



# LIFE

The Science of Biology  
TENTH EDITION

DAVID  
**SADAVA**  
The Claremont Colleges

DAVID M.  
**HILLIS**  
University of Texas

H. CRAIG  
**HELLER**  
Stanford University

MAY R.  
**BERENBAUM**  
University of Illinois



SINAUER



MACMILLAN

# Contents in Brief

## PART ONE ■ THE SCIENCE OF LIFE AND ITS CHEMICAL BASIS

- 1 Studying Life 1
- 2 Small Molecules and the Chemistry of Life 21
- 3 Proteins, Carbohydrates, and Lipids 39
- 4 Nucleic Acids and the Origin of Life 62

## PART TWO ■ CELLS

- 5 Cells: The Working Units of Life 77
- 6 Cell Membranes 105
- 7 Cell Communication and Multicellularity 125

## PART THREE ■ CELLS AND ENERGY

- 8 Energy, Enzymes, and Metabolism 144
- 9 Pathways that Harvest Chemical Energy 165
- 10 Photosynthesis: Energy from Sunlight 185

## PART FOUR ■ GENES AND HEREDITY

- 11 The Cell Cycle and Cell Division 205
- 12 Inheritance, Genes, and Chromosomes 232
- 13 DNA and Its Role in Heredity 259
- 14 From DNA to Protein: Gene Expression 281
- 15 Gene Mutation and Molecular Medicine 304
- 16 Regulation of Gene Expression 328

## PART FIVE ■ GENOMES

- 17 Genomes 352
- 18 Recombinant DNA and Biotechnology 373
- 19 Differential Gene Expression in Development 392
- 20 Genes, Development, and Evolution 412

## PART SIX ■ THE PATTERNS AND PROCESSES OF EVOLUTION

- 21 Mechanisms of Evolution 427
- 22 Reconstructing and Using Phylogenies 449
- 23 Speciation 467
- 24 Evolution of Genes and Genomes 485
- 25 The History of Life on Earth 505

## PART SEVEN ■ THE EVOLUTION OF DIVERSITY

- 26 Bacteria, Archaea, and Viruses 525
- 27 The Origin and Diversification of Eukaryotes 549
- 28 Plants without Seeds: From Water to Land 569

- 29 The Evolution of Seed Plants 588
- 30 The Evolution and Diversity of Fungi 608
- 31 Animal Origins and the Evolution of Body Plans 629
- 32 Protostome Animals 651
- 33 Deuterostome Animals 678

## PART EIGHT ■ FLOWERING PLANTS: FORM AND FUNCTION

- 34 The Plant Body 708
- 35 Transport in Plants 726
- 36 Plant Nutrition 740
- 37 Regulation of Plant Growth 756
- 38 Reproduction in Flowering Plants 778
- 39 Plant Responses to Environmental Challenges 797

## PART NINE ■ ANIMALS: FORM AND FUNCTION

- 40 Physiology, Homeostasis, and Temperature Regulation 815
- 41 Animal Hormones 834
- 42 Immunology: Animal Defense Systems 856
- 43 Animal Reproduction 880
- 44 Animal Development 902
- 45 Neurons, Glia, and Nervous Systems 924
- 46 Sensory Systems 946
- 47 The Mammalian Nervous System 967
- 48 Musculoskeletal Systems 986
- 49 Gas Exchange 1005
- 50 Circulatory Systems 1025
- 51 Nutrition, Digestion, and Absorption 1048
- 52 Salt and Water Balance and Nitrogen Excretion 1071
- 53 Animal Behavior 1093

## PART TEN ■ ECOLOGY

- 54 Ecology and the Distribution of Life 1121
- 55 Population Ecology 1149
- 56 Species Interactions and Coevolution 1169
- 57 Community Ecology 1188
- 58 Ecosystems and Global Ecology 1207
- 59 Biodiversity and Conservation Biology 1228

# Contents

## PART ONE

### The Science of Life and Its Chemical Basis

#### 1 Studying Life 1

##### 1.1 What Is Biology? 2

Life arose from non-life via chemical evolution 3

Cellular structure evolved in the common ancestor of life 3

Photosynthesis allows some organisms to capture energy from the sun 4

Biological information is contained in a genetic language common to all organisms 5

Populations of all living organisms evolve 6

Biologists can trace the evolutionary tree of life 6

Cellular specialization and differentiation underlie multicellular life 9

Living organisms interact with one another 9

Nutrients supply energy and are the basis of biosynthesis 10

Living organisms must regulate their internal environment 10

##### 1.2 How Do Biologists Investigate Life? 11

Observing and quantifying are important skills 11

Scientific methods combine observation, experimentation, and logic 11

Good experiments have the potential to falsify hypotheses 12

Statistical methods are essential scientific tools 13

Discoveries in biology can be generalized 14

Not all forms of inquiry are scientific 14

##### 1.3 Why Does Biology Matter? 15

Modern agriculture depends on biology 15



Biology is the basis of medical practice 15

Biology can inform public policy 16

Biology is crucial for understanding ecosystems 17

Biology helps us understand and appreciate biodiversity 17

#### 2

### Small Molecules and the Chemistry of Life 21

##### 2.1 How Does Atomic Structure Explain the Properties of Matter? 22

An element consists of only one kind of atom 22

Each element has a unique number of protons 22

The number of neutrons differs among isotopes 22

The behavior of electrons determines chemical bonding and geometry 24

##### 2.2 How Do Atoms Bond to Form Molecules? 26

Covalent bonds consist of shared pairs of electrons 26

Ionic attractions form by electrical attraction 28

Hydrogen bonds may form within or between molecules with polar covalent bonds 30

Hydrophobic interactions bring together nonpolar molecules 30

van der Waals forces involve contacts between atoms 30

##### 2.3 How Do Atoms Change Partners in Chemical Reactions? 31

##### 2.4 What Makes Water So Important for Life? 32

Water has a unique structure and special properties 32

The reactions of life take place in aqueous solutions 33

Aqueous solutions may be acidic or basic 34

#### 3

### Proteins, Carbohydrates, and Lipids 39

##### 3.1 What Kinds of Molecules Characterize Living Things? 40

Functional groups give specific properties to biological molecules 40

Isomers have different arrangements of the same atoms 41

The structures of macromolecules reflect their functions 41



Most macromolecules are formed by condensation and broken down by hydrolysis 42

### 3.2 What Are the Chemical Structures and Functions of Proteins? 42

Amino acids are the building blocks of proteins 43

Peptide linkages form the backbone of a protein 43

The primary structure of a protein is its amino acid sequence 45

The secondary structure of a protein requires hydrogen bonding 45

The tertiary structure of a protein is formed by bending and folding 46

The quaternary structure of a protein consists of subunits 48

Shape and surface chemistry contribute to protein function 48

Environmental conditions affect protein structure 50

Protein shapes can change 50

Molecular chaperones help shape proteins 51

### 3.3 What Are the Chemical Structures and Functions of Carbohydrates? 51

Monosaccharides are simple sugars 52

Glycosidic linkages bond monosaccharides 53

Polysaccharides store energy and provide structural materials 53

Chemically modified carbohydrates contain additional functional groups 55

### 3.4 What Are the Chemical Structures and Functions of Lipids? 56

Fats and oils are triglycerides 56

Phospholipids form biological membranes 57

Some lipids have roles in energy conversion, regulation, and protection 57

## 4

## Nucleic Acids and the Origin of Life 62

### 4.1 What Are the Chemical Structures and Functions of Nucleic Acids? 63

Nucleotides are the building blocks of nucleic acids 63

Base pairing occurs in both DNA and RNA 63

DNA carries information and is expressed through RNA 65

The DNA base sequence reveals evolutionary relationships 66

Nucleotides have other important roles 66

### 4.2 How and Where Did the Small Molecules of Life Originate? 67

Experiments disproved the spontaneous generation of life 67

Life began in water 68

Life may have come from outside Earth 69

Prebiotic synthesis experiments model early Earth 69

### 4.3 How Did the Large Molecules of Life Originate? 71

Chemical evolution may have led to polymerization 71

RNA may have been the first biological catalyst 71

### 4.4 How Did the First Cells Originate? 71

Experiments explore the origin of cells 73

Some ancient cells left a fossil imprint 74

## PART TWO Cells

## 5

## Cells: The Working Units of Life 77

### 5.1 What Features Make Cells the Fundamental Units of Life? 78

Cell size is limited by the surface area-to-volume ratio 78

Microscopes reveal the features of cells 79

The plasma membrane forms the outer surface of every cell 79

Cells are classified as either prokaryotic or eukaryotic 81

### 5.2 What Features Characterize Prokaryotic Cells? 82

Prokaryotic cells share certain features 82

Specialized features are found in some prokaryotes 83

### 5.3 What Features Characterize Eukaryotic Cells? 84

Compartmentalization is the key to eukaryotic cell function 84

Organelles can be studied by microscopy or isolated for chemical analysis 84

Ribosomes are factories for protein synthesis 84

The nucleus contains most of the genetic information 85

The endomembrane system is a group of interrelated organelles 88

Some organelles transform energy 91

There are several other membrane-enclosed organelles 93

The cytoskeleton is important in cell structure and movement 94

Biologists can manipulate living systems to establish cause and effect 98

### 5.4 What Are the Roles of Extracellular Structures? 99

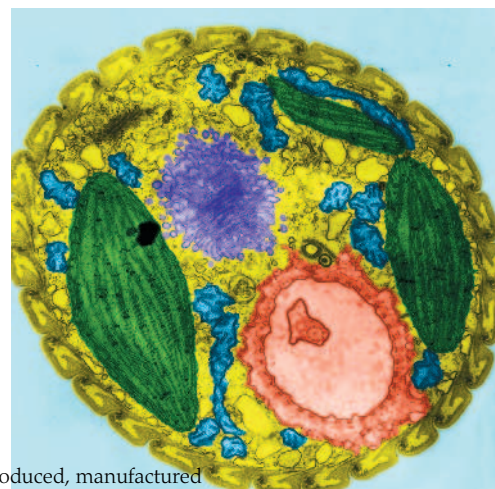
The plant cell wall is an extracellular structure 99

The extracellular matrix supports tissue functions in animals 100

### 5.5 How Did Eukaryotic Cells Originate? 101

Internal membranes and the nuclear envelope probably came from the plasma membrane 101

Some organelles arose by endosymbiosis 102



## 6 Cell Membranes 105

### 6.1 What Is the Structure of a Biological Membrane? 106

- Lipids form the hydrophobic core of the membrane 106
- Membrane proteins are asymmetrically distributed 107
- Membranes are constantly changing 109
- Plasma membrane carbohydrates are recognition sites 109

