

Contents

About the Authors 11

Preface 15

Acknowledgments 21

UNIT 1 The Foundations of Microbiology

1 The Microbial World 37

MICROBIOLOGYNOW Microbiology in Motion 37

I • Exploring the Microbial World 38

- 1.1 Microorganisms, Tiny Titans of the Earth 38
- 1.2 Structure and Activities of Microbial Cells 39
- 1.3 Cell Size and Morphology 41
- 1.4 An Introduction to Microbial Life 46
- 1.5 Microorganisms and the Biosphere 48
- 1.6 The Impact of Microorganisms on Human Society 49

II • Microscopy and the Origins of Microbiology 54

- 1.7 Light Microscopy and the Discovery of Microorganisms 54
- 1.8 Improving Contrast in Light Microscopy 56
- 1.9 Imaging Cells in Three Dimensions 58
- 1.10 Probing Cell Structure: Electron Microscopy 59

III • Microbial Cultivation Expands the Horizon of Microbiology 61

- 1.11 Pasteur and Spontaneous Generation 61
- 1.12 Koch, Infectious Diseases, and Pure Cultures 63
- 1.13 Discovery of Microbial Diversity 65

IV • Molecular Biology and the Unity and Diversity of Life 67

- 1.14 Molecular Basis of Life 67
- 1.15 Woese and the Tree of Life 68

Explore the Microbial World
Tiny Cells 45

2

Microbial Cell Structure and Function 74

MICROBIOLOGYNOW Exploring the Microbial Cell 74

I • The Cell Envelope 75

- 2.1 The Cytoplasmic Membrane 75
- 2.2 Transporting Nutrients into the Cell 78
- 2.3 The Cell Wall 80
- 2.4 LPS: The Outer Membrane 83
- 2.5 Diversity of Cell Envelope Structure 85

II • Cell Surface Structures and Inclusions 87

- 2.6 Cell Surface Structures 87
- 2.7 Cell Inclusions 89
- 2.8 Endospores 91

III • Cell Locomotion 94

- 2.9 Flagella, Archaeella, and Swimming Motility 94
- 2.10 Surface Motility 97
- 2.11 Chemotaxis 99
- 2.12 Other Forms of Taxis 101

IV • Eukaryotic Microbial Cells 102

- 2.13 The Nucleus and Cell Division 102
- 2.14 Mitochondria and Chloroplasts 104
- 2.15 Other Eukaryotic Cell Structures 106

3

Microbial Metabolism 111

MICROBIOLOGYNOW Life Begins with Metabolism 111

I • Fundamentals of Metabolism 112

- 3.1 Defining the Requirements for Life 112
- 3.2 Electron Transfer Reactions 114
- 3.3 Calculating Changes in Free Energy 116
- 3.4 Cellular Energy Conservation 118
- 3.5 Catalysis and Enzymes 120

II • Catabolism: Chemoorganotrophs 121

- 3.6 Glycolysis, the Citric Acid Cycle, and the Glyoxylate Cycle 122
- 3.7 Principles of Fermentation 124

- 3.8 Principles of Respiration: Electron Carriers 125
- 3.9 Principles of Respiration: Generating a Proton Motive Force 127

III • **Catabolism: Electron Transport and Metabolic Diversity** 130

- 3.10 Anaerobic Respiration and Metabolic Modularity 130
- 3.11 Chemolithotrophy and Phototrophy 132

IV • **Biosynthesis** 134

- 3.12 Autotrophy and Nitrogen Fixation 134
- 3.13 Sugars and Polysaccharides 137
- 3.14 Amino Acids and Nucleotides 138
- 3.15 Fatty Acids and Lipids 139

4

Microbial Growth and Its Control 144

MICROBIOLOGYNOW Growing Their Own Way 144

I • **Culturing Microbes and Measuring Their Growth** 145

- 4.1 Feeding the Microbe: Cell Nutrition 145
- 4.2 Growth Media and Laboratory Culture 147
- 4.3 Microscopic Counts of Microbial Cell Numbers 150
- 4.4 Viable Counting of Microbial Cell Numbers 151
- 4.5 Turbidimetric Measures of Microbial Cell Numbers 153

II • **Dynamics of Microbial Growth** 154

- 4.6 Binary Fission and the Microbial Growth Cycle 154
- 4.7 Quantitative Aspects of Microbial Growth 156
- 4.8 Continuous Culture 158
- 4.9 Biofilm Growth 159
- 4.10 Alternatives to Binary Fission 160

III • **Environmental Effects on Growth: Temperature** 162

- 4.11 Temperature Classes of Microorganisms 162
- 4.12 Microbial Life in the Cold 163
- 4.13 Microbial Life at High Temperatures 165

IV • **Environmental Effects on Growth: pH, Osmolarity, and Oxygen** 167

- 4.14 Effects of pH on Microbial Growth 168
- 4.15 Osmolarity and Microbial Growth 169
- 4.16 Oxygen and Microbial Growth 171

V • **Controlling Microbial Growth** 173

- 4.17 General Principles and Microbial Growth Control by Heat 174
- 4.18 Other Physical Control Methods: Radiation and Filtration 175
- 4.19 Chemical Control of Microbial Growth 177

5

Viruses and Their Multiplication 184

MICROBIOLOGYNOW When Antibiotics Fail, Bacteriophage Therapy to the Rescue 184

I • **The Nature of Viruses** 185

- 5.1 What Is a Virus? 185
- 5.2 Structure of the Virion 187
- 5.3 Culturing, Detecting, and Counting Viruses 189

