

Contents

1 Introduction to Biological Concepts and Research 1

- 1.1 What Is Life? Characteristics of Living Organisms 2
- 1.2 Biological Evolution 7
- 1.3 Biodiversity and the Tree of Life 9
- 1.4 Biological Research 14
 - Review Key Concepts 21
 - Test Your Knowledge 22
- CLOSER LOOK** Figure 1.11: Phylogenetic View of the Tree of Life 11
- CLOSER LOOK** Figure 1.14: The Process of Science 15
- Figure 1.15 Experimental Research** Hypothetical Experiment Illustrating the Use of Control Treatment and Replicates 17
- Figure 1.16 Observational Research** A Field Study Using a Null Hypothesis 19

Unit One Molecules and Cells

2 Life, Chemistry, and Water 24

- 2.1 The Organization of Matter: Elements and Atoms 24
- 2.2 Atomic Structure 26
- 2.3 Chemical Bonds and Chemical Reactions 30
- 2.4 Hydrogen Bonds and the Properties of Water 35
- 2.5 Water Ionization and Acids, Bases, and Buffers 38
 - Review Key Concepts 42
 - Test Your Knowledge 42
- Focus on Research** Applied Research: Using Radioisotopes in Medicine 27

3 Biological Molecules: The Carbon Compounds of Life 44

- 3.1 Formation and Modification of Biological Molecules 45
- 3.2 Carbohydrates 49
- 3.3 Lipids 52
- 3.4 Proteins 57
- 3.5 Nucleotides and Nucleic Acids 65
 - Review Key Concepts 70
 - Test Your Knowledge 71
- Focus on Research** Applied Research: Fats, Cholesterol, and Coronary Artery Disease 54
- Figure 3.21 Experimental Research** Anfinsen's Experiment Demonstrating That the Amino Acid Sequence of a Protein Specifies Its Tertiary Structure 63
- Molecular Insights** A Big Bang in Protein Structure Evolution: How did the domain organization in proteins evolve? 65

4 Cells 73

- 4.1 Basic Features of Cell Structure and Function 74
- 4.2 Prokaryotic Cells 78
- 4.3 Eukaryotic Cells 79
- 4.4 Specialized Structures of Plant Cells 95
- 4.5 The Animal Cell Surface 98
 - Review Key Concepts 100
 - Test Your Knowledge 101
- Figure 4.4 Research Method** Light and Electron Microscopy 76
- Figure 4.8 Research Method** Cell Fractionation 80
- Figure 4.11 Experimental Research** Discovery of the Nuclear Localization Signal 84
- Molecular Insights** Identification of Human Proteins That Regulate Secretion Using a Genome-Wide Analysis 88
- CLOSER LOOK** Figure 4.17: Vesicle Traffic in the Cytoplasm 90

5 Membranes and Transport 104

- 5.1 Membrane Structure and Function 105
- 5.2 Functions of Membranes in Transport: Passive Transport 111
- 5.3 Passive Water Transport and Osmosis 114
- 5.4 Active Transport 116
- 5.5 Exocytosis and Endocytosis 119
 - Review Key Concepts 123
 - Test Your Knowledge 124
- Focus on Research** Basic Research: Keeping Membranes Fluid at Cold Temperatures 108
- Figure 5.6 Experimental Research** The Frye–Edidin Experiment Demonstrating That the Phospholipid Bilayer Is Fluid 109
- Figure 5.7 Research Method** Freeze Fracture 110
- CLOSER LOOK** Figure 5.11: Active Transport: The Na^+/K^+ Pump, an Active Transport Protein in the Plasma Membrane 117
- Molecular Insights** Research Serendipity: The discovery of receptor-mediated endocytosis 121

6 Energy, Enzymes, and Biological Reactions 126

- 6.1 Energy, Life, and the Laws of Thermodynamics 127
- 6.2 Free Energy and Spontaneous Reactions 129
- 6.3 Adenosine Triphosphate (ATP): The Energy Currency of the Cell 131
- 6.4 Role of Enzymes in Biological Reactions 133
- 6.5 Conditions and Factors That Affect Enzyme Activity 136
- 6.6 RNA-Based Biological Catalysts: Ribozymes 140
 - Review Key Concepts 142
 - Test Your Knowledge 143
- Molecular Insights** Ribozymes: Can RNA catalyze peptide bond formation in protein synthesis? 141

7 Cellular Respiration: Harvesting Chemical Energy 146

- 7.1 Overview of Cellular Respiration 147
 - 7.2 Glycolysis: Splitting the Sugar in Half 151
 - 7.3 Pyruvate Oxidation and the Citric Acid Cycle 153
 - 7.4 Oxidative Phosphorylation: The Electron Transfer System and Chemiosmosis 155
 - 7.5 Anaerobic Respiration and Fermentation 161
 - 7.6 Interrelationships of Catabolic and Anabolic Pathways
- Review Key Concepts 166
- Test Your Knowledge 167

CLOSER LOOK Figure 7.11: Oxidative Phosphorylation: The Mitochondrial Electron Transfer System and Chemiosmosis 156

Molecular Insights The Mitochondrial Proteome: How does the mitochondrial proteome vary among organs and organisms? 158

Figure 7.13 Experimental Research The Racker and Stoekienius Experiment Demonstrating That an H^+ Gradient Powers ATP Synthesis by ATP Synthase 159