### 6.2 How Is the Plasma Membrane Involved in Cell Adhesion and Recognition? 110

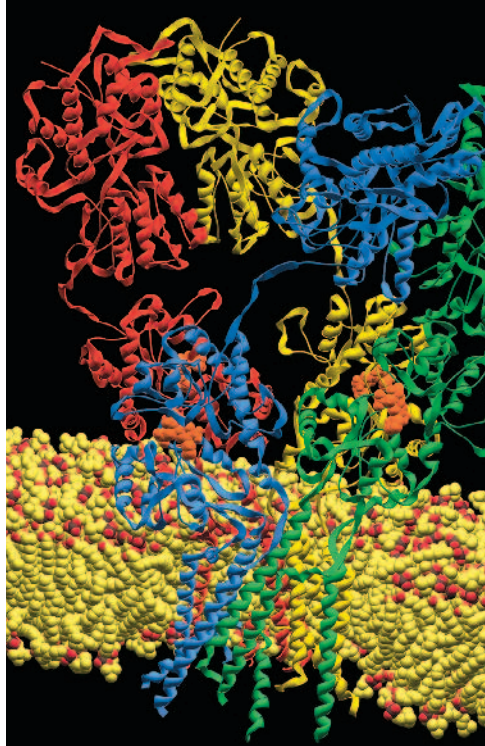
- Cell recognition and adhesion involve proteins and carbohydrates at the cell surface 111
- Three types of cell junctions connect adjacent cells 111
- Cell membranes adhere to the extracellular matrix 111

### 6.3 What Are the Passive Processes of Membrane Transport? 113

- Diffusion is the process of random movement toward a state of equilibrium 113
- Simple diffusion takes place through the phospholipid bilayer 114
- Osmosis is the diffusion of water across membranes 114
- Diffusion may be aided by channel proteins 115
- Carrier proteins aid diffusion by binding substances 117

### 6.4 What are the Active Processes of Membrane Transport? 118

- Active transport is directional 118



Different energy sources distinguish different active transport systems 118

### 6.5 How Do Large Molecules Enter and Leave a Cell? 120

- Macromolecules and particles enter the cell by endocytosis 120
- Receptor-mediated endocytosis is highly specific 121
- Exocytosis moves materials out of the cell 122

## 7 Cell Communication and Multicellularity 125

### 7.1 What Are Signals, and How Do Cells Respond to Them? 126

- Cells receive signals from the physical environment and from other cells 126

A signal transduction pathway involves a signal, a receptor, and responses 126

### 7.2 How Do Signal Receptors Initiate a Cellular Response? 127

- Receptors that recognize chemical signals have specific binding sites 127
- Receptors can be classified by location and function 128
- Intracellular receptors are located in the cytoplasm or the nucleus 130

### 7.3 How Is the Response to a Signal Transduced through the Cell? 131

- A protein kinase cascade amplifies a response to ligand binding 131
- Second messengers can amplify signals between receptors and target molecules 132
- Signal transduction is highly regulated 136

### 7.4 How Do Cells Change in Response to Signals? 137

- Ion channels open in response to signals 137
- Enzyme activities change in response to signals 138
- Signals can initiate DNA transcription 139

### 7.5 How Do Cells in a Multicellular Organism Communicate Directly? 139

- Animal cells communicate through gap junctions 139
- Plant cells communicate through plasmodesmata 140
- Modern organisms provide clues about the evolution of cell-cell interactions and multicellularity 140

## PART THREE Cells and Energy

## 8 Energy, Enzymes, and Metabolism 144

### 8.1 What Physical Principles Underlie Biological Energy Transformations? 145

- There are two basic types of energy 145
- There are two basic types of metabolism 145
- The first law of thermodynamics: Energy is neither created nor destroyed 146
- The second law of thermodynamics: Disorder tends to increase 146

- Chemical reactions release or consume energy 147
- Chemical equilibrium and free energy are related 148

### 8.2 What Is the Role of ATP in Biochemical Energetics? 149

- ATP hydrolysis releases energy 149

ATP couples exergonic and endergonic reactions 150

### 8.3 What Are Enzymes? 151

To speed up a reaction, an energy barrier must be overcome 151

Enzymes bind specific reactants at their active sites 152

Enzymes lower the energy barrier but do not affect equilibrium 153

### 8.4 How Do Enzymes Work? 154

Enzymes can orient substrates 154

Enzymes can induce strain in the substrate 154

Enzymes can temporarily add chemical groups to substrates 154

Molecular structure determines enzyme function 155

Some enzymes require other molecules in order to function 155

The substrate concentration affects the reaction rate 156

### 8.5 How Are Enzyme Activities Regulated? 156

Enzymes can be regulated by inhibitors 157

Allosteric enzymes are controlled via changes in shape 159

Allosteric effects regulate many metabolic pathways 160

Many enzymes are regulated through reversible phosphorylation 161

Enzymes are affected by their environment 161

## 9 Pathways That Harvest Chemical Energy 165

### 9.1 How Does Glucose Oxidation Release Chemical Energy? 166

Cells trap free energy while metabolizing glucose 166

Redox reactions transfer electrons and energy 167

The coenzyme  $\text{NAD}^+$  is a key electron carrier in redox reactions 167

An overview: Harvesting energy from glucose 168

### 9.2 What Are the Aerobic Pathways of Glucose Catabolism? 169

In glycolysis, glucose is partially oxidized and some energy is released 169

Pyruvate oxidation links glycolysis and the citric acid cycle 170

The citric acid cycle completes the oxidation of glucose to  $\text{CO}_2$  170

Pyruvate oxidation and the citric acid cycle are regulated by the concentrations of starting materials 171

### 9.3 How Does Oxidative Phosphorylation Form ATP? 171

The respiratory chain transfers electrons and protons, and releases energy 172

Proton diffusion is coupled to ATP synthesis 173

Some microorganisms use non- $\text{O}_2$  electron acceptors 176

### 9.4 How Is Energy Harvested from Glucose in the Absence of Oxygen? 177

Cellular respiration yields much more energy than fermentation 178

The yield of ATP is reduced by the impermeability of mitochondria to  $\text{NADH}$  178

### 9.5 How Are Metabolic Pathways Interrelated and Regulated? 179

Catabolism and anabolism are linked 179

Catabolism and anabolism are integrated 180

Metabolic pathways are regulated systems 181

## 10 Photosynthesis: Energy from Sunlight 185

### 10.1 What Is Photosynthesis 186

Experiments with isotopes show that  $\text{O}_2$  comes from  $\text{H}_2\text{O}$  in oxygenic photosynthesis 186

Photosynthesis involves two pathways 188

### 10.2 How Does Photosynthesis Convert Light Energy into Chemical Energy? 188

Light energy is absorbed by chlorophyll and other pigments 188

Light absorption results in photochemical change 190

Reduction leads to ATP and NADPH formation 191

Chemiosmosis is the source of the ATP produced in photophosphorylation 192

### 10.3 How Is Chemical Energy Used to Synthesize Carbohydrates? 193

Radioisotope labeling experiments revealed the steps of the Calvin cycle 193

The Calvin cycle is made up of three processes 194

Light stimulates the Calvin cycle 196

### 10.4 How Have Plants Adapted Photosynthesis to Environmental Conditions? 197

Rubisco catalyzes the reaction of RuBP with  $\text{O}_2$  or  $\text{CO}_2$  197

$\text{C}_3$  plants undergo photorespiration but  $\text{C}_4$  plants do not 198

CAM plants also use PEP carboxylase 200

### 10.5 How Does Photosynthesis Interact with Other Pathways? 200





## PART FOUR

### Genes and Heredity

#### 11 The Cell Cycle and Cell Division 205

##### 11.1 How Do Prokaryotic and Eukaryotic Cells Divide? 206

Prokaryotes divide by binary fission 206

Eukaryotic cells divide by mitosis or meiosis followed by cytokinesis 207

##### 11.2 How Is Eukaryotic Cell Division Controlled? 208

Specific internal signals trigger events in the cell cycle 208

Growth factors can stimulate cells to divide 211

##### 11.3 What Happens during Mitosis? 211

Prior to mitosis, eukaryotic DNA is packed into very compact chromosomes 211

Overview: Mitosis segregates copies of genetic information 212

The centrosomes determine the plane of cell division 212

The spindle begins to form during prophase 213

Chromosome separation and movement are highly organized 214

Cytokinesis is the division of the cytoplasm 216

##### 11.4 What Role Does Cell Division Play in a Sexual Life Cycle? 217

Asexual reproduction by mitosis results in genetic constancy 217

Sexual reproduction by meiosis results in genetic diversity 218

##### 11.5 What Happens during Meiosis? 219

Meiotic division reduces the chromosome number 219

Chromatid exchanges during meiosis I generate genetic diversity 219

During meiosis homologous chromosomes separate by independent assortment 220

Meiotic errors lead to abnormal chromosome structures and numbers 222

The number, shapes, and sizes of the metaphase chromosomes constitute the karyotype 224

Polyploids have more than two complete sets of chromosomes 224

##### 11.6 In a Living Organism, How Do Cells Die? 225

##### 11.7 How Does Unregulated Cell Division Lead to Cancer? 227

Cancer cells differ from normal cells 227

Cancer cells lose control over the cell cycle and apoptosis 228

Cancer treatments target the cell cycle 228

#### 12 Inheritance, Genes, and Chromosomes 232

##### 12.1 What Are the Mendelian Laws of Inheritance? 233

Mendel used the scientific method to test his hypotheses 233

Mendel's first experiments involved monohybrid crosses 234

Mendel's first law states that the two copies of a gene segregate 236

Mendel verified his hypotheses by performing test crosses 237

Mendel's second law states that copies of different genes assort independently 237

