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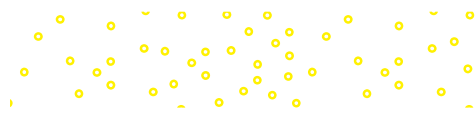
Integrated Principles of **ZOOLOGY**

Nineteenth Edition

A photograph of four vibrant parrots, likely Sun Conures, perched on a thick, textured tree branch. The parrots have bright yellow bodies with orange-red heads and chests. They are looking in various directions, with one looking directly at the camera. The background is a soft-focus green, suggesting a natural habitat.

Cleveland P. Hickman, Jr.
Susan L. Keen
David J. Eisenhour
Allan Larson
Helen I'Anson

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INTEGRATED PRINCIPLES OF

ZOOLOGY

NINETEENTH EDITION

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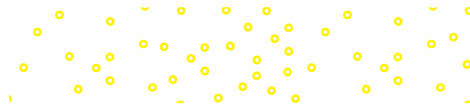
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INTEGRATED PRINCIPLES OF ZOOLOGY

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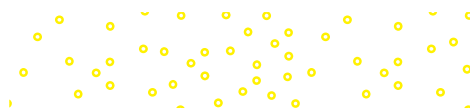
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About the Authors ix
Preface x

PART ONE

Introduction to Living Animals

- 1 Life: Biological Principles and the Science of Zoology 1
- 2 The Origin and Chemistry of Life 20
- 3 Cells as Units of Life 36
- 4 Cellular Metabolism 57

PART TWO

Continuity and Evolution of Animal Life

- 5 Genetics: A Review 73
- 6 Organic Evolution 103
- 7 The Reproductive Process 137
- 8 Principles of Development 158

PART THREE

Diversity of Animal Life

- 9 Architectural Pattern of an Animal 187
- 10 Taxonomy and Phylogeny of Animals 201
- 11 Unicellular Eukaryotes 220
- 12 Sponges and Placozoans 253
- 13 Cnidarians and Ctenophores 268
- 14 Xenacoelomorpha, Platyhelminthes, Gastrotricha, Gnathifera, and Mesozoa 298
- 15 Polyzoa and Trochozoa 329
- 16 Molluscs 342
- 17 Annelids 373
- 18 Smaller Ecdysozoans 395
- 19 Trilobites, Chelicerates, and Myriapods 413

- 20 Crustaceans 432
- 21 Hexapods 454
- 22 Echinoderms and Hemichordates 484
- 23 Chordates 509
- 24 Fishes 527
- 25 Early Tetrapods and Modern Amphibians 555
- 26 Amniote Origins and Nonavian Reptiles 574
- 27 Birds 596
- 28 Mammals 623

PART FOUR

Activity of Life

- 29 Support, Protection, and Movement 652
- 30 Homeostasis: Osmotic Regulation, Excretion, and Temperature Regulation 673
- 31 Homeostasis: Internal Fluids and Respiration 693
- 32 Digestion and Nutrition 715
- 33 Nervous Coordination: Nervous System and Sense Organs 733
- 34 Chemical Coordination: Endocrine System 759
- 35 Immunity 777
- 36 Animal Behavior 792

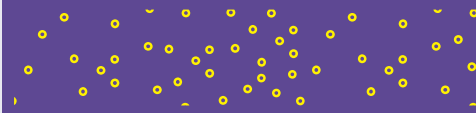
PART FIVE

Animals and Their Environments

- 37 Animal Distributions 811
- 38 Animal Ecology 831

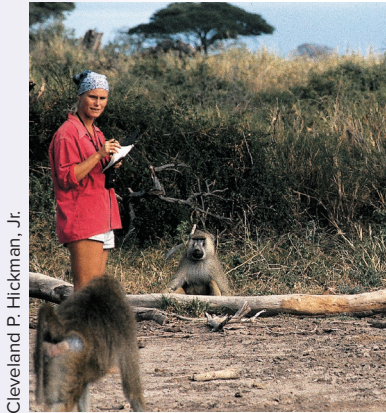
Appendix A: Cladogram of All Animal Phyla A-1
Appendix B: Timeline of Major Biological Events B-1
Glossary G-1
Index I-1

TABLE OF CONTENTS



About the Authors ix
Preface x

PART ONE



Cleveland P. Hickman, Jr.

Introduction to Living Animals

CHAPTER 1

Life: Biological Principles and the Science of Zoology 1

- 1.1 Fundamental Properties of Life 2
- 1.2 Zoology as a Part of Biology 9
- 1.3 Principles of Science 9
- 1.4 Theories of Evolution and Heredity 13
- Summary 18

CHAPTER 2

The Origin and Chemistry of Life 20

- 2.1 Water and Life 21
- 2.2 Macromolecules 23
- 2.3 Chemical Evolution 26
- 2.4 Origin of Living Systems 29
- 2.5 Precambrian Life 31
- Summary 34

CHAPTER 3

Cells as Units of Life 36

- 3.1 Cell Concept 37
- 3.2 Organization of Cells 39
- 3.3 Membrane Function 46

3.4 Mitosis and Cell Division 51
Summary 54

CHAPTER 4

Cellular Metabolism 57

- 4.1 Energy and the Laws of Thermodynamics 58
- 4.2 The Role of Enzymes 59
- 4.3 Enzyme Regulation 61
- 4.4 Chemical Energy Transfer by Atp 62
- 4.5 Cellular Respiration 63
- 4.6 Metabolism of Lipids 69
- 4.7 Metabolism of Proteins 70
- Summary 71

PART TWO



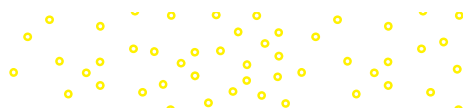
Larry S. Roberts

Continuity and Evolution of Animal Life

CHAPTER 5

Genetics: A Review 73

- 5.1 Mendel's Investigations 74
- 5.2 Chromosomal Basis of Inheritance 74
- 5.3 Mendelian Laws of Inheritance 79
- 5.4 Gene Theory 88
- 5.5 Storage and Transfer of Genetic Information 88
- 5.6 Gene Mutations 98
- 5.7 Molecular Genetics of Cancer 99
- Summary 99



CHAPTER 6**Organic Evolution 103**

-
- 6.1 Origins of Darwinian Evolutionary Theory 104
 - 6.2 Darwinian Evolutionary Theory: the Evidence 107
 - 6.3 Revisions of Darwin's Theory 125
 - 6.4 Microevolution: Genetic Variation and Change Within Species 126
 - 6.5 Macroevolution: Major Evolutionary Events 132
 - Summary* 134

CHAPTER 7**The Reproductive Process 137**

-
- 7.1 Nature of the Reproductive Process 138
 - 7.2 The Origin and Maturation of Germ Cells 142
 - 7.3 Reproductive Patterns 146
 - 7.4 Structure of Reproductive Systems 147
 - 7.5 Endocrine Events that Orchestrate Reproduction 149
 - Summary* 156

CHAPTER 8**Principles of Development 158**

-
- 8.1 Early Concepts: Preformation Versus Epigenesis 159
 - 8.2 Fertilization 160
 - 8.3 Cleavage and Early Development 163
 - 8.4 An Overview of Development Following Cleavage 165
 - 8.5 Mechanisms of Development 168
 - 8.6 Gene Expression During Development 170
 - 8.7 Developmental Patterns in Animals 173
 - 8.8 Evolutionary Developmental Biology 178
 - 8.9 Vertebrate Development 178
 - 8.10 Development of Systems and Organs 181
 - Summary* 185

PART THREE

Larry S. Roberts

Diversity of Animal Life**CHAPTER 9****Architectural Pattern of an Animal 187**

-
- 9.1 Hierarchical Organization of Animal Complexity 188
 - 9.2 Animal Body Plans 189
 - 9.3 Components of Animal Bodies 193
 - 9.4 Complexity and Body Size 198
 - Summary* 199

CHAPTER 10**Taxonomy and Phylogeny of Animals 201**

-
- 10.1 Linnaeus and Taxonomy 202
 - 10.2 Species 204
 - 10.3 Taxonomic Characters and Phylogenetic Reconstruction 209
 - 10.4 Theories of Taxonomy 211
 - 10.5 Major Subdivisions of the Animal Kingdom 218
 - Summary* 218

CHAPTER 11**Unicellular Eukaryotes 220**

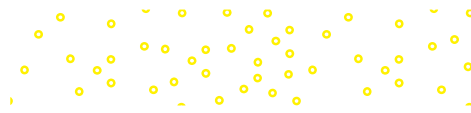
-
- 11.1 Naming and Identifying Unicellular Eukaryotic Taxa 221
 - 11.2 Form and Function 223
 - 11.3 Nutrition and Digestion 230
 - 11.4 Excretion and Osmoregulation 232
 - 11.5 Reproduction and Life Cycles 232
 - 11.6 Major Unicellular Eukaryotic Taxa 233
 - 11.7 Phylogeny and Adaptive Diversification 248
 - Summary* 250

CHAPTER 12**Sponges and Placozoans 253**

-
- 12.1 Origin of Animals 254
 - 12.2 Phylum Porifera: Sponges 254
 - 12.3 Form and Function in Sponges 257
 - 12.4 Survey of Sponges 261
 - 12.5 Phylum Placozoa 265
 - Summary* 266

CHAPTER 13**Cnidarians and Ctenophores 268**

-
- 13.1 Phylum Cnidaria 269
 - 13.2 Form and Function 270
 - 13.3 Survey of Cnidarians 274
 - 13.4 Phylum Ctenophora 291
 - 13.5 Phylogeny and Adaptive Diversification 294
 - Summary* 296