8 Photosynthesis 169

- 8.1 Photosynthesis: An Overview 170
 - 8.2 The Light-Dependent Reactions of Photosynthesis 172
 - 8.3 The Light-Independent Reactions of Photosynthesis 180
 - 8.4 Photorespiration and Alternative Processes of Carbon Fixation 183
 - 8.5 Photosynthesis and Cellular Respiration Compared 187
- Review Key Concepts 189
- Test Your Knowledge 190

Figure 8.4 Experimental Research Engelmann's Experiment Showing the Action Spectrum of Light Used in Photosynthesis 173

CLOSER LOOK Figure 8.10: The Chloroplast Electron Transfer System (Steps 1–9) and Chemiosmosis (Steps 10–12), Illustrating the Synthesis of NADPH and ATP by the Linear (Noncyclic) Electron Flow Pathway 178

Focus on Research Basic Research: Elucidation of the Calvin Cycle Using Two-Dimensional Paper Chromatography 182

Molecular Insights Growth and Photosynthesis in a C_3 Plant: What is the response to water deficit? 185

9 Cell Communication 192

- 9.1 Cell Communication: An Overview 193
 - 9.2 Cell Communication Systems with Surface Receptors 197
 - 9.3 Signaling Pathways Triggered by Surface Receptors 199
 - 9.4 Signaling Pathways Triggered by Internal Receptors 206
 - 9.5 Integration of Cell Communication Pathways 209
- Review Key Concepts 211
- Test Your Knowledge 212

Figure 9.2 Experimental Research Sutherland's Experiments Discovering a Second Messenger Molecule 196

CLOSER LOOK Figure 9.7: The Action of a Receptor Tyrosine Kinase, a Receptor Type with Built-In Protein Kinase Activity 200

CLOSER LOOK Figure 9.9: Response Pathways Activated by G-Protein-Coupled Receptors, in which Protein Kinase Activity Is Separate from the Receptor 202

Molecular Insights Genomics of Breast Cancer: How does binding of estrogen receptor β to the genome affect breast cancer progression? 208

10 Cell Division and Mitosis 214

- 10.1 The Cycle of Cell Growth and Division: An Overview 215
- 10.2 The Mitotic Cell Cycle 216
- 10.3 Formation and Action of the Mitotic Spindle 222
- 10.4 Cell Cycle Regulation 226
- 10.5 Cell Division in Bacteria 232

Review Key Concepts 234

Test Your Knowledge 235

CLOSER LOOK Figure 10.4: The Stages of Mitosis 218

Figure 10.8 Research Method Preparing a Human Karyotype 222

Figure 10.13 Experimental Research Movement of Chromosomes during Anaphase of Mitosis 225

Focus on Research Model Organisms: The Yeast *Saccharomyces cerevisiae* 226

Figure 10.15 Experimental Research Demonstrating the Existence of Molecules Controlling the Cell Cycle by Cell Fusion 227

Molecular Insights The Cell Cycle: How do proteins vary in level and localization in the cell cycle? 230

Unit Two Genetics

11 Meiosis: The Cellular Basis of Sexual Reproduction 237

- 11.1 The Mechanisms of Meiosis 238
 - 11.2 Mechanisms That Generate Genetic Variability 244
 - 11.3 The Time and Place of Meiosis in Organismal Life Cycles 246
- Review Key Concepts 248
- Test Your Knowledge 249

Molecular Insights Meiosis and Mammalian Gamete Formation: What determines whether an egg or a sperm will form? 243

12 Mendel, Genes, and Inheritance 251

- 12.1 The Beginnings of Genetics: Mendel's Garden Peas 252
 - 12.2 Later Modifications and Additions to Mendel's Principles 264
- Review Key Concepts 271
- Test Your Knowledge 272

Figure 12.3 Research Method Making a Genetic Cross between Two Pea Plants 253

Figure 12.5 Experimental Research The Principles of Segregation: Inheritance of Flower Color in Garden Peas 256

Figure 12.8 Experimental Research Testing the Predicted Outcomes of Genetic Crosses 259

Figure 12.9 Experimental Research The Principle of Independent Assortment 261

Molecular Insights Mendel's Dwarf Pea Plants: How does a gene defect produce dwarfing? 262

Figure 12.13 Experimental Research Experiment Showing Incomplete Dominance of a Trait 266

13 Genes, Chromosomes, and Human Genetics 274

13.1 Genetic Linkage and Recombination 275

13.2 Sex-Linked Genes 279

13.3 Chromosomal Mutations That Affect Inheritance 285

13.4 Human Genetic Traits, Pedigree Analysis, and Genetic Counseling 290

13.5 Non-Mendelian Patterns of Inheritance 293

Review Key Concepts 297

Test Your Knowledge 298

Focus on Research Model Organisms: The Marvelous Fruit Fly, *Drosophila melanogaster* 275

Figure 13.2 Experimental Research Evidence for Gene Linkage 276

Figure 13.8 Experimental Research Evidence for Sex-Linked Genes 282

Molecular Insights X-Chromosome Inactivation in Mammals: What is the process of inactivation? 284

14 DNA Structure and Replication 300

14.1 Establishing DNA as the Hereditary Molecule 301

14.2 DNA Structure 304

14.3 DNA Replication 306

14.4 Repair of Errors in DNA 318

Review Key Concepts 320

Test Your Knowledge 321

Figure 14.2 Experimental Research Griffith's Experiment with Virulent and Nonvirulent Strains of *Streptococcus pneumoniae* 302

Figure 14.3 Experimental Research The Hershey and Chase Experiment Demonstrating That DNA Is the Hereditary Molecule 303

Figure 14.9 Experimental Research The Meselson and Stahl Experiment Demonstrating the Semiconservative Model for DNA Replication to Be Correct 309