Probability can be used to predict inheritance 239

Mendel's laws can be observed in human pedigrees 240

##### 12.2 How Do Alleles Interact? 241

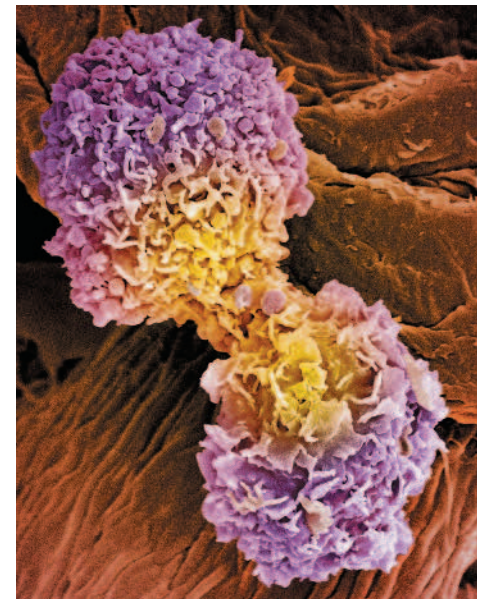
New alleles arise by mutation 241

Many genes have multiple alleles 242

Dominance is not always complete 242

In codominance, both alleles at a locus are expressed 243

Some alleles have multiple phenotypic effects 243



##### 12.3 How Do Genes Interact? 244

Hybrid vigor results from new gene combinations and interactions 244

The environment affects gene action 245

Most complex phenotypes are determined by multiple genes and the environment 246

##### 12.4 What Is the Relationship between Genes and Chromosomes? 247

Genes on the same chromosome are linked 247

Genes can be exchanged between chromatids and mapped 247

Linkage is revealed by studies of the sex chromosomes 249

##### 12.5 What Are the Effects of Genes Outside the Nucleus? 252

##### 12.6 How Do Prokaryotes Transmit Genes? 253

Bacteria exchange genes by conjugation 253

Bacterial conjugation is controlled by plasmids 254

#### 13 DNA and Its Role in Heredity 259

##### 13.1 What Is the Evidence that the Gene Is DNA? 260

DNA from one type of bacterium genetically transforms another type 260

Viral infection experiments confirmed that DNA is the genetic material 261

Eukaryotic cells can also be genetically transformed by DNA 263

### 13.2 What Is the Structure of DNA? 264

Watson and Crick used modeling to deduce the structure of DNA 264

Four key features define DNA structure 265

The double-helical structure of DNA is essential to its function 266

### 13.3 How Is DNA Replicated? 267

Three modes of DNA replication appeared possible 267

An elegant experiment demonstrated that DNA replication is semiconservative 268

There are two steps in DNA replication 268

DNA polymerases add nucleotides to the growing chain 269

Many other proteins assist with DNA polymerization 272

The two DNA strands grow differently at the replication fork 272

Telomeres are not fully replicated and are prone to repair 275

### 13.4 How Are Errors in DNA Repaired? 276

### 13.5 How Does the Polymerase Chain Reaction Amplify DNA? 277

The polymerase chain reaction makes multiple copies of DNA sequences 277

## 14

## From DNA to Protein: Gene Expression 281

### 14.1 What Is the Evidence that Genes Code for Proteins? 282

Observations in humans led to the proposal that genes determine enzymes 282

Experiments on bread mold established that genes determine enzymes 282

One gene determines one polypeptide 283

### 14.2 How Does Information Flow from Genes to Proteins? 284

Three types of RNA have roles in the information flow from DNA to protein 285

In some cases, RNA determines the sequence of DNA 285

### 14.3 How Is the Information Content in DNA Transcribed to Produce RNA? 286

RNA polymerases share common features 286

Transcription occurs in three steps 286

The information for protein synthesis lies in the genetic code 288

### 14.4 How Is Eukaryotic DNA Transcribed and the RNA Processed? 290

Many eukaryotic genes are interrupted by noncoding sequences 290

Eukaryotic gene transcripts are processed before translation 291

### 14.5 How Is RNA Translated into Proteins? 293

Transfer RNAs carry specific amino acids and bind to specific codons 293

Each tRNA is specifically attached to an amino acid 294

The ribosome is the workbench for translation 294

Translation takes place in three steps 295

Polysome formation increases the rate of protein synthesis 297

### 14.6 What Happens to Polypeptides after Translation? 298

Signal sequences in proteins direct them to their cellular destinations 298

Many proteins are modified after translation 300

## 15 Gene Mutation and Molecular Medicine 304

### 15.1 What Are Mutations? 305

Mutations have different phenotypic effects 305

Point mutations are changes in single nucleotides 306

Chromosomal mutations are extensive changes in the genetic material 307

Retroviruses and transposons can cause loss of function mutations or duplications 308

Mutations can be spontaneous or induced 308

Mutagens can be natural or artificial 310

Some base pairs are more vulnerable than others to mutation 310

Mutations have both benefits and costs 310

### 15.2 What Kinds of Mutations Lead to Genetic Diseases? 311

Genetic mutations may make proteins dysfunctional 311

Disease-causing mutations may involve any number of base pairs 312

Expanding triplet repeats demonstrate the fragility of some human genes 313

Cancer often involves somatic mutations 314





Most diseases are caused by multiple genes and environment 314

### 15.3 How Are Mutations Detected and Analyzed? 315

Restriction enzymes cleave DNA at specific sequences 315  
Gel electrophoresis separates DNA fragments 316  
DNA fingerprinting combines PCR with restriction analysis and electrophoresis 317  
Reverse genetics can be used to identify mutations that lead to disease 318  
Genetic markers can be used to find disease-causing genes 318  
The DNA barcode project aims to identify all organisms on Earth 319

### 15.4 How Is Genetic Screening Used to Detect Diseases? 320

Screening for disease phenotypes involves analysis of proteins and other chemicals 320  
DNA testing is the most accurate way to detect abnormal genes 320  
Allele-specific oligonucleotide hybridization can detect mutations 321

### 15.5 How Are Genetic Diseases Treated? 322

Genetic diseases can be treated by modifying the phenotype 322  
Gene therapy offers the hope of specific treatments 323

## PART FIVE Genomes

### 17 Genomes 352

#### 17.1 How Are Genomes Sequenced? 353

New methods have been developed to rapidly sequence DNA 353  
Genome sequences yield several kinds of information 355

### 16 Regulation of Gene Expression 328

#### 16.1 How Is Gene Expression Regulated in Prokaryotes? 329

Regulating gene transcription conserves energy 329  
Operons are units of transcriptional regulation in prokaryotes 330  
Operator–repressor interactions control transcription in the *lac* and *trp* operons 330  
Protein synthesis can be controlled by increasing promoter efficiency 332  
RNA polymerases can be directed to particular classes of promoters 332

#### 16.2 How Is Eukaryotic Gene Transcription Regulated? 333

General transcription factors act at eukaryotic promoters 333  
Specific proteins can recognize and bind to DNA sequences and regulate transcription 335  
Specific protein–DNA interactions underlie binding 335  
The expression of transcription factors underlies cell differentiation 336  
The expression of sets of genes can be coordinately regulated by transcription factors 336

#### 16.3 How Do Viruses Regulate Their Gene Expression? 339

Many bacteriophages undergo a lytic cycle 339  
Some bacteriophages can undergo a lysogenic cycle 340  
Eukaryotic viruses can have complex life cycles 341  
HIV gene regulation occurs at the level of transcription elongation 341

#### 16.4 How Do Epigenetic Changes Regulate Gene Expression? 343

DNA methylation occurs at promoters and silences transcription 343  
Histone protein modifications affect transcription 344  
Epigenetic changes can be induced by the environment 344  
DNA methylation can result in genomic imprinting 344  
Global chromosome changes involve DNA methylation 345

#### 16.5 How Is Eukaryotic Gene Expression Regulated after Transcription? 346

Different mRNAs can be made from the same gene by alternative splicing 346  
Small RNAs are important regulators of gene expression 347  
Translation of mRNA can be regulated by proteins and riboswitches 348

#### 17.2 What Have We Learned from Sequencing Prokaryotic Genomes? 356

Prokaryotic genomes are compact 356  
The sequencing of prokaryotic and viral genomes has many potential benefits 357  
Metagenomics allows us to describe new organisms and ecosystems 357  
Some sequences of DNA can move about the genome 358



Will defining the genes required for cellular life lead to artificial life? 359

### 17.3 What Have We Learned from Sequencing Eukaryotic Genomes? 361

Model organisms reveal many characteristics of eukaryotic genomes 361

Eukaryotes have gene families 363

Eukaryotic genomes contain many repetitive sequences 364

### 17.4 What Are the Characteristics of the Human Genome? 366

The human genome sequence held some surprises 366

Comparative genomics reveals the evolution of the human genome 366

Human genomics has potential benefits in medicine 367

### 17.5 What Do the New Disciplines of Proteomics and Metabolomics Reveal? 369

The proteome is more complex than the genome 369

Metabolomics is the study of chemical phenotype 370

## 18 Recombinant DNA and Biotechnology 373

### 18.1 What Is Recombinant DNA? 374

### 18.2 How Are New Genes Inserted into Cells? 375

Genes can be inserted into prokaryotic or eukaryotic cells 376

A variety of methods are used to insert recombinant DNA into host cells 376

Reporter genes help select or identify host cells containing recombinant DNA 377

### 18.3 What Sources of DNA Are Used in Cloning? 379

Libraries provide collections of DNA fragments 379

cDNA is made from mRNA transcripts 379

Synthetic DNA can be made by PCR or by organic chemistry 380

### 18.4 What Other Tools Are Used to Study DNA Function? 380

Genes can be expressed in different biological systems 380

DNA mutations can be created in the laboratory 381

Genes can be inactivated by homologous recombination 381

Complementary RNA can prevent the expression of specific genes 382

DNA microarrays reveal RNA expression patterns 382

### 18.5 What Is Biotechnology? 383

Expression vectors can turn cells into protein factories 384

### 18.6 How Is Biotechnology Changing Medicine and Agriculture? 384

Medically useful proteins can be made using biotechnology 384

DNA manipulation is changing agriculture 386

There is public concern about biotechnology 388

## 19 Differential Gene Expression in Development 392

### 19.1 What Are the Processes of Development? 393

Development involves distinct but overlapping processes 393

Cell fates become progressively more restricted during development 394

### 19.2 How Is Cell Fate Determined? 395

Cytoplasmic segregation can determine polarity and cell fate 395

Inducers passing from one cell to another can determine cell fates 395

### 19.3 What Is the Role of Gene Expression in Development? 397

Cell fate determination involves signal transduction pathways that lead to differential gene expression 397

Differential gene transcription is a hallmark of cell differentiation 398

### 19.4 How Does Gene Expression Determine Pattern Formation? 399

Multiple proteins interact to determine developmental programmed cell death 399

Plants have organ identity genes 400

Morphogen gradients provide positional information 401

A cascade of transcription factors establishes body segmentation in the fruit fly 401

### 19.5 Is Cell Differentiation Reversible? 405

Plant cells can be totipotent 405

Nuclear transfer allows the cloning of animals 406

Multipotent stem cells differentiate in response to environmental signals 408

Pluripotent stem cells can be obtained in two ways 408

## 20 Genes, Development, and Evolution 412

### 20.1 How Can Small Genetic Changes Result in Large Changes in Phenotype? 413

Developmental genes in distantly related organisms are similar 413



**20.2 How Can Mutations with Large Effects Change Only One Part of the Body? 415**

Genetic switches govern how the genetic toolkit is used 415  
Modularity allows for differences in the patterns of gene expression 416

**20.3 How Can Developmental Changes Result in Differences among Species? 418**

Differences in Hox gene expression patterns result in major differences in body plans 418  
Mutations in developmental genes can produce major morphological changes 418

**20.4 How Can the Environment Modulate Development? 420**

Temperature can determine sex 420

Dietary information can be a predictor of future conditions 421  
A variety of environmental signals influence development 421

**20.5 How Do Developmental Genes Constrain Evolution? 423**

Evolution usually proceeds by changing what's already there 423  
Conserved developmental genes can lead to parallel evolution 423

**PART SIX****The Patterns and Processes of Evolution****21 Mechanisms of Evolution 427****21.1 What Is the Relationship between Fact and Theory in Evolution? 428**

Darwin and Wallace introduced the idea of evolution by natural selection 428

Evolutionary theory has continued to develop over the past century 430

Genetic variation contributes to phenotypic variation 431

**21.2 What Are the Mechanisms of Evolutionary Change? 432**

Mutation generates genetic variation 432

Selection acting on genetic variation leads to new phenotypes 432

Gene flow may change allele frequencies 433

Genetic drift may cause large changes in small populations 434

Nonrandom mating can change genotype or allele frequencies 434

**21.3 How Do Biologists Measure Evolutionary Change? 436**

Evolutionary change can be measured by allele and genotype frequencies 436

Evolution will occur unless certain restrictive conditions exist 437

Deviations from Hardy–Weinberg equilibrium show that evolution is occurring 438

Natural selection acts directly on phenotypes 438

Natural selection can change or stabilize populations 439

**21.4 How Is Genetic Variation Distributed and Maintained within Populations? 441**

Neutral mutations accumulate in populations 441

Sexual recombination amplifies the number of possible genotypes 441

Frequency-dependent selection maintains genetic variation within populations 441

Heterozygote advantage maintains polymorphic loci 442

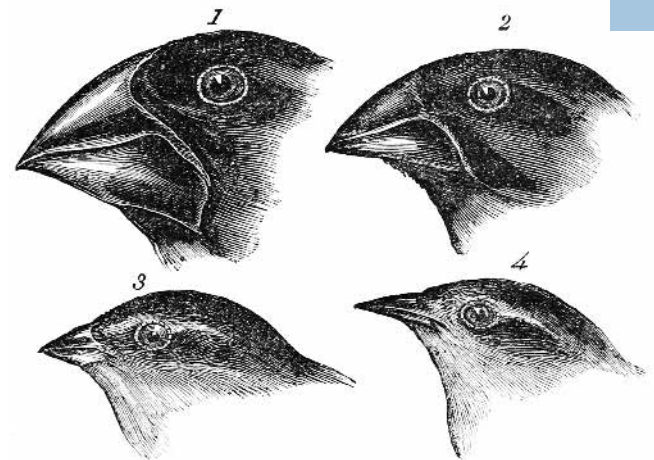
Genetic variation within species is maintained in geographically distinct populations 443

