# BIOLOGY

THE DYNAMIC SCIENCE THIRD EDITION

Russell Hertz McMillan

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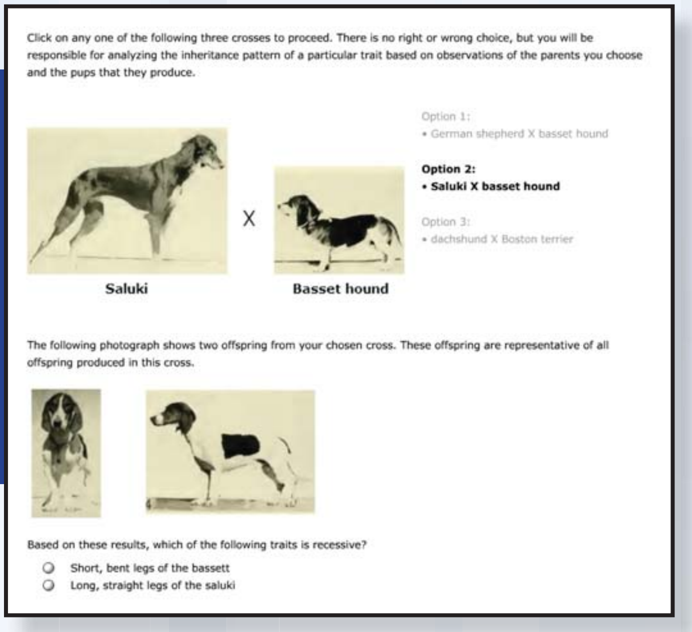


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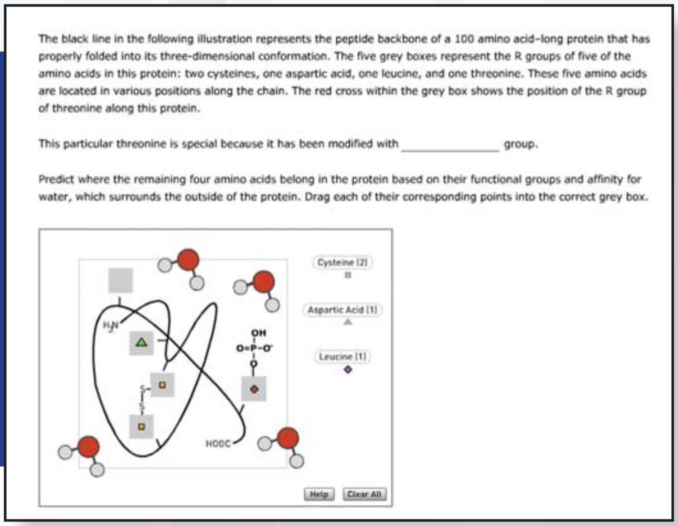

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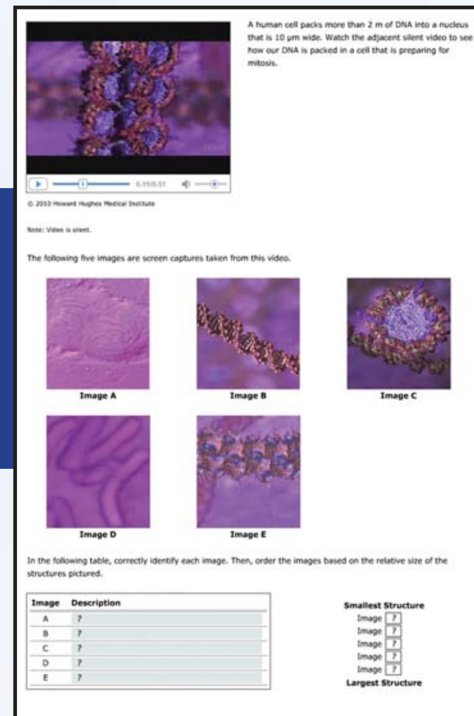


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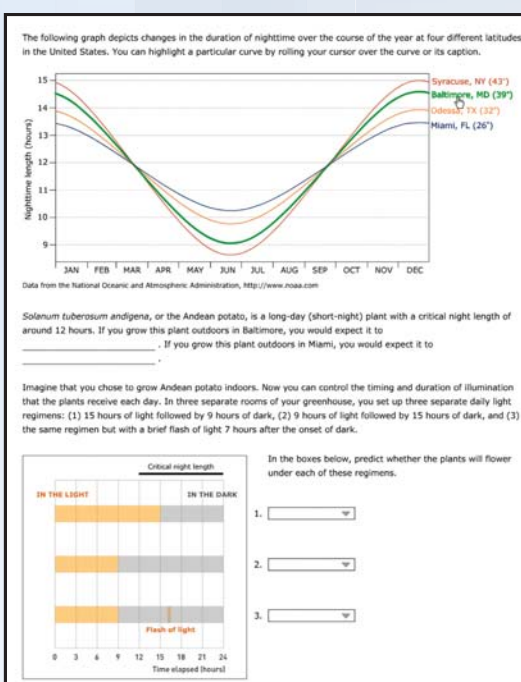


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# BIOLOGY

## THE DYNAMIC SCIENCE THIRD EDITION

Russell Hertz McMillan

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***Biology: The Dynamic Science,* Third Edition**
**Peter J. Russell, Paul E. Hertz, Beverly McMillan**

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About the Cover: The Philippine eagle is among the largest three eagles in the world. It is a rare species, little known and hardly ever photographed.

This eagle is endemic to the Philippines—a country whose population is ever-growing while its forest areas have come down to a mere 5 percent of what originally covered the whole country. As the Philippine eagle can survive only in the rainforest, the situation for this species is most dramatic.

Klaus Nigge has been to the Philippines three times, where he visited people who are working hard to rescue this eagle. Joint efforts enabled him to find a pair of this species in one of the last remaining forest areas of Mindanao, where he spent several weeks up in the treetops to record how the eagles raised their young.



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# Brief Contents

**Peter J. Russell** received a B.Sc. in Biology from the University of Sussex, England, in 1968 and a Ph.D. in Genetics from Cornell University in 1972. He has been a member of the Biology faculty of Reed College since 1972 and is currently a professor of biology, emeritus. Peter taught a section of the introductory biology course, a genetics course, and a research literature course on molecular virology. In 1987 he received the Burlington Northern Faculty Achievement Award from Reed College in recognition of his excellence in teaching. Since 1986, he has been the author of a successful genetics textbook; current editions are *iGenetics: A Molecular Approach, iGenetics: A Mendelian Approach,* and *Essential iGenetics.* Peter's research was in the area of molecular genetics, with a specific interest in characterizing the role of host genes in the replication of the RNA genome of a pathogenic plant virus, and the expression of the genes of the virus; yeast was used as the model host. His research has been funded by agencies including the National Institutes of Health, the National Science Foundation, the American Cancer Society, the Department of Defense, the Medical Research Foundation of Oregon, and the Murdoch Foundation. He has published his research results in a variety of journals, including *Genetics, Journal of Bacteriology, Molecular and General Genetics, Nucleic Acids Research, Plasmid,* and *Molecular and Cellular Biology.* Peter has a long history of encouraging faculty research involving undergraduates, including cofounding the biology division of the Council on Undergraduate Research in 1985. He was Principal Investigator/Program Director of a National Science Foundation Award for the Integration of Research and Education (NSF–AIRE) to Reed College, 1998 to 2002.

Aaron Kinard

**Paul E. Hertz** was born and raised in New York City. He received a B.S. in Biology from Stanford University in 1972, an A.M. in Biology from Harvard University in 1973, and a Ph.D. in Biology from Harvard University in 1977. While completing field research for the doctorate, he served on the Biology faculty of the University of Puerto Rico at Rio Piedras. After spending two years as an Isaac Walton Killam Postdoctoral Fellow at Dalhousie University, Paul accepted a teaching position at Barnard College, where he has taught since 1979. He was named Ann Whitney Olin Professor of Biology in 2000, and he received The Barnard Award for Excellence in Teaching in 2007. In addition to serving on numerous college committees, Paul chaired Barnard's Biology Department for eight years and served as Acting Provost and Dean of the Faculty from 2011 to 2012. He is the founding Program Director of the Hughes Science Pipeline Project at Barnard, an undergraduate curriculum and research program that has been funded continuously by the Howard Hughes Medical Institute since 1992. The Pipeline Project includes the Intercollegiate Partnership, a program for local community college students that facilitates their transfer to four-year colleges and universities. He teaches one semester of the introductory sequence for Biology majors and pre-professional students, lecture and laboratory courses in vertebrate zoology and ecology, and a year-long seminar that introduces first-year students to scientific research. Paul is an animal physiological ecologist with a specific research interest in the thermal biology of lizards. He has conducted fieldwork in the West Indies since the mid-1970s, most recently focusing on the lizards of Cuba. His work has been funded by the NSF, and he has published his research in such prestigious journals as *The American Naturalist, Ecology, Nature, Oecologia,* and *Proceedings of the Royal Society.* In 2010, he and his colleagues at three other universities received funding from NSF for a project designed to detect the effects of global climate warming on the biology of *Anolis* lizards in Puerto Rico.

Courtesy of Beverly McMillan

**Beverly McMillan** has been a science writer for more than 25 years. She holds undergraduate and graduate degrees from the University of California, Berkeley, and is coauthor of a college text in human biology, now in its tenth edition. She has also written or coauthored numerous trade books on scientific subjects and has worked extensively in educational and commercial publishing, including eight years in editorial management positions in the college divisions of Random House and McGraw-Hill.

Welcome to the third edition of *Biology: The Dynamic Science.* The book's title reflects the speed with which our knowledge of biology is growing. Although biologists have made enormous progress in solving the riddles posed by the living world, every discovery raises new questions and provides new opportunities for further research. As in the prior two editions, we have encapsulated the dynamic nature of biology in the third edition by explaining biological concepts—and the data from which they are derived—in the historical context of each discovery and by describing what we know now and what new discoveries will be likely to advance the field in the future.