Molecular Insights DNA Replication in Humans: Loading and unloading the sliding clamp 312

15 From DNA to Protein 323

15.1 The Connection between DNA, RNA, and Protein 324

15.2 Transcription: DNA-Directed RNA Synthesis 329

15.3 Production of mRNAs in Eukaryotes 331

15.4 Translation: mRNA-Directed Polypeptide Synthesis 336

15.5 Genetic Changes That Affect Protein Structure and Function 345

Review Key Concepts 351

Test Your Knowledge 352

Figure 15.1 Experimental Research The Gene-Enzyme Relationship 325

CLOSER LOOK Figure 15.5: Transcription of a Eukaryotic Protein-Coding Gene 330

Molecular Insights Gene Expression and Sleep-Wake Timing: How does a mistimed sleep cycle affect transcription? 332

16 Regulation of Gene Expression 354

16.1 Regulation of Gene Expression in Prokaryotes 355

16.2 Regulation of Transcription in Eukaryotes 361

16.3 Posttranscriptional, Translational, and Posttranslational Regulation 367

16.4 Genetic and Molecular Regulation of Development 370

16.5 The Genetics and Genomics of Cancer 377

Review Key Concepts 382

Test Your Knowledge 383

CLOSER LOOK Figure 16.2: Regulation of the Inducible *lac* Operon by the Lac Repressor in the Absence (A) and Presence (B) of Lactose 357

CLOSER LOOK Figure 16.4: Regulation of the Repressible *trp* Operon by the Trp Repressor in the Absence (A) and Presence (B) of Tryptophan 360

Molecular Insights Have a Heart: Critical role for a long noncoding RNA in cardiac development 376

17 Bacterial and Viral Genetics 385

17.1 Gene Transfer and Genetic Recombination in Bacteria 386

17.2 Viruses and Viral Genetics 393

17.3 Viroids and Prions, Infectious Agents Lacking Protein Coats 402

Review Key Concepts 404

Test Your Knowledge 405

Focus on Research Model Organisms: *Escherichia coli* 386

Figure 17.1 Experimental Research Genetic Recombination in Bacteria 387

CLOSER LOOK Figure 17.4: Transfer of Genetic Material during Conjugation between *E. coli* Cells 389

Figure 17.5 Research Method Replica Plating 391

Molecular Insights A 30,000-Year-Old Pathogenic Giant Virus 393

CLOSER LOOK Figure 17.8: The Infective Cycle of Lambda (λ), an Example of a Temperate Phage, which Can Go through the Lytic Cycle or the Lysogenic Cycle 398

18 DNA Technologies: Making and Using Genetically Altered Organisms, and Other Applications 407

18.1 Key DNA Technologies for Making Genetically Altered Organisms 408

18.2 Applications of Genetically Altered Organisms 415

18.3 Other Applications of DNA Technologies 425

Review Key Concepts 429

Test Your Knowledge 430

Figure 18.3 Research Method Identifying a Recombinant Plasmid Containing a Gene of Interest 411

Figure 18.4 Research Method The Polymerase Chain Reaction (PCR) 413

Figure 18.5 Research Method Separation of DNA Fragments by Agarose Gel Electrophoresis 414

Figure 18.7 Research Method Synthesis of DNA from mRNA Using Reverse Transcriptase 416

Figure 18.8 Research Method Making a Knockout Mouse 418

Focus on Research Basic and Applied Research: Programmable RNA-Guided Genome Editing System 419

Figure 18.10 Experimental Research The First Cloning of a Mammal 421

Figure 18.11 Research Method Using the Ti Plasmid of *Agrobacterium tumefaciens* to Produce Transgenic Plants 422

Molecular Insights Nutritional Quality of Genetically Modified Food: Comparisons of metabolomes in genetically modified and unmodified tomato fruits 424

19 Genomes and Proteomes 432

19.1 Genomics: An Overview 433

19.2 Genome Sequence Determination and Annotation 434

19.3 Determining the Functions of the Genes in a Genome 444

19.4 Genome Evolution 449

Review Key Concepts 454

Test Your Knowledge 455

Figure 19.1 Research Method Whole-Genome Shotgun Sequencing 434

Figure 19.2 Research Method Dideoxy (Sanger) Method for DNA Sequencing 435

Figure 19.3 Research Method Illumina/Solexa Method for DNA Sequencing 436

Figure 19.8 Research Method DNA Microarray Analysis of Gene Expression Levels 446

Unit Three Evolutionary Biology

20 Development of Evolutionary Thinking 457

20.1 Recognition of Evolutionary Change 458

20.2 Darwin's Journeys 460

20.3 Evolutionary Biology since Darwin 465

Review Key Concepts 474

Test Your Knowledge 474

Focus on Research Basic Research: Charles Darwin's Life as a Scientist 466

Figure 20.12 Experimental Research How Exposure to Insecticide Fosters the Evolution of Insecticide Resistance 467

CLOSER LOOK Figure 20.14: Genetics of Limb Loss in Snakes 470

Molecular Insights Our Best Friends: Where on Earth and when were dogs domesticated? 471

21 Microevolution: Genetic Changes within Populations 476

21.1 Variation in Natural Populations 477

21.2 Population Genetics 480

21.3 The Agents of Microevolution 482

21.4 Maintaining Genetic and Phenotypic Variation 492

21.5 Adaptation and Evolutionary Constraints 495

Review Key Concepts 498

Test Your Knowledge 499

Figure 21.6 Experimental Research Using Artificial Selection to Demonstrate That Activity Level in Mice Has a Genetic Basis 479