**21.5 What Are the Constraints on Evolution? 444**

Developmental processes constrain evolution 444

Trade-offs constrain evolution 445

Short-term and long-term evolutionary outcomes sometimes differ 446

**22 Reconstructing and Using Phylogenies 449****22.1 What Is Phylogeny? 450**

All of life is connected through evolutionary history 451

Comparisons among species require an evolutionary perspective 451

**22.2 How Are Phylogenetic Trees Constructed? 452**

Parsimony provides the simplest explanation for phylogenetic data 454

Phylogenies are reconstructed from many sources of data 454

Mathematical models expand the power of phylogenetic reconstruction 456

The accuracy of phylogenetic methods can be tested 457



**22.3 How Do Biologists Use Phylogenetic Trees? 458**

Phylogenetic trees can be used to reconstruct past events 458  
 Phylogenies allow us to compare and contrast living organisms 459  
 Phylogenies can reveal convergent evolution 459  
 Ancestral states can be reconstructed 460  
 Molecular clocks help date evolutionary events 461

**22.4 How Does Phylogeny Relate to Classification? 462**

Evolutionary history is the basis for modern biological classification 463  
 Several codes of biological nomenclature govern the use of scientific names 463

**23 Speciation 467****23.1 What Are Species? 468**

We can recognize many species by their appearance 468  
 Reproductive isolation is key 468  
 The lineage approach takes a long-term view 469  
 The different species concepts are not mutually exclusive 469

**23.2 What Is the Genetic Basis of Speciation? 470**

Incompatibilities between genes can produce reproductive isolation 470  
 Reproductive isolation develops with increasing genetic divergence 470

**23.3 What Barriers to Gene Flow Result in Speciation? 472**

Physical barriers give rise to allopatric speciation 472  
 Sympatric speciation occurs without physical barriers 473

**23.4 What Happens When Newly Formed Species Come into Contact? 475**

Prezygotic isolating mechanisms prevent hybridization 476

Postzygotic isolating mechanisms result in selection against hybridization 478

Hybrid zones may form if reproductive isolation is incomplete 478

**23.5 Why Do Rates of Speciation Vary? 480**

Several ecological and behavioral factors influence speciation rates 480  
 Rapid speciation can lead to adaptive radiation 481

**24 Evolution of Genes and Genomes 485****24.1 How Are Genomes Used to Study Evolution? 486**

Evolution of genomes results in biological diversity 486  
 Genes and proteins are compared through sequence alignment 486  
 Models of sequence evolution are used to calculate evolutionary divergence 487  
 Experimental studies examine molecular evolution directly 489

**24.2 What Do Genomes Reveal about Evolutionary Processes? 491**

Much of evolution is neutral 492  
 Positive and purifying selection can be detected in the genome 492  
 Genome size also evolves 494

**24.3 How Do Genomes Gain and Maintain Functions? 496**

Lateral gene transfer can result in the gain of new functions 496  
 Most new functions arise following gene duplication 496  
 Some gene families evolve through concerted evolution 498

**24.4 What Are Some Applications of Molecular Evolution? 499**

Molecular sequence data are used to determine the evolutionary history of genes 499  
 Gene evolution is used to study protein function 500

In vitro evolution is used to produce new molecules 500  
 Molecular evolution is used to study and combat diseases 501

**25 The History of Life on Earth 505****25.1 How Do Scientists Date Ancient Events? 506**

Radioisotopes provide a way to date fossils and rocks 507  
 Radiometric dating methods have been expanded and refined 507  
 Scientists have used several methods to construct a geological time scale 508

**25.2 How Have Earth's Continents and Climates Changed over Time? 508**

The continents have not always been where they are today 509  
 Earth's climate has shifted between hot and cold conditions 510  
 Volcanoes have occasionally changed the history of life 510  
 Extraterrestrial events have triggered changes on Earth 511  
 Oxygen concentrations in Earth's atmosphere have changed over time 511

**25.3 What Are the Major Events in Life's History? 514**

Several processes contribute to the paucity of fossils 514  
 Precambrian life was small and aquatic 515  
 Life expanded rapidly during the Cambrian period 516  
 Many groups of organisms that arose during the Cambrian later diversified 516  
 Geographic differentiation increased during the Mesozoic era 521  
 Modern biotas evolved during the Cenozoic era 521  
 The tree of life is used to reconstruct evolutionary events 522

## PART SEVEN

### The Evolution of Diversity

#### 26 Bacteria, Archaea, and Viruses 525

##### 26.1 Where Do Prokaryotes Fit into the Tree of Life? 526

- The two prokaryotic domains differ in significant ways 526
- The small size of prokaryotes has hindered our study of their evolutionary relationships 527
- The nucleotide sequences of prokaryotes reveal their evolutionary relationships 528
- Lateral gene transfer can lead to discordant gene trees 529
- The great majority of prokaryote species have never been studied 530

##### 26.2 Why Are Prokaryotes So Diverse and Abundant? 530

- The low-GC Gram-positives include some of the smallest cellular organisms 530
- Some high-GC Gram-positives are valuable sources of antibiotics 532
- Hyperthermophilic bacteria live at very high temperatures 532
- Hadobacteria live in extreme environments 532
- Cyanobacteria were the first photosynthesizers 532
- Spirochetes move by means of axial filaments 533
- Chlamydias are extremely small parasites 533
- The proteobacteria are a large and diverse group 534
- Gene sequencing enabled biologists to differentiate the domain Archaea 534
- Most crenarchaeotes live in hot or acidic places 536
- Euryarchaeotes are found in surprising places 536
- Korarchaeotes and nanoarchaeotes are less well known 537

##### 26.3 How Do Prokaryotes Affect Their Environments? 537

- Prokaryotes have diverse metabolic pathways 537
- Prokaryotes play important roles in element cycling 538
- Many prokaryotes form complex communities 539



- Prokaryotes live on and in other organisms 539
- Microbiomes are critical to human health 539
- A small minority of bacteria are pathogens 541

##### 26.4 How Do Viruses Relate to Life's Diversity and Ecology? 543

- Many RNA viruses probably represent escaped genomic components of cellular life 544
- Some DNA viruses may have evolved from reduced cellular organisms 544
- Vertebrate genomes contain endogenous retroviruses 545
- Viruses can be used to fight bacterial infections 545
- Viruses are found throughout the biosphere 546

#### 27 The Origin and Diversification of Eukaryotes 549

##### 27.1 How Did the Eukaryotic Cell Arise? 550

- The modern eukaryotic cell arose in several steps 550
- Chloroplasts have been transferred among eukaryotes several times 551

##### 27.2 What Features Account for Protist Diversity? 552

- Alveolates have sacs under their plasma membranes 553
- Stramenopiles typically have two flagella of unequal length 555

- Rhizaria typically have long, thin pseudopods 557
- Excavates began to diversify about 1.5 billion years ago 558
- Amoebozoans use lobe-shaped pseudopods for locomotion 559

##### 27.3 What Is the Relationship between Sex and Reproduction in Protists? 562

- Some protists reproduce without sex and have sex without reproduction 562
- Some protist life cycles feature alternation of generations 562

##### 27.4 How Do Protists Affect Their Environments? 563

- Phytoplankton are primary producers 563
- Some microbial eukaryotes are deadly 563
- Some microbial eukaryotes are endosymbionts 564
- We rely on the remains of ancient marine protists 565

#### 28 Plants without Seeds: From Water to Land 569

##### 28.1 How Did Photosynthesis Arise in Plants? 570

- Several distinct clades of algae were among the first photosynthetic eukaryotes 571

Two groups of green algae are the closest relatives of land plants 572

There are ten major groups of land plants 573

## 28.2 When and How Did Plants Colonize Land? 574

Adaptations to life on land distinguish land plants from green algae 574

Life cycles of land plants feature alternation of generations 574

Nonvascular land plants live where water is readily available 575

The sporophytes of nonvascular land plants are dependent on the gametophytes 575

Liverworts are the sister clade of the remaining land plants 577

Water and sugar transport mechanisms emerged in the mosses 577

Hornworts have distinctive chloroplasts and stalkless sporophytes 578

## 28.3 What Features Allowed Land Plants to Diversify in Form? 579

Vascular tissues transport water and dissolved materials 579

Vascular plants allowed herbivores to colonize the land 580

The closest relatives of vascular plants lacked roots 580

The lycophytes are sister to the other vascular plants 581

Horsetails and ferns constitute a clade 581

The vascular plants branched out 582

Heterospory appeared among the vascular plants 584



A change in stem anatomy enabled seed plants to grow to great heights 591

## 29.2 What Are the Major Groups of Gymnosperms? 592

There are four major groups of living gymnosperms 592

Conifers have cones and no swimming sperm 593

## 29.3 How Do Flowers and Fruits Increase the Reproductive Success of Angiosperms? 596

Angiosperms have many shared derived traits 596

The sexual structures of angiosperms are flowers 596

Flower structure has evolved over time 597

Angiosperms have coevolved with animals 598

The angiosperm life cycle produces diploid zygotes nourished by triploid endosperms 600

