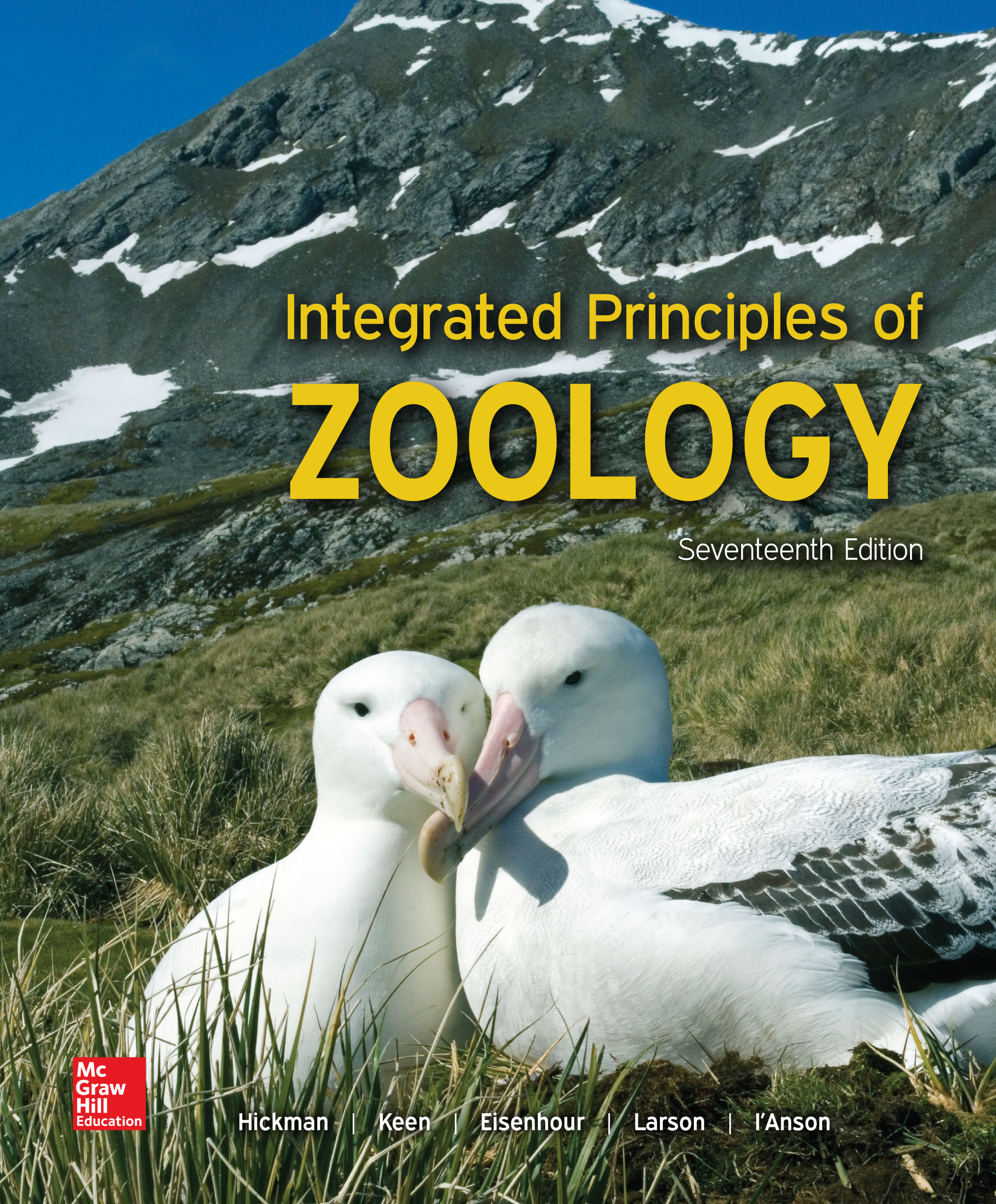

Integrated Principles of ZOOLOGY

Seventeenth Edition

McGraw Hill Education

Hickman | Keen | Eisenhour | Larson | I'Anson

INTEGRATED PRINCIPLES OF

ZOOLOGY

SEVENTEENTH EDITION

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INTEGRATED PRINCIPLES OF ZOOLOGY, SEVENTEENTH EDITION

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CONTENTS IN BRIEF

TABLE OF CONTENTS

CHAPTER 15
Polyzoa and Kryptrochozoa 319

CHAPTER 16
Molluscs 332

CHAPTER 17
Annelids and Allied Taxa 363

CHAPTER 18
Smaller Ecdysozoans 385

CHAPTER 19
Trilobites, Chelicerates, and Myriapods 402

CHAPTER 20
Crustaceans 421

CHAPTER 21
Hexapods 443

CHAPTER 22
Chaetognaths, Echinoderms, and Hemichordates 471

CHAPTER 23
Chordates 498

CHAPTER 24
Fishes 516

CHAPTER 25
Early Tetrapods and Modern Amphibians 543

CHAPTER 26

CHAPTER 27

CHAPTER 28

PART FOUR

Activity of Life

CHAPTER 29

CHAPTER 30

CHAPTER 31

CHAPTER 32

CHAPTER 33

CHAPTER 34

CHAPTER 35

PART FIVE

Animals and Their Environments

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PREFACE

Integrated Principles of Zoology continues to be the leading text for the introductory zoology course. With the seventeenth 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 proven to work well to help students understand the content. Distinctive features, especially the emphasis on principles of evolution and zoological science, have been strengthened. To aid in student learning, several pedagogical features have been retained: opening chapter prologues drawn from the chapter's theme; 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; literature citations; and an extensive glossary providing pronunciations, derivations, and definitions of terms used in the text.

NEW TO THE SEVENTEENTH EDITION

Revisions for the seventeenth edition are primarily for improved pedagogy, and guided by an electronic tabulation of student responses to questions. All parts of the sixteenth edition were linked to electronic questions designed to measure students' comprehension of their reading. Authors received a heat map of the sixteenth edition, showing for each paragraph the percentage of correct student responses for that material. We focused our revisions on improving explanations wherever the heat map showed less than 50% of the students responding correctly. With this detailed and insightful guidance, we have made our text more accessible to its readers.

