measurement
- 1.6 Derived Units: Volume and Its Measurement
- 1.7 Derived Units: Density and Its Measurement
- 1.8 Derived Units: Energy and Its Measurement
- 1.9 Accuracy, Precision, and Significant Figures in Measurement
- 1.10 Significant Figures in Calculations
- 1.11 Converting from One Unit to Another

STUDY GUIDE
PRACTICE TEST

Instruments for scientific measurements have changed greatly over the centuries. Modern technology has enabled scientists to make images of extremely tiny particles, even individual atoms, using instruments like this atomic force microscope.

What are the unique properties of nanoscale ($1 \text{ nm} = 10^{-9} \text{ m}$) materials?

The answer to this question can be found on page 23 in the





▲ The sequence of the approximately 5.8 billion nucleic acid units, or *nucleotides*, present in the human genome has been determined using instruments like this automated DNA sequencer.

Life has changed more in the past two centuries than in all the previously recorded span of human history. The Earth's population has increased sevenfold since 1800, and life expectancy has nearly doubled because of our ability to synthesize medicines, control diseases, and increase crop yields. Methods of transportation have changed from horses and buggies to automobiles and airplanes because of our ability to harness the energy in petroleum. Many goods are now made of polymers and ceramics instead of wood and metal because of our ability to manufacture materials with properties unlike any found in nature.

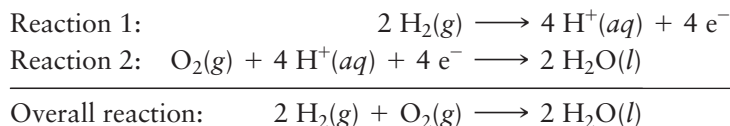
In one way or another, all these changes involve **chemistry**, the study of the composition, properties, and transformations of matter. Chemistry is deeply involved in both the changes that take place in nature and the profound social changes of the past two centuries. In addition, chemistry is central to the current revolution in molecular biology that is revealing the details of how life is genetically regulated. No educated person today can understand the modern world without a basic knowledge of chemistry.

1.1 THE SCIENTIFIC METHOD: NANOPARTICLE CATALYSTS FOR FUEL CELLS

By opening this book, you have already decided that you need to know more about chemistry to pursue your future goals. Perhaps you want to learn how living organisms function, how medicines are made, how human activities change the environment, or how alternative fuels produce clean energy. A good place to start is by learning the experimental approach used by scientists to make new discoveries. Do not worry if you do not understand all the details of the chemistry yet, as our focus is on the process of modern interdisciplinary research.

Let's examine a nanoscience application to illustrate the scientific method and how chemical principles are applied to make materials with novel properties. **Nanoscience** is the production and study of structures that have at least one dimension between 1 and 100 nm, where one nanometer is one billionth of a meter. Research on nanomaterials is a fast-growing, multidisciplinary enterprise spanning the fields of chemistry, physics, biology, medicine, materials science, and engineering. Inorganic crystals that have nanoscale dimensions exhibit different properties than bulk material as described in more detail the Inquiry section of this chapter. The properties depend on the size of the particle and can be tuned for applications such as tools for diagnosing and treating disease or platforms for sustainable energy.

One research area is the use of nanoparticle catalysts for reactions occurring in fuel cells. A **catalyst** is a substance that speeds up the rate of a chemical reaction. A **fuel cell** is a device that uses a fuel such as hydrogen to produce electricity. Fuel cells operate much like a battery, but they require a continuous input of fuel. Two reactions occur at two different electrodes in a hydrogen fuel cell. At one electrode, hydrogen (H_2) is converted to protons (H^+), and at the other electrode, oxygen (O_2) reacts with protons to produce water. The reactions in the fuel cell involve a transfer of electrons and are called **redox reactions**. The electrons produced by reaction 1 (below) travel through a wire and are used in reaction 2. The movement of electrons through a wire generates electricity. A fuel cell is considered to be *zero emission* because the overall reaction of hydrogen with oxygen produces electricity but pure water is the only product.