II • **Overview of the Viral Replication Cycle** 191

- 5.4 Steps in the Replication Cycle 191
- 5.5 Bacteriophage T4: A Model Lytic Virus 192
- 5.6 Temperate Bacteriophages and Lysogeny 195
- 5.7 An Overview of Viruses of Eukaryotes 195

UNIT 2 Molecular Biology and Genetics

6

Molecular Information Flow and Protein Processing 201

MICROBIOLOGYNOW Injectisomes: *Salmonella's* Mode of Attack 201

I • **Molecular Biology and Genetic Elements** 202

- 6.1 DNA and Genetic Information Flow 202
- 6.2 Genetic Elements: Chromosomes and Plasmids 205

II • **Copying the Genetic Blueprint: DNA Replication** 208

- 6.3 Templates, Enzymes, and the Replication Fork 208
- 6.4 Bidirectional Replication, the Replisome, and Proofreading 211

III • **RNA Synthesis: Transcription** 213

- 6.5 Transcription in *Bacteria* 213
- 6.6 Transcription in *Archaea* and *Eukarya* 217

IV • **Protein Synthesis: Translation** 219

- 6.7 Amino Acids, Polypeptides, and Proteins 219
- 6.8 Transfer RNA 222
- 6.9 Translation and the Genetic Code 223
- 6.10 The Mechanism of Protein Synthesis 225

V • **Protein Processing, Secretion, and Targeting** 228

- 6.11 Assisted Protein Folding and Chaperones 228
- 6.12 Protein Secretion: The Sec and Tat Systems 229
- 6.13 Protein Secretion: Gram-Negative Systems 230

7

Microbial Regulatory Systems 236**MICROBIOLOGYNOW** As Bacterial Cells Chatter, Viruses Eavesdrop 236**I • DNA-Binding Proteins and Transcriptional Regulation 237**

- 7.1 DNA-Binding Proteins 237
- 7.2 Transcription Factors and Effectors 238
- 7.3 Repression and Activation 240
- 7.4 Transcription Controls in *Archaea* 243

II • Sensing and Signal Transduction 245

- 7.5 Two-Component Regulatory Systems 245
- 7.6 Regulation of Chemotaxis 246
- 7.7 Cell-to-Cell Signaling 249

III • Global Control 251

- 7.8 The *lac* Operon 252
- 7.9 Stringent and General Stress Responses 254
- 7.10 The Phosphate (Pho) Regulon 256
- 7.11 The Heat Shock Response 257

IV • RNA-Based Regulation 258

- 7.12 Regulatory RNAs 259
- 7.13 Riboswitches 260
- 7.14 Attenuation 262

V • Regulation of Enzymes and Other Proteins 263

- 7.15 Feedback Inhibition 264
- 7.16 Post-Translational Regulation 264

8

Molecular Aspects of Microbial Growth 270**MICROBIOLOGYNOW** Membrane Vesicles: Nano Vehicles Transporting Important Cargo 270**I • Bacterial Cell Division 271**

- 8.1 Visualizing Molecular Growth 271
- 8.2 Chromosome Replication and Segregation 272
- 8.3 Cell Division and Fts Proteins 275
- 8.4 Determinants of Cell Morphology 277
- 8.5 Peptidoglycan Biosynthesis 279

II • Regulation of Development in Model *Bacteria* 282

- 8.6 Regulation of Endospore Formation 282
- 8.7 Regulation of Endospore Germination 283
- 8.8 *Caulobacter* Differentiation 284
- 8.9 Heterocyst Formation in *Anabaena* 286
- 8.10 Biofilm Formation 287

III • Antibiotics and Microbial Growth 291

- 8.11 Antibiotic Targets and Antibiotic Resistance 291
- 8.12 Persistence and Dormancy 293

9

Genetics of *Bacteria* and *Archaea* 297**MICROBIOLOGYNOW** Live Cell Imaging Captures Bacterial Promiscuity 297**I • Mutation 299**

- 9.1 Mutations and Mutants 299
- 9.2 Molecular Basis of Mutation 301
- 9.3 Reversions and Mutation Rates 303
- 9.4 Mutagenesis 304

II • Gene Transfer in *Bacteria* 306

- 9.5 Genetic Recombination 307
- 9.6 Transformation 309
- 9.7 Transduction 311
- 9.8 Conjugation 314
- 9.9 The Formation of Hfr Strains and Chromosome Mobilization 315

III • Gene Transfer in *Archaea* and Other Genetic Events 318

- 9.10 Horizontal Gene Transfer in *Archaea* 318
- 9.11 Mobile DNA: Transposable Elements 320
- 9.12 Preserving Genomic Integrity and CRISPR 322

UNIT 3 Genomics, Synthetic Biology, and Evolution

10

Microbial Genomics and Other Omics 328**MICROBIOLOGYNOW** Omics Tools Unravel Mysteries of "Fettuccine" Rocks 328**I • Genomics 329**

- 10.1 Introduction to Genomics 329
- 10.2 Sequencing and Annotating Genomes 331
- 10.3 Genome Size and Gene Content in *Bacteria* and *Archaea* 334
- 10.4 Organelle and Eukaryotic Microbial Genomes 338

II • Functional Omics 341

- 10.5 Functional Genomics 341
- 10.6 High-Throughput Functional Gene Analysis: Tn-Seq 344

- 10.7 Metagenomics 344
- 10.8 Gene Chips and Transcriptomics 347
- 10.9 Proteomics and the Interactome 350
- 10.10 Metabolomics 352

III • Systems Biology 353

- 10.11 Single-Cell Genomics 354
- 10.12 Integrating *Mycobacterium tuberculosis* Omics 355
- 10.13 Systems Biology and Human Health 357