Fruits aid angiosperm seed dispersal 601

Recent analyses have revealed the phylogenetic relationships of angiosperms 601

## 29.4 How Do Plants Benefit Human Society? 604

Seed plants have been sources of medicine since ancient times 604

Seed plants are our primary food source 605

# 30 The Evolution and Diversity of Fungi 608

## 30.1 What Is a Fungus? 609

Unicellular yeasts absorb nutrients directly 609

Multicellular fungi use hyphae to absorb nutrients 609

Fungi are in intimate contact with their environment 610

## 30.2 How Do Fungi Interact with Other Organisms? 611

Saprobic fungi are critical to the planetary carbon cycle 611

Some fungi engage in parasitic or predatory interactions 611

Mutualistic fungi engage in relationships that benefit both partners 612

Endophytic fungi protect some plants from pathogens, herbivores, and stress 615

## 30.3 How Do Major Groups of Fungi Differ in Structure and Life History? 615

Fungi reproduce both sexually and asexually 616

Microsporidia are highly reduced, parasitic fungi 617

Most chytrids are aquatic 617

Some fungal life cycles feature separate fusion of cytoplasm and nuclei 619

Arbuscular mycorrhizal fungi form symbioses with plants 619

The dikaryotic condition is a synapomorphy of sac fungi and club fungi 620

The sexual reproductive structure of sac fungi is the ascus 620

The sexual reproductive structure of club fungi is the basidium 622

## 30.4 What Are Some Applications of Fungal Biology? 623

Fungi are important in producing food and drink 623

Fungi record and help remediate environmental pollution 624

Lichen diversity and abundance are indicators of air quality 624

Fungi are used as model organisms in laboratory studies 624

Reforestation may depend on mycorrhizal fungi 626

# 29 The Evolution of Seed Plants 588

## 29.1 How Did Seed Plants Become Today's Dominant Vegetation? 589

Features of the seed plant life cycle protect gametes and embryos 589

The seed is a complex, well-protected package 591



Fungi provide important weapons against diseases and pests 626

## 31 Animal Origins and the Evolution of Body Plans 629

### 31.1 What Characteristics Distinguish the Animals? 630

Animal monophyly is supported by gene sequences and morphology 630

A few basic developmental patterns differentiate major animal groups 633

### 31.2 What Are the Features of Animal Body Plans? 634

Most animals are symmetrical 634

The structure of the body cavity influences movement 635

Segmentation improves control of movement 636

Appendages have many uses 636

Nervous systems coordinate movement and allow sensory processing 637

### 31.3 How Do Animals Get Their Food? 637

Filter feeders capture small prey 637

Herbivores eat plants 637

Predators and omnivores capture and subdue prey 638

Parasites live in or on other organisms 638

Detritivores live on the remains of other organisms 639

### 31.4 How Do Life Cycles Differ among Animals? 639

Many animal life cycles feature specialized life stages 639

Most animal life cycles have at least one dispersal stage 640

Parasite life cycles facilitate dispersal and overcome host defenses 640

Some animals form colonies of genetically identical, physiologically integrated individuals 640

No life cycle can maximize all benefits 641

### 31.5 What Are the Major Groups of Animals? 643

Sponges are loosely organized animals 643

Ctenophores are radially symmetrical and diploblastic 644

Placozoans are abundant but rarely observed 645

Cnidarians are specialized predators 645

Some small groups of parasitic animals may be the closest relatives of bilaterians 648

## 32 Protostome Animals 651

### 32.1 What Is a Protostome? 652

Cilia-bearing lophophores and trochophores evolved among the lophotrochozoans 652

Ecdysozoans must shed their cuticles 654

Arrow worms retain some ancestral developmental features 655

### 32.2 What Features Distinguish the Major Groups of Lophotrochozoans? 656

Most bryozoans and entoprocts live in colonies 656

Flatworms, rotifers, and gastrotrichs are structurally diverse relatives 656

Ribbon worms have a long, protrusible feeding organ 658

Brachiopods and phoronids use lophophores to extract food from the water 658

Annelids have segmented bodies 659

Mollusks have undergone a dramatic evolutionary radiation 662

### 32.3 What Features Distinguish the Major Groups of Ecdysozoans? 665

Several marine ecdysozoan groups have relatively few species 665

Nematodes and their relatives are abundant and diverse 666

### 32.4 Why Are Arthropods So Diverse? 667

Arthropod relatives have fleshy, unjointed appendages 667

Jointed appendages appeared in the trilobites 668

Chelicerates have pointed, nonchewing mouthparts 668

Mandibles and antennae characterize the remaining arthropod groups 669

More than half of all described species are insects 671

## 33 Deuterostome Animals 678

### 33.1 What Is a Deuterostome? 679

Deuterostomes share early developmental patterns 679

There are three major deuterostome clades 679

Fossils shed light on deuterostome ancestors 679

### 33.2 What Features Distinguish the Echinoderms, Hemichordates, and Their Relatives? 680

Echinoderms have unique structural features 680

Hemichordates are wormlike marine deuterostomes 682

### 33.3 What New Features Evolved in the Chordates? 683

Adults of most lancelets and tunicates are sedentary 684

A dorsal supporting structure replaces the notochord in vertebrates 684

The phylogenetic relationships of jawless fishes are uncertain 685

Jaws and teeth improved feeding efficiency 686

Fins and swim bladders improved stability and control over locomotion 686

### 33.4 How Did Vertebrates Colonize the Land? 689



Jointed limbs enhanced support and locomotion on land 689  
 Amphibians usually require moist environments 690  
 Amniotes colonized dry environments 692  
 Reptiles adapted to life in many habitats 693

Crocodylians and birds share their ancestry with the dinosaurs 693  
 Feathers allowed birds to fly 695  
 Mammals radiated after the extinction of non-avian dinosaurs 696

Two major lineages of primates split late in the Cretaceous 701  
 Bipedal locomotion evolved in human ancestors 702  
 Human brains became larger as jaws became smaller 704  
 Humans developed complex language and culture 705

### 33.5 What Traits Characterize the Primates? 701

## PART EIGHT

### Flowering Plants: Form and Function

#### 34 The Plant Body 708

##### 34.1 What Is the Basic Body Plan of Plants? 709

Most angiosperms are either monocots or eudicots 709  
 Plants develop differently than animals 710  
 Apical–basal polarity and radial symmetry are characteristics of the plant body 711

##### 34.2 What Are the Major Tissues of Plants? 712

The plant body is constructed from three tissue systems 712  
 Cells of the xylem transport water and dissolved minerals 714  
 Cells of the phloem transport the products of photosynthesis 714

##### 34.3 How Do Meristems Build a Continuously Growing Plant? 715

Plants increase in size through primary and secondary growth 715  
 A hierarchy of meristems generates the plant body 715  
 Indeterminate primary growth originates in apical meristems 715  
 The root apical meristem gives rise to the root cap and the root primary meristems 716  
 The products of the root's primary meristems become root tissues 716  
 The root system anchors the plant and takes up water and dissolved minerals 718  
 The products of the stem's primary meristems become stem tissues 719

The stem supports leaves and flowers 720  
 Leaves are determinate organs produced by shoot apical meristems 720  
 Many eudicot stems and roots undergo secondary growth 721

##### 34.4 How Has Domestication Altered Plant Form? 723

#### 35 Transport in Plants 726

##### 35.1 How Do Plants Take Up Water and Solutes? 727

Water potential differences govern the direction of water movement 727  
 Water and ions move across the root cell plasma membrane 728  
 Water and ions pass to the xylem by way of the apoplast and symplast 729

##### 35.2 How Are Water and Minerals Transported in the Xylem? 730

The transpiration–cohesion–tension mechanism accounts for xylem transport 731

##### 35.3 How Do Stomata Control the Loss of Water and the Uptake of CO<sub>2</sub>? 732

The guard cells control the size of the stomatal opening 733

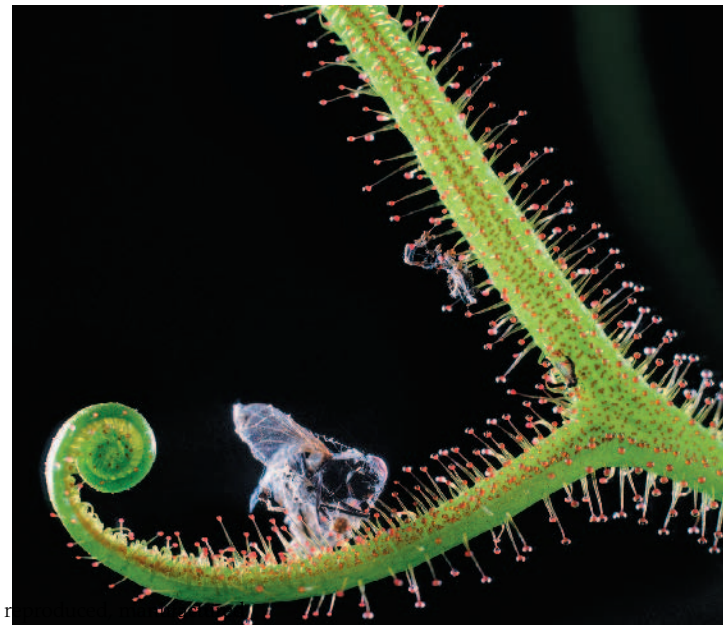
##### 35.4 How Are Substances Translocated in the Phloem? 734

Sucrose and other solutes are carried in the phloem 734  
 The pressure flow model appears to account for translocation in the phloem 735

#### 36 Plant Nutrition 740

##### 36.1 What Nutrients Do Plants Require? 741

All plants require specific macronutrients and micronutrients 741  
 Deficiency symptoms reveal inadequate nutrition 742  
 Hydroponic experiments identified essential elements 742



**36.2 How Do Plants Acquire Nutrients? 743**

Plants rely on growth to find nutrients 743

Nutrient uptake and assimilation are regulated 744

**36.3 How Does Soil Structure Affect Plants? 744**

Soils are complex in structure 745

Soils form through the weathering of rock 745

Soils are the source of plant nutrition 746

Fertilizers can be used to add nutrients to soil 746

**36.4 How Do Fungi and Bacteria Increase Nutrient Uptake by Plant Roots? 747**

Plants send signals for colonization 747

Mycorrhizae expand the root system 748

Soil bacteria are essential in getting nitrogen from air to plant cells 749

Nitrogenase catalyzes nitrogen fixation 749

Biological nitrogen fixation does not always meet agricultural needs 750

Plants and bacteria participate in the global nitrogen cycle 750

**36.5 How Do Carnivorous and Parasitic Plants Obtain a Balanced Diet? 751**

Carnivorous plants supplement their mineral nutrition 751

Parasitic plants take advantage of other plants 752

The plant–parasite relationship is similar to plant–fungus and plant–bacteria associations 753

**37 Regulation of Plant Growth 756****37.1 How Does Plant Development Proceed? 757**

In early development, the seed germinates and forms a growing seedling 757

Several hormones and photoreceptors help regulate plant growth 758

Genetic screens have increased our understanding of plant signal transduction 759

**37.2 What Do Gibberellins and Auxin Do? 760**

Gibberellins have many effects on plant growth and development 760

Auxin plays a role in differential plant growth 762

Auxin affects plant growth in several ways 765

At the molecular level, auxin and gibberellins act similarly 767

**37.3 What Are the Effects of Cytokinins, Ethylene, and Brassinosteroids? 768**

Cytokinins are active from seed to senescence 768

Ethylene is a gaseous hormone that hastens leaf senescence and fruit ripening 769

Brassinosteroids are plant steroid hormones 771

**37.4 How Do Photoreceptors Participate in Plant Growth Regulation? 771**

Phototropins, cryptochromes, and zeaxanthin are blue-light receptors 771

Phytochromes mediate the effects of red and far-red light 772

Phytochrome stimulates gene transcription 773

Circadian rhythms are entrained by light reception 774

**38****Reproduction in Flowering Plants 778****38.1 How Do Angiosperms Reproduce Sexually? 779**

The flower is an angiosperm's structure for sexual reproduction 779

Flowering plants have microscopic gametophytes 779

Pollination in the absence of water is an evolutionary adaptation 780

A pollen tube delivers sperm cells to the embryo sac 780



Many flowering plants control pollination or pollen tube growth to prevent inbreeding 782