Fuel cells are a promising technology in the quest for a carbon-neutral energy economy, but one obstacle to their use is the slow rate of conversion of oxygen to water in reaction 2. Platinum particles coated on the surface of the electrode have been used as a catalyst to speed up the reaction, but platinum is very expensive. Nanoparticles made

LOOKING AHEAD . . .

The rates of chemical reactions and how they are increased by **catalysts** are described in Chapter 14.

LOOKING AHEAD . . .

Chapter 4 describes different types of reactions including **redox reactions** that involve a transfer of electrons. We'll see in Chapter 19 how redox reactions can be used to generate electricity in a **fuel cell**.

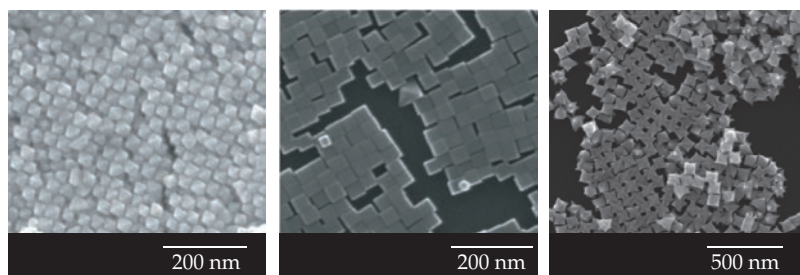
from palladium alloys have shown promise as a cost-effective alternative catalyst. An **alloy** is a mixture of metals, and therefore a palladium alloy is a mixture of palladium (Pd) and some other metal such as copper (Cu).

In order to develop a useful catalyst for hydrogen fuel cells, chemists apply the scientific method to carefully control different characteristics of PdCu nanoparticles and measure their effect on the rate of the oxygen reaction. Some characteristics of nanoparticles that can be varied are relative amounts of palladium and copper, the size of the particles, and the shape of the particles. Amazingly nanoparticles exist in a variety of shapes including spheres, cubes, and octopods (**FIGURE 1.1**)!



BIG IDEA Question 1

What is an obstacle to the widespread use of hydrogen fuel cells, and how can nanoparticles be used to overcome the problem?



◀ **FIGURE 1.1**

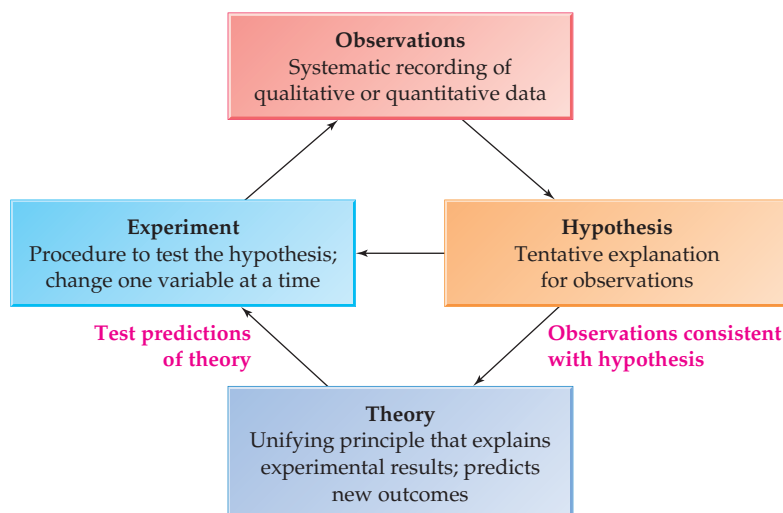
From left to right, scanning electron microscopy images of octahedral gold nanoparticles, cubic palladium nanoparticles, and eight-branched gold-palladium nanoparticles called “octopods.” Note that the orientation of the octopodal nanoparticles allows only four of the branches to be viewed at a time.

Images courtesy of the Skrabalak research group at Indiana University.