In addition to focused revision of the writing, we have replaced many photographs and diagrams throughout the book to improve clarity and vibrancy.

We summarize our major revisions in order by the book's five major parts.

Part One, Introduction to Living Animals

In Chapter 1, a new section, *Historical Continuity of Life,* replaces the section formerly titled *Does Life Have Defining Properties?* A new figure illustrating protein structure strengthens the visual correspondence between the bonding of amino acids and the three-dimensional macromolecular structure of a protein. Regarding general properties of living systems, we expand the explanation of speciation as part of the biological hierarchy, and extend the principle of movement to the macromolecular level, emphasizing reversible conformational changes in proteins. In Chapter 2, expanded captions for Figures 2.12–2.15 make the diagrams more independent of the text in conveying the fundamental structures of biological macromolecules. The important role of ATP in cellular metabolism and as a precursor to RNA gets expanded treatment, as does the role of membrane-bound vesicles in the evolution of biological polymers. Chapter 3 features a new explanation of electron microscopy, more information on the Golgi apparatus and on how cells adapt to temperature, and a more detailed description of how spindle fibers organize chromosomes for cellular division.

Part Two, Continuity and Evolution of Animal Life

Chapter 5 features greater detail on Mendel's investigations, plus a more detailed and precise explanation of how geneticists use the term "chromosome." Also given expanded explanations are the topics of chromosomal sex determination, how a new allele arises by mutation, occurrence of multiple alleles in a population, autosomal linkage and crossing over, DNA structure, and gene expression. Chapter 6 contains a more complete explanation of geological dating, a reorganized section, *Forces of Evolutionary Change*, and a new section describing studies of Caribbean ectoprocts as the best-documented case of punctuated equilibrium. New information on the CRISPR tool used to splice and to manipulate genes appears in Chapter 8. Chapter 8 includes updates on mesoderm and coelom formation, plus new and improved diagrams of development.

Part Three, Diversity of Animal Life

Chapters 9 and 11 update taxonomy of unicellular eukaryotes. Chapter 10 features more precise explanation of cladistic terminology, phylogenetic reconstruction, the conflicts among the major schools of taxonomy, and the major divisions of life. Chapter 11 emphasizes symbiogenesis as a major theme emerging from studies of eukaryotic origins. Chapter 11 also includes clarifications on saprozoic feeding and sexual reproduction in unicellular eukaryotes, and updates on recent U.S. outbreaks of *Cryptosporidium parvum*. Chapter 12 updates sponge taxonomy to use Calcispongiae instead of Calcarea, provides greater detail on Homoscleromorpha, and updates the debate on whether sponges have true tissue epithelia, including classification of pinacoderm as an incipient tissue. Chapter 13 is retitled *Cnidarians and Ctenophores*. "Jellyfishes" are now consistently called "jellies." The section on sea anemones is revised with greater detail, and the section on coral reefs now includes an example of coral bleaching in the Maldives. The section on phylogeny and adaptive diversification is substantially revised to include detail on the evolutionary biology of muscle cells in cnidarians and ctenophores. In Chapter 14, the section on Cestoda is updated with greater detail on the life cycle of pork tapeworms. New phylogenetic evidence groups acoelomorphs and xenoturbellids as a clade. The introduction to Chapter 15 now mentions controversy concerning homology of the lophophore across the three lophophorate phyla. The section on Phylum Ectoprocta now includes detail on *Tricellaria inopinate* as an invasive species.

Chapter 16 features a new description of evolution of terrestrial slugs, new information on how ocean acidification threatens marine molluscs, and the economic importance of molluscs. Chapter 17 presents a completely revised introductory section on annelids with updated information on the fluid-filled coelomic cavity, and more background on annelid evolutionary history. The section describing earthworms' peristaltic movement is augmented and improved. Chapter 18 reports that all plant parts have specialized nematode parasites. The section on form and function of nematodes is augmented and improved with updated information on the life cycle of *Ascaris* worms. Information from the CDC on filarial worms is updated. The evolutionary placement of the fossil *Hallucigenia* sheds light on the evolution of teeth in ecdysozoans and their loss in velvet worms. Additional detail appears on mating in nematomorphs. Chapter 19 features greater detail on spider respiration. Updates include the role of the *Varroa* mite in the dramatic loss of U.S. honeybees. Chapter 20 reports the first venomous crustacean and includes updates on the symbiotic feeding habits of yeti crabs. Chapter 21 features new phylogenetic data suggesting that insects arose far earlier than the fossil record indicates. The section on insect metamorphosis and growth includes new information on molting and ecdysis. The defense section includes a new box on luna moths. The section on insects and human welfare continues from Chapter 19 the discussion of colony collapse disorder in honeybees, plus updates on defoliation and the Zika virus. Chapter 22 adds information on species diversity of Chaetognatha, echinoderm larvae and nervous systems, and echinoderms of Class Ophiuroidea.

In Chapters 23–24, we adopt unranked nested clade names for vertebrate taxonomy. There is no longer a consensus system for placing the higher groups of vertebrates into a Linnaean system. We update hagfish and lamprey relationships; these are now considered sister groups, forming the clade Cyclostomata. Also presented is new information about hagfish development and reproduction, which includes the first documentation that at least some hagfishes do have vertebrae. Extensive clarification of wording throughout these chapters follows the guidance of the heat map. The fish cladogram was heavily modified, incorporating new ideas about relationships of placoderms and acanthodians. There is new lungfish art depicting aestivation behavior. An updated boxed essay describes the impact of dams, and their removals, on salmon populations. Chapter 25 presents more precise dating information on the Devonian origin of tetrapods in the text and accompanying figures. Chapter 26 features updated information on turtle evolution, highlighting evolutionary developmental biology of the shell. The opening section on enclosing the pond has been substantially revised for context and clarity, now specifying the four living reptile groups and noting that dinosaurs form a clade with birds. A new boxed essay describes the Burmese python as an invasive species in southern Florida. Chapter 27 features more precise terminology and description of the categories of bird flight. The boxed essay on flightless birds includes an update on the height of the largest bird, and the essay on Himalayan migration by bar-headed geese is updated. Chapter 28 presents an expanded section on mammalian omnivory. Updates to human evolution include new information from recent South African and European fossils and from DNA studies of Neanderthal and modern humans. The boxed essay on trade in rhinoceros horns is updated.