## Building on a strong foundation . . .

The first two editions of this book provided students with the tools they need to learn fundamental biological concepts, processes, and facts. More important, they enabled students to think like scientists. Our approach encourages students to think about biological questions and hypotheses through clear examples of hypothesis development, observational and experimental tests of hypotheses, and the conclusions that scientists draw from their data. The many instructors and students who have used the book have generously provided valuable feedback about the elements that enhanced student learning. We have also received comments from expert reviewers. As a result of these inputs, every chapter has been revised and updated, and some units have been reorganized. In addition, the third edition includes new or modified illustrations and photos as well as some new features.

## Emphasizing the big picture . . .

In this textbook, we have applied our collective experience as teachers, researchers, and writers to create a readable and understandable introduction that provides a foundation for students who choose to enroll in more advanced biology courses in the future. We provide straightforward explanations of fundamental concepts presented, where appropriate, from the evolutionary perspective that binds the biological sciences together. Recognizing that students in an introductory biology course face a potentially daunting amount of material, we strive to provide an appropriate balance between facts and concepts, taking great care to provide clear explanations while maintaining the narrative flow. In this way students not only see the big picture, but they understand how we achieved our present knowledge. Having watched our students struggle to navigate the many arcane details of college-level introductory biology, we constantly remind ourselves and each other to "include fewer facts, provide better explanations, and maintain the narrative flow," thereby enabling students to see the big picture. Clarity of presentation, thoughtful organization, a logical and seamless flow of topics within chapters, and carefully designed illustrations are key to our approach.

## Focusing on research to help students engage the living world as scientists . . .

A primary goal of this book is to sharpen and sustain students' curiosity about biology, rather than dulling it with a mountain of disconnected facts. We can help students develop the mental habits of scientists and a fascination with the living world by conveying our passion for biological research. We want to excite students not only with *what biologists know* about the living world but also with *how they know it* and *what they still need to learn.* In doing so, we can encourage some students to accept the challenge and become biologists themselves, posing and answering important new questions through their own innovative research. For students who pursue other careers, we hope that they will leave their introductory—and perhaps only—biology course armed with intellectual skills that will enable them to evaluate future discoveries with a critical eye.

In this book, we introduce students to a biologist's "ways of knowing." Research biologists constantly integrate new observations, hypotheses, questions, experiments, and insights with existing knowledge and ideas. To help students engage the world as biologists do, we must not simply introduce them to the current state of knowledge. We must also foster an appreciation of the historical context within which those ideas developed, and identify the future directions that biological research is likely to take.

To achieve these goals, our explanations are rooted in the research that established the basic facts and principles of biology. Thus, a substantial proportion of each chapter focuses on studies that define the state of biological knowledge today. When describing research, we first identify the hypothesis or question that inspired the work and then relate it to the broader topic under discussion. Our research-oriented theme teaches students, through example, how to ask scientific questions and pose hypotheses, two key elements of the scientific process.

Because advances in science occur against a background of research, we also give students a feeling for how biologists of the past formulated basic knowledge in the field. By fostering an appreciation of such discoveries, given the information and theories available to scientists in their own time, we can help students understand the successes and limitations of what we consider cutting edge today. This historical perspective also encourages students to view biology as a dynamic intellectual enterprise, not just a collection of facts and generalities to be memorized.

We have endeavored to make the science of biology come alive by describing how biologists formulate hypotheses and evaluate them using hard-won data; how data sometimes tell only part of a story; and how the results of studies often end up posing more questions than they answer. Although students might prefer simply to learn the "right" answer to a question, they must be encouraged to embrace "the unknown," those gaps in knowledge that create opportunities for further research. An appreciation of what biologists do *not* yet know will draw more students into the field. And by defining *why* scientists do not understand interesting phenomena, we encourage students to think critically about possible solutions and to follow paths dictated by their own curiosity. We hope that this approach will encourage students to make biology a part of their daily lives by having informal discussions and debates about new scientific discoveries.

## Presenting the story line of the research process . . .

In preparing this book, we developed several special features to help students broaden their understanding of the material presented and of the research process itself. A Visual Tour of these features and more begins on page xiii.

- The chapter openers, entitled *Why It Matters . . .*, are engaging, short vignettes designed to capture students' imaginations and whet their appetites for the topic that the chapter addresses. In many cases, this feature tells the story of how a researcher or researchers arrived at a key insight or how biological research solved a major societal problem, explained a fundamental process, or elucidated a phenomenon. The *Why It Matters . . .* also provides a brief summary of the contents of the chapter.
- To complement this historical or practical perspective, each chapter closes with a brief essay entitled *Unanswered Questions,* prepared by an expert or experts in the field. These essays identify important unresolved issues relating to the chapter topic and describe cutting-edge research that will advance our knowledge in the future.
- Each chapter includes a short, boxed essay entitled *Insights from the Molecular Revolution,* which describes how molecular tools allow scientists to answer questions that they could not have posed even 30 years ago. Most *Insights* focus on a single study and include sufficient detail for its content to stand alone.
- Many chapters are further supplemented with one or more short, boxed essays involving three different aspects of research. *Focus on Basic Research* essays describe how research has provided understanding of basic biological principles. *Focus on Applied Research* essays describe research designed to solve practical problems in the world, such as those relating to health or the environment. *Focus on Model Research Organisms* essays introduce model research organisms—such as *Escherichia coli, Drosophila, Arabidopsis, Caenorhabditis,* the mouse, and *Anolis*—and explain why they are used as subjects for in-depth analysis.

Three types of specially designed *research figures* provide more detailed information about how biologists formulate and test specific hypotheses by gathering and interpreting data. The research figures are listed on the endpapers at the back of the book.

- *Experimental Research* figures describe specific studies in which researchers used both experimental and control treatments—either in the laboratory or in the field—to test hypotheses or answer research questions by manipulating the system they studied.
- *Observational Research* figures describe specific studies in which biologists have tested hypotheses by comparing systems under varying natural circumstances.
- *Research Method* figures provide examples of important techniques, such as the scientific method, cloning a gene, DNA microarray analysis, plant cell culture, producing monoclonal antibodies, radiometric dating, and cladistic analysis. Each *Research Method* figure leads a student through the purpose of the technique and protocol and describes how scientists interpret the data it generates.

## Integrating effective, high-quality visuals into the narrative . . .

Today's students are accustomed to receiving ideas and information visually, making the illustrations and photographs in a textbook important. Our illustration program provides an exceptionally clear supplement to the narrative in a style that is consistent throughout the book. Graphs and anatomical drawings are annotated with interpretative explanations that lead students, step by step, through the major points they convey.

For the second edition, we undertook a rigorous review of all the art in the text. The publishing team identified the key elements of effective illustrations. In focus groups and surveys, instructors helped us identify the "Key Visual Learning Figures" covering concepts or processes that demand premier visual learning support. Each of these figures was critiqued by our Art Advisory Board to ensure its usability and accuracy. For the third edition, we again evaluated each illustration and photograph carefully and made appropriate changes to improve their use as teaching tools. New illustrations for the edition were created in the same style as existing ones.

For the third edition, important figures were developed as *Closer Look* figures; a Summary and a concluding *Think Like a Scientist* question are designed to enhance student learning. Many *Closer Look* figures involve key biological processes, such as meiosis, transcription, muscle contraction, the cohesion-tension mechanism of water transport in plants, ecological interactions between predators and prey, and the haplodiploidy genetic system in social insects.

## Organizing chapters around important concepts . . .

As authors and college teachers, we understand how easily students can get lost within a chapter. When students request advice about how to read a chapter and learn the material in it, we usually suggest that, after reading each section, they pause and quiz themselves on the material they have just encountered. After completing all of the sections in a chapter, they should quiz themselves again, even more rigorously, on the individual sections and, most important, on how the concepts developed in the different sections fit together. Accordingly, we have adopted a structure for each chapter to help students review concepts as they learn them.

- The organization within chapters presents material in digestible sections, building on students' knowledge and understanding as they acquire it. Each major section covers one broad topic. Each subsection, titled with a declarative sentence that summarizes the main idea of its content, explores a narrower range of material.
- Whenever possible, we include the derivation of unfamiliar terms so that students will see connections between words that share etymological roots. Mastery of the technical language of biology will allow students to discuss ideas and processes precisely. At the same time, we have minimized the use of unnecessary jargon.
- *Study Break* questions follow every major section. These questions encourage students to pause at the end of a section and review what they have learned before going on to the next topic within the chapter. Short answers to these questions appear in an appendix.

## Encouraging active learning, critical thinking, and self-assessment of learning outcomes . . .

The third edition of *Biology: The Dynamic Science* includes a new active learning feature, *Think Like a Scientist,* which is designed to help students think analytically and critically about research presented in the chapter. *Think Like a Scientist* questions appear at the ends of *Experimental Research* figures, *Observational Research* figures, *Closer Look* figures, *Insights from the Molecular Revolution* boxes, and *Unanswered Questions.*

The new edition also includes *Think Outside the Book,* an active learning feature introduced in the second edition. *Think Outside the Book* activities have been designed to encourage students to explore biology directly or through electronic resources. Students may engage in these activities either individually or in small groups.

Supplementary materials at the end of each chapter help students review the material they have learned, assess their understanding, and think analytically as they apply the principles developed in the chapter to novel situations. Many end-of-chapter questions also serve as good starting points for class discussions or out-of-class assignments.