The Scientific Method

A general approach to research is called the **scientific method**. The scientific method is an iterative process involving the formulation of questions arising from observations, careful design of experiments, and thoughtful analysis of results. The scientific method involves identifying ways to test the validity of new ideas, and seldom is there only one way to go about it. The main elements of the scientific method, outlined in **FIGURE 1.2**, are the following:

- **Observation.** **Observations** are a systematic recording of natural phenomena and may be **qualitative**, descriptive in nature, or **quantitative**, involving measurements.
- **Hypothesis.** A **hypothesis** is a possible explanation for the observation developed based upon facts collected from previous experiments as well as scientific knowledge



◀ **FIGURE 1.2**

The scientific method. An iterative experimental approach is used in scientific research. Hypotheses and theories are refined based on new experiments and observations.

◀ Figure It out

What is developed when numerous experimental observations support a hypothesis?

Answer: Theory

and intuition. The hypothesis may not be correct, but it must be testable with an experiment.

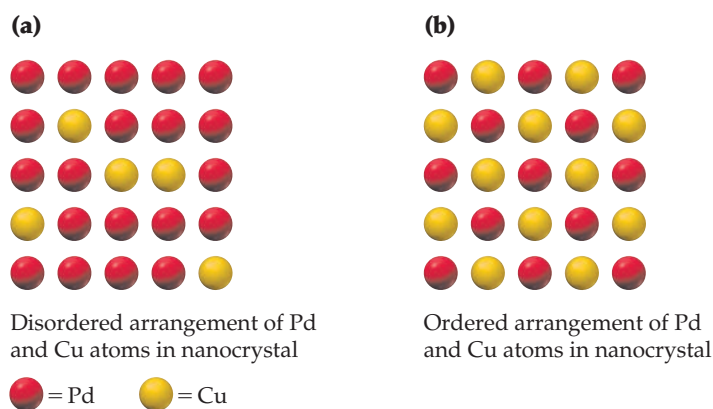
- **Experiment.** An **experiment** is a procedure for testing the hypothesis. Experiments are most useful when they are performed in a *controlled* manner, meaning that only one variable is changed at a time while all others remain constant.
- **Theory.** A **theory** is developed from a hypothesis consistent with experimental data and is a unifying principle that explains experimental results. It also makes predictions about related systems, and new experiments are carried out to verify the theory.

Keep in mind as you study chemistry or any other science that theories can never be absolutely proven. There's always the chance that a new experiment might give results that can't be explained by present theory. All a theory can do is provide the best explanation that we can come up with at the present time. Science is an ever-changing field where new observations are made with increasingly sophisticated equipment; it is always possible that existing theories may be modified in the future.