Focus on Research Basic Research: Using the Hardy-Weinberg Principle 482

CLOSER LOOK Figure 21.9: Three Modes of Natural Selection 487

Figure 21.10 Observational Research Do Humans Experience Stabilizing Selection? 488

Figure 21.11 Observational Research How Opposing Forces of Directional Selection Produce Stabilizing Selection 489

Molecular Insights My, What a Big Horn You Have: Does the size of a male's ornaments provide a true indicator of his success and the relative quality of his genes? 491

Figure 21.13 Experimental Research Sexual Selection in Action 492

Figure 21.15 Observational Research Habitat Variation in Color and Striping Patterns of European Garden Snails 494

Figure 21.16 Experimental Research Demonstration of Frequency-Dependent Selection 496

22 Speciation 501

22.1 What Is a Species? 502

22.2 Maintaining Reproductive Isolation 505

22.3 The Geography of Speciation 507

22.4 Genetic Mechanisms of Speciation 512

Review Key Concepts 518

Test Your Knowledge 519

Focus on Research Basic Research: Explosive Speciation in Hawaiian Fruit Flies 510

Molecular Insights A Dual-Function Gene: Ecological and behavioral isolation in two *Drosophila* species 513

CLOSER LOOK Figure 22.15: Polyploidy in Plants 514

Figure 22.17 Observational Research Chromosomal Similarities and Differences among Humans and the Great Apes 516

23 Paleobiology and Macroevolution 521

23.1 The Fossil Record 522

23.2 Earth History 527

23.3 Historical Biogeography and Convergent Biotas 530

23.4 The History of Biodiversity 533

23.5 Interpreting Evolutionary Lineages 537

Review Key Concepts 548

Test Your Knowledge 548

Figure 23.4 Research Method Radiometric Dating 526

CLOSER LOOK Figure 23.17: Evolving Views of Horse Ancestry 538

Figure 23.18 Observational Research Evidence of Phyletic Gradualism 539

Figure 23.19 Observational Research Evidence of a Punctuated Pattern of Morphological Change 540

Figure 23.22 Observational Research Paedomorphosis in *Delphinium* Flowers 542

Molecular Insights Fancy Footwork: From fins to fingers 546

24 Systematics and Phylogenetics: Revealing the Tree of Life 550

- 24.1 Nomenclature and Classification 551
- 24.2 Phylogenetic Trees 552
- 24.3 Sources of Data for Phylogenetic Analyses 556
- 24.4 Traditional Classification and Paraphyletic Groups 560
- 24.5 The Cladistic Revolution 561
- 24.6 Phylogenetic Trees as Research Tools 567
- 24.7 Molecular Phylogenetic Analyses 569

Review Key Concepts 574

Test Your Knowledge 574

CLOSER LOOK Figure 24.2: How to Read Phylogenetic Trees 554

Molecular Insights Electric Organs in Fishes: Deep homology fosters convergent evolution of electric organs 558

Figure 24.9 Research Method Using Cladistics to Construct a Phylogenetic Tree 564

CLOSER LOOK Figure 24.10: The Principle of Parsimony 566

Figure 24.11 Research Method Using Genetic Distances to Construct a Phylogenetic Tree 568

Figure 24.12 Observational Research Do Molecular Clocks Tick at a Constant Rate? 569

Unit Four Biodiversity

25 The Origin of Life 577

- 25.1 The Formation of Molecules Necessary for Life 578
- 25.2 The Origin of Cells 581
- 25.3 The Origins of Eukaryotic Cells 587

Review Key Concepts 590

Test Your Knowledge 591

Figure 25.2 Experimental Research The Miller-Urey Apparatus Demonstrating That Organic Molecules Can Be Synthesized Spontaneously under Conditions Simulating Primordial Earth 580

Molecular Insights Toward the Evolution of Life in the Lab: The construction of protocell-like vesicles containing an active ribozyme 583

26 Prokaryotes: Bacteria and Archaea 593

- 26.1 Prokaryotic Structure and Function 594
 - 26.2 The Domain Bacteria 601
 - 26.3 The Domain Archaea 609
- Review Key Concepts 612
- Test Your Knowledge 612

Figure 26.12 Experimental Research Demonstration of the Bacterial Cause of Peptic Ulcers 603

Molecular Insights Gums the Word: Genome-wide analysis of gene expression changes in an oral cavity pathogen associated with transition from free-living bacteria in the oral microbiome to biofilm 607

27 Protists 614

- 27.1 What Is a Protist? 615
- 27.2 The Protist Groups 618

Review Key Concepts 636

Test Your Knowledge 637

Focus on Research Applied Research: Malaria and the *Plasmodium* Life Cycle 623

Figure 27.11 Experimental Research The Evolutionary History of Diatoms as Revealed by Genome Analysis 625

Molecular Insights *Dictyostelium* the Farmer: Two different bacteria associated with a cellular slime mold 633

28 Seedless Plants 639

- 28.1 Plant Evolution: Adaptations to Life on Land 640
- 28.2 Bryophytes, the Nonvascular Land Plants 647
- 28.3 Seedless Vascular Plants 651
- 28.4 Ecological, Economic, and Research Importance of Seedless Plants 656

Review Key Concepts 658

Test Your Knowledge 659

Molecular Insights Comparative Genomics Probes Plant Evolution 657

29 Seed Plants 661

- 29.1 The Rise of Seed Plants 662
- 29.2 Gymnosperms: The "Naked Seed" Plants 665
- 29.3 Angiosperms: Flowering Plants 671
- 29.4 Insights from Plant Genome Research 677
- 29.5 Seed Plants and People 679