CHAPTER 14

Xenacoelomorpha, Platyhelminthes, Gastrotricha, Gnathifera, and Mesozoa 298

- 14.1 Phylum Xenacoelomorpha 299
- 14.2 Clades Within Protostomia 301
- 14.3 Phylum Platyhelminthes 301
- 14.4 Phylum Gastrotricha 317
- 14.5 Clade Gnathifera 318
- 14.6 Phylum Gnathostomulida 318
- 14.7 Phylum Chaetognatha 319
- 14.8 Phylum Micrognathozoa 320
- 14.9 Phylum Rotifera 320
- 14.10 Phylum Acanthocephala 323
- 14.11 Phylum Mesozoa 324
- 14.12 Phylogeny 326
- Summary* 326

CHAPTER 15

Polyzoa and Trochozoa 329

- 15.1 Clade Polyzoa 331
- 15.2 Phylum Cycliophora 331
- 15.3 Phylum Entoprocta 331
- 15.4 Phylum Ectoprocta (Bryozoa) 332
- 15.5 Clade Trochozoa 335
- 15.6 Clade Brachiozoa 335
- 15.7 Phylum Brachiopoda 335
- 15.8 Phylum Phoronida 336
- 15.9 Phylum Nemertea (Rhynchocoela) 337
- 15.10 Phylogeny 339
- Summary* 340

CHAPTER 16

Molluscs 342

- 16.1 Molluscs 343
- 16.2 Form and Function 345
- 16.3 Classes of Molluscs 348
- 16.4 Phylogeny and Adaptive Diversification 368
- Summary* 371

CHAPTER 17

Annelids 373

- 17.1 Phylum Annelida, Including Pogonophorans (Siboglinids), Sipunculans, and Echiurans 375
- 17.2 Errantia 378
- 17.3 Sedentaria 380
- 17.4 Clade Clitellata 385
- 17.5 Evolutionary Significance of a Coelom and Metamerism 392
- 17.6 Phylogeny and Adaptive Diversification 392
- Summary* 393

CHAPTER 18

Smaller Ecdysozoans 395

- 18.1 Phylum Nematoda: Roundworms 396
- 18.2 Phylum Nematomorpha 404
- 18.3 Phylum Loricifera 405
- 18.4 Phylum Kinorhyncha 405
- 18.5 Phylum Priapulida 406
- 18.6 Clade Panarthropoda 407
- 18.7 Phylum Onychophora 407
- 18.8 Phylum Tardigrada 408
- 18.9 Phylogeny and Adaptive Diversification 410
- Summary* 411

CHAPTER 19

Trilobites, Chelicerates, and Myriapods 413

- 19.1 Phylum Arthropoda 414
- 19.2 Subphylum Trilobita 417
- 19.3 Subphylum Chelicerata 418
- 19.4 Subphylum Myriapoda 426
- 19.5 Phylogeny and Adaptive Diversification 429
- Summary* 430

CHAPTER 20

Crustaceans 432

- 20.1 Subphylum Crustacea 434
- 20.2 A Brief Survey of Crustaceans 442
- 20.3 Phylogeny and Adaptive Diversification 450
- Summary* 452

CHAPTER 21

Hexapods 454

- 21.1 Classes Entognatha and Insecta 455
- 21.2 External Form and Function 455
- 21.3 Internal Form and Function 461
- 21.4 Metamorphosis and Growth 468
- 21.5 Behavior and Defense 470
- 21.6 Insects and Human Welfare 474
- 21.7 Phylogeny and Adaptive Diversification 480
- Summary* 481

CHAPTER 22

Echinoderms and Hemichordates 484

- 22.1 Clade Ambulacraria 485
- 22.2 Phylum Echinodermata 486
- 22.3 Phylogeny and Adaptive Diversification of Echinoderms 501
- 22.4 Phylum Hemichordata 503
- 22.5 Phylogeny and Adaptive Diversification of Hemichordates 506
- Summary* 507



CHAPTER 23**Chordates 509**

-
- 23.1 Ancestry and Evolution of the Chordates 510
 - 23.2 Five Chordate Characteristics 513
 - 23.3 Subphylum Tunicata (Urochordata) 515
 - 23.4 Subphylum Cephalochordata 517
 - 23.5 Subphylum Vertebrata 518
 - Summary* 525

CHAPTER 24**Fishes 527**

-
- 24.1 Ancestry and Relationships of Major Groups of Fishes 528
 - 24.2 Cyclostomata: Living Jawless Fishes 528
 - 24.3 Chondrichthyes: Cartilaginous Fishes 534
 - 24.4 Osteichthyes: Bony Fishes and Tetrapods 538
 - 24.5 Structural and Functional Adaptations of Fishes 542
 - Summary* 552

CHAPTER 25**Early Tetrapods and Modern Amphibians 555**

-
- 25.1 Devonian Origin of Tetrapods 556
 - 25.2 Temnospondyls and Modern Amphibians 558
 - 25.3 Caecilians: Order Gymnophiona (Apoda) 560
 - 25.4 Salamanders: Order Urodela (Caudata) 560
 - 25.5 Frogs and Toads: Order Anura (Salientia) 563
 - Summary* 572

CHAPTER 26**Amniote Origins and Nonavian Reptiles 574**

-
- 26.1 Origin and Early Evolution of Amniotes 575
 - 26.2 Changes in Traditional Classification of Reptiles 580
 - 26.3 Characteristics and Natural History of Reptilian Groups 580
 - Summary* 594

CHAPTER 27**Birds 596**

-
- 27.1 Origin And Relationships 597
 - 27.2 Structural and Functional Adaptations for Flight 600
 - 27.3 Flight 608
 - 27.4 Migration and Navigation 611
 - 27.5 Social Behavior and Reproduction 613
 - 27.6 Bird Populations and their Conservation 616
 - Summary* 620

CHAPTER 28**Mammals 623**

-
- 28.1 Origin and Evolution of Mammals 624
 - 28.2 Structural and Functional Adaptations of Mammals 627

- 28.3 Mammals and their Environments 639
- 28.4 Humans and Mammals 641
- 28.5 Human Evolution 642
- Summary* 650

PART FOUR

Eric Soder/Science Source

Activity of Life**CHAPTER 29****Support, Protection, and Movement 652**

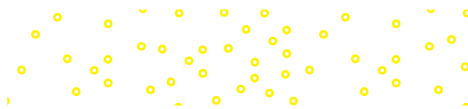
-
- 29.1 Integument 653
 - 29.2 Skeletal Systems 656
 - 29.3 Animal Movement 662
 - Summary* 671

CHAPTER 30**Homeostasis: Osmotic Regulation, Excretion, and Temperature Regulation 673**

-
- 30.1 Water and Osmotic Regulation 674
 - 30.2 Invertebrate Excretory Structures 678
 - 30.3 Vertebrate Kidney 680
 - 30.4 Temperature Regulation 686
 - Summary* 690

CHAPTER 31**Homeostasis: Internal Fluids and Respiration 693**

-
- 31.1 Internal Fluid Environment 694
 - 31.2 Composition of Blood 695
 - 31.3 Circulation 697
 - 31.4 Respiration 705
 - Summary* 713



PART FIVE

CHAPTER 32

Digestion and Nutrition 715

- 32.1 Feeding Mechanisms 716
- 32.2 Digestion 719
- 32.3 Organization and Regional Function of Alimentary Canals 721
- 32.4 Regulation of Food Intake 726
- 32.5 Nutritional Requirements 728
- Summary* 730

CHAPTER 33

Nervous Coordination: Nervous System and Sense Organs 733

- 33.1 Neurons: Functional Units of Nervous Systems 734
- 33.2 Synapses: Junctions Between Nerves 738
- 33.3 Evolution of Nervous Systems 740
- 33.4 Sense Organs 746
- Summary* 757

CHAPTER 34

Chemical Coordination: Endocrine System 759

- 34.1 Mechanisms of Hormone Action 760
- 34.2 Invertebrate Hormones 762
- 34.3 Vertebrate Endocrine Glands and Hormones 764
- Summary* 774

CHAPTER 35

Immunity 777

- 35.1 Susceptibility and Resistance 778
- 35.2 Innate Defense Mechanisms 778
- 35.3 Immunity in Invertebrates 783
- 35.4 Acquired Immune Response in Vertebrates 783
- 35.5 Blood Group Antigens 789
- Summary* 790

CHAPTER 36

Animal Behavior 792

- 36.1 Describing Behavior: Principles of Classical Ethology 794
- 36.2 Control of Behavior 795
- 36.3 Social Behavior 799
- Summary* 808



Animals and Their Environments

CHAPTER 37

Animal Distributions 811

- 37.1 Principles of Historical Biogeography 812
- 37.2 Distribution of Life on Earth 818
- Summary* 829

CHAPTER 38

Animal Ecology 831

- 38.1 The Hierarchy of Ecology 832
- 38.2 Populations 833
- 38.3 Community Ecology 837
- 38.4 Ecosystems 842
- 38.5 Extinction And Biodiversity 845
- Summary* 849

Appendix A: Cladogram of All Animal Phyla A-1
Appendix B: Timeline of Major Biological Events B-1
Glossary G-1
Index I-1



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Dr. Keen has been teaching evolution and animal diversity within the Introductory Biology series for 29 years. She enjoys all facets of the teaching process, from lectures and discussions to the design of effective laboratory exercises. She attended the National Academies Summer Institute on Undergraduate Education in Biology, and was a National Academies Education Fellow in the Life Sciences for 2005–2006. She is now part of a research collaborative network (VISABLI) examining the role of visualizations in teaching biology.