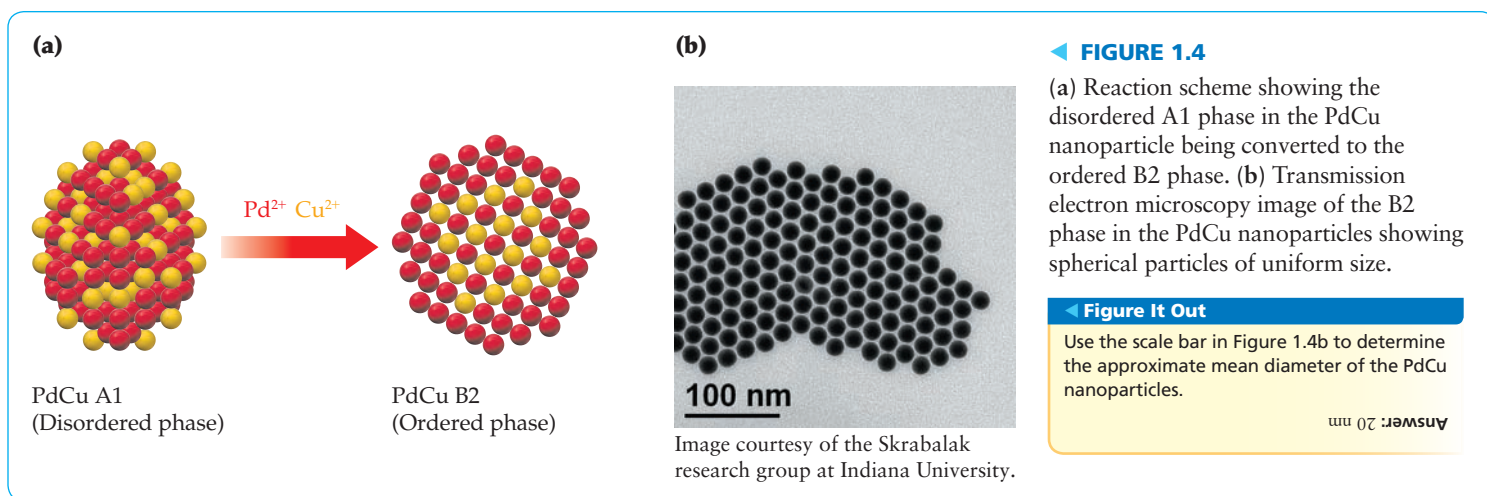
Scientific research begins with a driving question that is frequently based on experimental observations or a desire to learn about the unknown. In the case of PdCu nanoparticles, an observed increase in the fuel cell reaction rate led to the question "How can variables related to size, shape, and composition of nanoparticles be controlled to optimize catalytic activity?" Professor Sara Skrabalak at Indiana University leads a team of scientists researching methods for synthesizing high-quality nanomaterials, where these variables are precisely controlled. Although previous research projects involving numerous techniques attempted to control the size, shape, and composition of the nanoparticles, the distributions of palladium and copper atoms in the crystals were found to be statistically random. **FIGURE 1.3a** illustrates a random or disordered arrangement of Pd and Cu atoms in a crystal. **FIGURE 1.3b** illustrates an ordered arrangement with a pattern of alternating Pd and Cu atoms. Without fixed arrangements of atoms, it is impossible to correlate chemical structure with properties such as catalytic activity.

► **FIGURE 1.3**

Simple schematic of the arrangement of Pd and Cu atoms in a nanocrystal. (a) A disordered arrangement of Pd and Cu atoms does not have a repeating pattern. (b) An ordered arrangement of atoms has the repeating pattern of alternating Pd and Cu atoms.



The general hypothesis that the Skrabalak group tested was that larger PdCu nanoparticles with lower surface energies would facilitate the transition from disordered to ordered structures. Student researchers carefully controlled the rate of particle growth by depositing palladium and copper on the surface of a smaller particle. Then various imaging techniques were used to elucidate the atomic-level structure of the nanoparticles and measure their size distribution. Electron microscopy data revealed a thin shell of Pd over an ordered PdCu core called the B2 phase. **FIGURE 1.4a** shows a

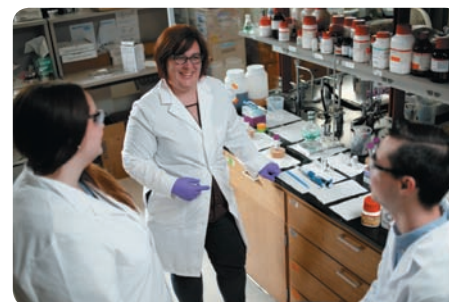


random distribution of Pd and Cu atoms in the A1 phase that was converted by new synthesis methods to the ordered B2 phase. **FIGURE 1.4b** shows a transmission electron microscope image of PdCu nanoparticles in the B2 phase. The spherical particles have a uniform size distribution with a mean diameter of 18.9 nm.

Many iterations of the scientific method were used by the researchers to devise controlled synthesis techniques for PdCu nanoparticles. Observations from experiments led to new hypotheses and additional experiments to test them. Once studies of the growth mechanism enabled reproducible synthesis of ordered PdCu nanoparticles, they were tested for catalytic activity. The ordered nanoparticles exhibited superior catalytic activity in increasing the rate of oxygen reaction in the fuel cell when compared with PdCu nanoparticles with disordered structures. In summary, Professor Skrabalak's research on nanomaterial synthesis leads to the design of better nanoparticle catalysts for fuel cells and other applications.