Review Key Concepts 681

Test Your Knowledge 682

Figure 29.19 Experimental Research Exploring a Possible Early Angiosperm Adaptation for Efficient Photosynthesis in Dim Environments 674

Molecular Insights Taming a Giant Conifer Genome 678

30 Fungi 684

- 30.1 General Characteristics of Fungi 685
- 30.2 Evolution of the Kingdom Fungi 689
- 30.3 Fungal Associations: Lichens and Mycorrhizae 699
- 30.4 Impacts of Fungi in Ecosystems and Society 701

Review Key Concepts 703

Test Your Knowledge 704

Molecular Insights Researching Relationships of "Hidden Fungi" 698

Focus on Research Applied Research: Lichens as Monitors of Air Pollution's Biological Damage 699

31 Animal Phylogeny, Acoelomates, and Protostomes 706

- 31.1 What Is an Animal? 707
- 31.2 Key Innovations in Animal Evolution 708
- 31.3 An Overview of Animal Phylogeny and Classification 711
- 31.4 Animals without Tissues: Parazoa 713
- 31.5 Eumetazoans with Radial Symmetry 715
- 31.6 Lophotrochozoan Protostomes 719
- 31.7 Ecdysozoan Protostomes 729
- Review Key Concepts 740
- Test Your Knowledge 741
- Focus on Research** Applied Research: Breaking the Life Cycles of Parasitic Worms 722
- Focus on Research** Model Organisms: *Caenorhabditis Elegans* 730
- Molecular Insights** Arthropod Relationships: Is Crustacea a monophyletic lineage? 732

32 Deuterostomes: Vertebrates and Their Closest Relatives 743

- 32.1 Invertebrate Deuterostomes 744
- 32.2 Overview of the Phylum Chordata 747
- 32.3 The Origin and Diversification of Vertebrates 749
- 32.4 "Agnathans": Hagfishes and Lampreys, Conodonts and Ostracoderms 752
- 32.5 Gnathostomata: The Evolution of Jaws 754
- 32.6 Tetrapoda: The Evolution of Limbs 759
- 32.7 Amniota: The Evolution of Fully Terrestrial Vertebrates 762
- 32.8 Living Lepidosaurs: Sphenodontids and Squamates 764
- 32.9 Living Archelosaurs: Turtles, Crocodilians, and Birds 767
- 32.10 Mammalia: Monotremes, Marsupials, and Placentals 770
- 32.11 Nonhuman Primates 773
- 32.12 The Evolution of Humans 777
- Review Key Concepts 783
- Test Your Knowledge 784
- CLOSER LOOK** Figure 32.8: *Hox* Genes and the Evolution of Vertebrates 750
- Focus on Research** Model Organisms: *Anolis* Lizards of the Caribbean 766
- Molecular Insights** Building a Better Nose: How did the sense of smell evolve in mammals? 772

Unit Five Plant Structure and Function

33 The Plant Body 786

- 33.1 Basic Concepts of Plant Structure and Growth 787
- 33.2 The Three Plant Tissue Systems 789
- 33.3 Root Systems 796
- 33.4 Primary Shoot Systems 799

- 33.5 Secondary Growth 806
- Review Key Concepts 809
- Test Your Knowledge 810
- CLOSER LOOK** Figure 33.3: Meristems in a Vascular Plant 789
- Molecular Insights** Networking the Secondary Cell Wall 792
- Focus on Research** Basic Research: Homeobox Genes: How the Meristem Gives Its Marching Orders 802

34 Transport in Plants 813

- 34.1 Overview of Water and Solute Movements in Plants 814
- 34.2 Roots: Moving Water and Minerals into the Plant 818
- 34.3 Transport of Water and Minerals in the Xylem 819
- 34.4 Stomata: Regulating the Loss of Water by Transpiration 823
- 34.5 Transport of Organic Substances in the Phloem 826
- Review Key Concepts 830
- Test Your Knowledge 831
- CLOSER LOOK** Figure 34.9: Cohesion-Tension Mechanism of Water Transport 822
- Molecular Insights** Going with the Phloem 826
- Figure 34.15 Experimental Research** Translocation Pressure 827
- CLOSER LOOK** Figure 34.16: The Pressure Flow Mechanism in the Phloem of Flowering Plants 828

35 Plant Nutrition 833

- 35.1 Plant Nutritional Requirements 833
- 35.2 Soil 837
- 35.3 Root Adaptations for Obtaining and Absorbing Nutrients 841
- Review Key Concepts 849
- Test Your Knowledge 850
- Figure 35.1 Research Method** Hydroponic Culture 834
- Focus on Research** Applied Research: Engineering Solutions to Heavy Metal Contamination 841
- Molecular Insights** Getting to the Roots of Plant Nutrition 842
- CLOSER LOOK** Figure 35.10: Root Nodule Formation in Legumes 846

36 Reproduction and Development in Flowering Plants 852

- 36.1 Overview of Flowering Plant Reproduction 853
- 36.2 The Formation of Flowers and Gametes 854
- 36.3 Pollination, Fertilization, and Germination 859
- 36.4 Asexual Reproduction of Flowering Plants 868
- 36.5 Early Plant Development 869
- Review Key Concepts 878
- Test Your Knowledge 879
- CLOSER LOOK** Figure 36.5: Trends in Flower Evolution 856
- CLOSER LOOK** Figure 36.9: Pollination and Double Fertilization 861
- Figure 36.20 Research Method** Plant Cell Culture 870
- Focus on Research** Model Organisms: *Arabidopsis thaliana* 871
- Molecular Insights** Trichomes: Window on development in a single plant cell 873
- Figure 36.25 Experimental Research** Probing the Roles of Floral Identity Genes 876