- *Review Key Concepts* provides a summary of important ideas developed in the chapter, referencing specific figures and tables in the chapter. These *Reviews* are no substitute for reading the chapter, but students may use them as a valuable outline of the material, filling in the details on their own.
- *Understand & Apply* includes five types of end-of-chapter questions and problems that focus on the chapter's factual content while encouraging students to apply what they have learned: (1) *Test Your Knowledge* is a set of 10 questions (with answers in an appendix) that focus on factual material; (2) *Discuss the Concepts* involves open-ended questions that emphasize key ideas, the interpretation of data, and practical applications of the material; (3) *Design an Experiment* questions help students hone their critical thinking skills by asking them to test hypotheses that relate to the chapter's main topic; (4) *Interpret the Data* questions help students develop analytical and quantitative skills by asking them to interpret graphical or tabular results of experimental or observational research experiments for which the hypotheses and methods of analysis are presented; and (5) *Apply Evolutionary Thinking* asks students to answer a question in relation to the principles of evolutionary biology.

## Helping students master key concepts throughout the course . . .

Teachers know that student effort is an important determinant of student success. Unfortunately, most teachers lack the time to develop novel learning tools for every concept—or even every chapter—in an introductory biology textbook. To help address this problem, we are pleased to offer **Aplia for Biology,** an automatically graded homework management system tailored to this edition. For students, Aplia provides a structure within which they can expand their efforts, master key concepts throughout the course, and increase their success. For faculty, Aplia can help transform teaching and raise productivity by requiring more—and more consistent—effort from students without increasing faculty workloads substantially. By providing students with continuous exposure to key concepts and their applications throughout the course, Aplia allows faculty to do what they do best—respond to questions, lead discussions, and challenge the students.

We hope you agree that we have developed a clear, fresh, and well-integrated introduction to biology as it is understood by researchers today. Just as important, we hope that our efforts will excite students about the research process and the biological discoveries it generates.

# New to This Edition

The enhancements we have made in the third edition of *Biology: The Dynamic Science* reflect our commitment to provide a text that introduces students to new developments in biology while fostering active learning and critical thinking. As a part of this effort, we have added *Closer Look* figures that integrate a major concept into a highlighted visual presentation. The key concept is stated briefly at the top, shown in detail through one or more illustrations, and summarized at the bottom. A *Think Like a Scientist* question invites students to apply the figure concept(s) to a related problem or issue. We have also incorporated *Think Like a Scientist* questions into *Insights from the Molecular Revolution* and *Unanswered Questions,* as well as into *Experimental Research* and *Observational Research* figures.

We have also made important changes in coverage to follow recent scientific advances. A new Chapter 19, Genomes and Proteomes, introduces methods of genomics and proteomics along with examples of new discoveries and insights. In addition, we now devote two chapters to plant diversity, discussing seedless plants in Chapter 28 and seed plants in Chapter 29. Finally, we've consolidated our treatment of animal behavior into a single Chapter 56 (Animal Behavior), which integrates various approaches to this subfield of biology. Beyond these major organizational changes, we have made numerous improvements to update and clarify scientific information and to engage students as interested readers and active learners, as well as responsive scientific thinkers. The following sections highlight some of the new content and organizational changes in this edition.

## Unit One: Molecules and Cells

To make molecular and cellular processes easier to grasp, this unit incorporates explanatory material into many more illustrations. For example, in Chapter 3 (Biological Molecules: The Carbon Compounds of Life), Table 3.1 now presents more information on the roles of functional groups of organic molecules and a new Figure 3.3 clarifies the concept of stereoisomers. In Chapter 5 (The Cell: An Overview), we have combined the diagrams of animal and plant cells in Figure 5.9 and labeled functions of the organelles. In Chapter 8 (Harvesting Chemical Energy: Cellular Respiration), a new overview diagram of glycolysis (Figure 8.7) helps students understand basic concepts. Chapter 10 (Cell Division and Mitosis) features a new discussion and illustration of the tight pairing of chromatids (sister chromatid cohesion) during mitosis.

New references to molecular aspects of evolution have been integrated into Unit One chapters to emphasize evolution as the theme unifying the subfields of the biological sciences. For example, in Chapter 5 (The Cell: An Overview), the discussion of the mitochondrial matrix now highlights how equivalent structures in bacteria led scientists to propose and develop the endosymbiotic theory. In Chapter 6 (Membranes and Transport), we point out that the close similarity of bilayer membranes in all cells—prokaryotic and eukaryotic—is evidence that the basic structure of membranes evolved during the earliest stages of life on Earth, and has been conserved ever since. In Chapter 9 (Photosynthesis), a new section, *Evolution of Photosynthesis and Cellular Respiration,* summarizes the evolutionary development of these processes.

## Unit Two: Genetics

Chapter 11 (Meiosis: The Cellular Basis of Sexual Reproduction) includes fuller descriptions of homologous chromosomes and sex chromosomes. Extensive revision and expansion of Chapter 16 (Regulation of Gene Expression) provides more thorough coverage of gene regulation and the operon model. We now introduce the role of DNA-binding proteins in prokaryotic as well as eukaryotic gene regulation and include more detail on the activation of regulatory molecules. We have also added detail on combinatorial gene regulation, along with a figure showing a specific example, and have added new information and an illustration of how growth factors and growth-inhibiting factors affect cell division. Chapter 17 (Bacterial and Viral Genetics) includes new information on how horizontal gene transfer contributes to genome evolution in prokaryotes, and evidence of its possible contribution to eukaryotic genome evolution.

A new Chapter 19 (Genomes and Proteomes) focuses on the methods of genomics and the information it generates. This chapter describes how genome sequences are determined and annotated, how genes in genomes are identified and characterized, and how studies have generated new information on the evolution of genes and of genomes. It also includes examples of how genomics has become a source of new discoveries in many fields, including human physiology and evolutionary biology.

## Unit Three: Evolutionary Biology

In Chapter 21 (Microevolution: Genetic Changes within Populations), *Observational Research* Figure 21.11 now shows more clearly how opposing forces of directional selection produce stabilizing selection. Plant speciation by alloploidy and polyploidy is shown in parallel illustrations in one figure (22.16), allowing easy comparison. In Chapter 23 (Paleobiology and Macroevolution), Figure 23.15 clarifies our understanding of the rise and fall of plant lineages through evolutionary time. Chapter 24 (Systematics and Phylogenetics: Revealing the Tree of Life) includes a new example of how systematists construct phylogenetic trees with genetic distance data and includes a clarified discussion of statistical methods used to construct phylogenetic trees. Reworked phylogenetic trees throughout Chapter 24 are now fully consistent in presentation.

## Unit Four: Biodiversity

In Chapter 26 (Prokaryotes: Bacteria and Archaea), a new *Insights from the Molecular Revolution* describes how changes in gene expression in the bacterium that causes gingivitis help govern its transition from a free-living state to a biofilm. A revised and expanded section discusses the five subgroups of proteobacteria. In Chapter 27 (Protists), we've added the nucleariids to the Opisthokont group, along with evidence that they may be more closely related to fungi than to animals.

Plant diversity is now covered in two chapters. Chapter 28 (Seedless Plants) describes trends in land plant evolution and the characteristics of bryophytes and seedless vascular plants, and Chapter 29 (Seed Plants) focuses on adaptations and distinguishing features of gymnosperms and flowering plants. Chapter 28 also includes a new *Unanswered Questions* essay, and Chapter 29 presents a new *Insights from the Molecular Revolution* feature on plant genome evolution. Chapter 30 (Fungi) presents an updated discussion of the evolution of multicellular animals and fungi from different opisthokont ancestors. Changes to Chapter 31 (Animal Phylogeny, Acoelomates, and Protostomes) include color-coding of anatomical illustrations of invertebrates to distinguish structures arising from endoderm, mesoderm, and ectoderm, and a new Table 31.1 providing a phylogenetic overview of the phyla presented in the chapter. In Chapter 32 (Deuterostomes: Vertebrates and Their Closest Relatives), a new *Insights from the Molecular Revolution* feature describes a study of the evolutionary gains and losses of genes that code for olfactory receptor proteins in various clades of mammals. Figure 32.38, which shows timelines for the species of hominins, has been updated with recently discovered fossils. The discussion of human evolution includes recent genomic studies of the relationship between Neanderthals and modern humans.

## Unit Five: Plant Structure and Function

Chapter 33 (The Plant Body) features clearer illustrations of plant growth. Chapter 34 (Transport in Plants) has more focused discussions and illustrations of water movements in roots and the physiology of stomatal function. A new *Unanswered Questions* explores research in plant metabolomics. Chapter 36 (Reproduction and Development in Flowering Plants) includes refined diagrams of floral whorls and self-incompatibility, an updated *Insights from the Molecular Revolution* on trichome development, and an updated *Experimental Research* figure on studies of floral organ identity genes. Chapter 37 (Plant Signals and Responses to the Environment) begins with a new *Why It Matters* essay presenting the diverse adaptations of creosote bush *(Larrea tridentata)* to environmental challenges such as extended drought. The chapter also has been reorganized, with the discussion of signal transduction pathways and second messenger systems now included in the introduction to plant hormones. New art illustrates current thinking on different signal transduction mechanisms in plant cells.