Many different chemical principles that you will learn about in this book are central to the design of nanomaterials. In Chapter 8, Bonding Theories and Molecular Structure, you will learn about bonds and forces that cause atoms to aggregate into nanoparticles. Chapter 4, Reactions in Aqueous Solutions, describes how to calculate solution concentrations important in synthetic techniques. Rates of reactions and factors that influence them are explored in Chapter 14, Kinetics. In Chapter 19, on electrochemistry, redox reactions central to forming nanoparticles are described.

At universities around the world, students participate in research projects like the one on nanoparticle synthesis and characterization just described. It is the authors' sincere hope that by reading this book you can gain an appreciation for how chemistry is used in solving many of the world's problems and you become competent with the essential chemical principles needed to contribute to important research projects.



▲ Professor Sara Skrabalak in the lab with undergraduate student researchers working on the synthesis of nanoparticles. Photo courtesy of Indiana University.

1.2 MEASUREMENTS: SI UNITS AND SCIENTIFIC NOTATION

Chemistry is an experimental science. But if our experiments are to be reproducible, we must be able to fully describe the substances we're working with—their amounts, volumes, temperatures, and so forth. Thus, one of the most important requirements in chemistry is that we have a way to measure things.

Under an international agreement concluded in 1960, scientists throughout the world now use the International System of Units for measurement, abbreviated **SI unit** for the French *Système Internationale d'Unités*. Based on the metric system, which is used in all industrialized countries of the world except the United States, the SI system has seven fundamental units (**TABLE 1.1**). These seven fundamental units, along with others derived from them, suffice for all scientific measurements. We'll look at three of

BIG IDEA Question 2

What are the fundamental SI units of measure for mass, length, and temperature?

TABLE 1.1 The Seven Fundamental SI Units of Measure

Physical Quantity	Name of Unit	Abbreviation
Mass	kilogram	kg
Length	meter	m
Temperature	kelvin	K
Amount of substance	mole	mol
Time	second	s
Electric current	ampere	A
Luminous intensity	candela	cd

the most common units in this chapter—those for mass, length, and temperature—and will discuss others as the need arises in later chapters.

One problem with any system of measurement is that the sizes of the units often turn out to be inconveniently large or small. For example, a chemist describing the diameter of a sodium atom (0.000 000 000 372 m) would find the meter (m) to be inconveniently large, but an astronomer describing the average distance from the Earth to the Sun (150,000,000,000 m) would find the meter to be inconveniently small. For this reason, SI units are modified through the use of prefixes when they refer to either smaller or larger quantities. Thus, the prefix *milli-* means one-thousandth, and a *millimeter* (mm) is 1/1000 of 1 meter. Similarly, the prefix *kilo-* means one thousand, and a *kilometer* (km) is 1000 meters. (Note that the SI unit for mass [kilogram] already contains the *kilo-* prefix.) A list of prefixes is shown in **TABLE 1.2**, with the most commonly used ones in red.

Notice how numbers that are either very large or very small are indicated in Table 1.2 using an exponential format called **scientific notation**. For example, the number 55,000 is written in scientific notation as 5.5×10^4 and the number 0.003 20 as 3.20×10^{-3} .