37 Plant Signals and Responses to the Environment 881

37.1 Introduction to Plant Hormones 882

37.2 Plant Chemical Defenses 896

37.3 Plant Movements 900

37.4 Plant Biological Clocks 903

Review Key Concepts 909

Test Your Knowledge 910

Figure 37.3 Experimental Research The Darwins' Experiments on Phototropism 884

Molecular Insights Investigating the Evolution of Hormone Signaling in Plants 892

Focus on Research Basic Research: Using DNA Microarray Analysis to Track Down Florigen 907

Unit Six

Animal Structure and Function

38 Introduction to Animal Organization and Physiology 912

38.1 Organization of the Animal Body 913

38.2 Animal Tissues 913

38.3 Coordination of Tissues in Organs and Organ Systems 921

38.4 Homeostasis 921

Review Key Concepts 927

Test Your Knowledge 928

Molecular Insights A Primate-Specific miRNA Regulator of Respiratory Tract Epithelial Cell Differentiation and Lung Carcinogenesis 916

39 Information Flow and the Neuron 930

39.1 Neurons and Their Organization in Nervous Systems 931

39.2 Signaling by Neurons 935

39.3 Transmission across Chemical Synapses 941

39.4 Integration of Incoming Signals by Neurons 944

Review Key Concepts 948

Test Your Knowledge 949

Figure 39.7 Experimental Research Demonstration of Chemical Transmission of Nerve Impulses at Synapses 934

Figure 39.8 Research Method Measuring Membrane Potential 936

CLOSER LOOK Figure 39.11: Changes in Voltage-Gated Na^+ and K^+ Channels that Produce the Action Potential 938

Molecular Insights Dissecting Neurotransmitter Receptor Functions 946

40 Nervous Systems 951

40.1 Invertebrate and Vertebrate Nervous Systems Compared 952

40.2 The Peripheral Nervous System 955

40.3 The Central Nervous System and Its Functions 957

40.4 Memory, Learning, and Consciousness 966

Review Key Concepts 969

Test Your Knowledge 970

CLOSER LOOK Figure 40.7: Organization of the Spinal Cord and the Patellar Tendon Reflex 959

Molecular Insights Sex Differences in the Neural Connections of the Human Brain 964

Figure 40.13 Experimental Research Investigating the Functions of the Cerebral Hemispheres 965

41 Sensory Systems 972

41.1 Overview of Sensory Receptors and Pathways 973

41.2 Mechanoreceptors and the Tactile and Spatial Senses 974

41.3 Mechanoreceptors and Hearing 977

41.4 Photoreceptors and Vision 980

41.5 Chemoreceptors 985

41.6 Thermoreceptors and Nociceptors 988

41.7 Magnetoreceptors and Electoreceptors 989

Review Key Concepts 991

Test Your Knowledge 992

Molecular Insights Taste Neuron Changes Associated with Emergence of an Adaptive Behavior in Cockroaches 986

42 The Endocrine System 994

42.1 Hormones and Their Secretion 995

42.2 Mechanisms of Hormone Action 997

42.3 The Hypothalamus and Pituitary 1001

42.4 Other Major Endocrine Glands of Vertebrates 1005

42.5 Endocrine Systems in Invertebrates 1011

Review Key Concepts 1013

Test Your Knowledge 1014

Figure 42.5 Experimental Research Demonstration That Binding of Epinephrine to β -Adrenergic Receptors Triggers a Signal Transduction Pathway within Cells 1000

Molecular Insights Fear-Enhancing Effects of Some Oxytocin Receptors in Mice 1006

Focus on Research Basic Research: Neuroendocrine and Behavioral Effects of Anabolic-Androgenic Steroids in Humans 1009

43 Muscles, Bones, and Body Movements 1016

43.1 Vertebrate Skeletal Muscle: Structure and Function 1017

43.2 Skeletal Systems 1023

43.3 Vertebrate Movement: The Interactions between Muscles and Bones 1025

Review Key Concepts 1028

Test Your Knowledge 1029

Figure 43.4 Experimental Research The Sliding Filament Model of Muscle Contraction 1019

CLOSER LOOK Figure 43.5: Molecular Model for Muscle Contraction 1020

Molecular Insights Genetics of Bone Formation: Insights from the elephant shark genome 1026

44 The Circulatory System 1031

44.1 Animal Circulatory Systems: An Introduction 1032

44.2 Blood and Its Components 1035

44.3 The Heart 1038

44.4 Blood Vessels of the Circulatory System 1042

44.5 Maintaining Blood Flow and Pressure 1045

44.6 The Lymphatic System 1046

Review Key Concepts 1049

Test Your Knowledge 1050

CLOSER LOOK Figure 44.13: The Electrical Control of the Cardiac Cycle 1041

Molecular Insights Identifying the Role of a Hormone Receptor in Blood Pressure Regulation Using Knockout Mice 1046

Figure 44.19 Experimental Research Demonstration of a Vasodilatory Signaling Molecule 1047

45 Defenses against Disease 1052

45.1 Three Lines of Defense against Pathogens 1053

45.2 Innate Immunity: Nonspecific Defenses 1054

45.3 Adaptive Immunity: Specific Defenses 1057

45.4 Malfunctions and Failures of the Immune System 1067

45.5 Evolved Defenses against Pathogens in Other Animals 1070

Review Key Concepts 1071

Test Your Knowledge 1072

Focus on Research Model Organisms: The Mighty Mouse 1058

CLOSER LOOK Figure 45.6: The Antibody-Mediated Immune Response, Illustrated for a Bacterial Pathogen 1062