Explore the Microbial World

DNA Sequencing in the Palm of Your Hand 336

11 Viral Genomics and Diversity 361

MICROBIOLOGYNOW Bacteriophages Mimicking Eukaryotes—Discovery of a Phage-Encoded Nucleus and Spindle 361

I • Viral Genomes and Classification 362

- 11.1 Size and Structure of Viral Genomes 362
- 11.2 Viral Taxonomy and Phylogeny 364

II • DNA Viruses 366

- 11.3 Single-Stranded DNA Bacteriophages: ϕ X174 and M13 366
- 11.4 Double-Stranded DNA Bacteriophages: T4, T7, and Lambda 368
- 11.5 Viruses of *Archaea* 371
- 11.6 Uniquely Replicating DNA Animal Viruses 374
- 11.7 DNA Tumor Viruses 375

III • RNA Viruses 377

- 11.8 Positive-Strand RNA Viruses 377
- 11.9 Negative-Strand RNA Animal Viruses 379
- 11.10 Double-Stranded RNA Viruses 381
- 11.11 Viruses That Use Reverse Transcriptase 382

IV • Subviral Agents 385

- 11.12 Viroids 385
- 11.13 Prions 386

12 Biotechnology and Synthetic Biology 390

MICROBIOLOGYNOW An Ingestible Biosensor: Using Bacteria to Monitor Gastrointestinal Health 390

I • Tools of the Genetic Engineer 391

- 12.1 Manipulating DNA: PCR and Nucleic Acid Hybridization 391
- 12.2 Molecular Cloning 394

- 12.3 Expressing Foreign Genes in *Bacteria* 398
- 12.4 Molecular Methods for Mutagenesis 400
- 12.5 Reporter Genes and Gene Fusions 401

II • Making Products from Genetically Engineered Microbes: Biotechnology 403

- 12.6 Somatotropin and Other Mammalian Proteins 403
- 12.7 Transgenic Organisms in Agriculture and Aquaculture 405
- 12.8 Engineered Vaccines and Therapeutic Agents 407
- 12.9 Mining Genomes and Engineering Pathways 411
- 12.10 Engineering Biofuels 413

III • Synthetic Biology and Genome Editing 415

- 12.11 Synthetic Metabolic Pathways, Biosensors, and Genetic Circuits 416
- 12.12 Synthetic Cells 419
- 12.13 Genome Editing and CRISPRs 420
- 12.14 Biocontainment of Genetically Modified Organisms 424

13 Microbial Evolution and Genome Dynamics 428

MICROBIOLOGYNOW Exploring Viral Genesis 428

I • Early Earth and the Origin and Diversification of Life 429

- 13.1 Formation and Early History of Earth 429
- 13.2 Photosynthesis and the Oxidation of Earth 432
- 13.3 Living Fossils: DNA Records the History of Life 434
- 13.4 Endosymbiotic Origin of Eukaryotes 435
- 13.5 Viral Evolution 438

II • Mechanisms of Microbial Evolution 439

- 13.6 The Evolutionary Process 439
- 13.7 Experimental Evolution 441
- 13.8 Gene Families, Duplications, and Deletions 443
- 13.9 Horizontal Gene Transfer 445
- 13.10 The Evolution of Microbial Genomes 446

III • Microbial Phylogeny and Systematics 448

- 13.11 Molecular Phylogeny: Making Sense of Molecular Sequences 448
- 13.12 Microbial Systematics 452

UNIT 4 Microbial Diversity

14 Metabolic Diversity of Microorganisms 460

MICROBIOLOGYNOW Ferreting Out the Peculiar Life of Iron Bacteria 460

I • Introduction to Metabolic Diversity 461

- 14.1 Foundational Principles of Metabolic Diversity: Energy and Redox 461
- 14.2 Autotrophic Pathways 464

II • Phototrophy 466

- 14.3 Photosynthesis and Chlorophylls 466
- 14.4 Carotenoids and Phycobilins 470
- 14.5 Anoxygenic Photosynthesis 471
- 14.6 Oxygenic Photosynthesis 474

III • Respiratory Processes Defined by Electron Donor 476

- 14.7 Oxidation of Sulfur Compounds 476
- 14.8 Iron (Fe^{2+}) Oxidation 478
- 14.9 Nitrification 479
- 14.10 Anaerobic Ammonia Oxidation (Anammox) 481

IV • Respiratory Processes Defined by Electron Acceptor 482

- 14.11 Nitrate Reduction and Denitrification 482
- 14.12 Sulfate and Sulfur Reduction 484
- 14.13 Other Electron Acceptors 486

V • One-Carbon (C_1) Metabolism 488

- 14.14 Acetogenesis 488
- 14.15 Methanogenesis 490
- 14.16 Methanotrophy 494

VI • Fermentation 496

- 14.17 Energetic and Redox Considerations 496
- 14.18 Lactic and Mixed-Acid Fermentations 498
- 14.19 Fermentations of Obligate Anaerobes 500
- 14.20 Secondary Fermentations 502
- 14.21 Fermentations That Lack Substrate-Level Phosphorylation 503
- 14.22 Syntrophy 505

VII • Hydrocarbon Metabolism 507

- 14.23 Aerobic Hydrocarbon Metabolism 507
- 14.24 Anaerobic Hydrocarbon Metabolism 508

15 Ecological Diversity of Bacteria 514

MICROBIOLOGYNOW Cyanobacterial Diversity and Environmental Change 514

I • Ecological Diversity Among Microorganisms 515

- 15.1 Making Sense of Microbial Diversity 515

II • Ecological Diversity of Phototrophic Bacteria 516

- 15.2 Overview of Phototrophic Bacteria 516
- 15.3 Cyanobacteria 517
- 15.4 Purple Sulfur Bacteria 521
- 15.5 Purple Nonsulfur Bacteria and Aerobic Anoxygenic Phototrophs 523
- 15.6 Green Sulfur Bacteria 524
- 15.7 Green Nonsulfur Bacteria 526
- 15.8 Other Phototrophic Bacteria 527