## Unit Six: Animal Structure and Function

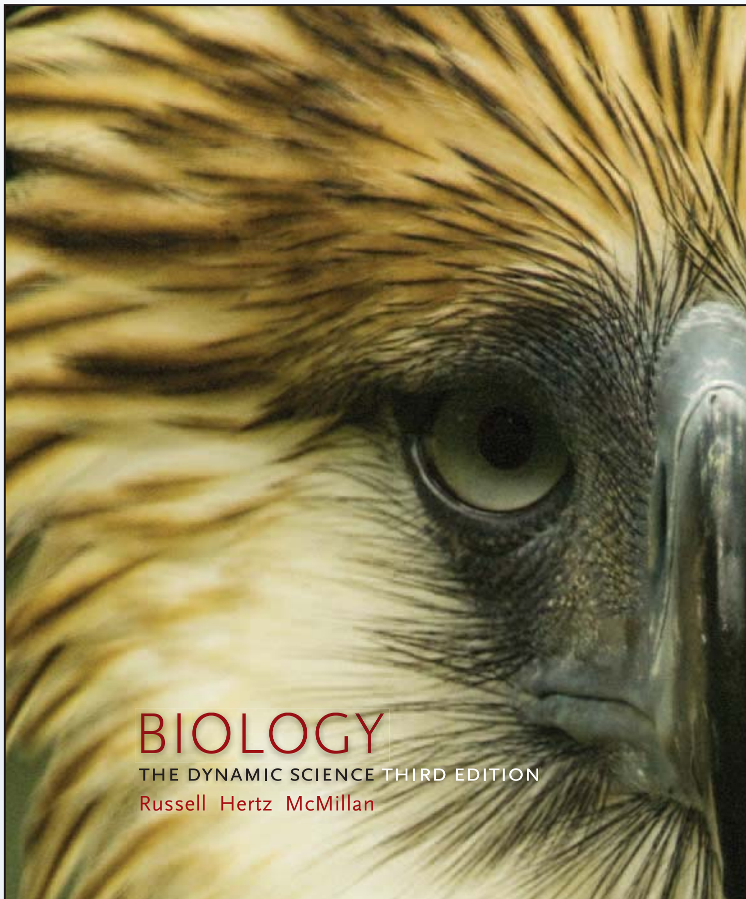
In Chapter 43 (Muscles, Bones, and Body Movements), a new *Insights from the Molecular Revolution* presents experiments on exercise training in racehorses. We have updated and clarified the discussion of immunity in Chapter 45 (Defenses against Disease) and added new material on how microbial pathogens are detected and how pathogens may sometimes escape recognition by the immune system. In Chapter 47 (Animal Nutrition), we have added detail on absorption in the small intestine. Chapter 48 (Regulating the Internal Environment) has expanded coverage of mammalian kidney function and the role of countercurrent heat exchanges in maintaining body temperature. In Chapter 50 (Animal Development), we have revised and expanded Section 50.5, The Cellular Basis of Development, including new information on apoptosis during development and on molecular mechanisms of induction.

## Unit Seven: Ecology and Behavior

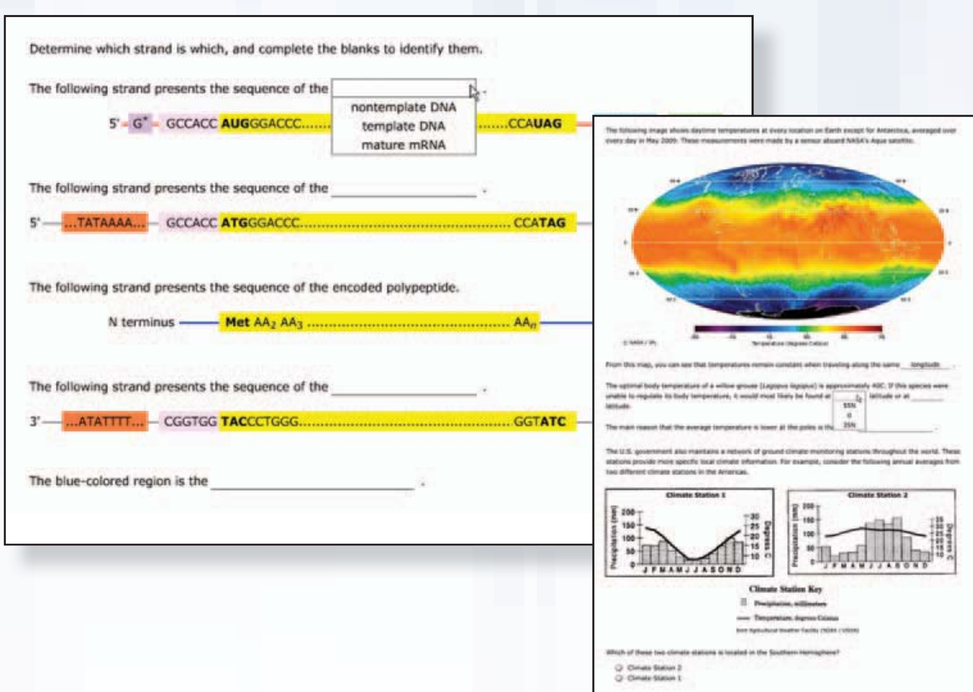
In Chapter 51 (Ecology and the Biosphere), improved illustrations clarify the effects of latitudinal and seasonal variations in incoming solar radiation. In Chapter 52 (Population Ecology), we have updated Figures 52.22 and 52.23 on human population growth. In Chapter 53 (Population Interactions and Community Ecology), we have improved Figure 53.22 showing the food web. We have also added informative labels to Figure 53.25, which shows the effects of storms on corals. Chapter 55 (Biodiversity and Conservation Biology) features a new Figure 55.16 illustrating the species–area relationship. A unified Chapter 56 (Animal Behavior) concludes the text, integrating the discussions of genetic and experiential bases of animal behavior, the neurophysiological and endocrinological control of specific behaviors, and the ecology and evolution of several broad categories of animal behavior.

# THINK AND ENGAGE LIKE A SCIENTIST!

**Develop a deep understanding of the core concepts in biology and build a strong foundation for future courses.**




Welcome to **Biology: The Dynamic Science, Third Edition,** by Peter J. Russell, Paul E. Hertz, and Beverly McMillan. The authors convey their passion for biology as they guide you to an understanding of what scientists know about the living world, how they know it, and what they still need to learn. The pages that follow highlight a few of the many ways that they have made this book a great learning tool for you. You'll also find information about dynamic online resources, as well as print materials that will help you master key concepts and succeed in the course.




**Aplia for Biology,** an interactive online tool that complements the text and helps you learn and understand key concepts through focused assignments, an engaging variety of problem types, exceptional text/art integration, and immediate feedback.

# A BIG PICTURE FOCUS

**Straightforward explanations of fundamental concepts bind the biological sciences together and enable you to see the big picture. Easy-to-use learning tools point out the topics covered in each chapter, show why they are important, and help you learn the material.**

22

Two closely related bird species, purple martins *(Progne subis)* and tree swallows *(Tachycineta bicolor)* perching together on a branch in Crane Creek, Ohio.

STUDY OUTLINE

22.1 What Is a Species?
22.2 Maintaining Reproductive Isolation
22.3 The Geography of Speciation
22.4 Genetic Mechanisms of Speciation

## Speciation

**FIGURE 22.1 Birds of paradise.** A male Count Raggi's bird of paradise *(Paradisaea raggiana)* tries to attract the attention of a female (not pictured) with his showy plumage and conspicuous display. There are 43 known bird of paradise species, 35 of them found only on the island of New Guinea.

**Why it matters . . .** In 1927, nearly 100 years after Darwin boarded the *Beagle,* a young German naturalist named Ernst Mayr embarked on his own journey, to the highlands of New Guinea. He was searching for rare "birds of paradise" **(Figure 22.1).** These birds were known in Europe only through their ornate and colorful feathers, which were used to decorate ladies' hats. On his trek through the remote Arfak Mountains, Mayr identified 137 bird species (including many birds of paradise) based on differences in their size, plumage, color, and other external characteristics.

To Mayr's surprise, the native Papuans—who were untrained in the ways of Western science, but who hunted these birds for food and feathers—had their own names for 136 of the 137 species he had identified. The close match between the two lists confirmed Mayr's belief that the *species* is a fundamental level of organization in nature. Each species has a unique combination of genes underlying its distinctive appearance and habits. Thus, people who observe them closely—whether indigenous hunters or Western scientists—can often distinguish one species from another.

Mayr also discovered some remarkable patterns in the geographical distributions of the bird species in New Guinea. For example, each mountain range he explored was home to some species that lived nowhere else. Closely related species often lived on different mountaintops, separated by deep valleys of unsuitable habitat. In 1942, Mayr published the book *Systematics and the Origin of Species,* in which he described the role of geography in the evolution of new species; the book quickly became a cornerstone of the modern synthesis (which was outlined in Section 20.3).

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**Study Outline** provides an overview of main chapter topics and key concepts. Each section breaks the material into a manageable amount of information, so you can develop understanding as you acquire knowledge.

**Why It Matters** sections at the beginning of each chapter capture the excitement of biology and help you understand why the topic is important and how the material that follows fits into the big picture.

**Study Break** sections encourage you to pause and think about the material you have just encountered before moving to the next section.

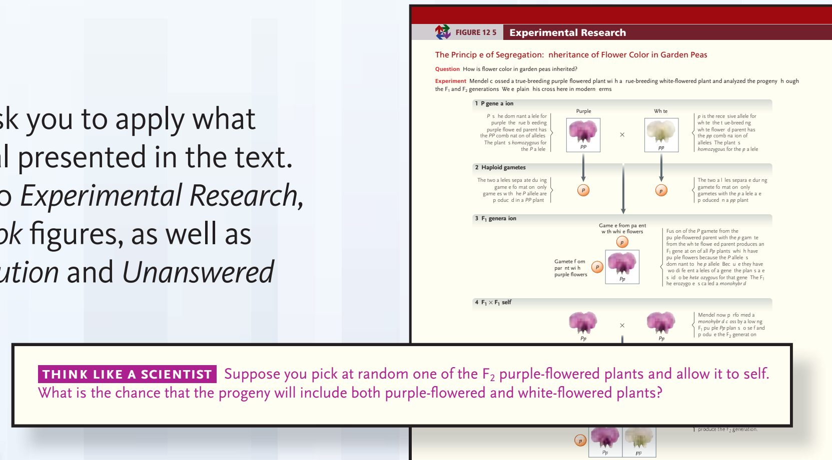
**STUDY BREAK 22.1**

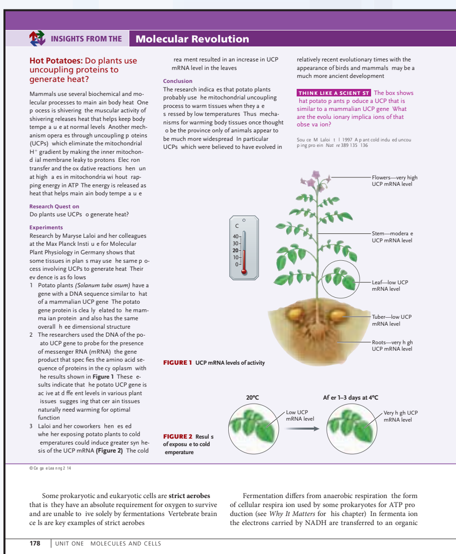
1. How do the morphological, biological, and phylogenetic species concepts differ?
2. What is clinal variation?