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Integrated Principles of Zoology continues to be the leading text for the introductory zoology course. With the nineteenth edition, the authors bring a wealth of real experience as they describe the diversity of animal life and the fascinating adaptations that enable animals to inhabit so many ecological niches.

The overall organization of this text has been effective through numerous past editions. Distinctive features, especially the emphasis on principles of evolution and zoological science, are strengthened. To aid student learning, we retain several pedagogical features: opening chapter prologues drawn from the chapter's theme; learning objectives, chapter summaries, and review questions to aid in comprehension and study; concise and visually appealing illustrations; chapter notes and essays that offer interesting sidelights to the narrative; and an extensive glossary providing pronunciations, derivations, and definitions of terms used in the text.

A list of Learning Objectives opens each chapter. These objectives are organized according to the chapter's main sections. Chapter summaries, many of which are expanded in content, are restructured in tabular form to list the main highlights of each section of the chapter. This correspondence between the learning objectives, chapter sections, and summary should help students to organize the main lessons of each chapter. Our extensive cross-referencing of material among the different parts of the book now uses section numbers, with live links available in electronic versions of the text.

Notes and essays separate from the main text are now numbered for reference and organized according to six Key Themes: (1) Adaptation and Physiology, (2) Ecology, (3) Evolution, (4) Genetics and Development, (5) Human Connections, and (6) Science Explained. Adaptation and Physiology connects the proximate and ultimate causes underlying organismal functioning. Ecology addresses the interactions of animal populations with their environments, including factors that influence their geographic distribution and abundance. Evolution highlights common descent of animal species and the historical processes that modify organismal characteristics in natural populations. Genetics and Development covers the mechanisms of heredity and the ways in which an organism uses genetic information to progress from a zygote ultimately to an adult animal. Human Connections highlights ways in which zoological findings influence human welfare, including medical applications and maintaining environmental health, or how human activities have affected animal species. Science Explained covers scientific methodology and the history of scientific discovery.

In addition to these organizational revisions, we have replaced many photographs and diagrams throughout the book to improve accessibility and vibrancy. We have reworded statements that were unnecessarily gender-biased.

We retain from the eighteenth edition updated geological periods on our phylogenetic trees throughout the book; for example, the former Tertiary period is replaced with the Paleogene and Neogene periods.

NEW TO THE NINETEENTH EDITION

We highlight some major revisions in order by the book's five major parts.

Part One, Introduction to Living Animals

Chapter 1 is our major statement of the characteristics and methodology of science, distinguishing features and the hierarchical organization of living systems, evolutionary and genetic theories, and microbiomes. We make small updates and revisions for clarity, particularly in explaining scientific methodology. Chapter 2 has only sporadic revisions, retaining the major pedagogical and factual updates introduced in the eighteenth edition. Chapter 3 retains the main content from the eighteenth edition with numerous small edits to increase precision in describing cellular structure and function. This critical explanation of cell biology prepares students for many subsequent topics and serves as a general reference. Chapter 4, covering cellular metabolism, is largely unchanged from the eighteenth edition.

Part Two, Continuity and Evolution of Animal Life

In Chapter 5, multiple independent evolutionary origins of an XY chromosomal sex-determination system are newly explained, including the first discovery of a Y chromosome in beetles by Nettie M. Stevens. Chapter 6 includes multiple small changes in the explanation of speciation. We note a recent challenge to the empirical demonstration of punctuated equilibrium. We add historical background to our criticism of eugenics. We add the Chicxalub Crater to evidence for an asteroid impact at the end of the Cretaceous Period. Chapter 7 contains numerous small updates on the endocrinology of reproduction. Revisions to Chapter 8 strengthen coverage of zygotic cleavage and early embryonic development, and improve connections to evolutionary developmental biology as presented in Chapter 6. Chapter 9 includes many small updates and retains material new to edition 18 on the organizational level of flatworms, the status of the spongocoel as a gut cavity in sponges, junctional complexes found between epithelial cells, and properties of oblique striated muscle.

Part Three, Diversity of Animal Life

In addition to many small changes, Chapter 10 has a new pedagogical boxed essay on how to read a cladogram or phylogenetic tree. We remove former section "Major Divisions of Life" to avoid redundancy with Chapter 11. Chapter 11 on unicellular eukaryotes is

completely revised to improve the description and images of unique cellular features such as the kinetoplast and the glicosome. Chapter 12 on sponges includes new descriptions of two canal systems. Chapter 13 has improved organization through greater subdivision, and a new key theme on jellies in oceanic dead zones. Chapter 14 now includes the phylum Chaetognatha to reflect its new placement within Protostomia. Group Platyzoa is removed. Except for some small edits, Chapter 15 is mostly unchanged from the eighteenth edition. Chapter 16 contains improved illustration of the veliger larva and less discussion of segmentation.

Chapter 17 includes revised text on the evolutionary significance of a coelom and metamerism in annelids. Chapter 18 contains rewritten material on nematode reproductive physiology, nematode infections of cats and dogs, and cryptobiosis in tardigrades. Chapter 19 contains only light revisions. In Chapter 20, we continue to present crustaceans and hexapods as sister taxa; however, we note recent evidence that hexapods are a clade nested within Crustacea, making crustaceans a paraphyletic group requiring taxonomic revision. Chapter 21 on hexapods now includes a discussion on the introduction of *Wolbachia* parasites in mosquitos as a mechanism for controlling the spread of dengue fever. Chapter 22 no longer includes chaetognaths and now includes a discussion of an important new echinoderm fossil and its implications for ancestral echinoderm symmetry.

Chapter 23 features a consolidated section on jaw evolution with new illustration. We replace Urochordata with Tunicata because Tunicata has nomenclatural priority and greater usage. We extensively revise our coverage of ostracoderms, placoderms, and acanthodians, with new illustrations, emphasis on different characters, and updated phylogenetic results. We condense discussion of paedomorphosis in chordate evolution. In Chapter 24, we modify the cladogram and phylogenetic tree to reflect current consensus. The Key Theme on shark fin soup is updated. We clarify differences between fish and reptile scales. A rewritten section on swim bladder/buoyancy clarifies how the swim bladder works.

Chapter 25 includes updated coverage of amphibian taxonomic diversity, revised text on respiration in terrestrial amphibians, and revised coverage of the endocrinology of metamorphic versus perennibranchiate *Ambystoma* salamanders. Chapter 26 has a new figure on heart flow in reptiles (Figure 26.6), and revised coverage of traditional taxonomy, world snakebite statistics, and dinosaur phylogeny and hip structure. We now recognize just one species of tuatara. Chapter 27 includes several small updates/revisions to bird evolution, giant birds, feather development, and skeletal weight, and more substantial revisions to how birds fly, and the contrasting altricial versus precocial life histories. Many illustrations are substantially revised. We adopt here the use of capital bird common names, following International Ornithological Committee Union, and usage of nearly every ornithological journal, although not Wikipedia. This is for specific bird names, but not groups of birds, so **Bald Eagle** but **eagles** for multiple eagle species, **Wood Duck** but **ducks** when used as a group. We have a new key theme on hunting and decline of Eurasian migratory birds, with a migration map of one heavily harvested species. We update the conservation status of the World's Birds with the 2018 report's data. Chapter 28 features a new section on lactation, with a new photo, and a new section on olfaction with new illustrations. Also added is a new Key Theme on olfaction, linked to

a recent Nobel Prize. We present a new Section 28.3 "Mammals and Their Environments." It includes new text on torpor and hibernation, with a new combo photo/art figure, and it incorporates existing text on migration and territories. A section on mammal populations and an associated key theme were deleted to avoid redundancy with Chapter 38.

Part Four, Activity of Life

Numerous small changes in Chapter 29 include revised descriptions of formation and loss of bone, and an update on the incidence of melanoma. Chapter 30 includes new information on thermoregulation in birds and mammals. Chapter 31 includes updates on disorders of the circulatory system and a new CRISPR-based treatment for sickle-cell anemia. Chapter 32 contains updates on the physiology of obesity and its impact on human health, and new information on the gut microbiome. Chapter 33 continues the new information on obesity by discussing how microglial cells are implicated in the associated disease metabolic syndrome. Also updated is the comparison of the nerve net of radiate animals to bilateral animals with unidirectional movement. In Chapter 34, we update medical information on use of steroid hormones by athletes, and incidence of diabetes. Chapter 35 on immunology benefits from new discoveries on SARS-CoV-2 virus (cause of COVID-19) and from continuing treatment of HIV/AIDS. Chapter 36 is mostly unchanged, but we acknowledge progression of the field of psychology to the new discipline "cognitive and behavior neuroscience."

Part Five, Animals and Their Environments

The major changes to Chapter 37 are conceptual improvements in the presentation of historical biogeography. The concept of endemism, introduced in Chapter 10, improves many explanations. We also distinguish more explicitly the concept of range expansion of a species from founding of geographically isolated populations. "Dispersal" often is used uncritically without these distinctions. The effects of global warming on freshwater resources are updated with unprecedented conditions in southern California and Nevada. Chapter 38 presents a new essay on the ongoing extinction crisis and efforts to halt it. Based largely on a 2019 report by the United Nations, this is our boldest commentary to date on the need for conservation. We retain our priority on traditional niche-based explanations of community ecology, but we introduce neutral theory as a contrarian approach. We update our coverage on the human demographic transition in Mexico.

TEACHING AND LEARNING AIDS

To help students in **vocabulary development**, key words are bold-faced and derivations of technical and zoological terms are provided, along with generic names of animals where they first appear in the text. In this way students gradually learn the more common roots that form many technical terms. An extensive **glossary** provides pronunciation, derivation, and definition for many terms, including new ones added to the glossary or existing ones rewritten for this edition.