III • Diversity of Bacteria Defined by Metabolic Traits 528

- 15.9 Diversity of Nitrogen Fixers 528
- 15.10 Diversity of Nitrifiers and Denitrifiers 530
- 15.11 Dissimilative Sulfur- and Sulfate-Reducers 532
- 15.12 Dissimilative Sulfur-Oxidizers 534
- 15.13 Dissimilative Iron-Reducers 538
- 15.14 Dissimilative Iron-Oxidizers 539
- 15.15 Methanotrophs and Methylophiles 540

IV • Morphologically and Ecologically Distinctive Bacteria 542

- 15.16 Microbial Predators 542
- 15.17 Spirochetes 544
- 15.18 Budding and Prosthecate/Stalked Bacteria 547
- 15.19 Sheathed Bacteria 550
- 15.20 Magnetic Microbes 551

16 Phylogenetic Diversity of Bacteria 555

MICROBIOLOGYNOW Bacterial Diversity and Human Health 555

I • Proteobacteria 556

- 16.1 Alphaproteobacteria 557
- 16.2 Betaproteobacteria 560
- 16.3 Gammaproteobacteria: Enterobacteriales 562
- 16.4 Gammaproteobacteria: Pseudomonadales and Vibrionales 564
- 16.5 Deltaproteobacteria and Epsilonproteobacteria 565

II • **Firmicutes, Tenericutes, and Actinobacteria** 567

- 16.6 *Firmicutes: Lactobacillales* 567
- 16.7 *Firmicutes: Nonsporulating Bacillales and Clostridiales* 569
- 16.8 *Firmicutes: Sporulating Bacillales and Clostridiales* 570
- 16.9 *Tenericutes: The Mycoplasmas* 571
- 16.10 *Actinobacteria: Coryneform and Propionic Acid Bacteria* 572
- 16.11 *Actinobacteria: Mycobacterium* 574
- 16.12 *Filamentous Actinobacteria: Streptomyces and Relatives* 575

III • **Bacteroidetes** 578

- 16.13 *Bacteroidales* 578
- 16.14 *Cytophagales, Flavobacteriales, and Sphingobacteriales* 579

IV • **Chlamydiae, Planctomycetes, and Verrucomicrobia** 580

- 16.15 *Chlamydiae* 580
- 16.16 *Planctomycetes* 582
- 16.17 *Verrucomicrobia* 583

V • **Hyperthermophilic Bacteria** 584

- 16.18 *Thermotogae and Thermodesulfobacteria* 584
- 16.19 *Aquificae* 585

VI • **Other Bacteria** 586

- 16.20 *Deinococcus-Thermus* 586
- 16.21 *Acidobacteria and Nitrospirae* 587
- 16.22 *Other Notable Phyla of Bacteria* 588

17

Diversity of Archaea 592

MICROBIOLOGYNOW Methanogens and Global Climate Change 592

I • **Euryarchaeota** 594

- 17.1 *Extremely Halophilic Archaea* 594
- 17.2 *Methanogenic Archaea* 597
- 17.3 *Thermoplasmatales* 601
- 17.4 *Thermococcales and Archaeoglobales* 602

II • **Thaumarchaeota and Cryptic Archaeal Phyla** 603

- 17.5 *Thaumarchaeota and Nitrification in Archaea* 604
- 17.6 *Nanoarchaeota and the "Hospitable Fireball"* 605
- 17.7 *Korarchaeota, the "Secret Filament"* 606
- 17.8 *Other Cryptic Archaeal Phyla* 607

III • **Crenarchaeota** 608

- 17.9 *Habitats and Energy Metabolism of Crenarchaeota* 608
- 17.10 *Crenarchaeota from Terrestrial Volcanic Habitats* 610
- 17.11 *Crenarchaeota from Submarine Volcanic Habitats* 612

IV • **Evolution and Life at High Temperature** 614

- 17.12 *An Upper Temperature Limit for Microbial Life* 614
- 17.13 *Molecular Adaptations to Life at High Temperature* 616
- 17.14 *Hyperthermophilic Archaea, H₂, and Microbial Evolution* 617

18

Diversity of Microbial Eukarya 621

MICROBIOLOGYNOW Coccolithophores, Engineers of Global Climate 621

I • **Organelles and Phylogeny of Microbial Eukarya** 622

- 18.1 *Endosymbioses and the Eukaryotic Cell* 622
- 18.2 *Phylogenetic Lineages of Eukarya* 624

II • **Protists** 625

- 18.3 *Excavates* 625
- 18.4 *Alveolata* 627
- 18.5 *Stramenopiles* 629
- 18.6 *Rhizaria* 631
- 18.7 *Haptophytes* 632
- 18.8 *Amoebozoa* 633

III • **Fungi** 635

- 18.9 *Fungal Physiology, Structure, and Symbioses* 635
- 18.10 *Fungal Reproduction and Phylogeny* 637
- 18.11 *Microsporidia and Chytridiomycota* 638
- 18.12 *Mucoromycota and Glomeromycota* 639
- 18.13 *Ascomycota* 640
- 18.14 *Basidiomycota* 641