Angiosperms perform double fertilization 783

Embryos develop within seeds contained in fruits 784

Seed development is under hormonal control 785

**38.2 What Determines the Transition from the Vegetative to the Flowering State? 785**

Shoot apical meristems can become inflorescence meristems 785

A cascade of gene expression leads to flowering 786

Photoperiodic cues can initiate flowering 787

Plants vary in their responses to photoperiodic cues 787

Night length is a key photoperiodic cue that determines flowering 788

The flowering stimulus originates in a leaf 788

Florigen is a small protein 790

Flowering can be induced by temperature or gibberellin 790

Some plants do not require an environmental cue to flower 792

**38.3 How Do Angiosperms Reproduce Asexually? 792**

Many forms of asexual reproduction exist 792

Vegetative reproduction has a disadvantage 793

Vegetative reproduction is important in agriculture 793



## 39 Plant Responses to Environmental Challenges 797

### 39.1 How Do Plants Deal with Pathogens? 798

Physical barriers form constitutive defenses 798

Plants can seal off infected parts to limit damage 798

General and specific immunity both involve multiple responses 799

Specific immunity involves gene-for-gene resistance 800

Specific immunity usually leads to the hypersensitive response 800

Systemic acquired resistance is a form of long-term immunity 801

### 39.2 How Do Plants Deal with Herbivores? 801

Mechanical defenses against herbivores are widespread 801

Plants produce constitutive chemical defenses against herbivores 802

Some secondary metabolites play multiple roles 803

Plants respond to herbivory with induced defenses 803

Jasmonates trigger a range of responses to wounding and herbivory 805

Why don't plants poison themselves? 805

Plants don't always win the arms race 806

### 39.3 How Do Plants Deal with Environmental Stresses? 806

Some plants have special adaptations to live in very dry conditions 806

Some plants grow in saturated soils 808

Plants can respond to drought stress 809

Plants can cope with temperature extremes 810

### 39.4 How Do Plants Deal with Salt and Heavy Metals? 810

Most halophytes accumulate salt 811

Some plants can tolerate heavy metals 811

## PART NINE Animals: Form and Function

## 40 Physiology, Homeostasis, and Temperature Regulation 815

### 40.1 How Do Multicellular Animals Supply the Needs of Their Cells? 816

An internal environment makes complex multicellular animals possible 816

Physiological systems are regulated to maintain homeostasis 816

### 40.2 What Are the Relationships between Cells, Tissues, and Organs? 817

Epithelial tissues are sheets of densely packed, tightly connected cells 817

Muscle tissues generate force and movement 818

Connective tissues include bone, blood, and fat 818

Neural tissues include neurons and glial cells 819

Organs consist of multiple tissues 820

### 40.3 How Does Temperature Affect Living Systems? 820

$Q_{10}$  is a measure of temperature sensitivity 821

Animals acclimatize to seasonal temperatures 821

### 40.4 How Do Animals Alter Their Heat Exchange with the Environment? 822

Endotherms produce substantial amounts of metabolic heat 822

Ectotherms and endotherms respond differently to changes in environmental temperature 822

Energy budgets reflect adaptations for regulating body temperature 823

Both ectotherms and endotherms control blood flow to the skin 824

Some fish conserve metabolic heat 825

Some ectotherms regulate metabolic heat production 825

### 40.5 How Do Endotherms Regulate Their Body Temperatures? 826

Basal metabolic rates correlate with body size 826



Endotherms respond to cold by producing heat and adapt to cold by reducing heat loss 827

Evaporation of water can dissipate heat, but at a cost 829

The mammalian thermostat uses feedback information 829

Fever helps the body fight infections 830

Some animals conserve energy by turning down the thermostat 830

## 41 Animal Hormones 834

### 41.1 What Are Hormones and How Do They Work? 835

Endocrine signaling can act locally or at a distance 835  
 Hormones can be divided into three chemical groups 836  
 Hormone action is mediated by receptors on or within their target cells 836  
 Hormone action depends on the nature of the target cell and its receptors 837

#### 41.2 What Have Experiments Revealed about Hormones and Their Action? 838

The first hormone discovered was the gut hormone secretin 838  
 Early experiments on insects illuminated hormonal signaling systems 839  
 Three hormones regulate molting and maturation in arthropods 840

#### 41.3 How Do the Nervous and Endocrine Systems Interact? 842

The pituitary is an interface between the nervous and endocrine systems 842  
 The anterior pituitary is controlled by hypothalamic neurohormones 844  
 Negative feedback loops regulate hormone secretion 844

#### 41.4 What Are the Major Endocrine Glands and Hormones? 845

The thyroid gland secretes thyroxine 845  
 Three hormones regulate blood calcium concentrations 847  
 PTH lowers blood phosphate levels 848  
 Insulin and glucagon regulate blood glucose concentrations 848  
 The adrenal gland is two glands in one 849  
 Sex steroids are produced by the gonads 850  
 Melatonin is involved in biological rhythms and photoperiodicity 851  
 Many chemicals may act as hormones 851

#### 41.5 How Do We Study Mechanisms of Hormone Action? 852

Hormones can be detected and measured with immunoassays 852  
 A hormone can act through many receptors 853

## 42 Immunology: Animal Defense Systems 856

### 42.1 What Are the Major Defense Systems of Animals? 857

Blood and lymph tissues play important roles in defense 857  
 White blood cells play many defensive roles 858  
 Immune system proteins bind pathogens or signal other cells 858

### 42.2 What Are the Characteristics of the Innate Defenses? 859

Barriers and local agents defend the body against invaders 859  
 Cell signaling pathways stimulate the body's defenses 860  
 Specialized proteins and cells participate in innate immunity 860  
 Inflammation is a coordinated response to infection or injury 861  
 Inflammation can cause medical problems 862

### 42.3 How Does Adaptive Immunity Develop? 862

Adaptive immunity has four key features 862  
 Two types of adaptive immune responses interact: an overview 863  
 Adaptive immunity develops as a result of clonal selection 865  
 Clonal deletion helps the immune system distinguish self from nonself 865  
 Immunological memory results in a secondary immune response 865  
 Vaccines are an application of immunological memory 866

### 42.4 What Is the Humoral Immune Response? 867

Some B cells develop into plasma cells 867  
 Different antibodies share a common structure 867  
 There are five classes of immunoglobulins 868  
 Immunoglobulin diversity results from DNA rearrangements and other mutations 868  
 The constant region is involved in immunoglobulin class switching 869

Monoclonal antibodies have many uses 871

### 42.5 What Is the Cellular Immune Response? 871

T cell receptors bind to antigens on cell surfaces 871  
 MHC proteins present antigen to T cells 872  
 T-helper cells and MHC II proteins contribute to the humoral immune response 872  
 Cytotoxic T cells and MHC I proteins contribute to the cellular immune response 874  
 Regulatory T cells suppress the humoral and cellular immune responses 874  
 MHC proteins are important in tissue transplants 874

### 42.6 What Happens When the Immune System Malfunctions? 875

Allergic reactions result from hypersensitivity 875  
 Autoimmune diseases are caused by reactions against self antigens 876  
 AIDS is an immune deficiency disorder 876

## 43 Animal Reproduction 880

### 43.1 How Do Animals Reproduce without Sex? 881

Budding and regeneration produce new individuals by mitosis 881  
 Parthenogenesis is the development of unfertilized eggs 881

### 43.2 How Do Animals Reproduce Sexually? 882

Gametogenesis produces eggs and sperm 882  
 Fertilization is the union of sperm and egg 884  
 Getting eggs and sperm together 887  
 Some individuals can function as both male and female 887  
 The evolution of vertebrate reproductive systems parallels the move to land 888  
 Animals with internal fertilization are distinguished by where the embryo develops 889

**43.3 How Do the Human Male and Female Reproductive Systems Work? 889**

Male sex organs produce and deliver semen 889

Male sexual function is controlled by hormones 892

Female sex organs produce eggs, receive sperm, and nurture the embryo 892

The ovarian cycle produces a mature egg 893

The uterine cycle prepares an environment for a fertilized egg 893

Hormones control and coordinate the ovarian and uterine cycles 894

FSH receptors determine which follicle ovulates 895

In pregnancy, hormones from the extraembryonic membranes take over 896

Childbirth is triggered by hormonal and mechanical stimuli 896

**43.4 How Can Fertility Be Controlled? 897**

Humans use a variety of methods to control fertility 897

Reproductive technologies help solve problems of infertility 897

**44 Animal Development 902****44.1 How Does Fertilization Activate Development? 903**

The sperm and the egg make different contributions to the zygote 903

Rearrangements of egg cytoplasm set the stage for determination 903

**44.2 How Does Mitosis Divide Up the Early Embryo? 904**

Cleavage repackages the cytoplasm 904

Early cell divisions in mammals are unique 905

Specific blastomeres generate specific tissues and organs 906

Germ cells are a unique lineage even in species with regulative development 908

**44.3 How Does Gastrulation Generate Multiple Tissue Layers? 908**

Invasion of the vegetal pole characterizes gastrulation in the sea urchin 908

Gastrulation in the frog begins at the gray crescent 909

The dorsal lip of the blastopore organizes embryo formation 910

Transcription factors and growth factors underlie the organizer's actions 911

The organizer changes its activity as it migrates from the dorsal lip 912

Reptilian and avian gastrulation is an adaptation to yolky eggs 913

The embryos of placental mammals lack yolk 914

**44.4 How Do Organs and Organ Systems Develop? 915**

The stage is set by the dorsal lip of the blastopore 915

Body segmentation develops during neurulation 916

Hox genes control development along the anterior–posterior axis 916

**44.5 How Is the Growing Embryo Sustained? 918**

Extraembryonic membranes form with contributions from all germ layers 918

Extraembryonic membranes in mammals form the placenta 919

**44.6 What Are the Stages of Human Development? 919**

Organ development begins in the first trimester 920

Organ systems grow and mature during the second and third trimesters 920

Developmental changes continue throughout life 920

**45 Neurons, Glia, and Nervous Systems 924****45.1 What Cells Are Unique to the Nervous System? 925**

The structure of neurons reflects their functions 925

Glia are the “silent partners” of neurons 926

**45.2 How Do Neurons Generate and Transmit Electric Signals? 927**

Simple electrical concepts underlie neural function 927

Membrane potentials can be measured with electrodes 928

Ion transporters and channels generate membrane potentials 928

Ion channels and their properties can now be studied directly 929

Gated ion channels alter membrane potential 930

Graded changes in membrane potential can integrate information 932

Sudden changes in Na<sup>+</sup> and K<sup>+</sup> channels generate action potentials 932

Action potentials are conducted along axons without loss of signal 934

Action potentials jump along myelinated axons 935

**45.3 How Do Neurons Communicate with Other Cells? 936**

The neuromuscular junction is a model chemical synapse 936

The arrival of an action potential causes the release of neurotransmitter 936

Synaptic functions involve many proteins 936

The postsynaptic membrane responds to neurotransmitter 936

Synapses can be excitatory or inhibitory 938

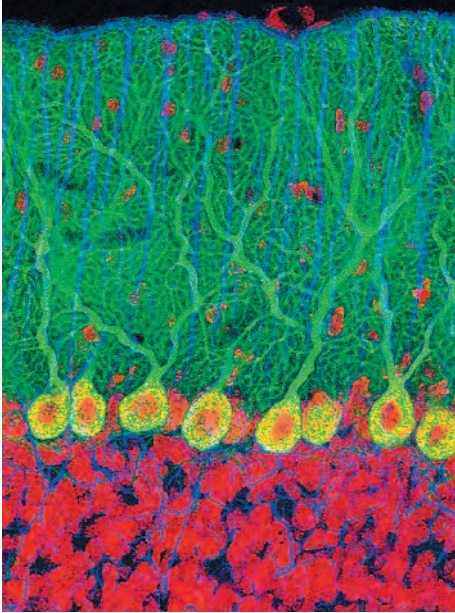
The postsynaptic cell sums excitatory and inhibitory input 938

