

CAMPBELL BIOLOGY IN FOCUS

THIRD EDITION
GLOBAL EDITION



Lisa A. Urry

Mills College, Oakland, California

Michael L. Cain

New Mexico State University

Steven A. Wasserman

University of California, San Diego

Peter V. Minorsky

Mercy College, Dobbs Ferry, New York

Rebecca B. Orr

Collin College, Plano, Texas



Detailed Contents

1 Introduction: Evolution and the Foundations of Biology 48

OVERVIEW Inquiring About Life 48

- CONCEPT 1.1** The study of life reveals unifying themes 49
- Theme: New Properties Emerge at Successive Levels of Biological Organization 49
 - Theme: Life's Processes Involve the Expression and Transmission of Genetic Information 52
 - Theme: Life Requires the Transfer and Transformation of Energy and Matter 54
 - Theme: Organisms Interact with Other Organisms and the Physical Environment 54

- CONCEPT 1.2** The Core Theme: Evolution accounts for the unity and diversity of life 55
- Classifying the Diversity of Life 56
 - Unity in the Diversity of Life 57
 - Charles Darwin and the Theory of Natural Selection 57
 - The Tree of Life 58

- CONCEPT 1.3** In studying nature, scientists form and test hypotheses 59
- Exploration and Discovery 59
 - Gathering and Analyzing Data 60
 - Forming and Testing Hypotheses 60
 - The Flexibility of the Scientific Process 61
 - A Case Study in Scientific Inquiry: Investigating Coat Coloration in Mouse Populations* 62
 - Variables and Controls in Experiments 62
 - Theories in Science 63
 - Science as a Social Process 64

UNIT 1 Chemistry and Cells 67

2 The Chemical Context of Life 68

OVERVIEW The Importance of Chemistry to Life 68

- CONCEPT 2.1** Matter consists of chemical elements in pure form and in combinations called compounds 69
- Elements and Compounds 69
 - The Elements of Life 69
 - Evolution of Tolerance to Toxic Elements 69

- CONCEPT 2.2** An element's properties depend on the structure of its atoms 70
- Subatomic Particles 70
 - Atomic Number and Atomic Mass 70
 - Isotopes 71
 - The Energy Levels of Electrons 71
 - Electron Distribution and Chemical Properties 72



- CONCEPT 2.3** The formation and function of molecules depend on chemical bonding between atoms 73
- Covalent Bonds 74
 - Ionic Bonds 75
 - Weak Chemical Interactions 76
 - Molecular Shape and Function 77

CONCEPT 2.4 Chemical reactions make and break chemical bonds 78

- CONCEPT 2.5** Hydrogen bonding gives water properties that help make life possible on Earth 79
- Cohesion of Water Molecules 79
 - Moderation of Temperature by Water 80
 - Floating of Ice on Liquid Water 82
 - Water: The Solvent of Life 82
 - Acids and Bases 84

3 Carbon and the Molecular Diversity of Life 90

OVERVIEW Carbon Compounds and Life 90

- CONCEPT 3.1** Carbon atoms can form diverse molecules by bonding to four other atoms 91
- The Formation of Bonds with Carbon 91
 - Molecular Diversity Arising from Variation in Carbon Skeletons 92
 - The Chemical Groups Most Important to Life 93
 - ATP: An Important Source of Energy for Cellular Processes 95

- CONCEPT 3.2** Macromolecules are polymers, built from monomers 95
- The Synthesis and Breakdown of Polymers 95
 - The Diversity of Polymers 96

- CONCEPT 3.3** Carbohydrates serve as fuel and building material 96
- Sugars 97
 - Polysaccharides 98

- CONCEPT 3.4** Lipids are a diverse group of hydrophobic molecules 100
- Fats 100
 - Phospholipids 102
 - Steroids 102

- CONCEPT 3.5** Proteins include a diversity of structures, resulting in a wide range of functions 103
- Amino Acid Monomers 103
 - Polypeptides (Amino Acid Polymers) 106
 - Protein Structure and Function 106

- CONCEPT 3.6** Nucleic acids store, transmit, and help express hereditary information 112
- The Roles of Nucleic Acids 112
 - The Components of Nucleic Acids 112
 - Nucleotide Polymers 113
 - The Structures of DNA and RNA Molecules 114

- CONCEPT 3.7** Genomics and proteomics have transformed biological inquiry and applications 114
- DNA and Proteins as Tape Measures of Evolution 115



4

A Tour of the Cell 120

OVERVIEW The Fundamental Units of Life 120

CONCEPT 4.1 Biologists use microscopes and biochemistry to study cells 121

Microscopy 121

Cell Fractionation 123

CONCEPT 4.2 Eukaryotic cells have internal membranes that compartmentalize their functions 123

Comparing Prokaryotic and Eukaryotic Cells 123

A Panoramic View of the Eukaryotic Cell 125

CONCEPT 4.3 The eukaryotic cell's genetic instructions are housed in the nucleus and carried out by the ribosomes 128

The Nucleus: Information Central 128

Ribosomes: Protein Factories 130

CONCEPT 4.4 The endomembrane system regulates protein traffic and performs metabolic functions 130

The Endoplasmic Reticulum: Biosynthetic Factory 131

The Golgi Apparatus: Shipping and Receiving Center 132

Lysosomes: Digestive Compartments 133

Vacuoles: Diverse Compartments 134

The Endomembrane System: *A Review* 135

CONCEPT 4.5 Mitochondria and chloroplasts change energy from one form to another 135

The Evolutionary Origins of Mitochondria and Chloroplasts 136

Mitochondria: Chemical Energy Conversion 136

Chloroplasts: Capture of Light Energy 137

Peroxisomes: Oxidation 138

CONCEPT 4.6 The cytoskeleton is a network of fibers that organizes structures and activities in the cell 138

Roles of the Cytoskeleton: Support and Motility 138

Components of the Cytoskeleton 139

CONCEPT 4.7 Extracellular components and connections between cells help coordinate cellular activities 142

Cell Walls of Plants 142

The Extracellular Matrix (ECM) of Animal Cells 143

Cell Junctions 144

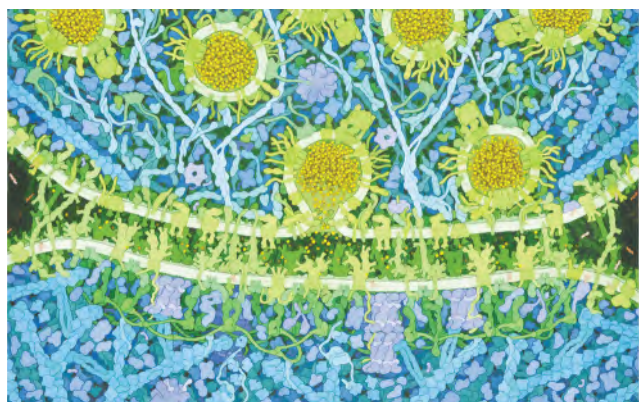
CONCEPT 4.8 A cell is greater than the sum of its parts 144