IV • **Archaeplastida** 642

- 18.15 *Red Algae* 642
- 18.16 *Green Algae* 643

UNIT 5 Microbial Ecology and Environmental Microbiology

19

Taking the Measure of Microbial Systems 648

MICROBIOLOGYNOW Touring Microbial Biogeography Using Combinatorial Imaging 648

I • **Culture-Dependent Analyses of Microbial Communities** 649

- 19.1 *Enrichment Culture Microbiology* 649

II • **Firmicutes, Tenericutes, and Actinobacteria** 567

- 16.6 *Firmicutes: Lactobacillales* 567
- 16.7 *Firmicutes: Nonsporulating Bacillales and Clostridiales* 569
- 16.8 *Firmicutes: Sporulating Bacillales and Clostridiales* 570
- 16.9 *Tenericutes: The Mycoplasmas* 571
- 16.10 *Actinobacteria: Coryneform and Propionic Acid Bacteria* 572
- 16.11 *Actinobacteria: Mycobacterium* 574
- 16.12 *Filamentous Actinobacteria: Streptomyces and Relatives* 575

III • **Bacteroidetes** 578

- 16.13 *Bacteroidales* 578
- 16.14 *Cytophagales, Flavobacteriales, and Sphingobacteriales* 579

IV • **Chlamydiae, Planctomycetes, and Verrucomicrobia** 580

- 16.15 *Chlamydiae* 580
- 16.16 *Planctomycetes* 582
- 16.17 *Verrucomicrobia* 583

V • **Hyperthermophilic Bacteria** 584

- 16.18 *Thermotogae and Thermodesulfobacteria* 584
- 16.19 *Aquificae* 585

VI • **Other Bacteria** 586

- 16.20 *Deinococcus–Thermus* 586
- 16.21 *Acidobacteria and Nitrospirae* 587
- 16.22 *Other Notable Phyla of Bacteria* 588

17 Diversity of Archaea 592

MICROBIOLOGYNOW Methanogens and Global Climate Change 592

I • **Euryarchaeota** 594

- 17.1 *Extremely Halophilic Archaea* 594
- 17.2 *Methanogenic Archaea* 597
- 17.3 *Thermoplasmatales* 601
- 17.4 *Thermococcales and Archaeoglobales* 602

II • **Thaumarchaeota and Cryptic Archaeal Phyla** 603

- 17.5 *Thaumarchaeota and Nitrification in Archaea* 604
- 17.6 *Nanoarchaeota and the “Hospitable Fireball”* 605
- 17.7 *Korarchaeota, the “Secret Filament”* 606
- 17.8 *Other Cryptic Archaeal Phyla* 607

III • **Crenarchaeota** 608

- 17.9 *Habitats and Energy Metabolism of Crenarchaeota* 608
- 17.10 *Crenarchaeota from Terrestrial Volcanic Habitats* 610
- 17.11 *Crenarchaeota from Submarine Volcanic Habitats* 612

IV • **Evolution and Life at High Temperature** 614

- 17.12 *An Upper Temperature Limit for Microbial Life* 614
- 17.13 *Molecular Adaptations to Life at High Temperature* 616
- 17.14 *Hyperthermophilic Archaea, H₂, and Microbial Evolution* 617

18 Diversity of Microbial Eukarya 621

MICROBIOLOGYNOW Coccolithophores, Engineers of Global Climate 621

I • **Organelles and Phylogeny of Microbial Eukarya** 622

- 18.1 *Endosymbioses and the Eukaryotic Cell* 622
- 18.2 *Phylogenetic Lineages of Eukarya* 624

II • **Protists** 625

- 18.3 *Excavates* 625
- 18.4 *Alveolata* 627
- 18.5 *Stramenopiles* 629
- 18.6 *Rhizaria* 631
- 18.7 *Haptophytes* 632
- 18.8 *Amoebozoa* 633

III • **Fungi** 635

- 18.9 *Fungal Physiology, Structure, and Symbioses* 635
- 18.10 *Fungal Reproduction and Phylogeny* 637
- 18.11 *Microsporidia and Chytridiomycota* 638
- 18.12 *Mucoromycota and Glomeromycota* 639
- 18.13 *Ascomycota* 640
- 18.14 *Basidiomycota* 641

IV • **Archaeplastida** 642

- 18.15 *Red Algae* 642
- 18.16 *Green Algae* 643

UNIT 5 Microbial Ecology and Environmental Microbiology

19 Taking the Measure of Microbial Systems 648

MICROBIOLOGYNOW Touring Microbial Biogeography Using Combinatorial Imaging 648

I • **Culture-Dependent Analyses of Microbial Communities** 649

- 19.1 *Enrichment Culture Microbiology* 649

- 19.2 Classical Procedures for Isolating Microbes 653
- 19.3 Selective Single-Cell Isolation: Laser Tweezers, Flow Cytometry, Microfluidics, and High-Throughput Methods 654

II • Culture-Independent Microscopic Analyses of Microbial Communities 656

- 19.4 General Staining Methods 656
- 19.5 Microscopic Specificity: Fluorescence In Situ Hybridization (FISH) 658

III • Culture-Independent Molecular Analyses of Microbial Communities 661

- 19.6 PCR Methods of Microbial Community Analysis 662
- 19.7 Microarrays for Analysis of Microbial Phylogenetic and Functional Diversity 666
- 19.8 Environmental Multi-omics: Integration of Genomics, Transcriptomics, Proteomics, and Metabolomics 667

IV • Measuring Microbial Activities in Nature 673

- 19.9 Chemical Assays, Radioisotopic Methods, Microsensors, and Nanosensors 674
- 19.10 Stable Isotopes and Stable Isotope Probing 677
- 19.11 Linking Functions to Specific Organisms 679
- 19.12 Linking Genes and Cellular Properties to Individual Cells 682