**Your study of biology focuses not only on *what* scientists know about the living world but also *how* they know it. Use these unique features to learn how scientists ask scientific questions, pose hypotheses, and test them.**

**NEW!**

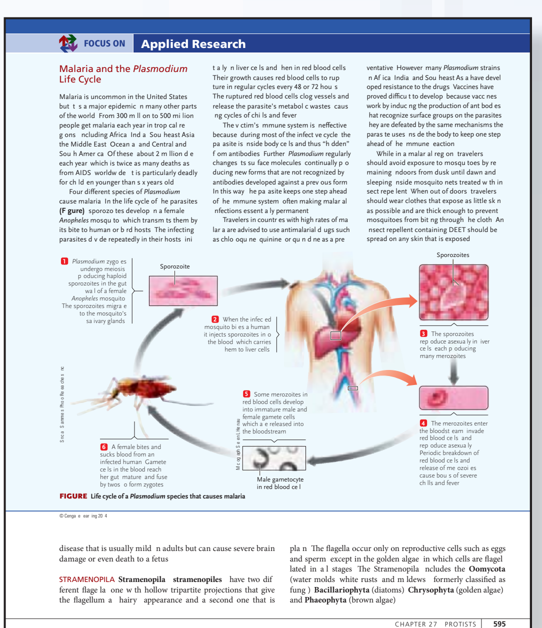
**"Think Like a Scientist"** questions ask you to apply what you have learned beyond the material presented in the text. These questions are incorporated into *Experimental Research*, *Observational Research*, and *Closer Look* figures, as well as into *Insights from the Molecular Revolution* and *Unanswered Questions* boxes.




**Insights from the Molecular Revolution** essays highlight how molecular technologies allow researchers to answer questions that they could not even pose 20 or 30 years ago.


**Unanswered Questions** explore important unresolved issues identified by experts in the field and describe cutting-edge research that will advance our knowledge in the future.




**Focus on Research** boxes present research topics in more depth.

***Focus on Applied Research*** describes how scientific research has solved everyday problems.

***Focus on Basic Research*** describes seminal research that provided insight into an important problem.

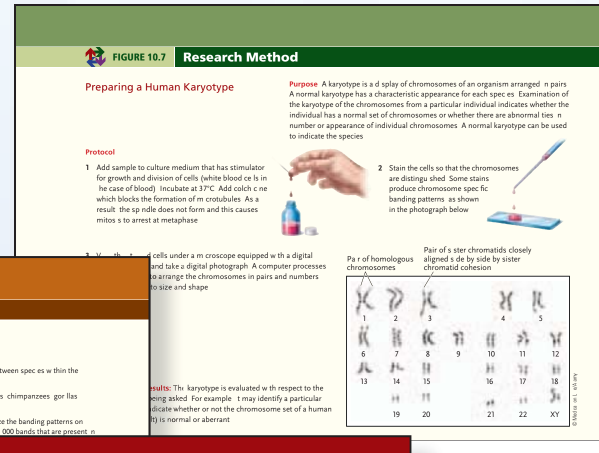
***Focus on Model Research Organisms*** explains why researchers use certain organisms as research subjects.

# ENGAGE LIKE A SCIENTIST

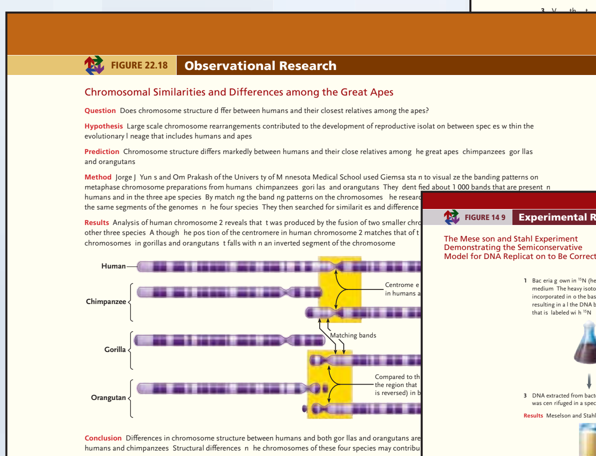
**Be Active. Get involved in the process of learning and doing biology.**

**Research Figures** provide information about how biologists formulate and test specific hypotheses by gathering and interpreting data.

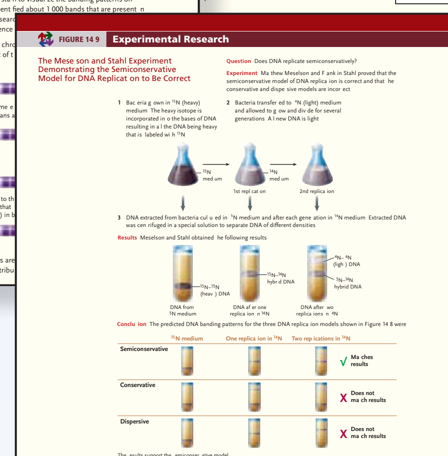
*Research Method*




*Observational Research*




*Experimental Research*

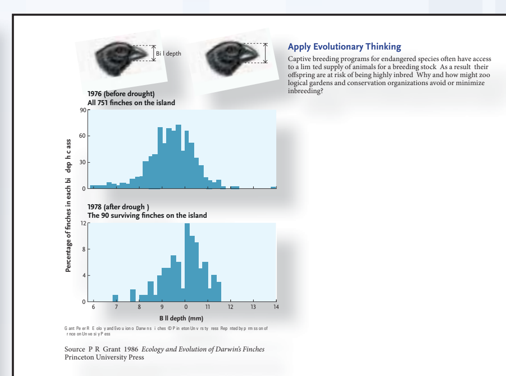



**Interpret the Data** exercises, drawn from published biological research, help you build your skills in analyzing figures and reading graphs or tables.

eat rather than by genetic factors.

### Interpret the Data

Peter and Rosemary Grant of Princeton University have studied the ecology and evolution of finches on the Galápagos Islands since the early 1970s. They have shown that finches with large bills (as measured by bill depth; see **Figure**) can eat both small seeds and large seeds, but finches with small bills can only eat small seeds. In 1977, a severe drought on the island of Daphne Major reduced seed production by plants. After the birds consumed whatever small seeds they found, only large seeds were still available. The resulting food shortage killed a majority of the medium ground finches *(Geospiza fortis)* on Daphne Major; their population plummeted from 751 in 1976 to just 90 in 1978. The Grants' research also documented a change in the distributions of bill depths in the birds from 1976 to 1978, as illustrated in the graphs to the right. In light of what you now know about the relationship between bill size and food size for these birds, interpret the change illustrated in the graph. What type of natural selection does this example illustrate?




**Think Outside the Book** activities help you think analytically and critically as you explore the biological world, either on your own or as part of a team.

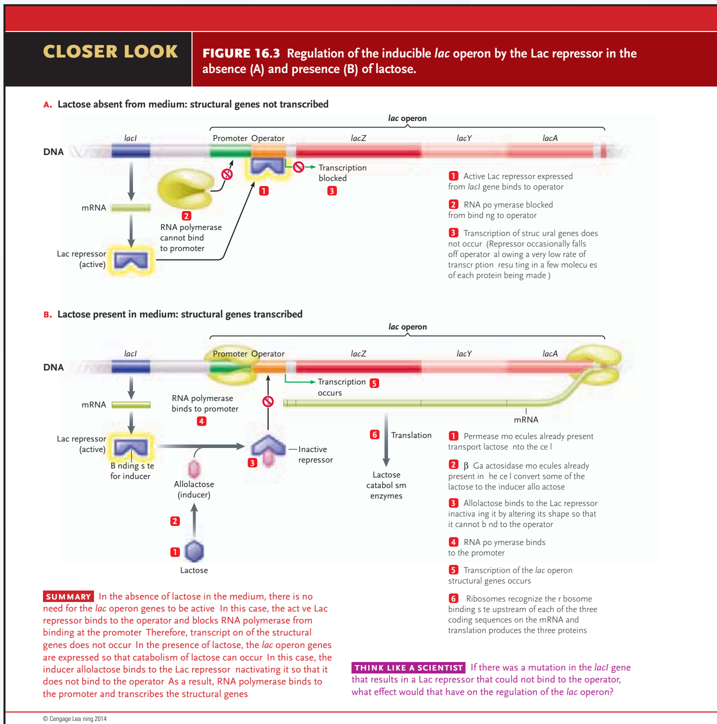
**THINK OUTSIDE THE BOOK**

Earlier in the chapter we mentioned the fact that cloned animals may have many genes whose expression is abnormal compared to gene expression in a nonclоned mammal. Individually or collaboratively, outline the steps you would take experimentally to determine, on a genome-wide scale, if genes are abnormally expressed in a cloned mammal. Your answer should include how the experiment reveals both qualitative and quantitative differences in gene expression.