Part Four, Activity of Life

The section on integument in Chapter 29 includes a new footnote directing readers to the Annual Report to the Nation on the Status of Cancer 1975–2011. The section on skeletal systems presents an update on the running capability and speed of *Tyrannosaurus*. The Chapter 31 subsection on excitation and control of the heart now features greater detail on how sympathetic nerves increase stroke volume and heart rate when activated. Chapter 32 presents additional detail on the functionality of pepsin. There are updated statistics and a new footnote on the prevalence of childhood and adult obesity in the United States, plus more detail on secretions of fat cells and inflammatory responses. The section on nutritional requirements includes updated statistics on meat consumption. Coverage of hearing in Chapter 33 includes new material on luna moth defenses. In the section on prostoglandins and cytokines, Chapter 34 features more information on secretion of these hormones and inflammatory responses. In the section on hormones of metabolism, more detail appears on possible consequences of defects in thyroid hormone production or receptors, along with more detail on the evolution of bone and parathyroid glands in fishes. A boxed essay on anabolic steroids has updated statistics. The Chapter 35 section on innate defense mechanisms adds current studies on the gut microbiome, which may be altered by obesity. In Chapter 36, the subsection on genetics of behavior includes greater detail on W. C. Dilger's hybridization of lovebirds and its disruption of genetically programmed behavior. The subsection on agonistic or competitive behavior features added detail on peck order. The subsection on cooperative behavior, altruism, and kin selection describes W. D. Hamilton's modification of Ronald Fisher's concept of the fitness of an allele and self-sacrifice. The subsection on the language of honeybees features a more detailed description.

Part Five, Animals and Their Environments

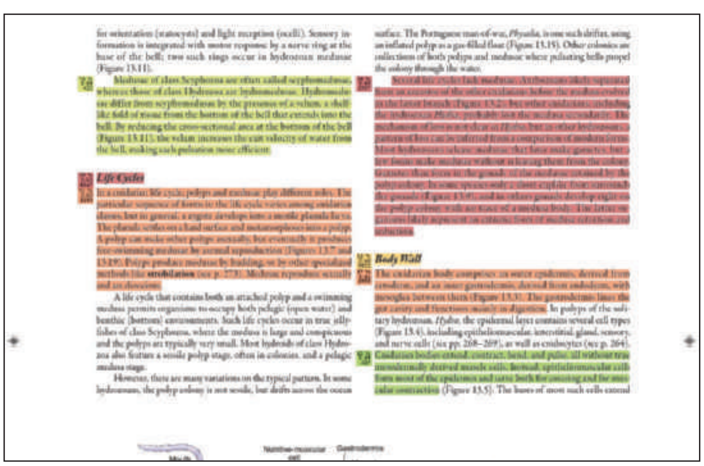
The Chapter 37 discussion of distribution by dispersal and vicariance includes more information on the geographic distribution of ratite birds. There is more information on glacial cycles in the section on climatic cycles and vicariance, and greater detail on the relationships between upwellings of phytoplankton in the Antarctic sea and krill. The Chapter 38 subsection on populations includes a new paragraph on the metapopulation model, plus greater detail and clarity on the three principal types of theoretical survivorship. Figure 38.3 has a revised and more detailed caption. This section also now includes a note on the United Nations' position that a world population of 7–11 billion people would reach the point of being unsustainable agriculturally. The section on community ecology is significantly revised and now includes coverage of ecological character displacement, microhabitat selection, and the theory of competitive exclusion. It also features new coverage of ectoparasites and endoparasites and the complexity of parasite/host relationships. The section on ecosystems is revised for clarity and to provide greater detail. The caption for Figure 38.13 is revised for better context.

OUR APPROACH TO THE REVISION

Our goal now is, as it has always been, to ensure student success. To that end, we approached this revision differently. To help guide our revision for this seventeenth edition, we were able to incorporate student usage data and input, derived from thousands of our SmartBook® users. SmartBook "heat maps" provided a quick visual snapshot of chapter usage data and the relative difficulty students experienced in mastering the content. With these data, we were able to hone not only our text content but also the SmartBook probes.

- If the data indicated that the subject was more difficult than other parts of the chapter, as evidenced by a high proportion of students responding incorrectly to the probes, we revised or reorganized the content to be as clear and illustrative as possible.
- In other cases, if one or more of the SmartBook probes for a section was not as clear as it might be or did not appropriately reflect the content, the probes were edited, rather than the text.

Below is an example of one of the heat maps from Chapter 13. The color-coding in highlighted sections indicates the various levels of difficulty students experienced in learning the material, topics highlighted in red being the most challenging for students.



TEACHING AND LEARNING AIDS

To help students in **vocabulary development,** key words are boldfaced 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 become familiar with 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.

Chapter notes, which appear throughout the book, augment the text material and offer interesting sidelights without interrupting the narrative. We prepared many new notes for this edition and revised several existing notes.