20 Microbial Ecosystems 687

MICROBIOLOGYNOW Living on Fumes 687

I • Microbial Ecology 688

- 20.1 General Ecological Concepts 688
- 20.2 Ecosystem Service: Biogeochemistry and Nutrient Cycles 689

II • The Microbial Environment 690

- 20.3 Environments and Microenvironments 690
- 20.4 Surfaces and Biofilms 692
- 20.5 Microbial Mats 695

III • Terrestrial Environments 697

- 20.6 Soils: General Properties 697
- 20.7 Prokaryotic Diversity in Soils 700
- 20.8 The Terrestrial Subsurface 702

IV • Aquatic Environments 705

- 20.9 Freshwaters 705
- 20.10 Oxygen Relationships in the Marine Environment 707
- 20.11 Major Marine Phototrophs 710
- 20.12 Pelagic *Bacteria* and *Archaea* 713
- 20.13 Pelagic Marine Viruses 716

- 20.14 The Deep Sea 718
- 20.15 Deep-Sea Sediments 721
- 20.16 Hydrothermal Vents 723

21 Nutrient Cycles 729

MICROBIOLOGYNOW An Uncertain Future for Coral Reef Ecosystems 729

I • Carbon, Nitrogen, and Sulfur Cycles 730

- 21.1 The Carbon Cycle 730
- 21.2 Syntrophy and Methanogenesis 733
- 21.3 The Nitrogen Cycle 735
- 21.4 The Sulfur Cycle 737

II • Other Nutrient Cycles 738

- 21.5 The Iron and Manganese Cycles: Reductive Activities 738
- 21.6 The Iron and Manganese Cycles: Oxidative Activities 742
- 21.7 The Phosphorus, Calcium, and Silicon Cycles 744

III • Humans and Nutrient Cycling 746

- 21.8 Mercury Transformations 747
- 21.9 Human Impacts on the Carbon and Nitrogen Cycles 749

Explore the Microbial World Solving the Marine Methane Paradox 746

22 Microbiology of the Built Environment 754

MICROBIOLOGYNOW Sending Microbes to Clean Up after Polluters 754

I • Mineral Recovery and Acid Mine Drainage 755

- 22.1 Mining with Microorganisms 755
- 22.2 Acid Mine Drainage 757

II • Bioremediation 758

- 22.3 Bioremediation of Uranium-Contaminated Environments 758
- 22.4 Bioremediation of Organic Pollutants: Hydrocarbons 759
- 22.5 Bioremediation and Microbial Degradation of Major Chemical Pollutants: Chlorinated Organics and Plastics 760

III • Wastewater and Drinking Water Treatment 763

- 22.6 Primary and Secondary Wastewater Treatment 764
- 22.7 Tertiary Wastewater Treatment: Further Removal of Phosphorus and Nitrogen 766

- 22.8 Sludge Processing and Contaminants of Emerging Concern 768
- 22.9 Drinking Water Purification and Stabilization 771
- 22.10 Water Distribution Systems 772

IV • Indoor Microbiology and Microbially Influenced Corrosion 773

- 22.11 The Microbiology of Homes and Public Spaces 773
- 22.12 Microbially Influenced Corrosion of Metals 775
- 22.13 Biodeterioration of Stone and Concrete 776

23

Microbial Symbioses with Microbes, Plants, and Animals 780

MICROBIOLOGYNOW Coral Fluorescence Provides the Guiding Light for Their Symbiotic Algae 780

I • Symbioses Between Microorganisms 781

- 23.1 Lichens 781
- 23.2 "*Chlorochromatium aggregatum*" 782
- 23.3 Methanotrophic Consortia: Direct Interspecies Electron Transfer 784

II • Plants as Microbial Habitats 785

- 23.4 The Legume–Root Nodule Symbiosis 785
- 23.5 Mycorrhizae 791
- 23.6 *Agrobacterium* and Crown Gall Disease 793

III • Insects as Microbial Habitats 795

- 23.7 Heritable Symbionts of Insects 795
- 23.8 Defensive Symbioses 798
- 23.9 Termites 799

IV • Other Invertebrates as Microbial Habitats 801

- 23.10 Bioluminescent Symbionts and the Squid Symbiosis 801
- 23.11 Marine Invertebrates at Hydrothermal Vents and Cold Seeps 805
- 23.12 Entomopathogenic Nematodes 806
- 23.13 Reef-Building Corals 807

V • Mammalian Gut Systems as Microbial Habitats 810

- 23.14 Alternative Mammalian Gut Systems 810
- 23.15 The Rumen and Rumen Activities 812
- 23.16 Rumen Microbes and Their Dynamic Relationships 813

Explore the Microbial World

Combating Mosquito-Borne Viral Diseases with an Insect Symbiont 797

UNIT 6 Microbe–Human Interactions and the Immune System

24

Microbial Symbioses with Humans 819

MICROBIOLOGYNOW One of the Most Abundant Viruses on Earth Discovered First in the Human Viral Microbiome 819

I • Structure and Function of the Healthy Adult Gastrointestinal and Oral Microbiomes 820

- 24.1 Overview of the Human Microbiome 820
- 24.2 Gastrointestinal Microbiota 821
- 24.3 Oral Cavity and Airways 827

II • Urogenital Tract and Skin Microbiomes and the Human Viral Microbiome 830

- 24.4 Urogenital Tracts and Their Microbes 830
- 24.5 The Skin and Its Microbes 831
- 24.6 The Human Virome 833

III • From Birth to Death: Development of the Human Microbiome 836

- 24.7 Human Study Groups and Animal Models 836
- 24.8 Colonization, Succession, and Stability of the Gut Microbiota 837