**THINK OUTSIDE THE BOOK**

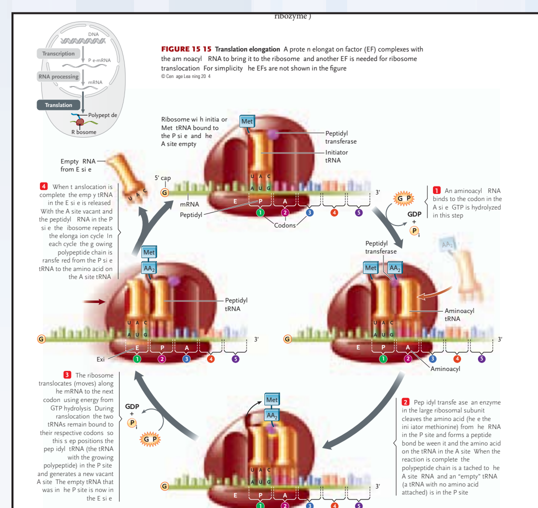
Access the web page for the Tree of Life project at http://www.tolweb.org/tree/. Select a group of animals or plants that is of interest to you, and study the structure of its phylogenetic tree. How many major clades does it include? On the basis of what shared derived characters are those clades defined?

## Spectacular illustrations—developed with great care—help you visualize biological processes, relationships, and structures.

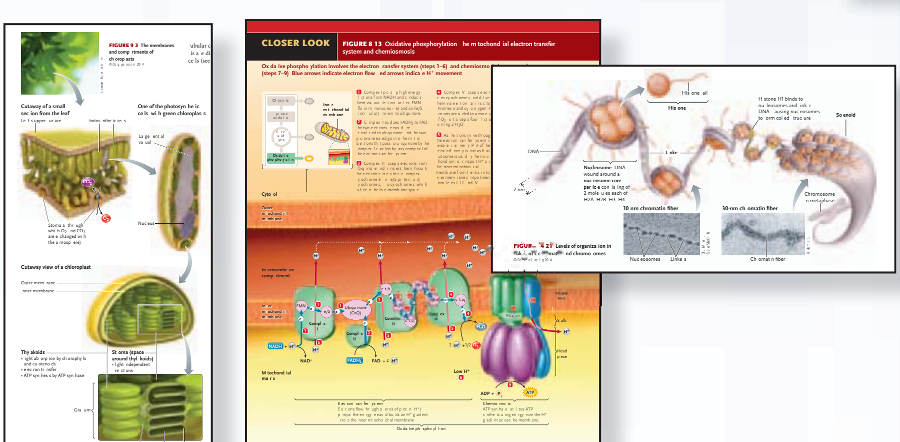



## NEW!

**"Closer Look" figures** help you gain a better understanding of a major concept through a visual presentation, usually a detailed, multistep diagram. The figures end with a *Summary* and a *Think Like a Scientist* question.




**Illustrations of complex biological processes** are annotated with ***numbered step-by-step explanations*** that lead you through all the major points. Orientation diagrams are inset on figures and help you identify the specific biological process being depicted and where the process takes place.




**Macro-to-Micro views** help you visualize the levels of organization of biological structures and how systems function as a whole.

# REVIEW

**End-of-chapter material encourages you to review, assess your understanding, think analytically, and apply what you have learned to novel situations.**

**Review Key Concepts** provides an outline summary of important ideas developed in the chapter and references the chapter's figures and tables.

### REVIEW KEY CONCEPTS

To access the course materials and companion resources for this text, please visit www.cengagebrain.com.

#### 18.1 DNA Cloning

- Producing multiple copies of genes by cloning is a common first step for studying the structure and function of genes, or for manipulating genes. Cloning involves cutting genomic DNA and a cloning vector with the same restriction enzyme, joining the fragments to produce recombinant plasmids, and introducing those plasmids into a living cell such as a bacterium, where replication of the plasmid takes place (Figures 18.1–18.3).
- A clone containing a gene of interest may be identified among a population of clones by using DNA hybridization with a labeled nucleic acid probe (Figure 18.5).
- A genomic library is a collection of clones that contains a copy of every DNA sequence in the genome. A cDNA (complementary DNA) library is the entire collection of cloned cDNAs made from the mRNAs isolated from a cell. A cDNA library contains only sequences from the genes that are active in the cell when the mRNAs are isolated

#### 18.2 Applications of DNA Technologies

- Recombinant DNA and PCR techniques are used in DNA molecular testing for human genetic disease mutations. One approach exploits restriction site differences between normal and mutant alleles of a gene that create restriction fragment length polymorphisms (RFLPs) which are detectable by DNA hybridization with a labeled nucleic acid probe (Figures 18.8 and 18.9).
- Human DNA fingerprints are produced from a number of loci in the genome characterized by short, tandemly repeated sequences that vary in number in all individuals (except identical twins). To produce a DNA fingerprint, the PCR is used to amplify the region of genomic DNA for each locus, and the lengths of the PCR products indicate the alleles an individual has for the repeated sequences at each locus. DNA fingerprints are widely used to establish paternity, ancestry, or criminal guilt (Figure 18.10).
- Genetic engineering is the introduction of new genes or genetic information to alter the genetic makeup of humans, other animals, plants, and microorganisms such as bacteria and yeast. Genetic engineering primarily aims to correct hereditary defects, improve domestic animals and crop plants, and provide proteins for medicine, research, and other applications (Figures 18.11–18.13 and 18.15).
- Genetic engineering has enormous potential for research and applications in medicine, agriculture, and industry. Potential risks include unintended damage to living organisms or to the environment.

Animation: How Dolly was created

Animation: DNA fingerprinting

Animation: Transferring genes into plants

### UNDERSTAND & APPLY

#### Test Your Knowledge

1 A complementary DNA library (cDNA) and a genomic library are similar in that both
  a use bacteria to make eukaryotic proteins
  b provide information on whether genes are active
  c contain all of the DNA of an organism cut into pieces
  d clone mRNA
  e depend on cloning in a living cell to produce multiple copies of the DNA of interest

2 Why do the cDNA libraries produced from two different cell types in the human body often conta n different cDNAs?
  a Because different expression vectors must be used to insert cDNAs into different cell types
  b Because different cell types contain different numbers of chromosomes
  c Because different cell types contain different genomic DNA sequences
  d Because different genes are transcribed in different cell types
  e Because different cell types contain different restriction enzymes

3 The point at which a restriction enzyme cuts DNA is deter mined by
  a the sequence of nuc eotides
  b the length of the DNA molecule
  c whether it is closer to the 5′ end or 3′ end of the DNA molecule
  d the number of copies of the DNA molecule in a bacterial cell
  e the location of a start codon in a gene

4 Restriction endonucleases ligases plasmids *E coli* electropho retic gels and a bacterial gene resistant to an antibiotic are all re quired for
  a dideoxyribonucleotide ana ysis
  b PCR
  c DNA cloning
  d DNA fingerprinting
  e DNA sequencing

5 After a polymerase chain reaction (PCR) agarose gel electropho resis is often used to
  a amplify the DNA
  b convert cDNA into genomic DNA
  c convert cDNA into messenger RNA
  d verify that the desired DNA sequence has been ampl fied
  e synthesize primer DNA mo ecules

6 Restriction fragment length po ymorphisms (RFLPs)
  a are produced by reaction with restriction endonucleases and are detected by Southern blot analysis
  b are of the same ength for mutant and normal β globin alle es
  c determine the sequence of bases in a DNA fragment
  d have in their middle short fragments of DNA that are palindromic
  e are used as vectors

7 DNA fingerprint ng which is often used n forensics paternity testing and for establishing ancestry
  a compares one stretch of the same DNA between two or more people
  b measures different engths of DNA from many repeating noncoding regions
  c requires the largest DNA engths to run the greatest distance on a gel
  d requires amplification after the gels are run
  e can easily differentiate DNA between identical twins

8 Which of the following is needed both in using bacteria to pro duce proteins and in genetic engineering of human cells?
  a DNA fingerprinting based on microsatellite sequences
  b insertion of a transgene into an expression vector
  c restriction fragment length polymorphism (RFLP)
  d screening of a cDNA library by DNA hybridization
  e antibiotic resistance

9 Dolly a sheep was an examp e of reproductive (germ line) clon ing Required to perform this process was
  a mplantation of uterine cells from one strain into the mam mary g and of another
  b fusion of the mammary cell from one strain with an enucle ated egg of another strain
  c fusion of an egg from one strain with the egg of a different strain
  d fusion of an embryonic diploid cell with an adult haploid cell
  e fusion of two nucleated mammary cells from two different strains

10 Which of the following is *not* true of somatic ce l gene therapy?
  a White blood cells can be used
  b Somatic cells are cultured and the desired DNA is intro duced into them
  c Cells with the introduced DNA are returned to the body
  d The technique is still very experimental
  e The inserted genes are passed to the offspring

**Understand & Apply** end-of-chapter questions focus on both factual and conceptual content in the chapter while encouraging you to apply what you have learned.

#### Apply Evolutionary Thinking

In PCR, researchers use a heat-stable form of DNA polymerase from microorganisms that are able to grow in extremely high temperatures. Given what you learned in Chapter 3 about protein folding, and in Chapter 4 about the effects of temperature on enzymes, would you predict that the amino acids of heat-stable DNA polymerase enzymes would have evolved so they can form stronger chemical attractions with each other, or weaker chemical attractions? Explain your answer.

**Apply Evolutionary Thinking** asks you to interpret a relevant topic in relation to the principles of evolutionary thinking.

#### Design an Experiment

Suppose a biotechnology company has developed a GMO, a transgenic plant that expresses *Bt* toxin. The company sells its seeds to a farmer under the condition that the farmer may plant the seed, but not collect seed from the plants that grow and use it to produce crops in the subsequent season. The seeds are expensive, and the farmer buys seeds from the company only once. How could the company show experimentally that the farmer has violated the agreement and is using seeds collected from the first crop to grow the next crop?