5

Membrane Transport and Cell Signaling 150

OVERVIEW Life at the Edge 150

CONCEPT 5.1 Cellular membranes are fluid mosaics of lipids and proteins 150



The Fluidity of Membranes 151

Evolution of Differences in Membrane Lipid Composition 152

Membrane Proteins and Their Functions 152

The Role of Membrane Carbohydrates in Cell-Cell Recognition 153

Synthesis and Sidedness of Membranes 154

CONCEPT 5.2 Membrane structure results in selective permeability 154

The Permeability of the Lipid Bilayer 155

Transport Proteins 155

CONCEPT 5.3 Passive transport is diffusion of a substance across a membrane with no energy investment 155

Effects of Osmosis on Water Balance 156

Facilitated Diffusion: Passive Transport Aided by Proteins 158

CONCEPT 5.4 Active transport uses energy to move solutes against their gradients 159

The Need for Energy in Active Transport 159

How Ion Pumps Maintain Membrane Potential 160

Cotransport: Coupled Transport by a Membrane Protein 161

CONCEPT 5.5 Bulk transport across the plasma membrane occurs by exocytosis and endocytosis 162

Exocytosis 162

Endocytosis 162

CONCEPT 5.6 The plasma membrane plays a key role in most cell signaling 164

Local and Long-Distance Signaling 164

The Three Stages of Cell Signaling: *A Preview* 165

Reception, the Binding of a Signaling Molecule to a Receptor Protein 165

Transduction by Cascades of Molecular Interactions 167

Response: Regulation of Transcription or Cytoplasmic Activities 169

6

An Introduction to Metabolism 172

OVERVIEW The Energy of Life 172

CONCEPT 6.1 An organism's metabolism transforms matter and energy 172

Metabolic Pathways 172

Forms of Energy 173

The Laws of Energy Transformation 174

CONCEPT 6.2 The free-energy change of a reaction tells us whether or not the reaction occurs spontaneously 175

Free-Energy Change (ΔG), Stability, and Equilibrium 175

Free Energy and Metabolism 176

CONCEPT 6.3 ATP powers cellular work by coupling exergonic reactions to endergonic reactions 178

The Structure and Hydrolysis of ATP 178

How ATP Provides Energy that Performs Work 179

The Regeneration of ATP 180

CONCEPT 6.4 Enzymes speed up metabolic reactions by lowering energy barriers 181

The Activation Energy Barrier 181

How Enzymes Speed Up Reactions 182

Substrate Specificity of Enzymes 182

Catalysis in the Enzyme's Active Site 183

Effects of Local Conditions on Enzyme Activity 185

The Evolution of Enzymes 186

CONCEPT 6.5 Regulation of enzyme activity helps control metabolism 186

Allosteric Regulation of Enzymes 187

Organization of Enzymes Within the Cell 188





7 Cellular Respiration and Fermentation 191

OVERVIEW Life Is Work 191

CONCEPT 7.1 Catabolic pathways yield energy by oxidizing organic fuels 192

Catabolic Pathways and Production of ATP 192

Redox Reactions: Oxidation and Reduction 192

The Stages of Cellular Respiration: *A Preview* 195

CONCEPT 7.2 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate 197

CONCEPT 7.3 After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules 198

CONCEPT 7.4 During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis 199

The Pathway of Electron Transport 200

Chemiosmosis: The Energy-Coupling Mechanism 201

An Accounting of ATP Production by Cellular Respiration 203

CONCEPT 7.5 Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen 204

Types of Fermentation 206

Comparing Fermentation with Anaerobic and Aerobic Respiration 206

The Evolutionary Significance of Glycolysis 207

CONCEPT 7.6 Glycolysis and the citric acid cycle connect to many other metabolic pathways 207

The Versatility of Catabolism 207

Biosynthesis (Anabolic Pathways) 208

8 Photosynthesis 211

OVERVIEW The Process That Feeds the Biosphere 211

CONCEPT 8.1 Photosynthesis converts light energy to the chemical energy of food 212

Chloroplasts: The Sites of Photosynthesis in Plants 212

Tracking Atoms Through Photosynthesis 213

The Two Stages of Photosynthesis: *A Preview* 214

CONCEPT 8.2 The light reactions convert solar energy to the chemical energy of ATP and NADPH 215

The Nature of Sunlight 215

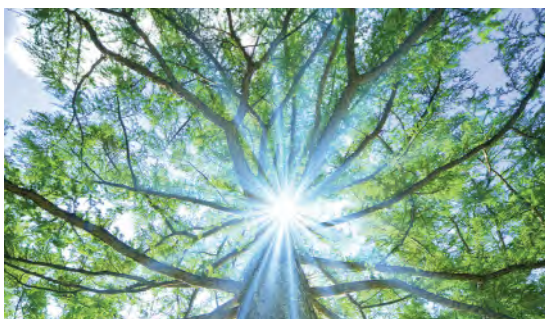
Photosynthetic Pigments: The Light Receptors 216

Excitation of Chlorophyll by Light 218

A Photosystem: A Reaction-Center Complex Associated with

Light-Harvesting Complexes 219

Linear Electron Flow 220



A Comparison of Chemiosmosis in Chloroplasts and Mitochondria 221

CONCEPT 8.3 The Calvin cycle uses the chemical energy of ATP and NADPH to reduce CO₂ to sugar 223

Evolution of Alternative Mechanisms of Carbon Fixation in Hot, Arid Climates 225

CONCEPT 8.4 Life depends on photosynthesis 227

9 The Cell Cycle 232

OVERVIEW The Key Roles of Cell Division 232

CONCEPT 9.1 Most cell division results in genetically identical daughter cells 233

Cellular Organization of the Genetic Material 233

Distribution of Chromosomes During Eukaryotic

Cell Division 233

CONCEPT 9.2 The mitotic phase alternates with interphase in the cell cycle 235

Phases of the Cell Cycle 235

The Mitotic Spindle:

A Closer Look 235

Cytokinesis: *A Closer Look* 238

Binary Fission in Bacteria 240

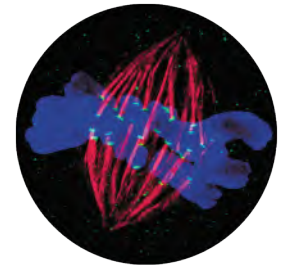
The Evolution of Mitosis 241

CONCEPT 9.3 The eukaryotic cell cycle is regulated by a molecular control system 242

Evidence for Cytoplasmic Signals 242

Checkpoints of the Cell Cycle Control System 242

Loss of Cell Cycle Controls in Cancer Cells 245



UNIT 2 Genetics 249

10 Meiosis and Sexual Life Cycles 250

OVERVIEW Variations on a Theme 250

CONCEPT 10.1 Offspring acquire genes from parents by inheriting chromosomes 251

Inheritance of Genes 251

Comparison of Asexual and Sexual Reproduction 251

CONCEPT 10.2 Fertilization and meiosis alternate in sexual life cycles 252

Sets of Chromosomes in Human Cells 252

Behavior of Chromosome Sets in the Human Life Cycle 253

The Variety of Sexual Life Cycles 254

CONCEPT 10.3 Meiosis reduces the number of chromosome sets from diploid to haploid 255