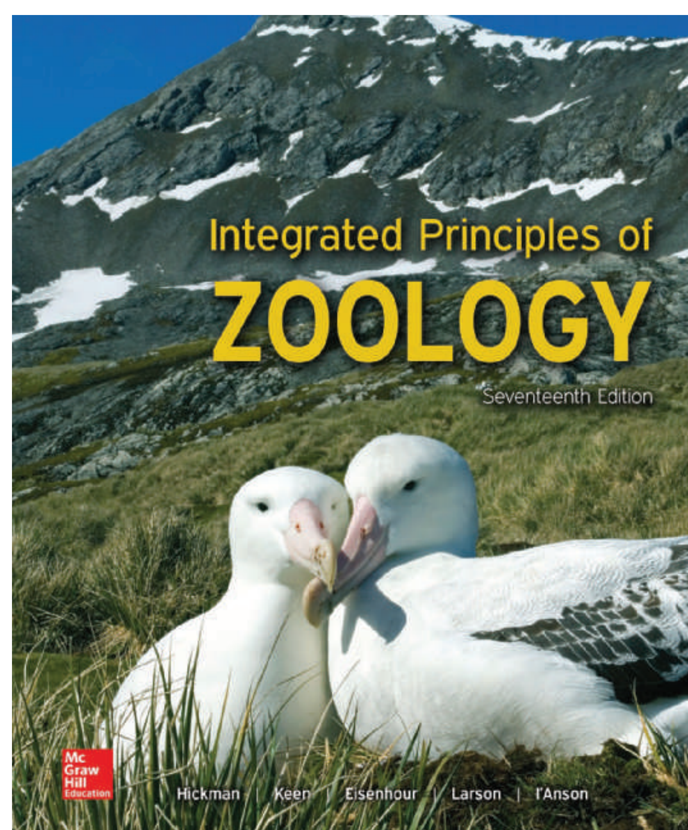
To assist students in chapter review, each chapter ends with a **concise summary,** a list of **review questions,** and **annotated selected references.** The review questions enable a student to self-test retention and understanding of the more important chapter material.

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., Susan Keen, and Lee B. Kats**

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



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Although we make every effort to bring to you an error-free text, errors of many kinds inevitably find their way into a textbook of this scope and complexity. We will be grateful to readers who have comments or suggestions concerning content and send their remarks to Patrick Reidy, Executive Marketing Manager, at patrick.reidy@mheducation.com

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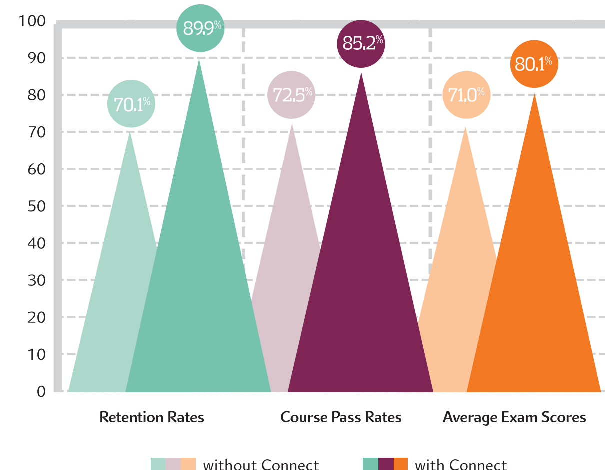

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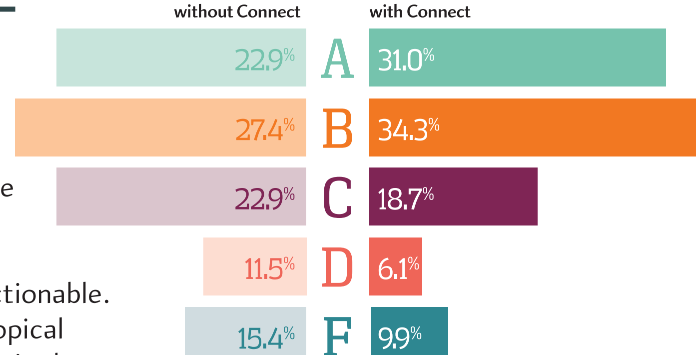

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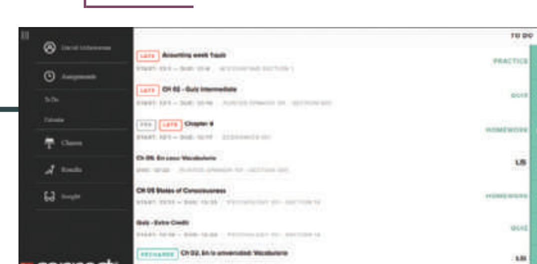

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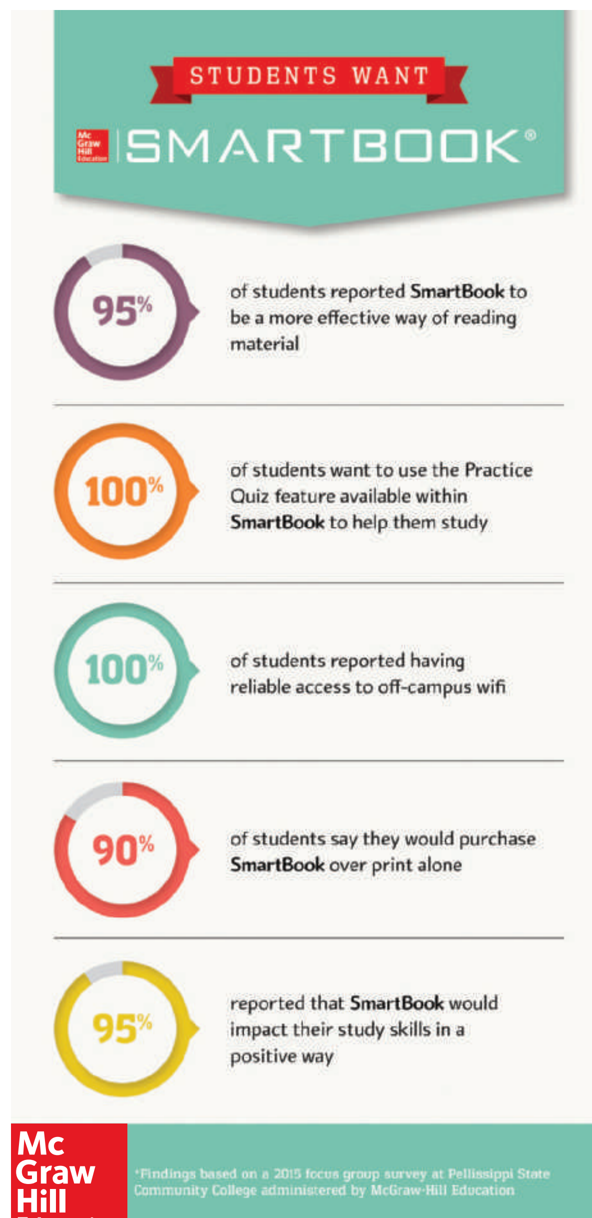