Figure 45.10 Research Method Production of Monoclonal Antibodies 1065

CLOSER LOOK Figure 45.11: The Cell-Mediated Immune Response 1066

Molecular Insights Unique Immune System of the Atlantic Cod 1070

46 Gas Exchange: The Respiratory System 1074

46.1 The Function of Gas Exchange 1075

46.2 Evolutionary Adaptations for Respiration 1077

46.3 The Mammalian Respiratory System 1080

46.4 Mechanisms of Gas Exchange and Transport 1083

46.5 Respiration at High Altitudes and in Ocean Depths 1086

Review Key Concepts 1090

Test Your Knowledge 1091

Molecular Insights Altitude Adaptation in Tibetans Caused by Gene Allele Inherited from an Extinct Species of Humans 1087

Figure 46.14 Experimental Research Demonstration of a Molecular Basis for High-Altitude Adaptation in Deer Mice 1088

47 Animal Nutrition 1093

47.1 Feeding and Nutrition 1094

47.2 Digestive Processes 1096

47.3 Digestion in Humans and Other Mammals 1098

47.4 Regulation of the Digestive Process 1109

47.5 Digestive Specializations in Vertebrates 1110

Review Key Concepts 1114

Test Your Knowledge 1116

Molecular Insights Association of Particular Bacterial Populations in the Gut Microbiome with Obesity in Humans 1113

48 Regulating the Internal Environment 1118

48.1 Introduction to Osmoregulation and Excretion 1119

48.2 Osmoregulation and Excretion in Invertebrates 1121

48.3 Osmoregulation and Excretion in Mammals 1123

48.4 Regulation of Mammalian Kidney Function 1128

48.5 Kidney Function in Nonmammalian Vertebrates 1131

48.6 Introduction to Thermoregulation 1132

48.7 Ectothermy 1136

48.8 Endothermy 1137

Review Key Concepts 1141

Test Your Knowledge 1142

Molecular Insights Involvement of miRNAs with the Development of Polycystic Kidney Disease 1124

Figure 48.11 Experimental Research ADH-Stimulated Water Reabsorption in the Kidney Collecting Duct 1132

49 Animal Reproduction 1144

49.1 Animal Reproductive Modes: Asexual and Sexual Reproduction 1145

49.2 Cellular Mechanisms of Sexual Reproduction 1147

49.3 Sexual Reproduction in Humans 1152

49.4 Methods for Preventing Pregnancy: Contraception 1160

Review Key Concepts 1163

Test Your Knowledge 1164

CLOSER LOOK Figure 49.12: The Ovarian and Uterine (Menstrual) Cycles of a Human Female 1154

Figure 49.13 Experimental Research Vocal Cues of Ovulation in Human Females 1155

Molecular Insights Egg on the Sperm 1158

50 Animal Development 1166

50.1 Mechanisms of Embryonic Development 1167

50.2 Major Patterns of Cleavage and Gastrulation 1169

50.3 From Gastrulation to Adult Body Structures: Organogenesis 1173

50.4 Embryonic Development of Humans and Other Mammals 1176

- 50.5 The Cellular Basis of Development** 1181
 Review Key Concepts 1190
 Test Your Knowledge 1191
CLOSER LOOK Figure 50.12: Implantation of a Human Blastocyst in the Endometrium of the Uterus and the Establishment of the Placenta 1178
Figure 50.17 Experimental Research Demonstrating the Selective Adhesion Properties of Cells 1183
Molecular Insights An Essential Role of Protein O-Mannosylation in Embryonic Development 1184
Figure 50.19 Experimental Research Spemann and Mangold's Experiment Demonstrating Induction in Embryos 1186

Unit Seven Ecology and Behavior

51 Ecology and the Biosphere 1193

- 51.1 The Science of Ecology** 1195
51.2 Environmental Diversity of the Biosphere 1196
51.3 Organismal Responses to Environmental Variation and Climate Change 1200
51.4 Terrestrial Biomes 1203
51.5 Freshwater Environments 1211
51.6 Marine Environments 1213
 Review Key Concepts 1219
 Test Your Knowledge 1220
Molecular Insights How Does an Octopus Function at 0°C? RNA editing and cold adaptation 1201
Figure 51.9 Observational Research How Do Lizards Compensate for Elevational Variation in Environmental Temperature? 1202
CLOSER LOOK Figure 51.11: Distribution of Biomes on a Climograph 1204
Focus on Research Basic Research: Exploring the Rainforest Canopy 1206
Figure 51.25 Experimental Research What Causes Lake Eutrophication? 1214

52 Population Ecology 1222

- 52.1 Population Characteristics** 1223
52.2 Demography 1226
52.3 The Evolution of Life Histories 1227
52.4 Models of Population Growth 1232
52.5 Population Dynamics 1236
52.6 Human Population Growth 1243
 Review Key Concepts 1248
 Test Your Knowledge 1249
Figure 52.3 Research Method Using Mark-Release-Recapture to Estimate Population Size 1224
Molecular Insights Red Harvester Ants: How can researchers construct a life table for a colonial species? 1228

Focus on Research Basic Research: The Evolution of Life History Traits in Guppies 1230

Figure 52.17 Experimental Research Evaluating Density-Dependent Interactions between Species 1239

Figure 52.19 Observational Research Do Immigrants from Source Populations Prevent Extinction of Sink Populations of the Bay Checkerspot Butterfly? 1241