The Stages of Meiosis 255

Crossing Over and Synapsis During Prophase I 258

A Comparison of Mitosis and Meiosis 258

CONCEPT 10.4 Genetic variation produced in sexual life cycles contributes to evolution 260

Origins of Genetic Variation Among Offspring 260

The Evolutionary Significance of Genetic Variation Within Populations 262

OVERVIEW Drawing from the Deck of Genes 264

CONCEPT 11.1 Mendel used the scientific approach to identify two laws of inheritance 265

- Mendel's Experimental, Quantitative Approach 265
- The Law of Segregation 265
- The Law of Independent Assortment 269

CONCEPT 11.2 Probability laws govern Mendelian inheritance 271

- The Multiplication and Addition Rules Applied to Monohybrid Crosses 271
- Solving Complex Genetics Problems with the Rules of Probability 272

CONCEPT 11.3 Inheritance patterns are often more complex than predicted by simple Mendelian genetics 273

- Extending Mendelian Genetics for a Single Gene 273
- Extending Mendelian Genetics for Two or More Genes 275
- Nature and Nurture: The Environmental Impact on Phenotype 276
- A Mendelian View of Heredity and Variation 276

CONCEPT 11.4 Many human traits follow Mendelian patterns of inheritance 278

- Pedigree Analysis 278
- Recessively Inherited Disorders 279
- Dominantly Inherited Disorders 281
- Multifactorial Disorders 281
- Genetic Counseling Based on Mendelian Genetics 281

12 The Chromosomal Basis of Inheritance 286

OVERVIEW Locating Genes Along Chromosomes 286

CONCEPT 12.1 Morgan showed that Mendelian inheritance has its physical basis in the behavior of chromosomes: *Scientific Inquiry* 288

- Morgan's Choice of Experimental Organism 288
- Correlating Behavior of a Gene's Alleles with Behavior of a Chromosome Pair 288

CONCEPT 12.2 Sex-linked genes exhibit unique patterns of inheritance 289

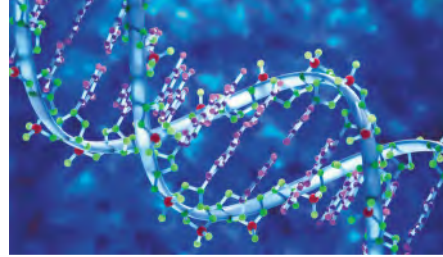
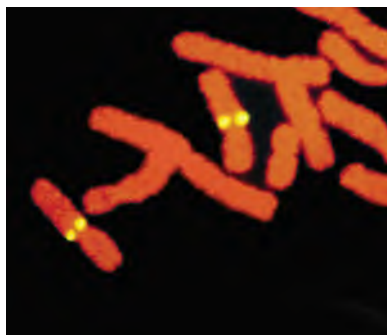
- The Chromosomal Basis of Sex 289
- Inheritance of X-Linked Genes 290
- X Inactivation in Female Mammals 291

CONCEPT 12.3 Linked genes tend to be inherited together because they are located near each other on the same chromosome 292

- How Linkage Affects Inheritance 292
- Genetic Recombination and Linkage 293
- Mapping the Distance Between Genes Using Recombination Data: *Scientific Inquiry* 295

CONCEPT 12.4 Alterations of chromosome number or structure cause some genetic disorders 298

- Abnormal Chromosome Number 298
- Alterations of Chromosome Structure 299
- Human Disorders Due to Chromosomal Alterations 299



13 The Molecular Basis of Inheritance 303

OVERVIEW Life's Operating Instructions 303

CONCEPT 13.1 DNA is the genetic material 304

- The Search for the Genetic Material: *Scientific Inquiry* 304
- Building a Structural Model of DNA: *Scientific Inquiry* 306

CONCEPT 13.2 Many proteins work together in DNA replication and repair 309

- The Basic Principle: Base Pairing to a Template Strand 310
- DNA Replication: *A Closer Look* 310
- Proofreading and Repairing DNA 316
- Evolutionary Significance of Altered DNA Nucleotides 316
- Replicating the Ends of DNA Molecules 317

CONCEPT 13.3 A chromosome consists of a DNA molecule packed together with proteins 317

CONCEPT 13.4 Understanding DNA structure and replication makes genetic engineering possible 320

- DNA Cloning: Making Multiple Copies of a Gene or Other DNA Segment 320
- Using Restriction Enzymes to Make a Recombinant DNA Plasmid 321
- Amplifying DNA: The Polymerase Chain Reaction (PCR) and Its Use in Cloning 322
- DNA Sequencing 324
- Editing Genes and Genomes 325

14 Gene Expression: From Gene to Protein 329

OVERVIEW The Flow of Genetic Information 329

CONCEPT 14.1 Genes specify proteins via transcription and translation 330

- Evidence from Studying Metabolic Defects 330
- Basic Principles of Transcription and Translation 331
- The Genetic Code 332

CONCEPT 14.2 Transcription is the DNA-directed synthesis of RNA: *A Closer Look* 335

- Molecular Components of Transcription 335
- Synthesis of an RNA Transcript 336

CONCEPT 14.3 Eukaryotic cells modify RNA after transcription 337

- Alteration of mRNA Ends 337
- Split Genes and RNA Splicing 338

CONCEPT 14.4 Translation is the RNA-directed synthesis of a polypeptide: *A Closer Look* 339

- Molecular Components of Translation 339
- Building a Polypeptide 342
- Completing and Targeting the Functional Protein 344
- Making Multiple Polypeptides in Bacteria and Eukaryotes 347

CONCEPT 14.5 Mutations of one or a few nucleotides can affect protein structure and function 349

- Types of Small-Scale Mutations 349
- New Mutations and Mutagens 352
- What Is a Gene? *Revisiting the Question* 352





15

Regulation of Gene Expression 355

OVERVIEW Beauty in the Eye of the Beholder 355

CONCEPT 15.1 Bacteria often respond to environmental change by regulating transcription 355

Operons: The Basic Concept 356

Repressible and Inducible Operons: Two Types of Negative Gene Regulation 357

Positive Gene Regulation 359

CONCEPT 15.2 Eukaryotic gene expression is regulated at many stages 360

Differential Gene Expression 360

Regulation of Chromatin Structure 361

Regulation of Transcription Initiation 361

Mechanisms of Post-transcriptional Regulation 366

CONCEPT 15.3 Noncoding RNAs play multiple roles in controlling gene expression 367