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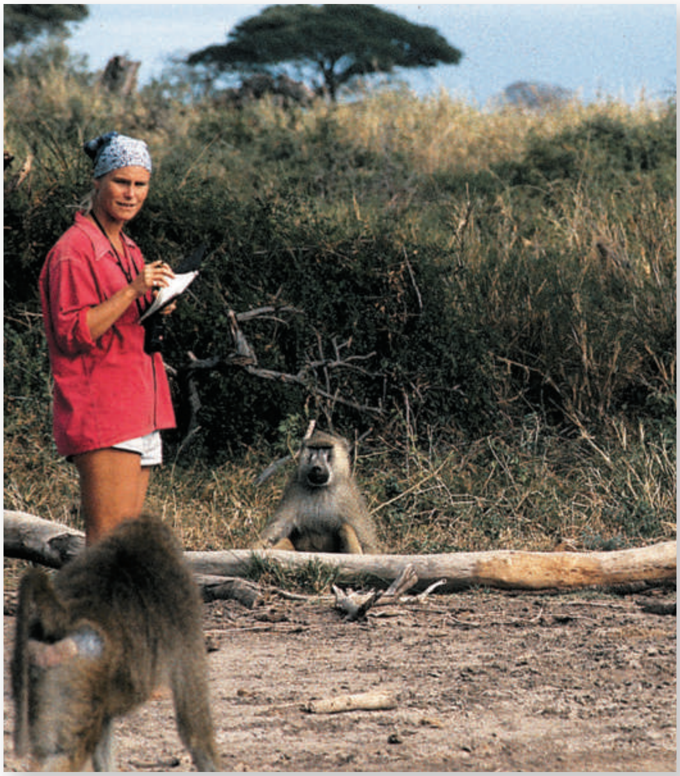
PART ONE

1

CHAPTER

Life: Biological Principles and the Science of Zoology



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

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 available technologies, exploration of the animal world depends critically on our questions, methods, and principles. 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 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

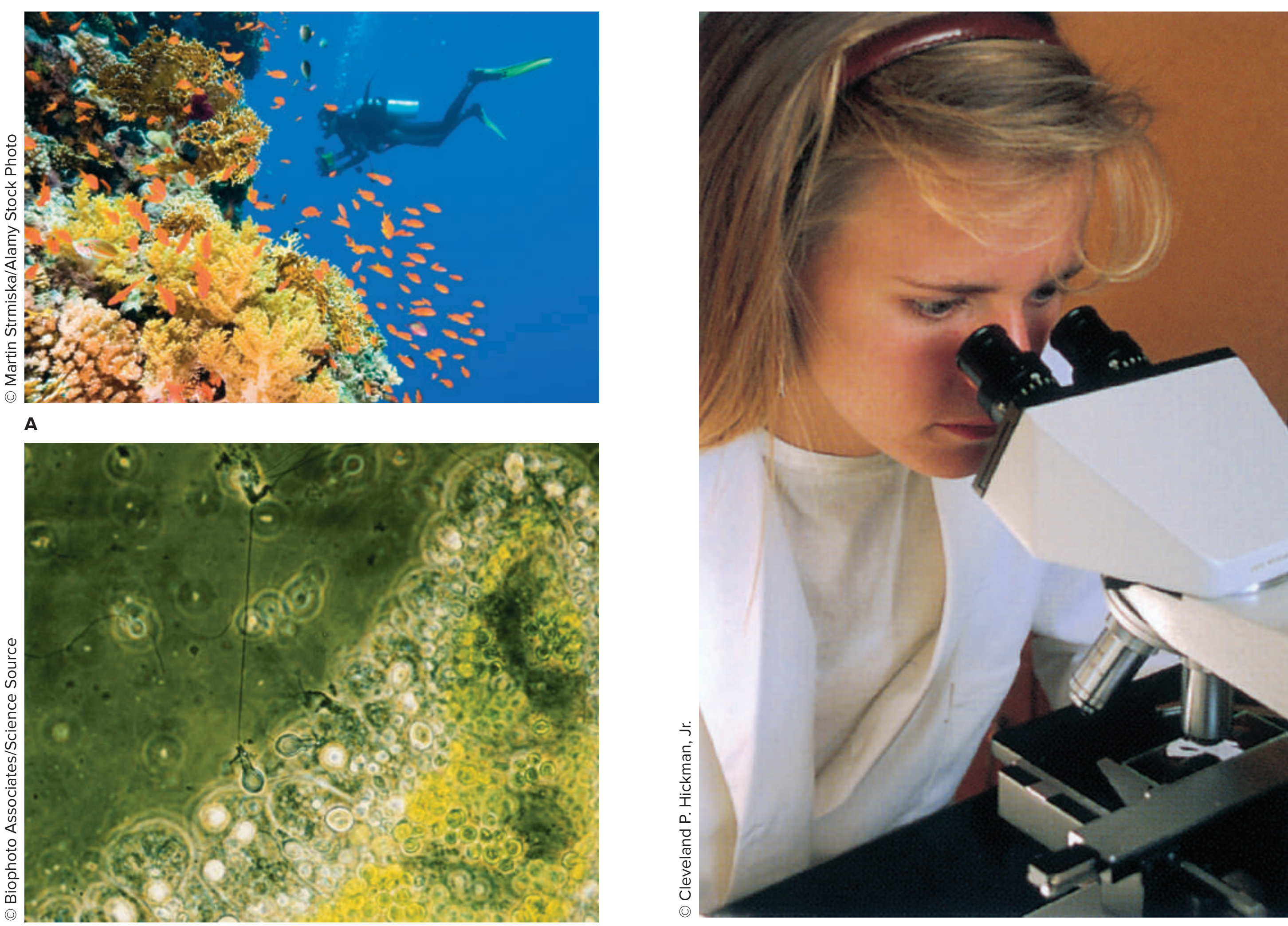


Figure 1.1 Examples of observation in zoological research. **A,** Observing a coral reef. **B,** Observing nematocyst discharge from cnidarian tentacles (**C,** see p. 260)