Synapses can be fast or slow 938

Electrical synapses are fast but do not integrate information well 939







The action of a neurotransmitter depends on the receptor to which it binds 939

To turn off responses, synapses must be cleared of neurotransmitter 940

The diversity of receptors makes drug specificity possible 940

#### 45.4 How Are Neurons and Glia Organized into Information-Processing Systems? 940

Nervous systems range in complexity 940

The knee-jerk reflex is controlled by a simple neural network 941

The vertebrate brain is the seat of behavioral complexity 943

## 46 Sensory Systems 946

### 46.1 How Do Sensory Receptor Cells Convert Stimuli into Action Potentials? 947

Sensory transduction involves changes in membrane potentials 947

Sensory receptor proteins act on ion channels 947

Sensation depends on which neurons receive action potentials from sensory cells 947

Many receptors adapt to repeated stimulation 948

### 46.2 How Do Sensory Systems Detect Chemical Stimuli? 949

Olfaction is the sense of smell 949

Some chemoreceptors detect pheromones 950

The vomeronasal organ contains chemoreceptors 950

Gustation is the sense of taste 951

### 46.3 How Do Sensory Systems Detect Mechanical Forces? 952

Many different cells respond to touch and pressure 952

Mechanoreceptors are also found in muscles, tendons, and ligaments 952

Hair cells are mechanoreceptors of the auditory and vestibular systems 953

Auditory systems use hair cells to sense sound waves 954

Flexion of the basilar membrane is perceived as sound 955

Various types of damage can result in hearing loss 956

The vestibular system uses hair cells to detect forces of gravity and momentum 956

### 46.4 How Do Sensory Systems Detect Light? 957

Rhodopsin is a vertebrate visual pigment 957

Invertebrates have a variety of visual systems 958

Image-forming eyes evolved independently in vertebrates and cephalopods 958

The vertebrate retina receives and processes visual information 959

Rod and cone cells are the photoreceptors of the vertebrate retina 960

Information flows through layers of neurons in the retina 962

## 47 The Mammalian Nervous System: Structure and Higher Functions 967

### 47.1 How Is the Mammalian Nervous System Organized? 968

Functional organization is based on flow and type of information 968

The anatomical organization of the CNS emerges during development 968

The spinal cord transmits and processes information 969

The brainstem carries out many autonomic functions 969

The core of the forebrain controls physiological drives, instincts, and emotions 970

Regions of the telencephalon interact to control behavior and produce consciousness 970

The size of the human brain is off the curve 973

### 47.2 How Is Information Processed by Neural Networks? 973

Pathways of the autonomic nervous system control involuntary physiological functions 974

The visual system is an example of information integration by the cerebral cortex 975

Three-dimensional vision results from cortical cells receiving input from both eyes 977

### 47.3 Can Higher Functions Be Understood in Cellular Terms? 978

Sleep and dreaming are reflected in electrical patterns in the cerebral cortex 978

Language abilities are localized in the left cerebral hemisphere 980

Some learning and memory can be localized to specific brain areas 981

We still cannot answer the question "What is consciousness?" 982

## 48 Musculoskeletal Systems 986

### 48.1 How Do Muscles Contract? 987

Sliding filaments cause skeletal muscle to contract 987

Actin–myosin interactions cause filaments to slide 988

Actin–myosin interactions are controlled by calcium ions 989

Cardiac muscle is similar to and different from skeletal muscle 991

Smooth muscle causes slow contractions of many internal organs 993

### 48.2 What Determines Skeletal Muscle Performance? 994



The strength of a muscle contraction depends on how many fibers are contracting and at what rate 994

Muscle fiber types determine endurance and strength 995

A muscle has an optimal length for generating maximum tension 996

Exercise increases muscle strength and endurance 996

Muscle ATP supply limits performance 997

Insect muscle has the greatest rate of cycling 997

### 48.3 How Do Skeletal Systems and Muscles Work Together? 999

A hydrostatic skeleton consists of fluid in a muscular cavity 999

Exoskeletons are rigid outer structures 999

Vertebrate endoskeletons consist of cartilage and bone 999

Bones develop from connective tissues 1001

Bones that have a common joint can work as a lever 1001

## 49 Gas Exchange 1005

### 49.1 What Physical Factors Govern Respiratory Gas Exchange? 1006

Diffusion of gases is driven by partial pressure differences 1006

Fick's law applies to all systems of gas exchange 1006

Air is a better respiratory medium than water 1007

High temperatures create respiratory problems for aquatic animals 1007

O<sub>2</sub> availability decreases with altitude 1007

CO<sub>2</sub> is lost by diffusion 1008

### 49.2 What Adaptations Maximize Respiratory Gas Exchange? 1008

Respiratory organs have large surface areas 1008

Ventilation and perfusion of gas exchange surfaces maximize partial pressure gradients 1009

Insects have airways throughout their bodies 1009

Fish gills use countercurrent flow to maximize gas exchange 1009

Birds use unidirectional ventilation to maximize gas exchange 1010

Tidal ventilation produces dead space that limits gas exchange efficiency 1012

### 49.3 How Do Human Lungs Work? 1013

Respiratory tract secretions aid ventilation 1013

Lungs are ventilated by pressure changes in the thoracic cavity 1015

### 49.4 How Does Blood Transport Respiratory Gases? 1016

Hemoglobin combines reversibly with O<sub>2</sub> 1016

Myoglobin holds an O<sub>2</sub> reserve 1017

Hemoglobin's affinity for O<sub>2</sub> is variable 1017

CO<sub>2</sub> is transported as bicarbonate ions in the blood 1018

### 49.5 How Is Breathing Regulated? 1019

Breathing is controlled in the brainstem 1019

Regulating breathing requires feedback 1020

## 50 Circulatory Systems 1025

### 50.1 Why Do Animals Need a Circulatory System? 1026

Some animals do not have a circulatory system 1026

Circulatory systems can be open or closed 1026

Open circulatory systems move extracellular fluid 1026

Closed circulatory systems circulate blood through a system of blood vessels 1026

### 50.2 How Have Vertebrate Circulatory Systems Evolved? 1027

Circulation in fish is a single circuit 1028

Lungfish evolved a gas-breathing organ 1028

Amphibians have partial separation of systemic and pulmonary circulation 1029

Reptiles have exquisite control of pulmonary and systemic circulation 1029

Birds and mammals have fully separated pulmonary and systemic circuits 1030

### 50.3 How Does the Mammalian Heart Function? 1030

Blood flows from right heart to lungs to left heart to body 1030

The heartbeat originates in the cardiac muscle 1032

A conduction system coordinates the contraction of heart muscle 1034

Electrical properties of ventricular muscles sustain heart contraction 1034

The ECG records the electrical activity of the heart 1035

### 50.4 What Are the Properties of Blood and Blood Vessels? 1037

Red blood cells transport respiratory gases 1038

Platelets are essential for blood clotting 1039

Arteries withstand high pressure, arterioles control blood flow 1039

Materials are exchanged in capillary beds by filtration, osmosis, and diffusion 1039

Blood flows back to the heart through veins 1041

Lymphatic vessels return interstitial fluid to the blood 1042

Vascular disease is a killer 1042

### 50.5 How Is the Circulatory System Controlled and Regulated? 1043

Autoregulation matches local blood flow to local need 1044

Arterial pressure is regulated by hormonal and neural mechanisms 1044

## 51 Nutrition, Digestion, and Absorption 1048

### 51.1 What Do Animals Require from Food? 1049

Energy needs and expenditures can be measured 1049  
Sources of energy can be stored in the body 1050  
Food provides carbon skeletons for biosynthesis 1051  
Animals need mineral elements for a variety of functions 1052  
Animals must obtain vitamins from food 1053  
Nutrient deficiencies result in diseases 1054

### 51.2 How Do Animals Ingest and Digest Food? 1054

The food of herbivores is often low in energy and hard to digest 1054  
Carnivores must find, capture, and kill prey 1055  
Vertebrate species have distinctive teeth 1055  
Digestion usually begins in a body cavity 1056  
Tubular guts have an opening at each end 1056  
Digestive enzymes break down complex food molecules 1057

### 51.3 How Does the Vertebrate Gastrointestinal System Function? 1058

The vertebrate gut consists of concentric tissue layers 1058  
Mechanical activity moves food through the gut and aids digestion 1059  
Chemical digestion begins in the mouth and the stomach 1060  
The stomach gradually releases its contents to the small intestine 1061  
Most chemical digestion occurs in the small intestine 1061  
Nutrients are absorbed in the small intestine 1063  
Absorbed nutrients go to the liver 1063  
Water and ions are absorbed in the large intestine 1063

Herbivores rely on microorganisms to digest cellulose 1063

### 51.4 How Is the Flow of Nutrients Controlled and Regulated? 1064

Hormones control many digestive functions 1065  
The liver directs the traffic of the molecules that fuel metabolism 1065  
The brain plays a major role in regulating food intake 1067

## 52 Salt and Water Balance and Nitrogen Excretion 1071

### 52.1 How Do Excretory Systems Maintain Homeostasis? 1072

Water enters or leaves cells by osmosis 1072  
Excretory systems control extracellular fluid osmolarity and composition 1072  
Aquatic invertebrates can conform to or regulate their osmotic and ionic environments 1072  
Vertebrates are osmoregulators and ionic regulators 1073

### 52.2 How Do Animals Excrete Nitrogen? 1074

Animals excrete nitrogen in a number of forms 1074  
Most species produce more than one nitrogenous waste 1074

### 52.3 How Do Invertebrate Excretory Systems Work? 1075

The protonephridia of flatworms excrete water and conserve salts 1075  
The metanephridia of annelids process coelomic fluid 1075  
Malpighian tubules of insects use active transport to excrete wastes 1076

### 52.4 How Do Vertebrates Maintain Salt and Water Balance? 1077

Marine fishes must conserve water 1077  
Terrestrial amphibians and reptiles must avoid desiccation 1077  
Mammals can produce highly concentrated urine 1078  
The nephron is the functional unit of the vertebrate kidney 1078  
Blood is filtered into Bowman's capsule 1078  
The renal tubules convert glomerular filtrate to urine 1079

### 52.5 How Does the Mammalian Kidney Produce Concentrated Urine? 1079

Kidneys produce urine and the bladder stores it 1080  
Nephrons have a regular arrangement in the kidney 1081  
Most of the glomerular filtrate is reabsorbed by the proximal convoluted tubule 1082  
The loop of Henle creates a concentration gradient in the renal medulla 1082  
Water permeability of kidney tubules depends on water channels 1084  
The distal convoluted tubule fine-tunes the composition of the urine 1084  
Urine is concentrated in the collecting duct 1084  
The kidneys help regulate acid-base balance 1084  
Kidney failure is treated with dialysis 1085