Effects on mRNAs by MicroRNAs and Small Interfering RNAs 367

Chromatin Remodeling and Effects on Transcription by Noncoding RNAs 368

CONCEPT 15.4 Researchers can monitor expression of specific genes 368

Studying the Expression of Single Genes 369

Studying the Expression of Groups of Genes 370

16

Development, Stem Cells, and Cancer 373

OVERVIEW Orchestrating Life's Processes 373

CONCEPT 16.1 A program of differential gene expression leads to the different cell types in a multicellular organism 374

A Genetic Program for Embryonic Development 374

Cytoplasmic Determinants and Inductive Signals 374

Sequential Regulation of Gene Expression during Cellular Differentiation 375

Pattern Formation: Setting Up the Body Plan 378

Genetic Analysis of Early Development: *Scientific Inquiry* 379

CONCEPT 16.2 Cloning of organisms showed that differentiated cells could be “reprogrammed” and ultimately led to the production of stem cells 382

Cloning Plants: Single-Cell Cultures 382

Cloning Animals: Nuclear Transplantation 382

Stem Cells of Animals 384

CONCEPT 16.3 Abnormal regulation of genes that affect the cell cycle can lead to cancer 386

Types of Genes Associated with Cancer 386

Interference with Cell-Signaling Pathways 387

The Multistep Model of Cancer Development 388

Inherited Predisposition and Other Factors Contributing to Cancer 389

17

Viruses 394

OVERVIEW A Borrowed Life 394

CONCEPT 17.1 A virus consists of a nucleic acid surrounded by a protein coat 394

Viral Genomes 395

Capsids and Envelopes 395

CONCEPT 17.2 Viruses replicate only in host cells 396

General Features of Viral Replicative Cycles 396

Replicative Cycles of Phages 397

Bacterial Defenses Against Phages 399

Replicative Cycles of Animal Viruses 399

Evolution of Viruses 401

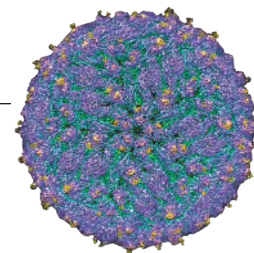
CONCEPT 17.3 Viruses and prions are formidable pathogens in animals and plants 403

Viral Diseases in Animals 403

Emerging Viruses 404

Viral Diseases in Plants 406

Prions: Proteins as Infectious Agents 406



18

Genomes and Their Evolution 409

OVERVIEW Mining the Genome 409

CONCEPT 18.1 The Human Genome Project fostered development of faster, less expensive sequencing techniques 410

CONCEPT 18.2 Scientists use bioinformatics to analyze genomes and their functions 411

Centralized Resources for Analyzing Genome Sequences 411

Understanding the Functions of Protein-Coding Genes 411

Understanding Genes and Gene Expression at the Systems Level 412

CONCEPT 18.3 Genomes vary in size, number of genes, and gene density 414

Genome Size 414

Number of Genes 414

Gene Density and

Noncoding DNA 415

CONCEPT 18.4 Multicellular eukaryotes have a lot of noncoding DNA and many multigene families 415

Transposable Elements and Related Sequences 416

Other Repetitive DNA, Including Simple Sequence DNA 417

Genes and Multigene Families 417

CONCEPT 18.5 Duplication, rearrangement, and mutation of DNA contribute to genome evolution 419

Duplication of Entire Chromosome Sets 419

Alterations of Chromosome Structure 419

Duplication and Divergence of Gene-Sized Regions of DNA 420

Rearrangements of Parts of Genes: Exon Duplication and Exon Shuffling 421

How Transposable Elements Contribute to Genome Evolution 423

CONCEPT 18.6 Comparing genome sequences provides clues to evolution and development 423

Comparing Genomes 424

Widespread Conservation of Developmental Genes Among Animals 426



UNIT 3 Evolution 430

19

Descent with Modification 431

OVERVIEW Endless Forms Most Beautiful 431

CONCEPT 19.1 The Darwinian revolution challenged traditional views of a young Earth inhabited by unchanging species 432

Scala Naturae and Classification of Species 432

Ideas About Change over Time 432

Lamarck's Hypothesis of Evolution 433

CONCEPT 19.2 Descent with modification by natural selection explains the adaptations of organisms and the unity and diversity of life 434

Darwin's Research 434

The Voyage of the *Beagle* 434

Darwin's Focus on Adaptation 435

Ideas from *The Origin of Species* 436

Artificial Selection, Natural Selection, and Adaptation 437

CONCEPT 19.3 Evolution is supported by an overwhelming amount of scientific evidence 439

Direct Observations of Evolutionary Change 439

Homology 441

The Fossil Record 442

Biogeography 443

What Is Theoretical About Darwin's View of Life? 444



20

Phylogeny 447

OVERVIEW Investigating the Evolutionary History of Life 447

CONCEPT 20.1 Phylogenies show evolutionary relationships 448

Binomial Nomenclature 448

Hierarchical Classification 448

Linking Classification and Phylogeny 449

What We Can and Cannot Learn from Phylogenetic Trees 449

Applying Phylogenies 451

CONCEPT 20.2 Phylogenies are inferred from morphological and molecular data 452

Morphological and Molecular Homologies 452

Sorting Homology from Analogy 452

Evaluating Molecular Homologies 452

CONCEPT 20.3 Shared characters are used to construct phylogenetic trees 453

Cladistics 453

Phylogenetic Trees with Proportional Branch Lengths 455

Maximum Parsimony 456

Phylogenetic Trees as Hypotheses 458

CONCEPT 20.4 Molecular clocks help track evolutionary time 459

Molecular Clocks 459

Applying a Molecular Clock: Dating the Origin of HIV 460

CONCEPT 20.5 New information continues to revise our understanding of evolutionary history 461

From Two Kingdoms to Three Domains 461

The Important Role of Horizontal Gene Transfer 462

21

The Evolution of Populations 466

OVERVIEW The Smallest Unit of Evolution 466

CONCEPT 21.1 Genetic variation makes evolution possible 467

Genetic Variation 467

Sources of Genetic Variation 468

CONCEPT 21.2 The Hardy-Weinberg equation can be used to test whether a population is evolving 469

Gene Pools and Allele Frequencies 470

The Hardy-Weinberg Equation 470

CONCEPT 21.3 Natural selection, genetic drift, and gene flow can alter allele frequencies in a population 473

Natural Selection 474

Genetic Drift 474

Gene Flow 476

CONCEPT 21.4 Natural selection is the only mechanism that consistently causes adaptive evolution 477

Natural Selection: *A Closer Look* 477

The Key Role of Natural Selection in Adaptive Evolution 479

Balancing Selection 479

Sexual Selection 482

Why Natural Selection Cannot Fashion Perfect Organisms 483



22

The Origin of Species 486

OVERVIEW That "Mystery of Mysteries" 486

CONCEPT 22.1 The biological species concept emphasizes reproductive isolation 487