A distinctive feature of this text is a **prologue** for each chapter that highlights a theme or fact relating to the chapter. Some prologues present biological, particularly evolutionary, principles; those in Part Three on animal diversity illuminate distinguishing characteristics of the group presented in the chapter.

Again, William C. Ober and Claire W. Ober have strengthened the art program for this text with many new full-color paintings that replace older art, or that illustrate new material. Bill's artistic skills, knowledge of biology, and experience gained from an earlier career as a practicing physician have enriched this text through 10 of its editions. Claire practiced pediatric and obstetric nursing before turning to scientific illustration as a full-time career. Texts illustrated by Bill and Claire have received national recognition and won awards from the Association of Medical Illustrators, American Institute of Graphic Arts, Chicago Book Clinic, Printing Industries of America, and Bookbuilders West. They are also recipients of the Art Directors Award.

For the Zoology Lab

Laboratory Studies in Integrated Principles of Zoology by Cleveland Hickman, Jr., Lee B. Kats, Susan Keen, and David J. Eisenhour

Now in its nineteenth edition, this lab manual was written to accompany *Integrated Principles of Zoology*, and can be easily adapted to fit a variety of course plans.

ACKNOWLEDGMENTS

The authors express their appreciation to the editors and support staff at McGraw Hill Higher Education who made this project possible. Special thanks are due to Michelle Vogler, Portfolio Director; Robin Reed, Product Development Manager; Krystal Faust, Product Developer; Kelly Brown, Senior Marketing Manager; Maria McGreal/Melissa Leick, Content Project Managers; Rachael Hillebrand, Assessment Content Project Manager; Laura Fuller, Manufacturing Project Manager; Beth Baugh, Freelance Product Developer; and Naveen Jhaldiyil, MPS Project Manager. We are indebted to them for their talents and dedication.

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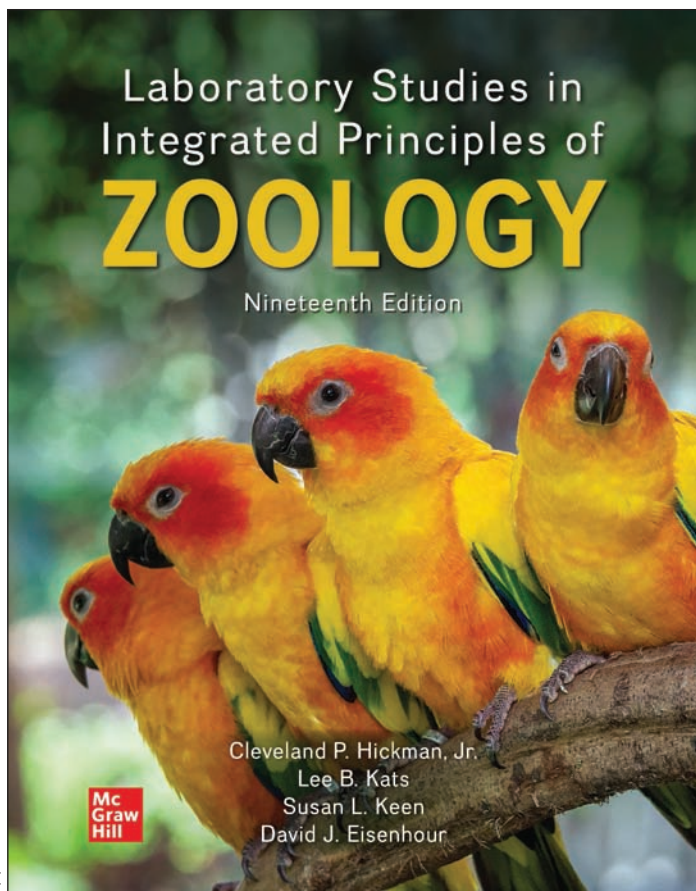
Cleveland P. Hickman, Jr.

Susan Keen

David J. Eisenhour

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Helen I'Anson



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You can rely on the following materials to help you and your students work through the material in the book; all are available in the Instructor Resources under the library tab in Connect (available only to instructors who are logged in to Connect).

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Professional Resources	Links to websites of interest
Chapter References	Listing of Selected References for each chapter
Cladogram	Zoology Wall Chart
Additional Labs	PDFs of Additional Labs that appeared in earlier editions of the lab manual

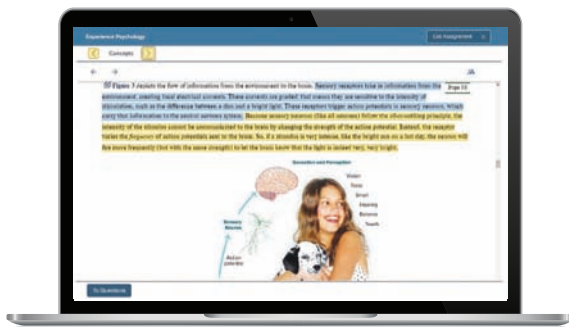
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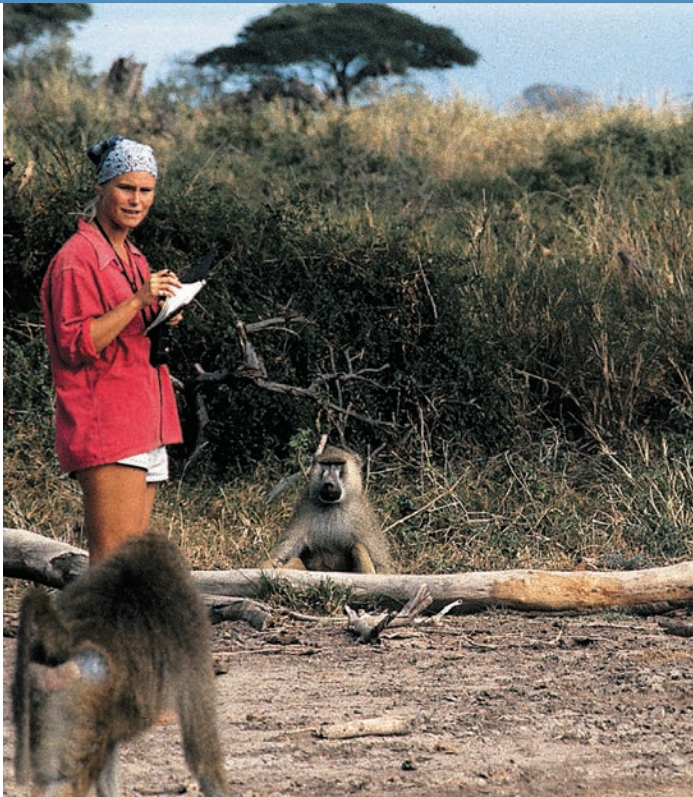
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Life: Biological Principles and the Science of Zoology

LEARNING OBJECTIVES

Readers will be able to:

- 1.1 Explain the unifying properties of living systems as outcomes of life's unique evolutionary history.
- 1.2 Explain the major features that occur uniquely within the animal branch of the evolutionary tree of life.
- 1.3 Explain how science consists in testing, possibly rejecting, and improving our simplest and best explanations using data, not in proving the correctness of a conjecture.
- 1.4 Explain the five major conjectures of Darwin's evolutionary theory—perpetual change, common descent, multiplication of species, gradualism, and natural selection—and the roles of Mendelian genetics and the chromosomal theory of inheritance in animal evolution.



*Zoologist studying the behavior of yellow baboons (*Papio cynocephalus*) in the Amboseli Reserve, Kenya.*

Cleveland P. Hickman, Jr.

The Uses of Principles

We explore the animal world by actively applying important guiding principles to our investigations. Just as the exploration of outer space is both guided and limited by such principles as the theories of gravitation and motion and their associated technologies, exploration of the animal world depends critically on the principles of evolution, genetics, and cellular organization, and the questions and methods derived from them. Zoology makes sense to us only when we understand the principles used to construct this knowledge.

The principles of modern zoology trace their long history to many sources. Some principles come from laws of physics and chemistry, which all living systems obey. Others come from the scientific method, which tells us that our hypothetical explanations of the animal world must guide us to gather data that potentially can refute these explanations. Many important principles come from previous studies of the living world, of which animals are one part.

Principles of heredity, variation, and organic evolution guide the study of life from the simplest unicellular forms to the most complex animals, fungi, and plants. Because life shares a common evolutionary origin, principles learned from the study of one group often provide insights into other groups as well. By tracing the origins of our operating principles, we see that zoologists are not an island unto themselves but part of a larger scientific community.

We begin our study of zoology by searching broadly through the history of science and biology for our most basic principles and their diverse sources. These principles simultaneously guide our studies of animals and integrate those studies into the broader context of human knowledge.

Zoology, the scientific study of animal life, builds on centuries of human observations of the animal world. Mythologies of nearly every human culture reveal early attempts to solve the mysteries of animal life and its origin. Zoologists now confront these same mysteries with the most advanced methods and technologies developed by all branches of science. We document the diversity of animal life and organize it in a systematic way. This complex and exciting process builds on the contributions of thousands of zoologists working in all dimensions of the biosphere (Figure 1.1). We strive to explain how animal diversity originated and how animals perform the basic processes of life that permit them to inhabit diverse environments.

This chapter introduces the fundamental properties of animal life, the methodological principles that govern their study, and two important theories that guide our research: (1) the theory of evolution, which is the central organizing principle of biology, and (2) the chromosomal theory of inheritance, which explains heredity and variation in animals. These theories unify our knowledge of the animal world.