**Design an Experiment** challenges your understanding of the chapter and helps you deepen your understanding of the scientific method as you consider how to develop and test hypotheses about a situation that relates to a main chapter topic.

#### Discuss the Concepts

1. What should juries know to be able to interpret DNA evidence? Why might juries sometimes ignore DNA evidence?
2. A forensic scientist obtained a small DNA sample from a crime scene. In order to examine the sample, he increased its quantity by cycling the sample through the polymerase chain reaction. He estimated that there were 50,000 copies of the DNA in his original sample. Derive a simple formula and calculate the number of copies he will have after 15 cycles of the PCR.

**Discuss the Concepts** enables you to participate in discussions on key questions to build your knowledge and learn from others.

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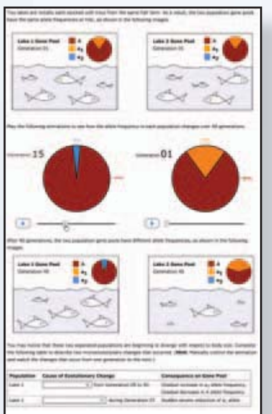
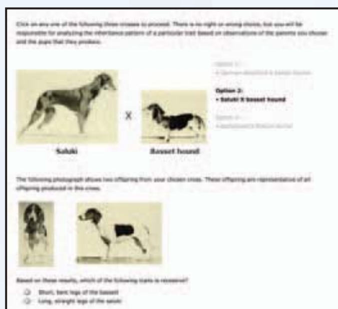


Interactive problems and figures help you visualize dynamic biological processes and integrate concepts, art, media, and homework practice.



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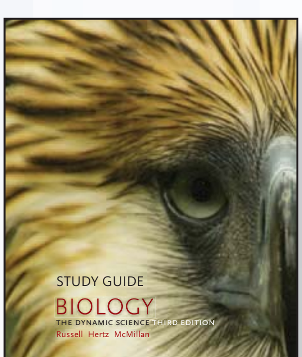


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# Contents


Earth, a planet teeming with life, is seen here in a satellite photograph.

1

# Introduction to Biological Concepts and Research

## STUDY OUTLINE



**Why it matters . . .** Life abounds in almost every nook and cranny on our planet Earth. A lion creeps across an African plain, ready to spring at a zebra. The leaves of a sunflower in Kansas turn slowly through the day, keeping their surfaces fully exposed to rays of sunlight. Fungi and bacteria in the soil of a Canadian forest obtain nutrients by decomposing dead organisms. A child plays in a park in Madrid, laughing happily as his dog chases a tennis ball. In one room of a nearby hospital, a mother hears the first cry of her newborn baby; in another room, an elderly man sighs away his last breath. All over the world, countless organisms are born, live, and die every moment of every day. How did life originate, how does it persist, and how is it changing? Biology, the science of life, provides scientific answers to these questions.

What *is* life? Offhandedly, you might say that although you cannot define it, you know it when you see it. The question has no simple answer, because life has been unfolding for billions of years, ever since nonliving materials assembled into the first organized, living cells. Clearly, any list of criteria for the living state only hints at the meaning of "life." Deeper scientific insight requires a wide-ranging examination of the characteristics of life, which is what this book is all about.

Over the next semester or two, you will encounter examples of how organisms are constructed, how they function, where they live, and what they do. The examples provide evidence in support of concepts that will greatly enhance your appreciation and understanding of the living world, including its fundamental unity and striking diversity. This chapter provides a brief overview of these basic concepts. It also describes some of the ways in which biologists conduct research, the process by which they observe nature, formulate explanations of their observations, and test their ideas.

**FIGURE 1.1 Living organisms and inanimate objects.** Living organisms, such as this lizard *(Iguana iguana)*, have characteristics that are fundamentally different from those of inanimate objects, like the rock on which it is sitting.

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# 1.1 What Is Life? Characteristics of Living Organisms

Picture a lizard on a rock, slowly turning its head to follow the movements of another lizard nearby **(Figure 1.1).** You know that the lizard is alive and that the rock is not. At the atomic and molecular levels, however, the differences between them blur. Lizards, rocks, and all other matter are composed of atoms and molecules, which behave according to the same physical laws. Nevertheless, living organisms share a set of characteristics that collectively set them apart from nonliving matter.

The differences between a lizard and a rock depend not only on the kinds of atoms and molecules present, but also on their organization and their interactions. Individual organisms are at the middle of a hierarchy that ranges from the atoms and molecules within their bodies to the assemblages of organisms that occupy Earth's environments. Within every individual, certain biological molecules contain instructions for building other molecules, which, in turn, are assembled into complex structures. Living organisms must gather energy and materials from their surroundings to build new biological molecules, grow in size, maintain and repair their parts, and produce offspring. They must also respond to environmental changes by altering their chemistry and activity in ways that allow them to survive. Finally, the structure and function of living organisms often change from one generation to the next.

## Life on Earth Exists at Several Levels of Organization, Each with Its Own Emergent Properties

The organization of life extends through several levels of a hierarchy **(Figure 1.2).** Complex biological molecules exist at the lowest level of organization, but by themselves, these molecules are not alive. The properties of life do not appear until they are arranged into cells. A **cell** is an organized chemical system that includes many spe-

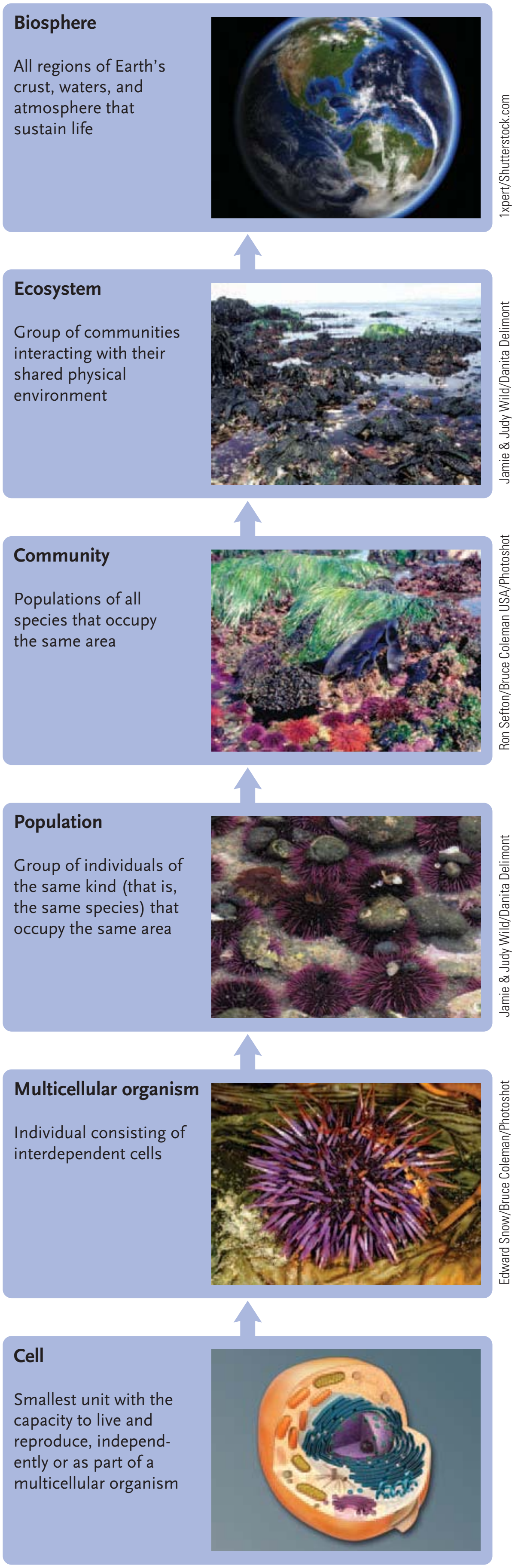


**FIGURE 1.2 The hierarchy of life.** Each level in the hierarchy of life exhibits emergent properties that do not exist at lower levels. The middle four photos depict a rocky intertidal zone on the coast of Washington State.
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cialized molecules surrounded by a membrane. A cell is the lowest level of biological organization that can survive and reproduce—as long as it has access to a usable energy source, the necessary raw materials, and appropriate environmental conditions. However, a cell is alive only as long as it is organized as a cell; if broken into its component parts, a cell is no longer alive even if the parts themselves are unchanged. Characteristics that depend on the level of organization of matter, but do not exist at lower levels of organization, are called **emergent properties.** Life is thus an emergent property of the organization of matter into cells.

Many single cells, such as bacteria and protozoans, exist as **unicellular organisms.** By contrast, plants and animals are **multicellular organisms.** Their cells live in tightly coordinated groups and are so interdependent that they cannot survive on their own. For example, human cells cannot live by themselves in nature because they must be bathed in body fluids and supported by the activities of other cells. Like individual cells, multicellular organisms have emergent properties that their individual components lack; for example, humans can learn biology.

The next, more inclusive level of organization is the **population,** a group of organisms of the same kind that live together in the same place. The humans who occupy the island of Tahiti and a group of sea urchins living together on the coast of Washington State are examples of populations. Like multicellular organisms, populations have emergent properties that do not exist at lower levels of organization. For example, a population has characteristics such as its birth or death rate—that is, the number of individual organisms who are born or die over a period of time—that do not exist for single cells or individual organisms.

Working our way up the biological hierarchy, all the populations of different organisms that live in the same place form a **community.** The algae, snails, sea urchins, and other organisms that live along the coast of Washington State, taken together, make up a community. The next higher level, the **ecosystem,** includes the community *and* the nonliving environmental factors with which it interacts. For example, a coastal ecosystem comprises a community of living organisms, as well as rocks, air, seawater, minerals, and sunlight. The highest level, the **biosphere,** encompasses all the ecosystems of Earth's waters, crust, and atmosphere. Communities, ecosystems, and the biosphere also have emergent properties. For example, communities can be described in terms of their *diversity*—the number and types of different populations they contain—and their *stability*—the degree to which the populations within the community remain the same through time.