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 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 Chapter 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

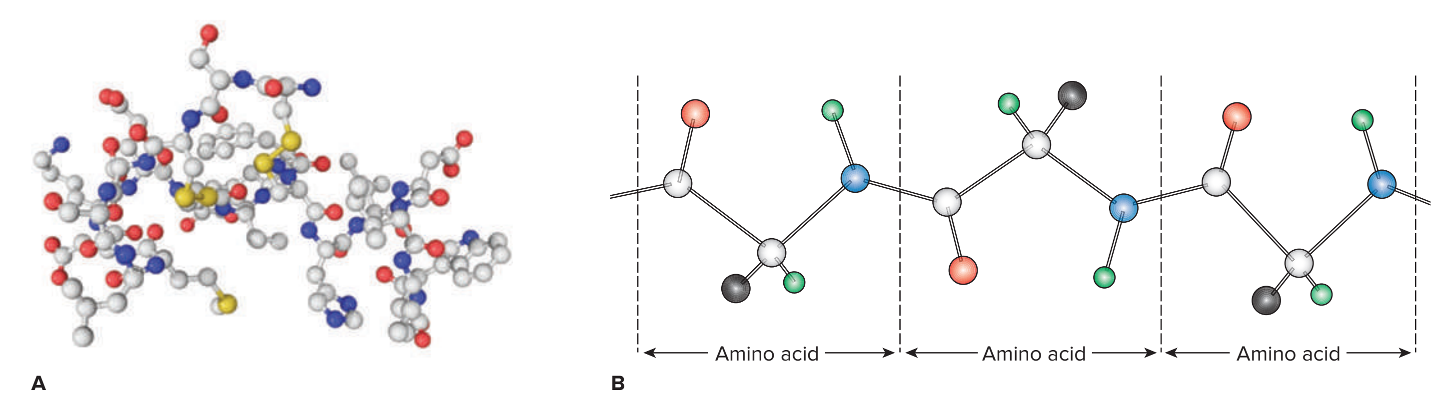


Figure 1.2 A computer simulation of the three-dimensional structure of the human endothelin-1 protein **(A),** which can constrict blood vessels to increase blood pressure. The protein is a linear string of molecular subunits called amino acids, connected as shown in **B,** which fold in a three dimensional 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.**

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; 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 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.

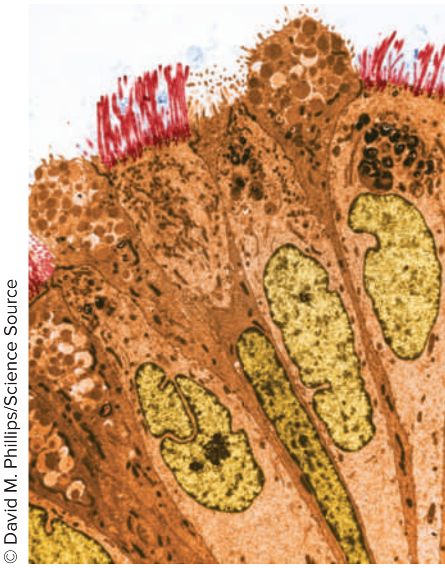


Figure 1.4 Electron micrograph of ciliated epithelial cells and mucus-secreting cells (see pp. 189–191) lining the interior of a rat oviduct. Cells are the basic building blocks of living organisms.

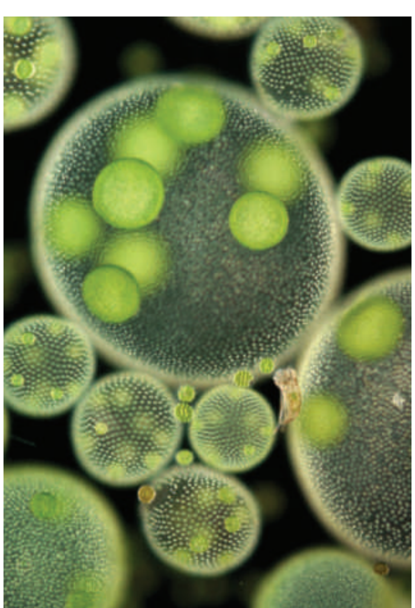


Figure 1.3 *Volvox globator* (see pp. 239–240) is a multicellular flagellate that illustrates three different levels of the biological hierarchy: cellular, organismal, and populational. Each individual spheroid (organism) contains cells embedded in a gelatinous matrix. The larger cells function in reproduction, and the smaller ones perform the general metabolic functions of the organism. The individual spheroids together form a population.

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.

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

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) 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