The Biological Species Concept 487

Other Definitions of Species 490

CONCEPT 22.2 Speciation can take place with or without geographic separation 490

Allopatric ("Other Country") Speciation 491

Sympatric ("Same Country") Speciation 492

Allopatric and Sympatric Speciation: *A Review* 495

CONCEPT 22.3 Hybrid zones reveal factors that cause reproductive isolation 496

Patterns Within Hybrid Zones 496

Hybrid Zones and Environmental Change 496

Hybrid Zones over Time 497

CONCEPT 22.4 Speciation can occur rapidly or slowly and can result from changes in few or many genes 500

The Time Course of Speciation 500

Studying the Genetics of Speciation 502

From Speciation to Macroevolution 503

OVERVIEW A Surprise in the Desert 505

CONCEPT 23.1 The fossil record documents life's history 506

The Fossil Record 506

How Rocks and Fossils Are Dated 507

Fossils Frame the Geologic Record 507

The Origin of New Groups of Organisms 509

CONCEPT 23.2 The rise and fall of groups of organisms reflect differences in speciation and extinction rates 511

Plate Tectonics 512

Mass Extinctions 514

Adaptive Radiations 517

CONCEPT 23.3 Major changes in body form can result from changes in the sequences and regulation of developmental genes 519

Effects of Developmental Genes 519

The Evolution of Development 520

CONCEPT 23.4 Evolution is not goal oriented 522

Evolutionary Novelties 522

Evolutionary Trends 524

UNIT 4 The Evolutionary History of Life 527

OVERVIEW The First Cells 528

CONCEPT 24.1 Conditions on early Earth made the origin of life possible 529

Synthesis of Organic Compounds on Early Earth 529

Abiotic Synthesis of Macromolecules 530

Protocells 530

Self-Replicating RNA 530

Fossil Evidence of Early Life 531

CONCEPT 24.2 Diverse structural and metabolic adaptations have evolved in prokaryotes 532

Cell-Surface Structures 532

Motility 534

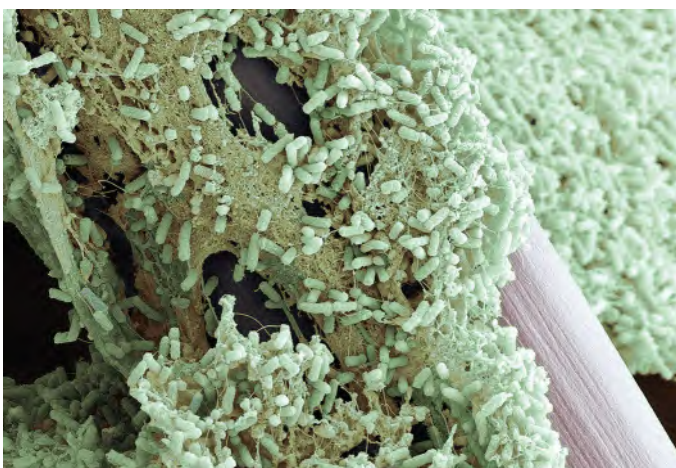
Internal Organization and DNA 534

Nutritional and Metabolic Adaptations 535

Reproduction 536

Adaptations of Prokaryotes: *A Summary* 536

CONCEPT 24.3 Rapid reproduction, mutation, and genetic recombination promote genetic diversity in prokaryotes 537



Rapid Reproduction and Mutation 537

Genetic Recombination 538

CONCEPT 24.4 Prokaryotes have radiated into a diverse set of lineages 540

An Overview of Prokaryotic Diversity 540

Bacteria 541

Archaea 541

CONCEPT 24.5 Prokaryotes play crucial roles in the biosphere 544

Chemical Recycling 545

Ecological Interactions 545

Impact on Humans 546

OVERVIEW Shape Changers 551

CONCEPT 25.1 Eukaryotes arose by endosymbiosis more than 1.8 billion years ago 551

The Fossil Record of Early Eukaryotes 553

Endosymbiosis in Eukaryotic Evolution 554

CONCEPT 25.2 Multicellularity has originated several times in eukaryotes 557

Multicellular Colonies 557

Independent Origins of Complex Multicellularity 557

Steps in the Origin of Multicellular Animals 558

CONCEPT 25.3 Four "supergroups" of eukaryotes have been proposed based on morphological and molecular data 559

Four Supergroups of Eukaryotes 559

Excavates 562

SAR: Stramenopiles, Alveolates, and Rhizarians 563

Archaeplastids 565

Unikonts 566

CONCEPT 25.4 Single-celled eukaryotes play key roles in ecological communities and affect human health 569

Structural and Functional Diversity in Protists 569

Photosynthetic Protists 569

Symbiotic Protists 570

Effects on Human Health 570



OVERVIEW The Greening of Earth 574

CONCEPT 26.1 Fossils show that plants colonized land more than 470 million years ago 575

Evidence of Algal Ancestry 575

Adaptations Enabling the Move to Land 575

Derived Traits of Plants 577

Early Plants 577

CONCEPT 26.2 Though not closely related to plants, fungi played a key role in the colonization of land 578

The Origin of Fungi 579

Fungal Adaptations for Life on Land 579

Diversification of Fungi 581

CONCEPT 26.3 Early plants radiated into a diverse set of lineages 584

Bryophytes: A Collection of Basal Plant Lineages 584

Seedless Vascular Plants: The First Plants to Grow Tall 585

CONCEPT 26.4 Seeds and pollen grains are key adaptations for life on land 587

Terrestrial Adaptations in Seed Plants 587

Early Seed Plants and the Rise of Gymnosperms 589

The Origin and Diversification of Angiosperms 590

CONCEPT 26.5 Plants and fungi fundamentally changed chemical cycling and biotic interactions 593

Physical Environment and Chemical Cycling 593

Biotic Interactions 594



CONCEPT 27.4 Vertebrates have been the ocean's dominant predators for more than 400 million years 609

Bilaterian Radiation II: Aquatic Vertebrates 609

Summary: Effects of Bilaterian Radiations I and II 612

CONCEPT 27.5 Several animal groups had features facilitating their colonization of land 612

Early Land Animals 612

Colonization of Land by Arthropods 614

Terrestrial Vertebrates 615

CONCEPT 27.6 Amniotes have key adaptations for life in a wide range of terrestrial environments 618

Terrestrial Adaptations in Amniotes 618

The Origin and Radiation of Amniotes 618

Human Evolution 622

CONCEPT 27.7 Animals have transformed ecosystems and altered the course of evolution 624

Ecological Effects of Animals 624

Evolutionary Effects of Animals 625



27

The Rise of Animal Diversity 599

OVERVIEW Life Becomes Dangerous 599

CONCEPT 27.1 Animals originated more than 700 million years ago 599

Fossil and Molecular Evidence 600

Early-Diverging Animal Groups 600

CONCEPT 27.2 The diversity of large animals increased dramatically during the "Cambrian explosion" 601