1.1 FUNDAMENTAL PROPERTIES OF LIFE

Historical Continuity of Life

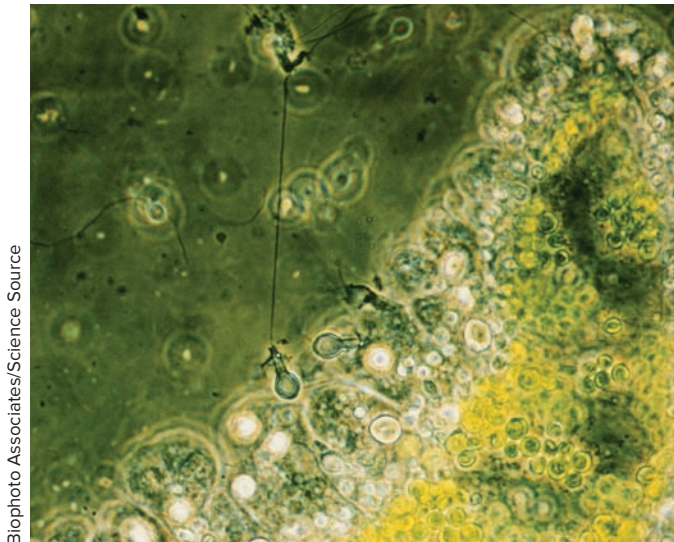
We begin by asking, *What is life?* Our definition lies in the historical continuity of life on earth. Life's history of common descent with modification gives it an identity separate from the nonliving world. We trace this common history backward through time from the diverse forms observed today and in the fossil record to a common ancestor that must have arisen almost 4 billion years ago (see Chapter 2). There are no traces in the fossil record or on earth's surface of what we postulate to have been the incipient stages of life, those that predate cells. Replicating molecular systems, which could not have produced fossils, must have preceded and given rise to cellular life, whose history appears in the fossil record. All descendants of life's common ancestor, past and present, lie within our concept of life.

Life's most fundamental attribute is its reproduction of individuals with heredity and variation. Replication of large molecules that



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A



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C



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B

Figure 1.1 Examples of observation in zoological research. **A**, Observing a coral reef. **B**, Observing nematocyst discharge from cnidarian tentacles, as shown in **C**, (see Section 13.1).

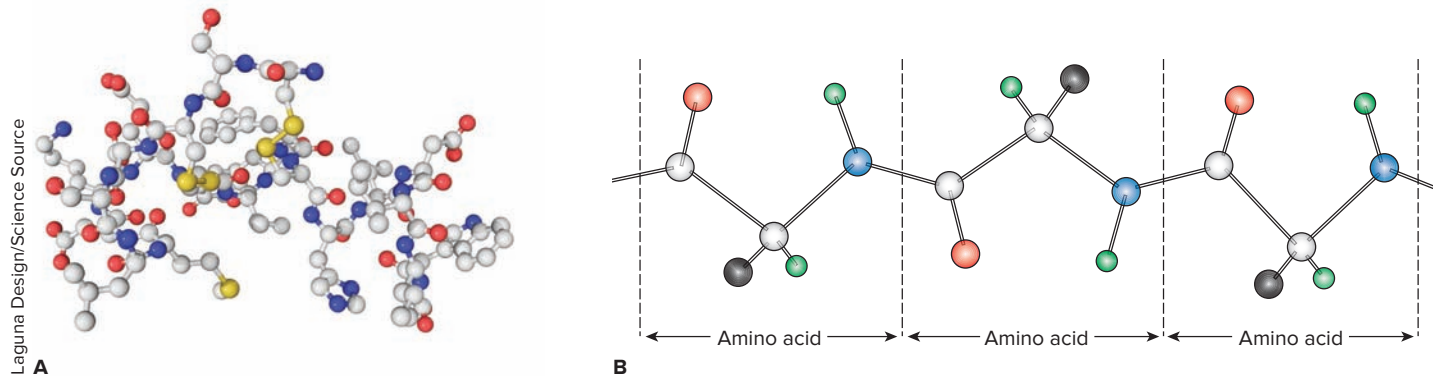


Figure 1.2 A computer simulation of the three-dimensional structure of the human endothelin-1 protein (**A**), which can constrict blood vessels to increase blood pressure. The protein is a linear string of molecular subunits called amino acids, connected as shown in **B**, which fold in a three-dimensional pattern to form the active protein. The white balls correspond to carbon atoms, the red balls to oxygen, the blue balls to nitrogen, the yellow balls to sulfur, the green balls to hydrogen, and the black balls (**B**) to molecular groups formed by various combinations of carbon, oxygen, nitrogen, hydrogen, and sulfur atoms that differ among amino acids. Hydrogen atoms are not shown in **A**.

store information is unique to life and must trace to life's origin. These properties establish a temporal continuity of ancestral and descendant populations showing extensive and ongoing change, which we call **evolution**. Through its evolution, life has generated many spectacular features that have no counterparts in the nonliving world. Novel properties emerge at all levels of life's hierarchical systems, from molecules and cells to organismal form and behavior.

We must resist giving life a definition based in essential characteristics that must occur in all living forms past and present. Such a definition would be particularly difficult for our theories of the origin of life from nonliving matter. Nonetheless, all living cells share metabolic processes and genetic information that reveal unmistakably their hereditary descent from life's common ancestor.

General Properties of Living Systems

Life's most outstanding general features include chemical uniqueness; complexity and hierarchical organization; reproduction (heredity and variation); possession of a genetic program; metabolism; development; environmental interaction; and movement.

1. **Chemical uniqueness.** *Living systems demonstrate a unique and complex molecular organization.* Living systems assemble large molecules, called macromolecules, that greatly exceed in complexity the small molecules of nonliving matter. Macromolecules contain the same kinds of atoms and chemical bonds that occur in nonliving matter and obey all fundamental laws of chemistry; it is only the complex organizational structure of these macromolecules that makes them unique to life. We recognize four major categories of biological macromolecules: nucleic acids, proteins, carbohydrates, and lipids (see Chapter 2). These categories differ in the structures of their component parts, the kinds of chemical bonds that link their subunits together, and their roles in living systems.

The general structures of these macromolecules evolved and stabilized early in the history of life. With some modifications, these same general structures occur in every form of life today. Proteins, for example, are built from 20 specific kinds of amino acid subunits linked together by peptide bonds in a linear

sequence (Figure 1.2). Additional bonds occurring between amino acids that are not adjacent to each other in the protein chain give the protein a complex, three-dimensional structure (see Figures 1.2 and 2.15). A typical protein contains several hundred amino acid subunits. Despite the stability of this basic protein structure, the ordering of the different amino acids in a protein molecule shows enormous variation. This variation underlies much of the diversity that we observe among different kinds of living organisms. The nucleic acids, carbohydrates, and lipids likewise contain characteristic bonds that link variable subunits (see Chapter 2). This organization gives living systems a common biochemical theme with great potential diversity.

2. **Complexity and hierarchical organization.** *Living systems demonstrate a unique and complex hierarchical organization.* Nonliving matter is organized at least into atoms and molecules and often has a higher degree of organization as well. However, atoms and molecules are combined into patterns in the living world that do not exist in nonliving matter. In living systems, we find a hierarchy of levels that includes, in ascending order of complexity, macromolecules, cells, organisms, populations, and species (Figure 1.3). Each level builds on the

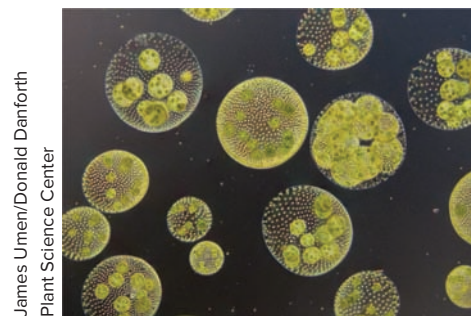
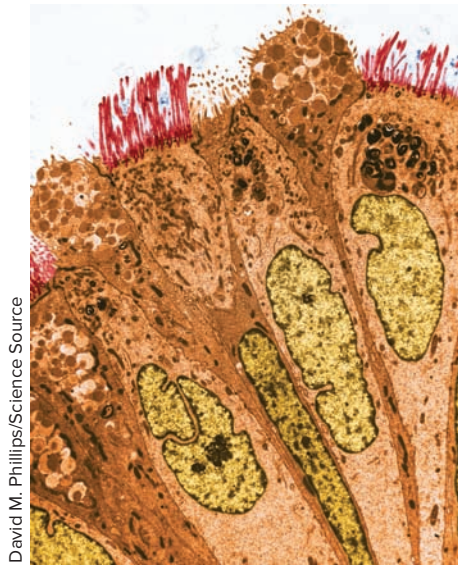


Figure 1.3 *Volvox carteri* (see Section 11.6: Viridiplantae) is a multicellular flagellate that illustrates three different levels of the biological hierarchy: cellular, organismal, and populational. Each individual spheroid (organism) contains cells embedded in a gelatinous matrix. The larger cells function in reproduction, and the smaller ones perform the general metabolic functions of the organism. The individual spheroids together form a population.



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Figure 1.4 Electron micrograph of ciliated epithelial cells and mucus-secreting cells (see Section 9.3) lining the interior of a rat oviduct. Cells are the basic building blocks of living organisms.

level below it and has its own internal structure, which is also often hierarchical. Within a cell, for example, macromolecules are assembled into structures such as ribosomes, chromosomes, and membranes, and these are likewise combined in various ways to form even more complex subcellular structures called organelles, such as mitochondria (see Chapters 3 and 4). The organismal level also has a hierarchical substructure; cells combine to form tissues, which combine to form organs, which likewise combine to form organ systems (see Chapter 9).