TABLE 1.2 Some Prefixes for Multiples of SI Units. Common prefixes and symbols in the chemical sciences are shown in red

Factor	Prefix	Symbol	Example
1,000,000,000,000 = 10^{12}	tera	T	1 teragram (Tg) = 10^{12} g
1,000,000,000 = 10^9	giga	G	1 gigameter (Gm) = 10^9 m
1,000,000 = 10^6	mega	M	1 megameter (Mm) = 10^6 m
1000 = 10^3	kilo	k	1 kilogram (kg) = 10^3 g
100 = 10^2	hecto	h	1 hectogram (hg) = 100 g
10 = 10^1	deka	da	1 dekagram (dag) = 10 g
0.1 = 10^{-1}	deci	d	1 decimeter (dm) = 0.1 m
0.01 = 10^{-2}	centi	c	1 centimeter (cm) = 0.01 m
0.001 = 10^{-3}	milli	m	1 milligram (mg) = 0.001 g
*0.000 001 = 10^{-6}	micro	μ	1 micrometer (μ m) = 10^{-6} m
*0.000 000 001 = 10^{-9}	nano	n	1 nanosecond (ns) = 10^{-9} s
*0.000 000 000 001 = 10^{-12}	pico	p	1 picosecond (ps) = 10^{-12} s
*0.000 000 000 000 001 = 10^{-15}	femto	f	1 femtomole (fmol) = 10^{-15} mol

*For very small numbers, it is becoming common in scientific work to leave a thin space every three digits to the right of the decimal point, analogous to the comma placed every three digits to the left of the decimal point in large numbers.

Review Appendix A if you are uncomfortable with scientific notation or if you need to brush up on how to do mathematical manipulations on numbers with exponents.

Notice also that all measurements contain both a number and a unit label. A number alone is not much good without a unit to define it. If you asked a friend how far it was to the nearest tennis court, the answer “3” alone wouldn’t tell you much: 3 blocks? 3 kilometers? 3 miles? Worked Example 1.1 explains how to write a number in scientific notation and represent the unit in prefix notation.

WORKED EXAMPLE 1.1

Expressing Measurements Using Scientific Notation and SI Units

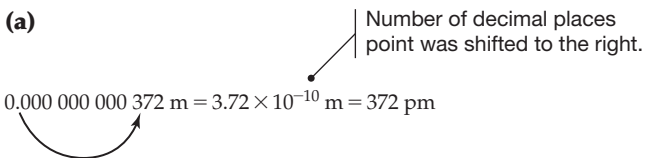
Express the following quantities in scientific notation and then express the number and unit with the most appropriate prefix.

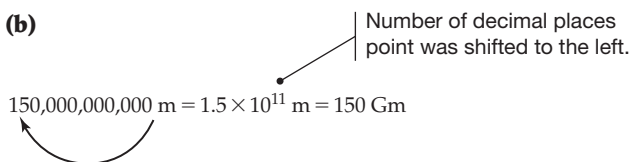
- (a) The diameter of a sodium atom, 0.000 000 000 372 m
 (b) The distance from the Earth to the Sun, 150,000,000,000 m

STRATEGY

To write a number in scientific notation, shift the decimal point to the right or left by n places until you obtain a number between 1 and 10. If the decimal is shifted to the right, n is negative, and if the decimal is shifted to the left, n is positive. Then multiply the result by 10^n . Choose a prefix for the unit that is close to the exponent of the number written in scientific notation.

SOLUTION

(a)  $0.000\,000\,000\,372\text{ m} = 3.72 \times 10^{-10}\text{ m} = 372\text{ pm}$

(b)  $150,000,000,000\text{ m} = 1.5 \times 10^{11}\text{ m} = 150\text{ Gm}$

► **PRACTICE 1.1** Express the diameter of a nanoparticle (0.000 000 050 m) in scientific notation, and then express the number and unit with the most appropriate prefix.

► **APPLY 1.2** Express the following quantities in scientific notation using fundamental SI units of mass and length given in Table 1.1.

- (a) The diameter of a human hair, 70 μm
 (b) The mass of carbon dioxide emitted from a large power plant each year, 20 Tg

All **PRACTICE** and **APPLY** problems are interactive in the eText.