IV • Disorders Attributed to the Human Microbiome 839

- 24.9 Syndromes Linked to the Gut Microbiota 840
- 24.10 Syndromes Linked to the Oral, Skin, and Vaginal Microbiota 843

V • Modulation of the Human Microbiome 845

- 24.11 Antibiotics and the Human Microbiome 845
- 24.12 Probiotics, Prebiotics, and Synbiotics 846

Explore the Microbial World

The Gut–Brain Axis 826

25

Microbial Infection and Pathogenesis 850

MICROBIOLOGYNOW Killing Pathogens on Contact 850

I • Human–Pathogen Interactions 851

- 25.1 Microbial Adherence 851
- 25.2 Colonization and Invasion 853

- 25.3 Pathogenicity, Virulence, and Virulence Attenuation 855
- 25.4 Genetics of Virulence and the Compromised Host 856
- II • Enzymes and Toxins of Pathogenesis 858**
- 25.5 Enzymes as Virulence Factors 858
- 25.6 AB-Type Exotoxins 860
- 25.7 Cytolytic and Superantigen Exotoxins 863
- 25.8 Endotoxins 864

26

Innate Immunity: Broadly Specific Host Defenses 868

MICROBIOLOGYNOW Periodontal Disease and Alzheimer's: Evidence for Causation? 868

- I • Fundamentals of Host Defense 869**
- 26.1 Basic Properties of the Immune System 869
- 26.2 Barriers to Pathogen Invasion 870
- II • Cells and Organs of the Immune System 872**
- 26.3 The Blood and Lymphatic Systems 872
- 26.4 Leukocyte Production and Diversity 874
- III • Phagocyte Response Mechanisms 876**
- 26.5 Pathogen Challenge and Phagocyte Recruitment 876
- 26.6 Pathogen Recognition and Phagocyte Signal Transduction 877
- 26.7 Phagocytosis and Phagocyte Inhibition 880
- IV • Other Innate Host Defenses 882**
- 26.8 Inflammation and Fever 882
- 26.9 The Complement System 884
- 26.10 Innate Defenses Against Viruses 887

Explore the Microbial World

Pattern Recognition Receptors of Hydrothermal Vent Tube Worms Facilitate Endosymbiosis 879

27

Adaptive Immunity: Highly Specific Host Defenses 892

MICROBIOLOGYNOW Controlling HIV through "Public" T Cell Receptors on CD4 T Cells 892

- I • Principles of Adaptive Immunity 893**
- 27.1 Specificity, Memory, Selection Processes, and Tolerance 893
- 27.2 Immunogens and Classes of Immunity 896

II • Antibodies 898

- 27.3 Antibody Production and Structural Diversity 898
- 27.4 Antigen Binding and the Genetics of Antibody Diversity 902

III • The Major Histocompatibility Complex (MHC) 905

- 27.5 MHC Proteins and Their Functions 905
- 27.6 MHC Polymorphism, Polygeny, and Peptide Binding 907

IV • T Cells and Their Receptors 909

- 27.7 T Cell Receptors: Proteins, Genes, and Diversity 910
- 27.8 T Cell Subsets and Their Functions 913

28

Immune Disorders and Antimicrobial Therapy 919

MICROBIOLOGYNOW Preventing Autoimmunity with . . . Parasitic Worms? 919

I • Disorders and Deficiencies of the Immune System 920

- 28.1 Allergy, Hypersensitivity, and Autoimmunity 920
- 28.2 Superantigens and Immunodeficiency 923

II • Vaccines and Immunotherapy 925

- 28.3 Vaccination Against Infectious Diseases 925
- 28.4 Immunotherapy 928

III • Drug Treatments for Infectious Diseases 930

- 28.5 Antibacterial Drugs 930
- 28.6 Antimicrobial Drugs That Target Nonbacterial Pathogens 936
- 28.7 Antimicrobial Drug Resistance and New Treatment Strategies 938

UNIT 7 Infectious Diseases

29

Diagnosing Infectious Diseases 943

MICROBIOLOGYNOW Shedding New Light on Diagnosing Tuberculosis 943

I • Microbiology and the Healthcare Environment 944

- 29.1 The Clinical Microbiology Laboratory 944
- 29.2 Healthcare-Associated Infections 945

II • Isolating and Characterizing Infectious Microorganisms 946

- 29.3 Workflow in the Clinical Laboratory 946
- 29.4 Choosing the Right Treatment 952

III • Immunological and Molecular Tools for Disease Diagnosis 954

- 29.5 Immunoassays and Disease 954
- 29.6 Precipitation, Agglutination, and Immunofluorescence 956
- 29.7 Enzyme Immunoassays, Rapid Tests, and Immunoblots 958
- 29.8 Nucleic Acid–Based Clinical Assays 961

Explore the Microbial World

MRSA—A Formidable Clinical Challenge 948

30 Epidemiology and Public Health 965

MICROBIOLOGYNOW A New Urgent Threat Is Emerging in Public Health Microbiology 965

I • Principles of Epidemiology 966

- 30.1 The Language of Epidemiology 966
- 30.2 The Host Community 968
- 30.3 Infectious Disease Transmission and Reservoirs 969
- 30.4 Characteristics of Disease Epidemics 971

II • Public and Global Health 973

- 30.5 Public Health and Infectious Disease 973
- 30.6 Global Health Comparisons 975

III • Emerging Infectious Diseases, Pandemics, and Other Threats 976

- 30.7 Emerging and Reemerging Infectious Diseases 976
- 30.8 Examples of Pandemics: HIV/AIDS, Cholera, and Influenza 979
- 30.9 Public Health Threats from Microbial Weapons 981