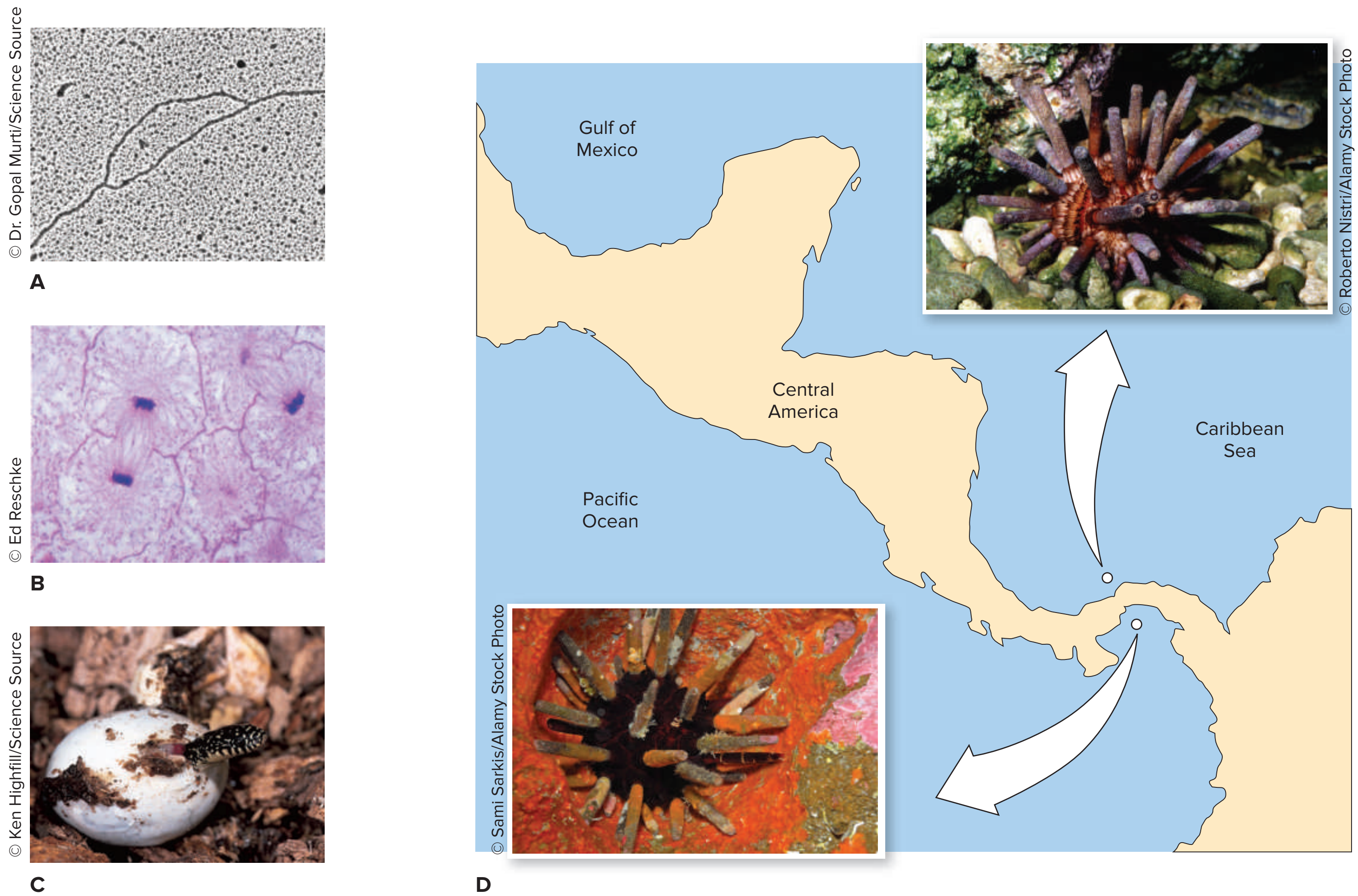


Figure 1.5 Reproductive processes observed at four different levels of biological complexity. **A,** Molecular level—electron micrograph of a replicating DNA molecule. **B,** Cellular level—micrograph of cell division at mitotic telophase. **C,** Organismal level—a king snake hatching. **D,** Species 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.

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.** 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 Chapter 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

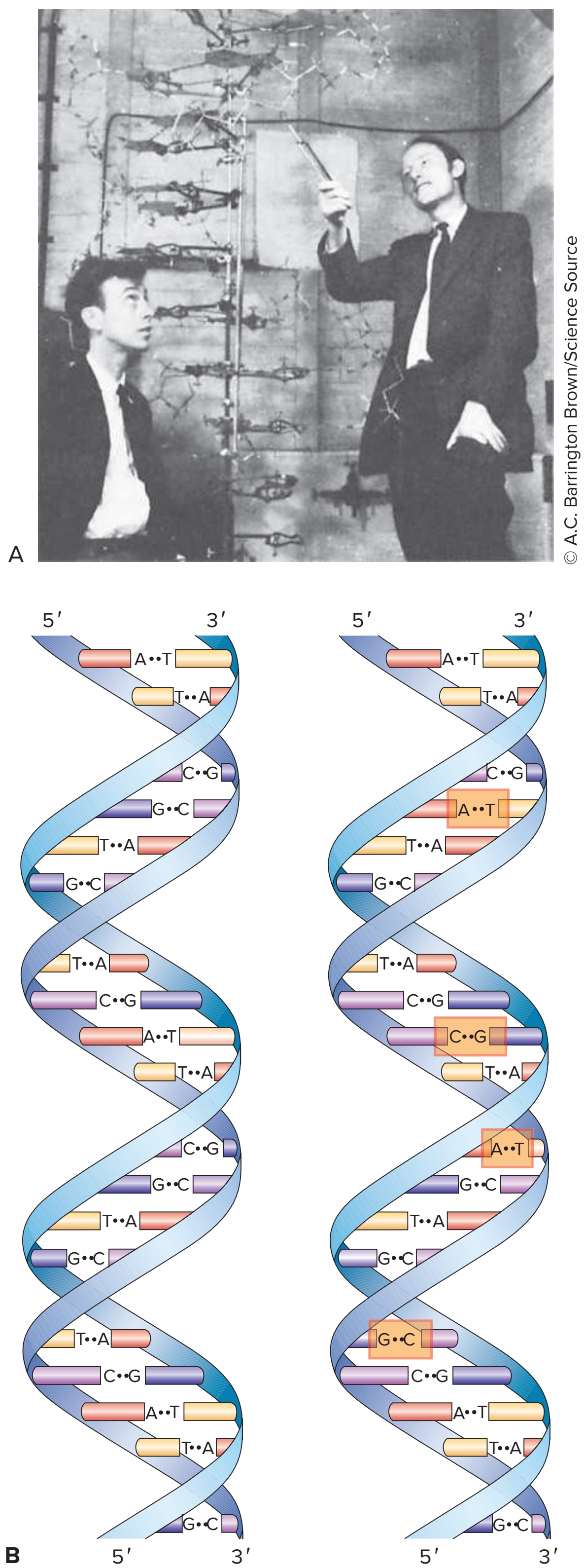


Figure 1.6 James Watson and Francis Crick with a model of the DNA double helix **(A).** The nucleotide base sequence inside the DNA molecule encodes genetic information. Genetic variation is shown **(B)** in DNA molecules that are similar in base sequence but differ from each other at four positions.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