Evolutionary Change in the Cambrian Explosion 602

Dating the Origin of Bilaterians 603

CONCEPT 27.3 Diverse animal groups radiated in aquatic environments 603

Animal Body Plans 603

The Diversification of Animals 605

Bilaterian Radiation I: Diverse Invertebrates 605



UNIT 5 Plant Form and Function 630

28 Vascular Plant Structure and Growth 631

OVERVIEW Beauty Through Repetition 631

CONCEPT 28.1 Plants have a hierarchical organization consisting of organs, tissues, and cells 632

The Three Basic Plant Organs: Roots, Stems, and Leaves 632

Dermal, Vascular, and Ground Tissue 635

Common Types of Plant Cells 636

CONCEPT 28.2 Different meristems generate new cells for primary and secondary growth 638

Gene Expression and Control of Cell Differentiation 638

Meristematic Control of the Transition to Flowering and the Life Spans of Plants 640

CONCEPT 28.3 Primary growth lengthens roots and shoots 640

Primary Growth of Roots 640

Primary Growth of Shoots 642

CONCEPT 28.4 Secondary growth increases the diameter of stems and roots in woody plants 644

The Vascular Cambium and Secondary Vascular Tissue 646

The Cork Cambium and the Production of Periderm 646



29 Resource Acquisition, Nutrition, and Transport in Vascular Plants 649

OVERVIEW A Whole Lot of Shaking Going On 649

CONCEPT 29.1 Adaptations for acquiring resources were key steps in the evolution of vascular plants 650

Shoot Architecture and Light Capture 650

Root Architecture and Acquisition of Water and Minerals 651

CONCEPT 29.2 Different mechanisms transport substances over short or long distances 652

The Apoplast and Symplast: Transport Continuums 652

Short-Distance Transport of Solutes Across Plasma Membranes 652

Short-Distance Transport of Water Across Plasma Membranes 653

Long-Distance Transport: The Role of Bulk Flow 655

CONCEPT 29.3 Plant roots absorb many types of essential elements from the soil 655

Macronutrients and Micronutrients 655

Symptoms of Mineral Deficiency 656

Soil Management 657

The Living, Complex Ecosystem of Soil 657

CONCEPT 29.4 Plant nutrition often involves relationships with other organisms 658

Bacteria and Plant Nutrition 660

Fungi and Plant Nutrition 662

Epiphytes, Parasitic Plants, and Carnivorous Plants 663

CONCEPT 29.5 Transpiration drives the transport of water and minerals from roots to shoots via the xylem 665

Absorption of Water and Minerals by Root Cells 665

Transport of Water and Minerals into the Xylem 665

Bulk Flow Transport via the Xylem 666

Xylem Sap Ascent by Bulk Flow: *A Review* 668

CONCEPT 29.6 The rate of transpiration is regulated by stomata 668

Stomata: Major Pathways for Water Loss 668

Mechanisms of Stomatal Opening and Closing 669

Stimuli for Stomatal Opening and Closing 669

Effects of Transpiration on Wilting and Leaf Temperature 670

Adaptations That Reduce Evaporative Water Loss 670

CONCEPT 29.7 Sugars are transported from sources to sinks via the phloem 671

Movement from Sugar Sources to Sugar Sinks 671

Bulk Flow by Positive Pressure: The Mechanism of Translocation in Angiosperms 672

30 Reproduction and Domestication of Flowering Plants 675

OVERVIEW Getting Hooked 675

CONCEPT 30.1 Flowers, double fertilization, and fruits are unique features of the angiosperm life cycle 676

Flower Structure and Function 676

Flower Formation 676

The Angiosperm Life Cycle: An Overview 678

Pollination: *A Closer Look* 680

Seed Development and Structure 681

Germination, Growth, and Flowering 683

Fruit Structure and Function 683

CONCEPT 30.2 Flowering plants reproduce sexually, asexually, or both 686

Mechanisms of Asexual Reproduction 686

Advantages and Disadvantages of Asexual Versus Sexual Reproduction 686

Mechanisms That Prevent Self-Fertilization 687

Totipotency, Vegetative Reproduction, and Tissue Culture 687

CONCEPT 30.3 People modify crops through breeding and genetic engineering 689

Plant Breeding 689

Plant Biotechnology and Genetic Engineering 690

The Debate over Plant Biotechnology 691

31 Plant Responses to Internal and External Signals 695

OVERVIEW Stimuli and a Stationary Life 695

CONCEPT 31.1 Plant hormones help coordinate growth, development, and responses to stimuli 696

The Discovery of Plant Hormones 696

A Survey of Plant Hormones 697

CONCEPT 31.2 Responses to light are critical for plant success 703

Photomorphogenesis 703

Biological Clocks and Circadian Rhythms 705

Photoperiodism and Responses to Seasons 706

CONCEPT 31.3 Plants respond to a wide variety of stimuli other than light 708

Gravity 709

Mechanical Stimuli 709

Environmental Stresses 710

CONCEPT 31.4 Plants respond to attacks by herbivores and pathogens 713

Defenses Against Herbivores 714

Defenses Against Pathogens 714

UNIT 6 Animal Form and Function 718

32 The Internal Environment of Animals: Organization and Regulation 719

OVERVIEW Diverse Forms, Common Challenges 719

CONCEPT 32.1 Animal form and function are correlated at all levels of organization 720

CONCEPT 32.2 The endocrine and nervous systems act individually and together in regulating animal physiology 724

An Overview of Coordination and Control 724

Endocrine Glands and Hormones 725

Regulation of Endocrine Signaling 725

Simple Endocrine Pathways 726

Neuroendocrine Signaling 726

Hormone Solubility 727

Multiple Effects of Hormones 728

CONCEPT 32.3 Feedback control maintains the internal environment in many animals 729

Regulating and Conforming 729

Homeostasis 730

Thermoregulation: *A Closer Look* 730



CONCEPT 32.4 A shared system mediates osmoregulation and excretion in many animals 733

Osmosis and Osmolarity 733

Osmoregulatory Challenges and Mechanisms 734

Nitrogenous Wastes 734

Excretory Processes 735

CONCEPT 32.5 The mammalian kidney's ability to conserve water is a key terrestrial adaptation 738

From Blood Filtrate to Urine: *A Closer Look* 738

Concentrating Urine in the Mammalian Kidney 740

Adaptations of the Vertebrate Kidney to Diverse Environments 740

Homeostatic Regulation of the Kidney 741

33 Animal Nutrition 744

OVERVIEW The Need to Feed 744

CONCEPT 33.1 An animal's diet must supply chemical energy, organic building blocks, and essential nutrients 745

Essential Nutrients 745

Dietary Deficiencies 746

CONCEPT 33.2 Food processing involves ingestion, digestion, absorption, and elimination 747

Digestive Compartments 747

CONCEPT 33.3 Organs specialized for sequential stages of food processing form the mammalian digestive system 749

The Oral Cavity, Pharynx, and Esophagus 749

Digestion in the Stomach 750

Digestion in the Small Intestine 751

Absorption in the Small Intestine 752

Processing in the Large Intestine 753

CONCEPT 33.4 Evolutionary adaptations of vertebrate digestive systems correlate with diet 754