1.3 MASS AND ITS MEASUREMENT

Mass is defined as the amount of *matter* in an object. **Matter**, in turn, is a catch-all term used to describe anything with a physical presence—anything you can touch, taste, or smell. (Stated more scientifically, matter is anything that has mass.) Mass is measured in SI units by the **kilogram (kg)**; 1 kg = 2.205 U.S. lb). Because the kilogram is too large for many purposes in chemistry, the metric **gram (g)**; 1 g = 0.001 kg), the **milligram (mg)**; 1 mg = 0.001 g = 10^{-6} kg), and the **microgram (μg)**; 1 μg = 0.001 mg = 10^{-6} g = 10^{-9} kg) are more commonly used. (The symbol μ is the lowercase Greek letter mu.) One gram is a bit less than half the mass of a new U.S. dime.



▲ The mass of a U.S. dime is approximately 2.27 g.

$$\begin{aligned}
 1 \text{ kg} &= 1000 \text{ g} = 1,000,000 \text{ mg} = 1,000,000,000 \text{ } \mu\text{g} && (2.205 \text{ lb}) \\
 1 \text{ g} &= 1000 \text{ mg} = 1,000,000 \text{ } \mu\text{g} && (0.035 27 \text{ oz}) \\
 1 \text{ mg} &= 1000 \text{ } \mu\text{g}
 \end{aligned}$$

The standard kilogram is set as the mass of a cylindrical bar of platinum–iridium alloy stored in a vault in a suburb of Paris, France. There are 40 copies of this bar distributed throughout the world, with two (Numbers 4 and 20) stored at the U.S. National Institute of Standards and Technology near Washington, D.C.

The terms *mass* and *weight*, although often used interchangeably, have quite different meanings. *Mass* is a physical property that measures the amount of matter in an object, whereas *weight* measures the force with which gravity pulls on an object. Mass is independent of an object's location: your body has the same amount of matter whether you're on Earth or on the moon. Weight, however, *does* depend on an object's location. If you weigh 140 lb on Earth, you would weigh only about 23 lb on the moon, which has a lower gravity than the Earth.

At the same location on Earth, two objects with identical masses experience an identical pull of the Earth's gravity and have identical weights. Thus, the mass of an object can be measured by comparing its weight to the weight of a reference standard of known mass. Much of the confusion between mass and weight is simply due to a language problem. We speak of “weighing” when we really mean that we are measuring mass by comparing two weights. **FIGURE 1.5** shows balances typically used for measuring mass in the laboratory.

BIG IDEA Question 3



Which prefix for the unit of grams is most appropriate for reporting the mass of a grain of sand?

► FIGURE 1.5

Some balances used for measuring mass in the laboratory.



BIG IDEA Question 4



Which prefix for the unit of meter is most appropriate for reporting the diameter of a molecule?

1.4 LENGTH AND ITS MEASUREMENT

The **meter (m)** is the standard unit of length in the SI system. Although originally defined in 1790 as being 1 ten-millionth of the distance from the equator to the North Pole, the meter was redefined in 1889 as the distance between two thin lines on a bar of platinum–iridium alloy stored near Paris, France. To accommodate an increasing need for precision, the meter was redefined again in 1983 as equal to the distance traveled by light through a vacuum in 1/299,792,458 second. Although this new definition isn't as easy to grasp as the distance between two scratches on a bar, it has the great advantage that it can't be lost or damaged.

One meter is 39.37 inches, about 10% longer than an English yard and much too large for most measurements in chemistry. Other more commonly used measures of length are the **centimeter (cm)**; 1 cm = 0.01 m, a bit less than half an inch), the **millimeter (mm)**; 1 mm = 0.001 m, about the thickness of a U.S. dime), the **micrometer (μm)**; 1 μm = 10^{-6} m), the **nanometer (nm)**; 1 nm = 10^{-9} m), and the **picometer (pm)**; 1 pm = 10^{-12} m). Thus, a chemist might refer to the diameter of a sodium atom as 372 pm (3.72×10^{-10} m).