Cells (Figure 1.4) are the smallest units of the biological hierarchy that are semiautonomous in their ability to

conduct basic functions, including reproduction. Replication of molecules and subcellular components occurs only within a cellular context, not independently. Cells are therefore considered the basic units of living systems (see Chapter 3). We can isolate cells from an organism and cause them to grow and to multiply under laboratory conditions in the presence of nutrients alone. This semiautonomous replication cannot occur for any individual molecules or subcellular components, which require additional cellular constituents for their reproduction.

Each successively higher level of the biological hierarchy is composed of units of the preceding lower level in the hierarchy. An important consequence of this hierarchy is that we cannot infer the properties at any given level even from the most complete knowledge of the properties of its component parts. A physiological feature, such as blood pressure, is a property of the organismal level; it is impossible to predict someone's blood pressure simply by knowing the physical characteristics of individual cells of the body. Likewise, systems of social interaction, as seen in bees, appear at the populational level; one cannot infer properties of this social system by studying individual bees in isolation.

Appearance of new characteristics at a given level of organization is called **emergence**, and these characteristics are called **emergent properties**. These properties arise from interactions among the component parts of a system. For this reason, we must study all levels directly, each one being the focus of a different subfield of biology (molecular biology; cell biology; organismal anatomy, physiology, and genetics; population biology; see Table 1.1). Emergent properties expressed at a particular level of the biological hierarchy are certainly influenced and restricted by properties of the lower-level components. For example, a population of organisms that lack hearing could not develop a spoken language. Nonetheless, properties of parts of a living system do not rigidly determine properties of the whole. Many different spoken languages have

TABLE 1.1

Different Hierarchical Levels of Biological Complexity That Display Reproduction, Variation, and Heredity

Level	Timescale of Reproduction	Fields of Study	Methods of Study	Some Emergent Properties
Cell	Hours (mammalian cell = ~16 hours)	Cell biology, molecular biology	Microscopy (light, electron), biochemistry	Chromosomal replication (meiosis, mitosis), synthesis of macromolecules (DNA, RNA, proteins, lipids, polysaccharides)
Organism	Hours to days (unicellular); days to years (multicellular)	Organismal anatomy, physiology, genetics	Dissection, genetic crosses, clinical studies, physiological experimentation	Structure, functions and coordination of tissues, organs and organ systems (blood pressure, body temperature, sensory perception, feeding)
Population	Up to thousands of years	Population biology, population genetics, ecology	Statistical analysis of variation, abundance, geographical distribution	Social structures, systems of mating, age distribution of organisms, levels of variation, action of natural selection
Species	Thousands to millions of years	Systematics and evolutionary biology, community ecology	Study of reproductive barriers, phylogeny, paleontology, ecological interactions	Method of reproduction, reproductive barriers

emerged in human culture from the same basic anatomical structures that permit hearing and speech. The freedom of the parts to interact in different ways makes possible a great diversity of potential emergent properties at each level of the biological hierarchy.

Different levels of the biological hierarchy and their particular emergent properties are built by evolution. Before multicellular organisms evolved, there was no distinction between the organismal and cellular levels, and this distinction remains absent from single-celled organisms (see Chapter 11). The diversity of emergent properties that we see at all levels of the biological hierarchy contributes to the difficulty of giving life a simple definition or description.

3. **Reproduction.** *Living systems can reproduce themselves.* Life does not arise spontaneously but comes only from prior life, through reproduction. Although life certainly originated from nonliving matter at least once (see Chapter 2), this origin featured enormously long periods of time and conditions very different from the current biosphere. At each level of the

biological hierarchy, living forms reproduce to generate others like themselves (Figure 1.5). Genes replicate to produce new genes. Cells divide to produce new cells. Organisms reproduce, sexually or asexually, to produce new organisms (see Chapter 7). Populations reproduce themselves through time to form lineages of ancestral-descendant populations. Should a geographic barrier split a population into spatially isolated parts, multiple population lineages can emerge from a common ancestral one. Evolutionary divergence of character among separated population lineages can produce a multiplication of species, in a process called speciation. Reproduction at any hierarchical level usually features an increase in numbers. Individual genes, cells, organisms, populations, or species may fail to reproduce themselves, but reproduction is nonetheless an expected property of these individuals.

Reproduction at each of these levels shows the complementary, and yet apparently contradictory, phenomena of **heredity** and **variation**. Heredity is the faithful transmission of traits from parents to offspring, usually (but not necessarily)

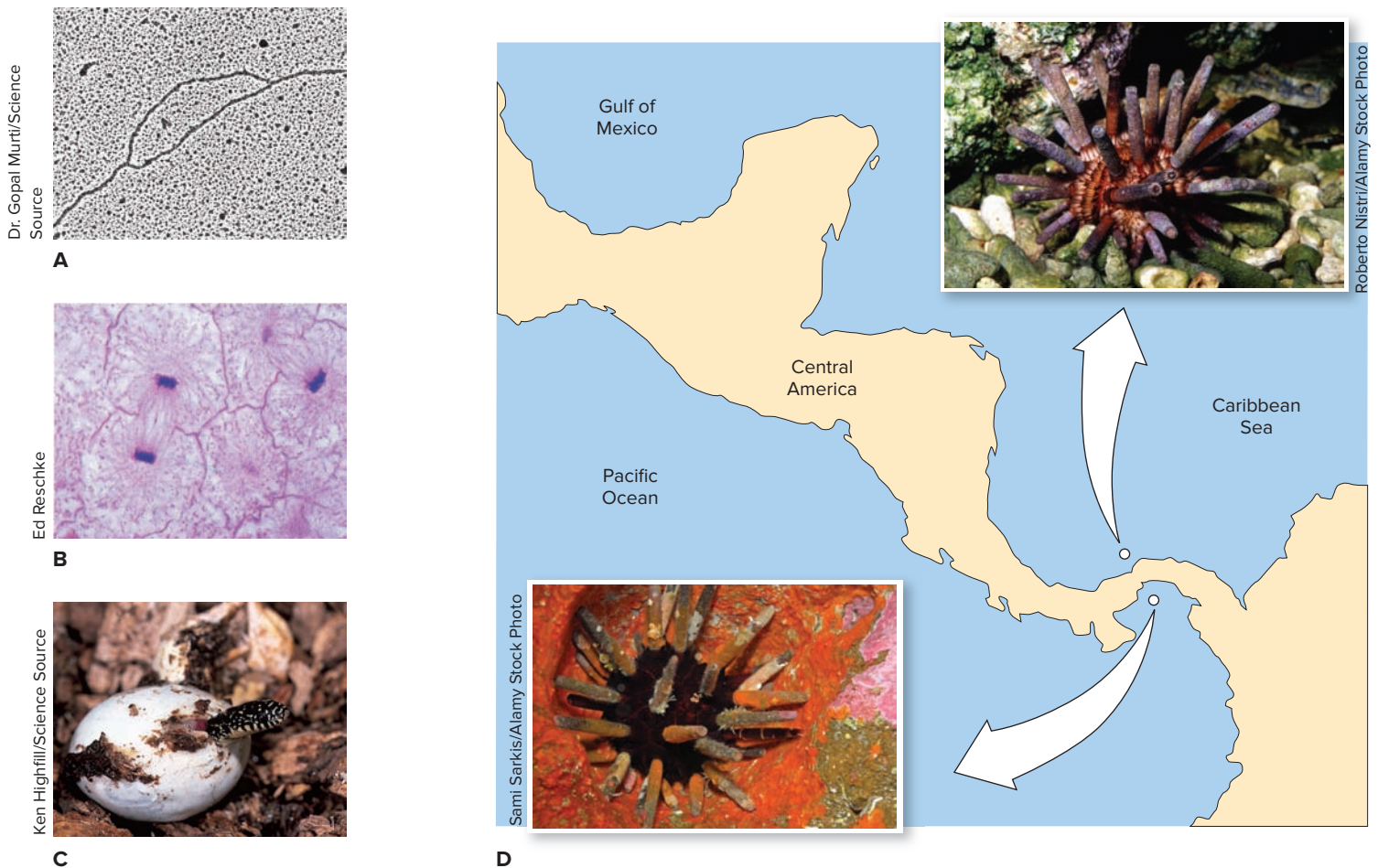


Figure 1.5 Reproductive processes observed at four different levels of biological complexity. **A**, Molecular level—electron micrograph of a replicating DNA molecule. **B**, Cellular level—micrograph of cell division at mitotic telophase. **C**, Organismal level—a king snake hatching. **D**, Species level—formation of new species in sea urchins (*Eucidaris*) after geographic separation of Caribbean (*E. tribuloides*) and Pacific (*E. thouarsi*) populations by a land bridge that formed approximately 3.5 million years ago.

observed at the organismal level. Variation is the production of *differences* among the traits of different individuals. In a reproductive process, properties of descendants resemble those of their parents to varying degrees but usually are not identical to them. Replication of deoxyribonucleic acid (DNA) occurs with high fidelity, but errors occur at repeatable rates. Cell division is exceptionally precise, especially with regard to nuclear material, but chromosomal changes occur nonetheless at measurable rates. Organismal reproduction likewise demonstrates both heredity and variation, the latter most obvious in sexually reproducing forms. Production of new populations and species also demonstrates conservation of some properties and changes of others. Two closely related frog species may have similar mating calls but differ in the rhythms of repeated sounds.

Interaction of heredity and variation in the reproductive process makes organic evolution possible and inevitable (see Chapter 6). If heredity were perfect, living systems would never change; if variation were uncontrolled by heredity, biological systems would lack the stability that allows them to persist through time.