Dental Adaptations 754

Stomach and Intestinal Adaptations 754

Mutualistic Adaptations in Humans 755

Mutualistic Adaptations in Herbivores 756

CONCEPT 33.5 Feedback circuits regulate digestion, energy allocation, and appetite 756

Regulation of Digestion 756

Energy Allocation 757

Regulation of Appetite and Consumption 759

34 Circulation and Gas Exchange 762

OVERVIEW Trading Places 762

CONCEPT 34.1 Circulatory systems link exchange surfaces with cells throughout the body 763

Open and Closed Circulatory Systems 763

Organization of Vertebrate Circulatory Systems 764

CONCEPT 34.2 Coordinated cycles of heart contraction drive double circulation in mammals 766

Mammalian Circulation 766

The Mammalian Heart: *A Closer Look* 766

Maintaining the Heart's Rhythmic Beat 768

CONCEPT 34.3 Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels 768

Blood Vessel Structure and Function 769

Blood Flow Velocity 769

Blood Pressure 770

Capillary Function 771

Fluid Return by the Lymphatic System 772

CONCEPT 34.4 Blood components function in exchange, transport, and defense 772

Blood Composition and Function 773

Cardiovascular Disease 775

CONCEPT 34.5 Gas exchange occurs across specialized respiratory surfaces 776

Partial Pressure Gradients in Gas Exchange 777

Respiratory Media 778

Respiratory Surfaces 778

Gills in Aquatic Animals 779

Tracheal Systems in Insects 779

Lungs 780

CONCEPT 34.6 Breathing ventilates the lungs 782

How a Mammal Breathes 782

Control of Breathing in Humans 783

CONCEPT 34.7 Adaptations for gas exchange include pigments that bind and transport gases 784

Coordination of Circulation and Gas Exchange 784

Respiratory Pigments 784

Carbon Dioxide Transport 785

Respiratory Adaptations of Diving Mammals 786

35

The Immune System 789

OVERVIEW Recognition and Response 789

CONCEPT 35.1 In innate immunity, recognition and response rely on traits common to groups of pathogens 790

Innate Immunity of Invertebrates 790

Innate Immunity of Vertebrates 790

Evasion of Innate Immunity by Pathogens 793

CONCEPT 35.2 In adaptive immunity, receptors provide pathogen-specific recognition 793

Antigen Recognition by B Cells and Antibodies 793

Antigen Recognition by T Cells 794

B Cell and T Cell Development 795

CONCEPT 35.3 Adaptive immunity defends against infection of body fluids and body cells 798

Helper T Cells: Activating Adaptive Immunity 798

B Cells and Antibodies: A Response to Extracellular Pathogens 798

Cytotoxic T Cells: A Response to Infected Host Cells 800

Summary of the Humoral and Cell-Mediated

Immune Responses 800

Immunization 800

Active and Passive Immunity 801

Antibodies as Tools 802

Immune Rejection 802

Disruptions in Immune System Function 802

Cancer and Immunity 805

36

Reproduction and Development 807

OVERVIEW Let Me Count the Ways 807

CONCEPT 36.1 Both asexual and sexual reproduction occur in the animal kingdom 807

Mechanisms of Asexual Reproduction 808

Sexual Reproduction: An Evolutionary Enigma 808

Reproductive Cycles 809

Variation in Patterns of Sexual Reproduction 809

External and Internal Fertilization 810

Ensuring the Survival of Offspring 810

CONCEPT 36.2 Reproductive organs produce and transport gametes 811

Variation in Reproductive Systems 811

Human Male Reproductive

Anatomy 811

Human Female Reproductive

Anatomy 813

Gametogenesis 813

CONCEPT 36.3 The interplay of tropic and sex hormones regulates reproduction in mammals 816

Biological Sex, Gender Identity, and Sexual Orientation in Human Sexuality 816

Hormonal Control of the Male Reproductive System 817

Hormonal Control of Female Reproductive Cycles 818

Human Sexual Response 820

CONCEPT 36.4 Development of an egg into a mature embryo requires fertilization, cleavage, gastrulation, and organogenesis 820

Fertilization 821

Cleavage 821

Conception, Cleavage, and Embryo Implantation in Humans 822

Gastrulation 822

Embryonic Development in Humans 824

Fetal Development and Birth 824

Contraception 825

Infertility and *in Vitro* Fertilization 826



37

Neurons, Synapses, and Signaling 828

OVERVIEW Lines of Communication 828

CONCEPT 37.1 Neuron structure and organization reflect function in information transfer 829

Neuron Structure and Function 829

Introduction to Information Processing 830

CONCEPT 37.2 Ion pumps and ion channels establish the resting potential of a neuron 831

Formation of the Resting Potential 831

Modeling the Resting Potential 832

CONCEPT 37.3 Action potentials are the signals conducted by axons 834

Hyperpolarization and Depolarization 834

Graded Potentials and Action Potentials 834

Generation of Action Potentials: *A Closer Look* 835

Conduction of Action Potentials 837

CONCEPT 37.4 Neurons communicate with other cells at synapses 839

Generation of Postsynaptic Potentials 840

Summation of Postsynaptic Potentials 840

Modulated Signaling at Synapses 840

Neurotransmitters 841

38

Nervous and Sensory Systems 846

OVERVIEW Command and Control Center 846

CONCEPT 38.1 Nervous systems consist of circuits of neurons and supporting cells 846

Glia 847

Organization of the Vertebrate Nervous System 848

The Peripheral Nervous System 848

CONCEPT 38.2 The vertebrate brain is regionally specialized 849

Functional Imaging of the Brain 849

Arousal and Sleep 849

Biological Clock Regulation 852

Emotions 852

The Brain's Reward System and Drug Addiction 853

CONCEPT 38.3 The cerebral cortex controls voluntary movement and cognitive functions 854

Language and Speech 854

Lateralization of Cortical Function 854

Information Processing 855

Frontal Lobe Function 855

Evolution of Cognition in Vertebrates 855

Neuronal Plasticity 856

Memory and Learning 857

Future Directions in Brain Research 857

CONCEPT 38.4 Sensory receptors transduce stimulus energy and transmit signals to the central nervous system 857

Sensory Reception and Transduction 857

Transmission 858

Perception 858

Amplification and Adaptation 858

Types of Sensory Receptors 858

CONCEPT 38.5 In hearing and equilibrium, mechanoreceptors detect moving fluid or settling particles 860