### 52.6 How Are Kidney Functions Regulated? 1087

Glomerular filtration rate is regulated 1087





Regulation of GFR uses feedback information from the distal tubule 1087

Blood osmolarity and blood pressure are regulated by ADH 1088

The heart produces a hormone that helps lower blood pressure 1090

## 53 Animal Behavior 1093

### 53.1 What Are the Origins of Behavioral Biology? 1094

Conditioned reflexes are a simple behavioral mechanism 1094

Ethologists focused on the behavior of animals in their natural environment 1094

Ethologists probed the causes of behavior 1095

### 53.2 How Do Genes Influence Behavior? 1096

Breeding experiments can produce behavioral phenotypes 1096

Knockout experiments can reveal the roles of specific genes 1096

Behaviors are controlled by gene cascades 1097

### 53.3 How Does Behavior Develop? 1098

Hormones can determine behavioral potential and timing 1098

Some behaviors can be acquired only at certain times 1099

Birdsong learning involves genetics, imprinting, and hormonal timing 1099

The timing and expression of birdsong are under hormonal control 1101

### 53.4 How Does Behavior Evolve? 1102

Animals are faced with many choices 1103

Behaviors have costs and benefits 1103

Territorial behavior carries significant costs 1103

Cost-benefit analysis can be applied to foraging behavior 1104

### 53.5 What Physiological Mechanisms Underlie Behavior? 1106

Biological rhythms coordinate behavior with environmental cycles 1106

Animals must find their way around their environment 1109

Animals use multiple modalities to communicate 1110

### 53.6 How Does Social Behavior Evolve? 1113

Mating systems maximize the fitness of both partners 1113

Fitness can include more than your own offspring 1114

Eusociality is the extreme result of kin selection 1115

Group living has benefits and costs 1116

Can the concepts of sociobiology be applied to humans? 1116

## PART TEN Ecology

## 54 Ecology and the Distribution of Life 1121

### 54.1 What Is Ecology? 1122

Ecology is not the same as environmentalism 1122

Ecologists study biotic and abiotic components of ecosystems 1122

### 54.2 Why Do Climates Vary Geographically? 1122

Solar radiation varies over Earth's surface 1123

Solar energy input determines atmospheric circulation patterns 1124

Atmospheric circulation and Earth's rotation result in prevailing winds 1124

Prevailing winds drive ocean currents 1124

Organisms adapt to climatic challenges 1125



### 54.3 How Is Life Distributed in Terrestrial Environments? 1126

Tundra is found at high latitudes and high elevations 1128

Evergreen trees dominate boreal and temperate evergreen forests 1129

Temperate deciduous forests change with the seasons 1130

Temperate grasslands are widespread 1131

Hot deserts form around 30° latitude 1132

Cold deserts are high and dry 1133

- Chaparral has hot, dry summers and wet, cool winters 1134
- Thorn forests and tropical savannas have similar climates 1135
- Tropical deciduous forests occur in hot lowlands 1136
- Tropical rainforests are rich in species 1137

#### 54.4 How Is Life Distributed in Aquatic Environments? 1139

- The marine biome can be divided into several life zones 1139
- Freshwater biomes may be rich in species 1140
- Estuaries have characteristics of both freshwater and marine environments 1141

#### 54.5 What Factors Determine the Boundaries of Biogeographic Regions? 1141

- Geological history influences the distribution of organisms 1141
- Two scientific advances changed the field of biogeography 1142
- Discontinuous distributions may result from vicariant or dispersal events 1143
- Humans exert a powerful influence on biogeographic patterns 1145

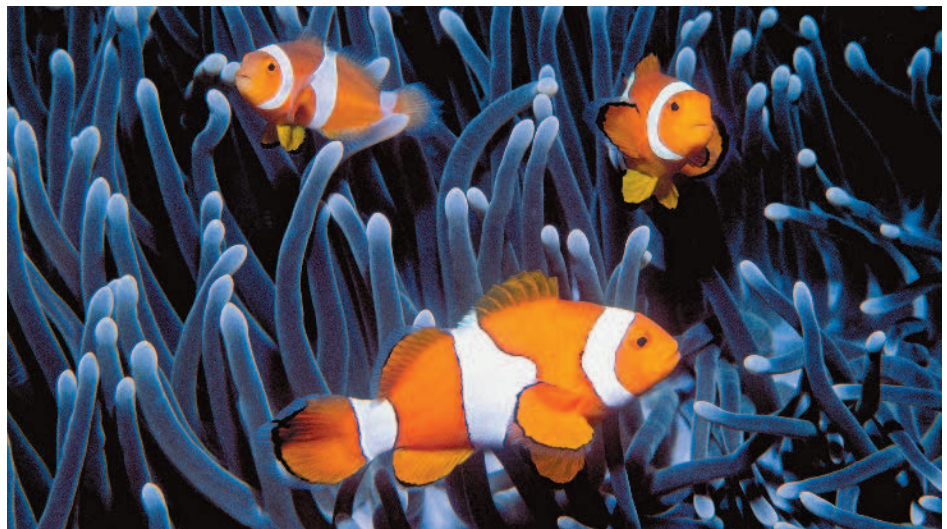
## 55 Population Ecology 1149

#### 55.1 How Do Ecologists Measure Populations? 1150

- Ecologists use a variety of approaches to count and track individuals 1150
- Ecologists can estimate population densities from samples 1151
- A population's age structure influences its capacity to grow 1151
- A population's dispersion pattern reflects how individuals are distributed in space 1152

#### 55.2 How Do Ecologists Study Population Dynamics? 1153

- Demographic events determine the size of a population 1153



- Life tables track demographic events 1154
- Survivorship curves reflect life history strategies 1155

#### 55.3 How Do Environmental Conditions Affect Life Histories? 1156

- Survivorship and fecundity determine a population's growth rate 1156
- Life history traits vary with environmental conditions 1156
- Life history traits are influenced by interspecific interactions 1157

#### 55.4 What Factors Limit Population Densities? 1157

- All populations have the potential for exponential growth 1157
- Logistic growth occurs as a population approaches its carrying capacity 1158
- Population growth can be limited by density-dependent or density-independent factors 1159
- Different population regulation factors lead to different life history strategies 1159
- Several ecological factors explain species' characteristic population densities 1159
- Some newly introduced species reach high population densities 1160
- Evolutionary history may explain species abundances 1160

#### 55.5 How Does Habitat Variation Affect Population Dynamics? 1161

- Many populations live in separated habitat patches 1161
- Corridors may allow subpopulations to persist 1162

#### 55.6 How Can We Use Ecological Principles to Manage Populations? 1163

- Management plans must take life history strategies into account 1163
- Management plans must be guided by the principles of population dynamics 1163
- Human population growth has been exponential 1164

## 56 Species Interactions and Coevolution 1169

#### 56.1 What Types of Interactions Do Ecologists Study? 1170

- Interactions among species can be grouped into several categories 1170
- Interaction types are not always clear-cut 1171
- Some types of interactions result in coevolution 1171

#### 56.2 How Do Antagonistic Interactions Evolve? 1172



- Predator–prey interactions result in a range of adaptations 1172
- Herbivory is a widespread interaction 1175
- Parasite–host interactions may be pathogenic 1176

**56.3 How Do Mutualistic Interactions Evolve? 1177**

- Some mutualistic partners exchange food for care or transport 1178
- Some mutualistic partners exchange food or housing for defense 1178
- Plants and pollinators exchange food for pollen transport 1180
- Plants and frugivores exchange food for seed transport 1181

**56.4 What Are the Outcomes of Competition? 1182**

- Competition is widespread because all species share resources 1182
- Interference competition may restrict habitat use 1183
- Exploitation competition may lead to coexistence 1183
- Species may compete indirectly for a resource 1184
- Competition may determine a species' niche 1184

**57 Community Ecology 1188**

**57.1 What Are Ecological Communities? 1189**

- Energy enters communities through primary producers 1189
- Consumers use diverse sources of energy 1190
- Fewer individuals and less biomass can be supported at higher trophic levels 1190
- Productivity and species diversity are linked 1192

**57.2 How Do Interactions among Species Influence Communities? 1193**

- Species interactions can cause trophic cascades 1193
- Keystone species have disproportionate effects on their communities 1194



**57.3 What Patterns of Species Diversity Have Ecologists Observed? 1195**

- Diversity comprises both the number and the relative abundance of species 1195
- Ecologists have observed latitudinal gradients in diversity 1196
- The theory of island biogeography suggests that immigration and extinction rates determine diversity on islands 1196

**57.4 How Do Disturbances Affect Ecological Communities? 1199**

- Succession is the predictable pattern of change in a community after a disturbance 1199
- Both facilitation and inhibition influence succession 1201
- Cyclical succession requires adaptation to periodic disturbances 1201
- Heterotrophic succession generates distinctive communities 1202

**57.5 How Does Species Richness Influence Community Stability? 1202**

- Species richness is associated with productivity and stability 1202
- Diversity, productivity, and stability differ between natural and managed communities 1202

**58 Ecosystems and Global Ecology 1207**

**58.1 How Does Energy Flow through the Global Ecosystem? 1208**

- Energy flows and chemicals cycle through ecosystems 1208
- The geographic distribution of energy flow is uneven 1208
- Human activities modify the flow of energy 1210

**58.2 How Do Materials Move through the Global Ecosystem? 1210**

- Elements move between biotic and abiotic compartments of ecosystems 1211
- The atmosphere contains large pools of the gases required by living organisms 1211
- The terrestrial surface is influenced by slow geological processes 1213
- Water transports elements among compartments 1213
- Fire is a major mover of elements 1214

**58.3 How Do Specific Nutrients Cycle through the Global Ecosystem? 1214**

- Water cycles rapidly through the ecosystem 1215
- The carbon cycle has been altered by human activities 1216



The nitrogen cycle depends on both biotic and abiotic processes 1218

The burning of fossil fuels affects the sulfur cycle 1219

The global phosphorus cycle lacks a significant atmospheric component 1220

Other biogeochemical cycles are also important 1221

Biogeochemical cycles interact 1221

#### **58.4 What Goods and Services Do Ecosystems Provide? 1223**

#### **58.5 How Can Ecosystems Be Sustainably Managed? 1224**

## **59 Biodiversity and Conservation Biology 1228**

#### **59.1 What Is Conservation Biology? 1229**

Conservation biology aims to protect and manage biodiversity 1229

Biodiversity has great value to human society 1230

#### **59.2 How Do Conservation Biologists Predict Changes in Biodiversity? 1230**

Our knowledge of biodiversity is incomplete 1230

We can predict the effects of human activities on biodiversity 1231

#### **59.3 What Human Activities Threaten Species Persistence? 1232**

Habitat losses endanger species 1233

Overexploitation has driven many species to extinction 1234

Invasive predators, competitors, and pathogens threaten many species 1235

Rapid climate change can cause species extinctions 1236

#### **59.4 What Strategies Are Used to Protect Biodiversity? 1237**

Protected areas preserve habitat and prevent overexploitation 1237

Degraded ecosystems can be restored 1237

Disturbance patterns sometimes need to be restored 1239

Ending trade is crucial to saving some species 1240

Species invasions must be controlled or prevented 1241

Biodiversity has economic value 1241

Changes in human-dominated landscapes can help protect biodiversity 1243

Captive breeding programs can maintain a few species 1244

Earth is not a ship, a spaceship, or an airplane 1244

#### **APPENDIX A The Tree of Life 1248**

#### **APPENDIX B Statistics Primer 1255**

#### **APPENDIX C Some Measurements Used in Biology 1264**

#### **ANSWERS TO CHAPTER REVIEW QUESTIONS A-1**

#### **GLOSSARY G-1**

#### **ILLUSTRATION CREDITS C-1**

#### **INDEX I-1**