4. **Possession of a genetic program.** A genetic program provides fidelity of inheritance (Figure 1.6). **Nucleic acids** encode structures of the protein molecules needed for organismal development and functioning (see Chapter 5). For animals and most other organisms, **DNA** stores genetic information. DNA is a very long, linear chain of subunits called nucleotides, each of which contains a sugar phosphate (deoxyribose phosphate) and one of four nitrogenous bases (adenine, cytosine, guanine, or thymine, abbreviated A, C, G, and T, respectively). The sequence of nucleotide bases contains a code for the order of amino acids in the protein specified by the DNA molecule. The correspondence between the sequence of bases in DNA and the sequence of amino acids in a protein is the **genetic code**.

The genetic code arose early in the evolutionary history of life, and the same code occurs in bacteria and in the nuclear genomes of almost all animals and plants. The near constancy of this code among living forms provides strong evidence for a single origin of life. The genetic code has undergone very little evolutionary change since its origin because an alteration would disrupt the structure of nearly every protein, which would in turn severely disrupt cellular functions that require very specific protein structures. Only in the rare instance that the altered protein structures maintained their cellular functions would such a change possibly survive and be reproduced. Evolutionary change in the genetic code has occurred in the DNA contained in animal mitochondria, the organelles that regulate cellular energy. The genetic code in animal mitochondrial DNA therefore is slightly different from the standard code of nuclear and bacterial DNA. Because mitochondrial DNA specifies far fewer proteins than does nuclear DNA, the likelihood of getting a change in the code that maintains cellular functions is greater there than in the nucleus.

5. **Metabolism.** Living organisms maintain themselves by acquiring nutrients from their environments (Figure 1.7). Nutrients supply the chemical energy and molecular components for building and maintaining a living system (see Chapter 4). We call these essential chemical processes **metabolism**.



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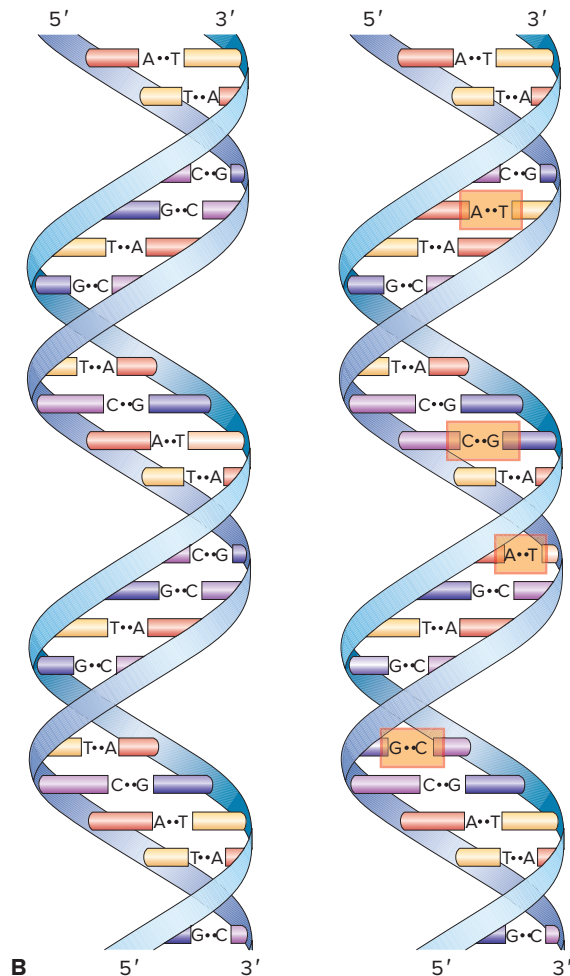
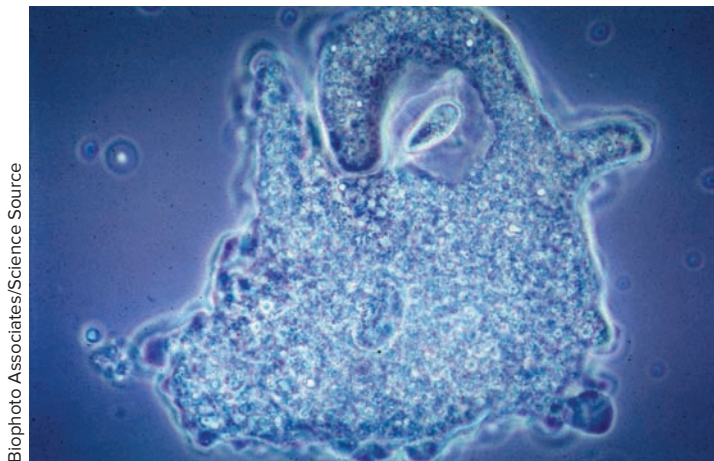


Figure 1.6 James Watson and Francis Crick with a model of the DNA double helix (**A**). The nucleotide base sequence inside the DNA molecule encodes genetic information. Genetic variation is shown (**B**) in DNA molecules that are similar in base sequence but differ from each other at four positions. Such differences can specify alternative traits, such as different eye colors.



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A



suebgl photography/Moment/Getty Images

B

Figure 1.7 Feeding processes illustrated by **(A)** an amoeba surrounding food and **(B)** a chameleon capturing insect prey with its projectile tongue.

They include digestion, acquisition of energy (respiration), and synthesis of molecules and structures. Metabolism is an interaction of destructive (catabolic) and constructive (anabolic) reactions. The most fundamental anabolic and catabolic chemical processes used by living systems arose early in the evolutionary history of life, and all living forms share them. These reactions include synthesis of carbohydrates, lipids, nucleic acids, and proteins and their constituent parts and cleavage of chemical bonds to recover energy stored in them. In animals, many fundamental metabolic reactions occur at the cellular level, often in specific organelles present throughout the animal kingdom. Cellular respiration occurs, for example, in mitochondria. Cellular and nuclear membranes regulate metabolism by controlling the movement of molecules across the cellular and nuclear boundaries, respectively. The study of metabolic functions from the biochemical to the organismal levels is called **physiology**. We devote a large portion of this book to describing and comparing the diverse tissues, organs, and organ systems that different groups of animals have

evolved to perform basic physiological functions of life (see Chapters 11 through 36).

6. **Development.** *All organisms pass through a characteristic life cycle.* Development describes the characteristic changes that an organism undergoes from its origin (usually the fertilization of an egg by sperm) to its final adult form (see Chapter 8). Development usually features changes in size and shape, and differentiation of structures within an organism. Even the simplest one-celled organisms grow in size and replicate their component parts until they divide into two or more cells. Multicellular organisms undergo more dramatic changes during their lives. Different developmental stages of some multicellular forms are so dissimilar that they are hardly recognizable as belonging to the same species. Embryos are distinctly different from juvenile and adult forms into which they develop. Even postembryonic development of some organisms includes stages dramatically different from each other. The transformation that occurs from one stage to another is called **metamorphosis**. There is little resemblance, for example, among the egg, larval, pupal, and adult stages of metamorphic insects (Figure 1.8). Early stages of development are often more similar among organisms of different species than are later developmental stages. In our survey of animal diversity, we describe all stages of observed life histories but concentrate on adult stages, in which diversity tends to be most obvious.
7. **Environmental interaction.** *All animals interact with their environments.* The study of organismal interaction with an environment is called **ecology**. Of special interest are the factors that influence geographic distribution and abundance of animals (see Chapters 37 and 38). The science of ecology reveals how an organism perceives environmental stimuli and responds in appropriate ways by adjusting its metabolism and physiology (Figure 1.9). All organisms respond to environmental stimuli, a property called **irritability**. The stimulus and response may be simple, such as a unicellular organism moving from or toward a light source or away from a noxious substance, or it



Ken Cavanagh/McGraw Hill

A

Ken Cavanagh/McGraw Hill

B

Figure 1.8 **A**, Adult monarch butterfly emerging from its pupal case. **B**, Fully formed adult monarch butterfly.

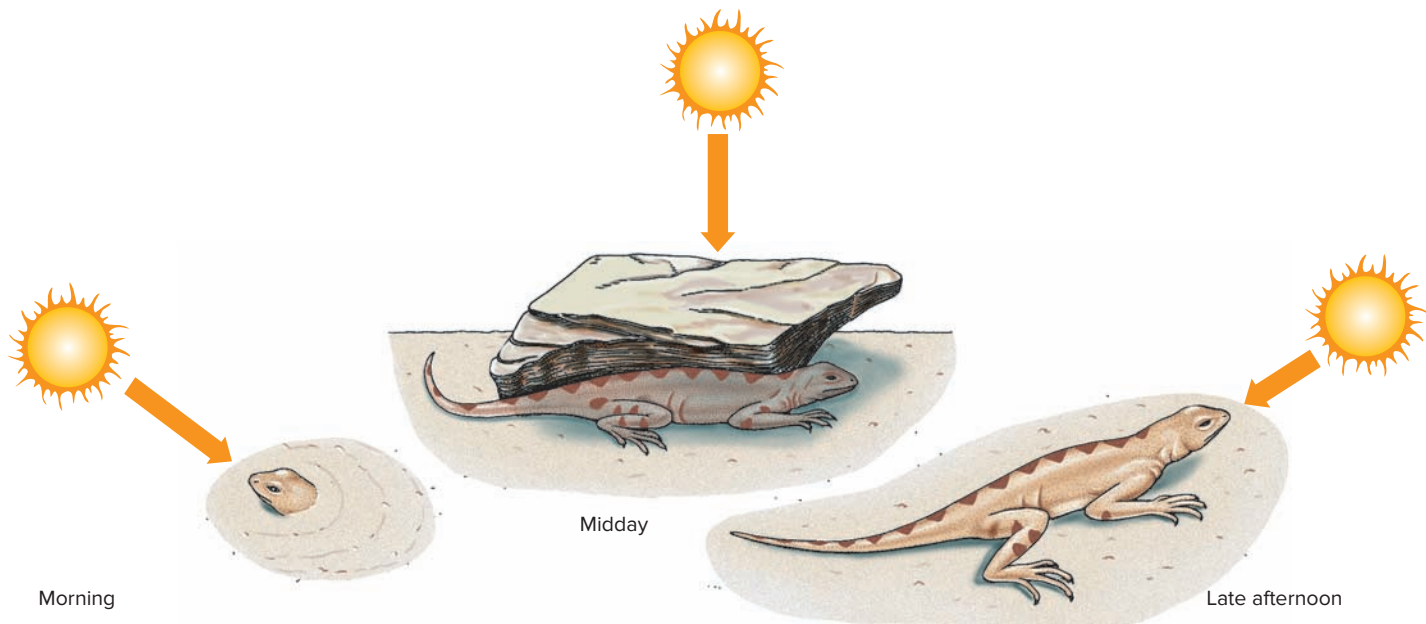


Figure 1.9 A lizard regulates its body temperature by choosing different locations (microhabitats) at different times of day.

may be quite complex, such as a bird responding to a complicated series of signals in a mating ritual (see Chapter 36). Life and environment are inseparable. We cannot isolate the evolutionary history of a lineage of populations from the environments in which it occurred.