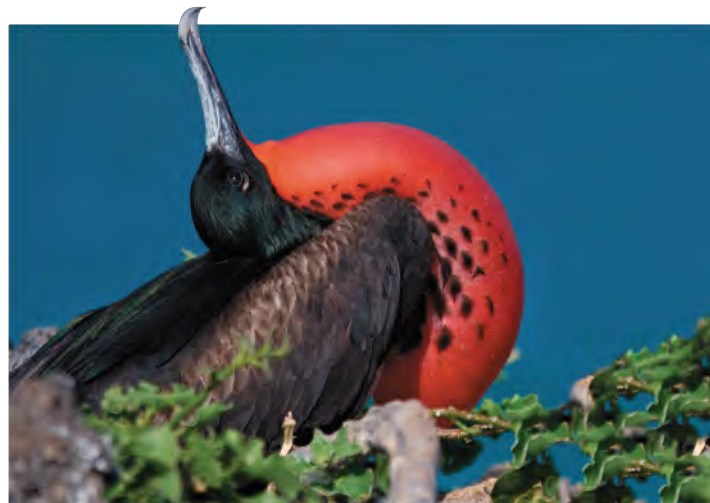
Sensing of Gravity and Sound in Invertebrates 860

Hearing and Equilibrium in Mammals 860

CONCEPT 38.6 The diverse visual receptors of animals depend on light-absorbing pigments 863

Evolution of Visual Perception 863

The Vertebrate Visual System 865



39 Motor Mechanisms and Behavior 870

OVERVIEW The How and Why of Animal Activity 870

CONCEPT 39.1 The physical interaction of protein filaments is required for muscle function 871

Vertebrate Skeletal Muscle 871

Other Types of Vertebrate Muscle 876

CONCEPT 39.2 Skeletal systems transform muscle contraction into locomotion 877

Types of Skeletal Systems 877

Types of Locomotion 879

CONCEPT 39.3 Discrete sensory inputs can stimulate both simple and complex behaviors 881

Fixed Action Patterns 882

Migration 882

Behavioral Rhythms 882

Animal Signals and Communication 883

CONCEPT 39.4 Learning establishes specific links between experience and behavior 884

Experience and Behavior 884

Learning 884

CONCEPT 39.5 Selection for individual survival and reproductive success can explain diverse behaviors 887

Evolution of Foraging Behavior 887

Mating Behavior and Mate Choice 888

CONCEPT 39.6 Genetic analyses and the concept of inclusive fitness provide a basis for studying the evolution of behavior 890

Genetic Basis of Behavior 890

Genetic Variation and the Evolution of Behavior 890

Altruism 891

Inclusive Fitness 891

UNIT 7 Ecology 895

40 Population Ecology and the Distribution of Organisms 896

OVERVIEW Discovering Ecology 896

CONCEPT 40.1 Earth's climate influences the distribution of terrestrial biomes 899

Global Climate Patterns 899

Regional and Local Effects on Climate 899

Climate and Terrestrial Biomes 900

General Features of Terrestrial Biomes 901

CONCEPT 40.2 Aquatic biomes are diverse and dynamic systems that cover most of Earth 905

CONCEPT 40.3 Interactions between organisms and the environment limit the distribution of species 908

Dispersal and Distribution 908

Biotic Factors 909

Abiotic Factors 909

CONCEPT 40.4 Biotic and abiotic factors affect population density, dispersion, and demographics 910

Density and Dispersion 910

Demographics 912

CONCEPT 40.5 The exponential and logistic models describe the growth of populations 913

Changes in Population Size 913

Exponential Growth 914

Carrying Capacity 914

The Logistic Growth Model 915

The Logistic Model and Real Populations 916

CONCEPT 40.6 Population dynamics are influenced strongly by life history traits and population density 917

"Trade-offs" and Life Histories 917



Population Change and Population Density 918
Mechanisms of Density-Dependent Population Regulation 918
Population Dynamics 919



41 Ecological Communities 923

OVERVIEW Communities in Motion 923

CONCEPT 41.1 Interactions between species may help, harm, or have no effect on the individuals involved 924

Competition 924
Exploitation 925
Positive Interactions 928

CONCEPT 41.2 Biological communities can be characterized by their diversity and trophic structure 929

Species Diversity 929
Diversity and Community Stability 930
Trophic Structure 931
Species with a Large Impact 932
Bottom-Up and Top-Down Controls 932

CONCEPT 41.3 Disturbance influences species diversity and composition 934

Characterizing Disturbance 934
Ecological Succession 935
Human Disturbance 936

CONCEPT 41.4 Biogeographic factors affect community diversity 937

Latitudinal Gradients 937
Area Effects 938

CONCEPT 41.5 Pathogens alter community structure locally and globally 938

Effects on Community Structure 939
Community Ecology and Zoonotic Diseases 939

42 Ecosystems and Energy 942

OVERVIEW Transformed to Tundra 942

CONCEPT 42.1 Physical laws govern energy flow and chemical cycling in ecosystems 943

Conservation of Energy 943
Conservation of Mass 943
Energy, Mass, and Trophic Levels 944

CONCEPT 42.2 Energy and other limiting factors control primary production in ecosystems 944

Ecosystem Energy Budgets 945
Primary Production in Aquatic Ecosystems 946
Primary Production in Terrestrial Ecosystems 947

CONCEPT 42.3 Energy transfer between trophic levels is typically only 10% efficient 950

Production Efficiency 950
Trophic Efficiency and Ecological Pyramids 950

CONCEPT 42.4 Biological and geochemical processes cycle nutrients and water in ecosystems 952

Decomposition and Nutrient Cycling Rates 952
Biogeochemical Cycles 953
Case Study: Nutrient Cycling in the Hubbard Brook Experimental Forest 956

CONCEPT 42.5 Restoration ecologists return degraded ecosystems to a more natural state 957

Bioremediation 957
Biological Augmentation 959
Ecosystems: A Review 959

43 Conservation Biology and Global Change 964

OVERVIEW Psychedelic Treasure 964

CONCEPT 43.1 Human activities threaten Earth's biodiversity 965

Three Levels of Biodiversity 965
Biodiversity and Human Welfare 966
Threats to Biodiversity 967

CONCEPT 43.2 Population conservation focuses on population size, genetic diversity, and critical habitat 970

Small-Population Approach 970
Declining-Population Approach 972
Weighing Conflicting Demands 973

CONCEPT 43.3 Landscape and regional conservation help sustain biodiversity 973

Landscape Structure and Biodiversity 974
Establishing Protected Areas 975

CONCEPT 43.4 Earth is changing rapidly as a result of human actions 977

Nutrient Enrichment 977
Toxins in the Environment 978
Greenhouse Gases and Climate Change 979

CONCEPT 43.5 The human population is no longer growing exponentially but is still increasing rapidly 984

The Global Human Population 984
Global Carrying Capacity 985

CONCEPT 43.6 Sustainable development can improve human lives while conserving biodiversity 986

Sustainable Development 986
The Future of the Biosphere 987

Appendix A Answers A-1

Appendix B Periodic Table of the Elements B-1

Appendix C The Metric System C-1

Appendix D A Comparison of the Light Microscope and the Electron Microscope D-1

Appendix E Classification of Life E-1

Appendix F Scientific Skills Review F-1

Credits CR-1

Glossary G-1

Index I-1