CLOSER LOOK Figure 52.20: Population Cycles in Predators and Their Prey 1242

53 Population Interactions and Community Ecology 1251

- 53.1 Population Interactions** 1252
53.2 The Nature of Ecological Communities 1261
53.3 Community Characteristics 1263
53.4 Effects of Population Interactions of Community Characteristics 1267
53.5 Effects of Disturbance on Community Characteristics 1268
53.6 Ecological Succession: Responses to Disturbance 1271
53.7 Variations in Species Richness among Communities 1274
 Review Key Concepts 1280
 Test Your Knowledge 1281
Figure 53.8 Experimental Research Gause's Experiments on Interspecific Competition in *Paramecium* 1256
Figure 53.12 Experimental Research Demonstration of Competition between Two Species of Barnacles 1258
Figure 53.24 Experimental Research Effect of a Predator on the Species Richness of Its Prey 1268
Figure 53.25 Experimental Research The Complex Effects of an Herbivorous Snail on Algal Species Richness 1269
CLOSER LOOK Figure 53.28: Primary Succession Following Glacial Retreat 1272
Molecular Insights The Species–Area Effect: Does bacterial species richness vary with “island” size? 1278

54 Ecosystems and Global Change 1283

- 54.1 Modeling Ecosystem Processes** 1285
54.2 Energy Flow and Ecosystem Energetics 1287
54.3 Nutrient Cycling in Ecosystems 1295
54.4 Human Activities and Anthropogenic Global Change 1301
 Review Key Concepts 1306
 Test Your Knowledge 1307
Figure 54.7 Observational Research What Is the Pattern of Energy Flow within the Silver Springs Ecosystem? 1290
Figure 54.10 Experimental Research A Trophic Cascade in Salt Marshes 1294
Focus on Research Basic Research: Studies of the Hubbard Brook Watershed 1296
Molecular Insights Ocean Acidification: Does it affect gene expression? 1304

55 Biodiversity and Conservation Biology 1309

- 55.1 The Biodiversity Crisis on Land, in the Sea, and in River Systems 1310
- 55.2 Specific Threats to Biodiversity 1313
- 55.3 Ecosystem Services That Biodiversity Provides 1318
- 55.4 Which Species and Ecosystems Are Most Threatened by Human Activities? 1320
- 55.5 Conservation Biology: Principles and Theory 1322
- 55.6 Conservation Biology: Practical Strategies and Economic Tools 1327

Review Key Concepts 1331

Test Your Knowledge 1332

Figure 55.6 Observational Research Near-Complete Extinction of Small Mammals in Tropical Forest Fragments 1314

Molecular Insights Developing a DNA Barcode System 1323

Focus on Research Applied Research: Preserving the Yellow-Bellied Glider 1325

Figure 55.19 Experimental Research Effect of Landscape Corridors on Plant Species Richness in Habitat Fragments 1327

56 Animal Behavior 1334

- 56.1 Instinctive and Learned Behaviors 1335
- 56.2 Neurophysiological and Endocrine Control of Behavior 1341
- 56.3 Migration and Wayfinding 1345

56.4 Habitat Selection and Territoriality 1348

56.5 The Evolution of Communication 1349

56.6 The Evolution of Reproductive Behavior and Mating Systems 1352

56.7 The Evolution of Social Behavior 1355

Review Key Concepts 1360

Test Your Knowledge 1362

Figure 56.2 Experimental Research The Role of Sign Stimuli in Parent-Offspring Interactions 1337

Molecular Insights A Knockout by a Whisker: What is the function of *disheveled* genes in mice? 1339

Figure 56.10 Experimental Research Effects of the Social Environment on Brain Anatomy and Chemistry 1344

Figure 56.13 Experimental Research Experimental Analysis of the Indigo Bunting's Star Compass 1346

Figure 56.27 Research Method Calculating Coefficients of Relatedness 1357

CLOSER LOOK Figure 56.29: Haplodiploidy in Some Eusocial Insects 1359

Appendix A: Answers A-1

Appendix B: Classification System A-36

Glossary G-1

Index I-1

Why it matters . . . Life abounds in almost every nook and cranny on our planet. Earth is a vast expanse across an African plain, ready to spring at a zebra. The leaves of a sunflower in Kansas turn slowly through the day, keeping their surfaces fully exposed to rays of sunlight. Fungi and bacteria in the soil of a Canadian forest obtain nutrients by decomposing dead organisms. A child plays in a park in Madrid, laughing happily as his dog chases a tennis ball. In one room of a nearby hospital, a mother hears the first cry of her newborn baby; in another room, an elderly man sighs away his last breath. All over the world, countless organisms are born, live, and die every moment of every day. How did life originate, how does it persist, and how is it changing? Biology, the science of life, provides scientific answers to these questions.

What is life? Offhandedly, you might say that although you cannot define it, you know it when you see it. The question has no simple answer, because life has been unfolding for billions of years ever since nonliving materials assembled into the first organized, living cells. Clearly, the list of criteria for the living state only hints at the meaning of "life." Deeper scientific insight requires a wide-ranging examination of the characteristics of life, which is what this book will do.

Over the next semester or two, you will encounter examples of how organisms are constructed, how they function, where they live, and what they do. The examples provide evidence in support of concepts that will greatly enhance your appreciation and understanding of the living world, including its fundamental unity and striking diversity. This chapter provides a brief overview of these basic concepts. It also describes some of the ways in which biologists conduct research, the process by which they observe nature, formulate explanations of their observations, and test their ideas.