31 Person-to-Person Bacterial and Viral Diseases 986

MICROBIOLOGYNOW Reversing Antibiotic Resistance in a Recalcitrant Pathogen 986

I • Airborne Bacterial Diseases 987

- 31.1 Airborne Pathogens 987
- 31.2 Streptococcal Syndromes 988
- 31.3 Diphtheria and Pertussis 991
- 31.4 Tuberculosis and Leprosy 992
- 31.5 Meningitis and Meningococemia 994

II • Airborne Viral Diseases 995

- 31.6 MMR and Varicella-Zoster Infections 995
- 31.7 The Common Cold 997
- 31.8 Influenza 998

III • Direct-Contact Bacterial and Viral Diseases 1000

- 31.9 *Staphylococcus aureus* Infections 1001
- 31.10 *Helicobacter pylori* and Gastric Diseases 1002
- 31.11 Hepatitis 1003
- 31.12 Ebola: A Deadly Threat 1005

IV • Sexually Transmitted Infections 1006

- 31.13 Gonorrhea, Syphilis, and Chlamydia 1007
- 31.14 Herpes Simplex Viruses (HSV) and Human Papillomavirus (HPV) 1011
- 31.15 Human Immunodeficiency Virus (HIV) and AIDS 1012

32 Vectorborne and Soilborne Bacterial and Viral Diseases 1019

MICROBIOLOGYNOW The Historical Emergence of an Ancient and Deadly Pathogen 1019

I • Animal-Transmitted Viral Diseases 1020

- 32.1 Rabies Virus and Rabies 1020
- 32.2 Hantavirus and Hantavirus Syndromes 1022

II • Arthropod-Transmitted Bacterial and Viral Diseases 1023

- 32.3 Rickettsial Diseases 1023
- 32.4 Lyme Disease and *Borrelia* 1025
- 32.5 Yellow Fever, Dengue Fever, Chikungunya, and Zika 1027
- 32.6 West Nile Fever 1029
- 32.7 Plague 1030

III • Soilborne Bacterial Diseases 1032

- 32.8 Anthrax 1032
- 32.9 Tetanus and Gas Gangrene 1033

33 Waterborne and Foodborne Bacterial and Viral Diseases 1037

MICROBIOLOGYNOW Reverse Zoonosis in the Southern Ocean 1037

I • Water as a Disease Vehicle 1038

- 33.1 Agents and Sources of Waterborne Diseases 1038
- 33.2 Public Health and Water Quality 1039

- II • Waterborne Diseases** 1040
 - 33.3 *Vibrio cholerae* and Cholera 1040
 - 33.4 Legionellosis 1042
 - 33.5 Typhoid Fever and Norovirus Illness 1043
- III • Food as a Disease Vehicle** 1044
 - 33.6 Food Spoilage and Food Preservation 1044
 - 33.7 Foodborne Diseases and Food Epidemiology 1046
- IV • Food Poisoning** 1048
 - 33.8 Staphylococcal Food Poisoning 1048
 - 33.9 Clostridial Food Poisoning 1049
- V • Food Infection** 1050
 - 33.10 Salmonellosis 1050
 - 33.11 Pathogenic *Escherichia coli* 1051
 - 33.12 *Campylobacter* 1052
 - 33.13 Listeriosis 1053
 - 33.14 Other Foodborne Infectious Diseases 1054

- II • Visceral Parasitic Infections** 1064
 - 34.3 Amoebae and Ciliates: *Entamoeba*, *Naegleria*, and *Balantidium* 1064
 - 34.4 Other Visceral Parasites: *Giardia*, *Trichomonas*, *Cryptosporidium*, *Toxoplasma*, and *Cyclospora* 1065

- III • Blood and Tissue Parasitic Infections** 1067
 - 34.5 *Plasmodium* and Malaria 1067
 - 34.6 Leishmaniasis, Trypanosomiasis, and Chagas Disease 1069
 - 34.7 Parasitic Helminths: Schistosomiasis and Filariases 1070

Photo Credits 1075

Glossary Terms 1079

Index 1083

34

Eukaryotic Pathogens: Fungi, Protozoa, and Helminths 1059

MICROBIOLOGY NOW A Silver Bullet to Kill Brain-Eating Amoebae? 1059

- I • Fungal Infections** 1060
 - 34.1 Pathogenic Fungi and Classes of Infection 1060
 - 34.2 Fungal Diseases: Mycoses 1062

Cell structure and function: Chapter 1, 2, 5, 8, 11, 18
 Microbial systems: Chapter 1, 2, 5, 8, 11, 18
 Impact of microorganisms: Chapter 1, 2, 5, 8, 11, 18
 Microorganisms are ubiquitous and live in diverse and dynamic ecosystems.
 Many bacteria in nature live in highly organized communities.
 Microorganisms and their environmental interactions with and modify each other.
 Microorganisms, including viruses, can interact with both human and nonhuman hosts in beneficial, neutral, or detrimental ways.
 Microorganisms are abundant in natural and artificial environments.
 Microorganisms are essential for life as we know it and the processes that support life (e.g., biogeochemical cycles and plant and/or animal microbiota) to sustain a habitable planet.
 Microorganisms provide essential models that give us fundamental knowledge about the processes that sustain life and their products.
 Human activities and diseases microorganisms and their products.
 Because the diversity of microbial life is largely unknown, its effects and potential benefits have not been fully explored.
Listeria is a pathogenic bacterium that causes severe foodborne illness.

Source: Kortbe, M., et al. 2017. *Listeria monocytogenes* within the epithelial cells. *PLoS Pathog.* 13:e1006734.