8. **Movement.** *Living systems and their parts show precise and controlled movements arising from within the system.* The energy that living systems extract from their environments permits them to initiate controlled movements. Such movements at the cellular level are essential for reproduction, growth, and many responses to stimuli in all living forms and for development in multicellular ones. Semiautonomous movement occurs even in some biological macromolecules. An enzymatic protein undergoes characteristic and reversible changes in shape as it binds a substrate, catalyzes a reaction, and releases a product. These characteristic molecular movements occur even when the enzyme is removed from its cellular context and used as a reagent to catalyze reactions in a laboratory. Autonomous movement reaches great diversity in animals, and much of this book comprises descriptions of animal movement and the many adaptations that animals have evolved for locomotion. On a larger scale, entire populations or species may disperse from one geographic location to another one over time through their powers of movement. Movement characteristic of nonliving matter, such as that of particles in solution, radioactive decay of nuclei, and eruption of volcanoes is not precisely controlled by the moving objects themselves and often involves forces entirely external to them. The adaptive and often purposeful movements initiated by living systems are absent from the nonliving world.

Life Obeys Physical Laws

To untrained observers, these eight properties of life might appear to violate basic laws of physics. Vitalism, the idea that life

has a mystical vital force that violates physical and chemical laws, was once widely advocated. Biological research has consistently rejected vitalism, showing instead that all living systems obey basic laws of physics and chemistry. Laws governing energy and its transformations (thermodynamics) are particularly important for understanding life (see Chapter 4). The **first law of thermodynamics** is the law of conservation of energy. Energy is neither created nor destroyed but can be transformed from one form to another. All aspects of life require energy and its transformation. The energy to support life on earth flows from the fusion reactions in our sun and reaches the earth as light and heat. Photosynthesis in green plants and cyanobacteria transforms energy captured as sunlight into chemical bonds. Energy in chemical bonds is a form of potential energy released when the bond is broken; the energy is used to perform numerous cellular tasks. Energy transformed and stored in plants is then used by animals that eat the plants, and these animals may in turn provide energy for predators.

The **second law of thermodynamics** states that physical systems tend to proceed toward a state of greater disorder, or **entropy**. Energy obtained and stored by plants is subsequently released by various mechanisms and finally dissipated as heat. Living cells maintain complex molecular organization only as long as energy fuels the organization. The ultimate fate of materials in the cells is degradation and dissipation of their chemical-bond energy as heat. An evolutionary increase over time in organismal complexity may appear at first to violate the second law of thermodynamics, but it does not. Organismal complexity is achieved and maintained only by the perpetual use and dissipation of energy flowing into the biosphere from the sun. Survival, growth, and reproduction of animals require energy that comes from breaking complex food molecules into simple organic waste. The processes by which animals acquire energy through nutrition and respiration reveal themselves to us through the many physiological sciences.

1.2 ZOOLOGY AS A PART OF BIOLOGY

Animals form a distinct branch on the evolutionary tree of life. It is a large and old branch that originated in the Precambrian seas over 600 million years ago. Animals form part of an even larger limb called **eukaryotes**, organisms whose cells contain membrane-enclosed nuclei. This larger limb includes plants, fungi, and numerous unicellular forms. Perhaps the most distinctive characteristic of animals as a group is their means of nutrition, which consists in eating other organisms. Animal evolution has elaborated this basic way of life through diverse systems for capturing and processing a wide array of food items and for locomotion.

We distinguish animals also by the absence of characteristics that have evolved in other eukaryotes but not in animals. Plants, for example, use light energy to produce organic compounds (photosynthesis), and they have evolved rigid cell walls that surround their cell membranes; photosynthesis and cell walls do not occur in animals. Fungi acquire nutrition by absorption of small organic molecules from their environments, and their body plan contains tubular filaments called *hyphae*; these structures do not occur in the animal kingdom.

Some organisms that are neither animals nor plants combine properties of animals and plants. For example, *Euglena* (Figure 1.10) is a motile, single-celled organism that resembles plants in being photosynthetic, but resembles animals in its ability to eat food particles. *Euglena* is part of a separate eukaryotic lineage that diverged from those of plants and animals early in the evolutionary history of eukaryotes. *Euglena* and other unicellular eukaryotes formerly were grouped as the kingdom Protista, although this kingdom is an arbitrary grouping of taxa that are not each other's closest relatives and thus violates taxonomic principles (see Chapter 10).

The **microbiome** is a major characteristic of animal life that is often overlooked: animal bodies typically harbor thousands of species of bacteria and archaea, primarily in the gut. These species typically exist in a harmless symbiosis with their animal hosts, with fewer than 100 species of bacteria being sources of infectious disease. It is estimated that the microbial species in a human body collectively contain 500 times the number of genes present in our nuclear genomes. Because many of these microbes are hard to culture, their diversity was fully appreciated only after development of technology for sequencing DNA isolated from

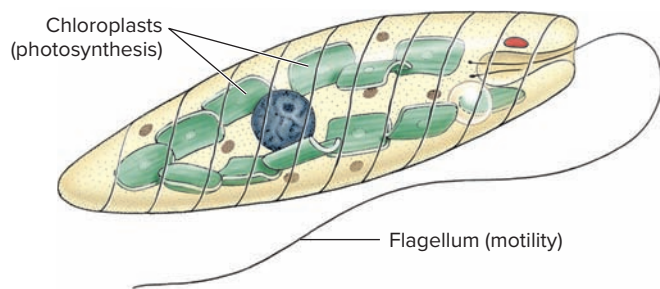


Figure 1.10 Some organisms that are neither animals nor plants, such as single-celled *Euglena* (shown here) and *Volvox* (see Figure 1.3), combine properties that distinguish animals (locomotion) from plants (photosynthetic ability).

our symbiotic microbes. The microbiome influences our digestion of food, and variation in the content of the microbiome among individuals can influence our body weight and susceptibility to malnutrition. Studies in mice suggest that imbalances in gut microbial diversity might influence pathology of Alzheimer's disease. The microbiome is not essential for survival of humans or mice, but it is critical to the survival of many other species. Cattle would be unable to digest food without the bacteria present in their foregut. Among insects, termites depend on bacteria to digest their food, and aphids and cicadas depend upon bacteria for nutrition. Corals become weak and decline in the absence of their symbiotic bacteria and algae. An animal's microbiome is not strictly constant in species diversity, and is subject to change as microbes are exchanged among animals of the same and different species. Studies of animal microbiology are still at an early stage and likely a source of interesting surprises ahead in our understanding of zoology.

We summarize in Chapters 8 and 9 the fundamental structural and developmental features evolved by the animal kingdom.

1.3 PRINCIPLES OF SCIENCE

Nature of Science

A basic understanding of zoology requires understanding what science is, what it is not, and how we gain knowledge using the scientific method.

Science is a way of asking questions about the natural world and sometimes obtaining precise answers to them. Although science, in the modern sense, arose within the last 200 years or so, a tradition of asking questions about the natural world is ancient. In this section, we examine the methodology that zoology shares with science as a whole. These procedures for constructing data-based explanations of natural phenomena distinguish sciences from activities that we exclude from the realm of science, such as art and religion.

Despite an enormous impact of science on our lives, many people have only a minimal understanding of science. For example, on March 19, 1981, the governor of Arkansas signed into law the Balanced Treatment for Creation-Science and Evolution-Science Act (Act 590 of 1981). This act falsely presented "creation-science" as a valid scientific endeavor. "Creation-science" is instead a religious position advocated by a minority of the American religious community, and it does not qualify as science. Enactment of this law led to a historic lawsuit tried in December 1981 in the court of Judge William R. Overton, U.S. District Court, Eastern District of Arkansas. The American Civil Liberties Union brought this suit on behalf of 23 plaintiffs, including religious leaders and groups representing several denominations, individual parents, and educational associations. The plaintiffs contended that the law violated the First Amendment to the U.S. Constitution, which prohibits "establishment of religion" by government. This prohibition precludes passing a law that would aid one religion or prefer one religion over another. On January 5, 1982, Judge Overton permanently stopped the State of Arkansas from enforcing Act 590.

Considerable testimony during the trial described the process of science. Some witnesses defined science simply, if not very informatively, as "what is accepted by the scientific community" and