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

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

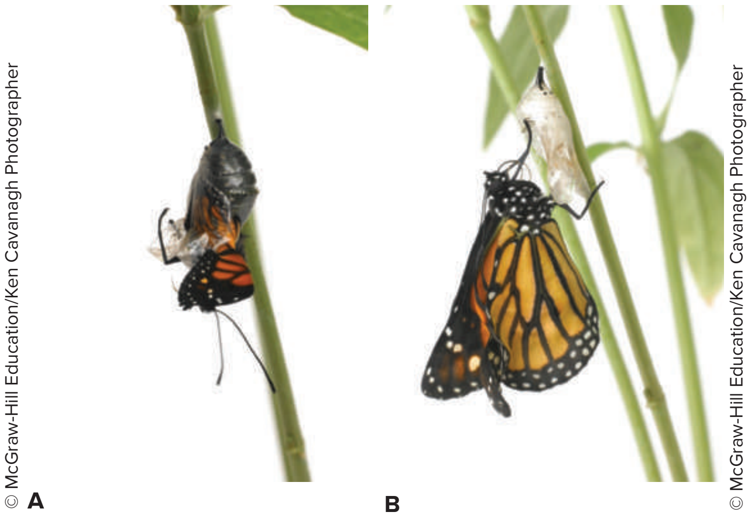


Figure 1.8 **A,** Adult monarch butterfly emerging from its pupal case. **B,** Fully formed adult monarch butterfly.

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 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

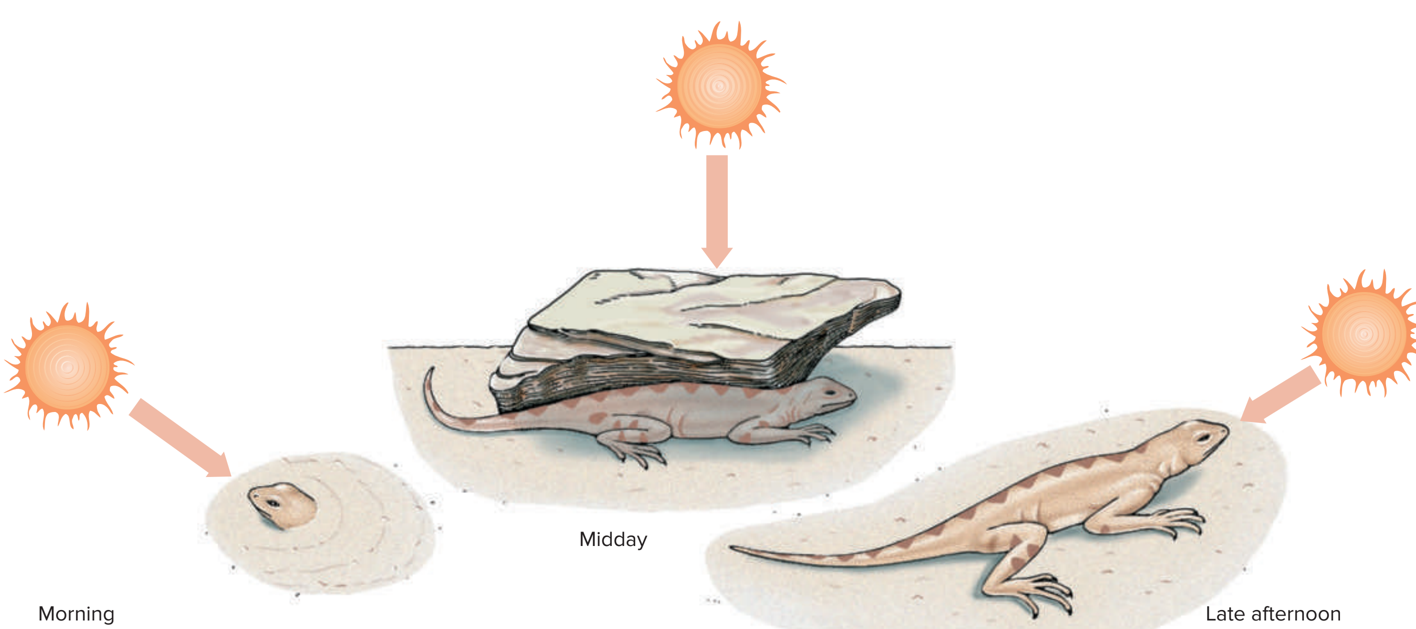


Figure 1.9 A lizard regulates its body temperature by choosing different locations (microhabitats) at different times of day.

(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).

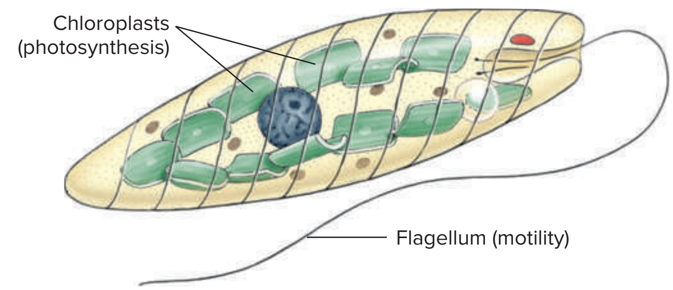


Figure 1.10 Some organisms that are neither animals nor plants, such as single-celled *Euglena* (shown here) and *Volvox* (see Figure 1.3), combine properties that distinguish animals (locomotion) from plants (photosynthetic ability).

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 "what