1 m = 100 cm = 1000 mm = 1,000,000 μm = 1,000,000,000 nm (1.0936 yd)
 1 cm = 10 mm = 10,000 μm = 10,000,000 nm (0.3937 in.)
 1 mm = 1000 μm = 1,000,000 nm

1.5 TEMPERATURE AND ITS MEASUREMENT

Just as the kilogram and the meter are slowly replacing the pound and the yard as common units for mass and length measurement in the United States, the Celsius degree ($^{\circ}\text{C}$) is slowly replacing the degree Fahrenheit ($^{\circ}\text{F}$) as the common unit for temperature measurement. In scientific work, however, the kelvin (**K**) has replaced both. (Note that we say only “kelvin,” not “degree kelvin.”)

For all practical purposes, the kelvin and the degree Celsius are the same—both are one-hundredth of the interval between the freezing point of water and the boiling point of water at standard atmospheric pressure. The only real difference between the two units is that the numbers assigned to various points on the scales differ. Whereas the Celsius scale assigns a value of 0°C to the freezing point of water and 100°C to the boiling point of water, the Kelvin scale assigns a value of 0 K to the coldest possible temperature, -273.15°C , sometimes called *absolute zero*. Thus, $0\text{ K} = -273.15^{\circ}\text{C}$ and $273.15\text{ K} = 0^{\circ}\text{C}$. For example, a warm spring day with a Celsius temperature of 25°C has a Kelvin temperature of $25 + 273.15 = 298\text{ K}$.



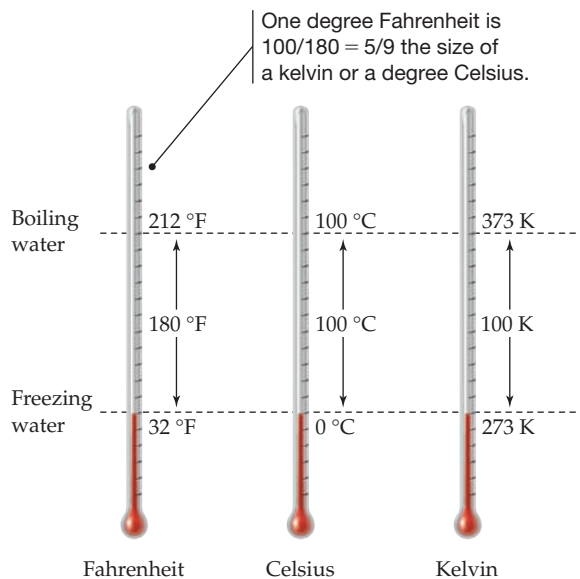
▲ The length of the bacteria on the tip of this pin is about $5 \times 10^{-7}\text{ m}$ or 500 nm.

Relationship between the Kelvin and Celsius scales

$$\begin{aligned} \text{Temperature in K} &= \text{Temperature in } ^{\circ}\text{C} + 273.15 \\ \text{Temperature in } ^{\circ}\text{C} &= \text{Temperature in K} - 273.15 \end{aligned}$$

In contrast to the Kelvin and Celsius scales, the common Fahrenheit scale specifies an interval of 180° between the freezing point (32°F) and the boiling point (212°F) of water. Thus, it takes 180 degrees Fahrenheit to cover the same range as 100 degrees Celsius (or kelvins), and a degree Fahrenheit is therefore only $100/180 = 5/9$ as large as a degree Celsius. **FIGURE 1.6** compares the Fahrenheit, Celsius, and Kelvin scales.

Two adjustments are needed to convert between Fahrenheit and Celsius scales—one to adjust for the difference in degree size and one to adjust for the difference in zero points. The size adjustment is made using the relationships $1^{\circ}\text{C} = (9/5)^{\circ}\text{F}$



◀ **FIGURE 1.6**

A comparison of the Fahrenheit, Celsius, and Kelvin temperature scales.

◀ Figure It Out

Which represents the largest increase in temperature: $+10^{\circ}\text{F}$, $+10^{\circ}\text{C}$, or $+10\text{ K}$?

Answer: Temperature changes of $+10^{\circ}\text{C}$ or $+10\text{ K}$ are equal and larger than $+10^{\circ}\text{F}$.