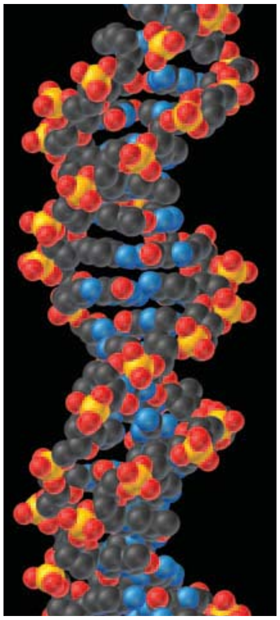


**FIGURE 1.3 Deoxyribonucleic acid (DNA).** A computer-generated model of DNA illustrates that it is made up of two strands twisted into a double helix.



## Living Organisms Contain Chemical Instructions That Govern Their Structure and Function

The most fundamental and important molecule that distinguishes living organisms from nonliving matter is **deoxyribonucleic acid (DNA; Figure 1.3).** DNA is a large, double-stranded, helical molecule that contains instructions for assembling a living organism from simpler molecules. We recognize bacteria, trees, fishes, and humans as different because differences in their DNA produce differences in their appearance and function. (Some nonliving systems, notably certain viruses, also contain DNA, but biologists do not consider viruses to be alive because they cannot reproduce independently of the organisms they infect.)

DNA functions similarly in all living organisms. As you will discover in Chapters 14 and 15, the instructions in DNA are copied into molecules of a related substance, **ribonucleic acid (RNA),** which then directs the synthesis (production) of different protein molecules **(Figure 1.4). Proteins** carry out most of the activities of life, including the synthesis of all other biological

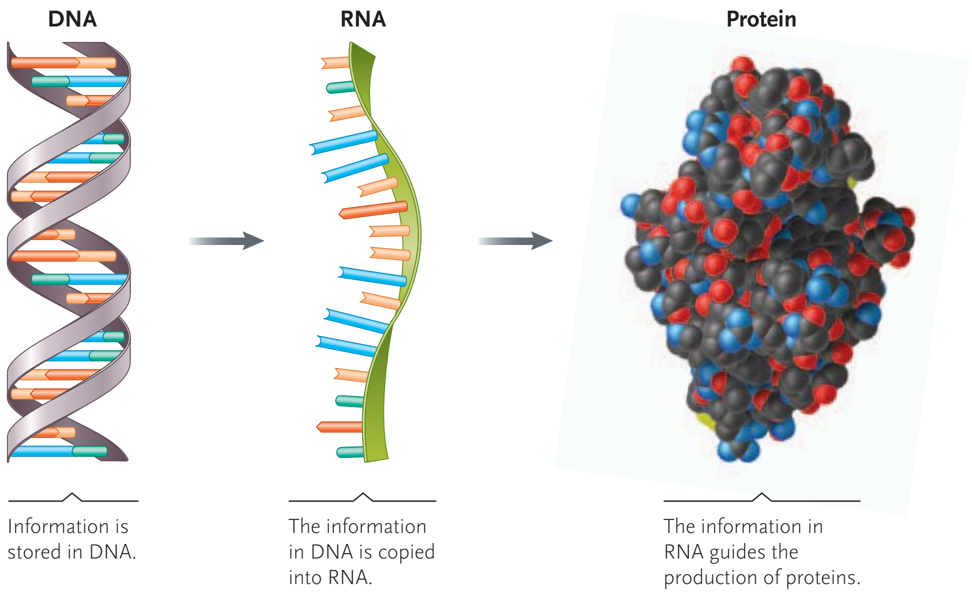



**FIGURE 1.4 The pathway of information flow in living organisms.** Information stored in DNA is copied into RNA, which then directs the construction of protein molecules. The protein shown here is lysozyme.

molecules. This pathway is preserved from generation to generation by the ability of DNA to copy itself so that offspring receive the same basic molecular instructions as their parents.

## Living Organisms Engage in Metabolic Activities

Metabolism, described in Chapters 8 and 9, is another key property of living cells and organisms. **Metabolism** describes the ability of a cell or organism to extract energy from its surroundings and use that energy to maintain itself, grow, and reproduce. As a part of metabolism, cells carry out chemical reactions that assemble, alter, and disassemble molecules **(Figure 1.5).** For example, a growing sunflower plant carries out **photosynthesis,** in which the electromagnetic energy in sunlight is absorbed and converted into chemical energy. The cells of the plant store some chemical energy in sugar and starch molecules, and they use the rest to manufacture other biological molecules from simple raw materials obtained from the environment.

Sunflowers concentrate some of their energy reserves in seeds from which more sunflower plants may grow. The chemical energy stored in the seeds also supports other organisms, such as insects, birds, and humans, that eat them. Most organisms, including sunflower plants, tap stored chemical energy through another metabolic process, **cellular respiration.** In cellular respiration complex biological molecules are broken down with oxygen, releasing some of their energy content for cellular activities.

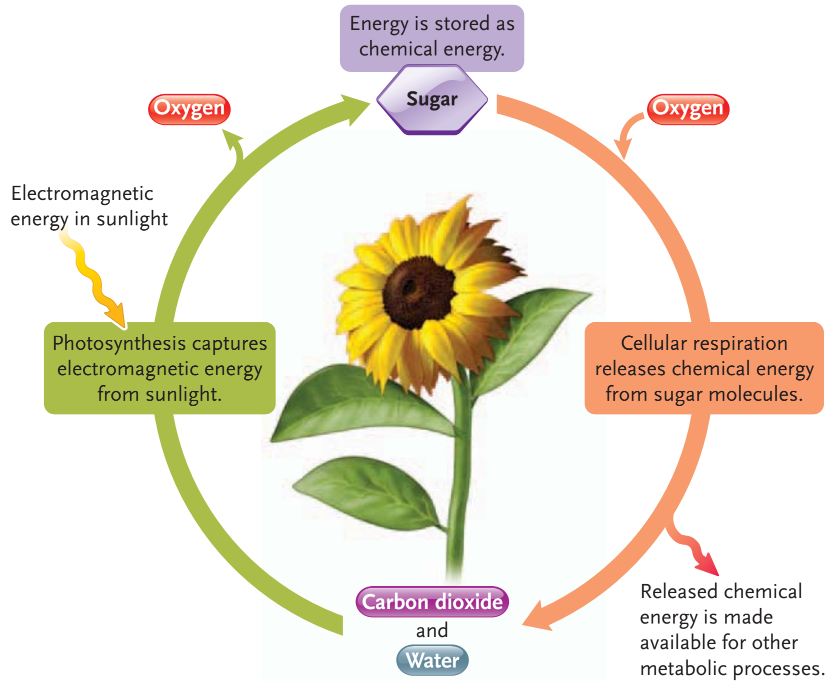



**FIGURE 1.5 Metabolic activities.** Photosynthesis converts the electromagnetic energy in sunlight into chemical energy, which is stored in sugars and starches built from carbon dioxide and water; oxygen is released as a by-product of the reaction. Cellular respiration uses oxygen to break down sugar molecules, releasing their chemical energy and making it available for other metabolic processes.



## Energy Flows and Matter Cycles through Living Organisms

With few exceptions, energy from sunlight supports life on Earth. Plants and other photosynthetic organisms absorb energy from sunlight and convert it into chemical energy. They use this chemical energy to assemble complex molecules, such as sugars, from simple raw materials, such as water and carbon dioxide. As such, photosynthetic organisms are the **primary producers** of the food on which all other organisms rely **(Figure 1.6).** By contrast, animals are **consumers:** directly or indirectly, they feed on the complex molecules manufactured by plants. For example, zebras tap directly into the molecules of plants when they eat grass, and lions tap into it indirectly when they eat zebras. Certain bacteria and fungi are **decomposers:** they feed on the remains of dead organisms, breaking down complex biological molecules into simpler raw materials, which may then be recycled by the producers.

As you will see in Chapter 54, much of the energy that photosynthetic organisms trap from sunlight *flows* within and between populations, communities, and ecosystems. But because the transfer of energy from one organism to another is not 100% efficient, a portion of that energy is lost as heat. Although some animals can use this form of energy to maintain body temperature, it cannot sustain other life processes. By contrast, matter—nutrients such as carbon and nitrogen—*cycles* between living organisms and the nonliving components of the biosphere, to be used again and again (see Figure 1.6).

## Living Organisms Compensate for Changes in the External Environment

All objects, whether living or nonliving, respond to changes in the environment; for example, a rock warms up on a sunny day and cools at night. But only living organisms have the capacity to detect environmental changes and *compensate* for them through controlled responses. Diverse and varied *receptors*—molecules or larger structures located on individual cells and body surfaces—can detect changes in external and internal conditions. When stimulated, the receptors trigger reactions that produce a compensating response.

For example, your internal body temperature remains reasonably constant, even though the environment in which you live is usually either cooler or warmer than you are. Your body compensates for these environmental variations and maintains its internal temperature at about 37° Celsius (C). When the environmental temperature drops significantly, receptors in your skin detect the change and transmit that information to your brain. Your brain may send a signal to your muscles, causing you to shiver, thereby releasing heat that keeps your body temperature from dropping below its optimal level. When the environmental temperature rises significantly, glands in your skin secrete sweat, which evaporates, cooling the skin and its underlying blood supply. The cooled blood circulates internally and keeps your body temperature from rising above 37°C. People also compensate behaviorally by dressing warmly on a cold winter day or jumping into a swimming pool in the heat of summer. Keeping your internal temperature within a narrow range is one example of **homeostasis**—a steady internal condition maintained by responses that compensate for changes in the external environment. As described in Units 5 and 6, all organisms have mechanisms that maintain homeostasis in relation to temperature, blood chemistry, and other important factors.

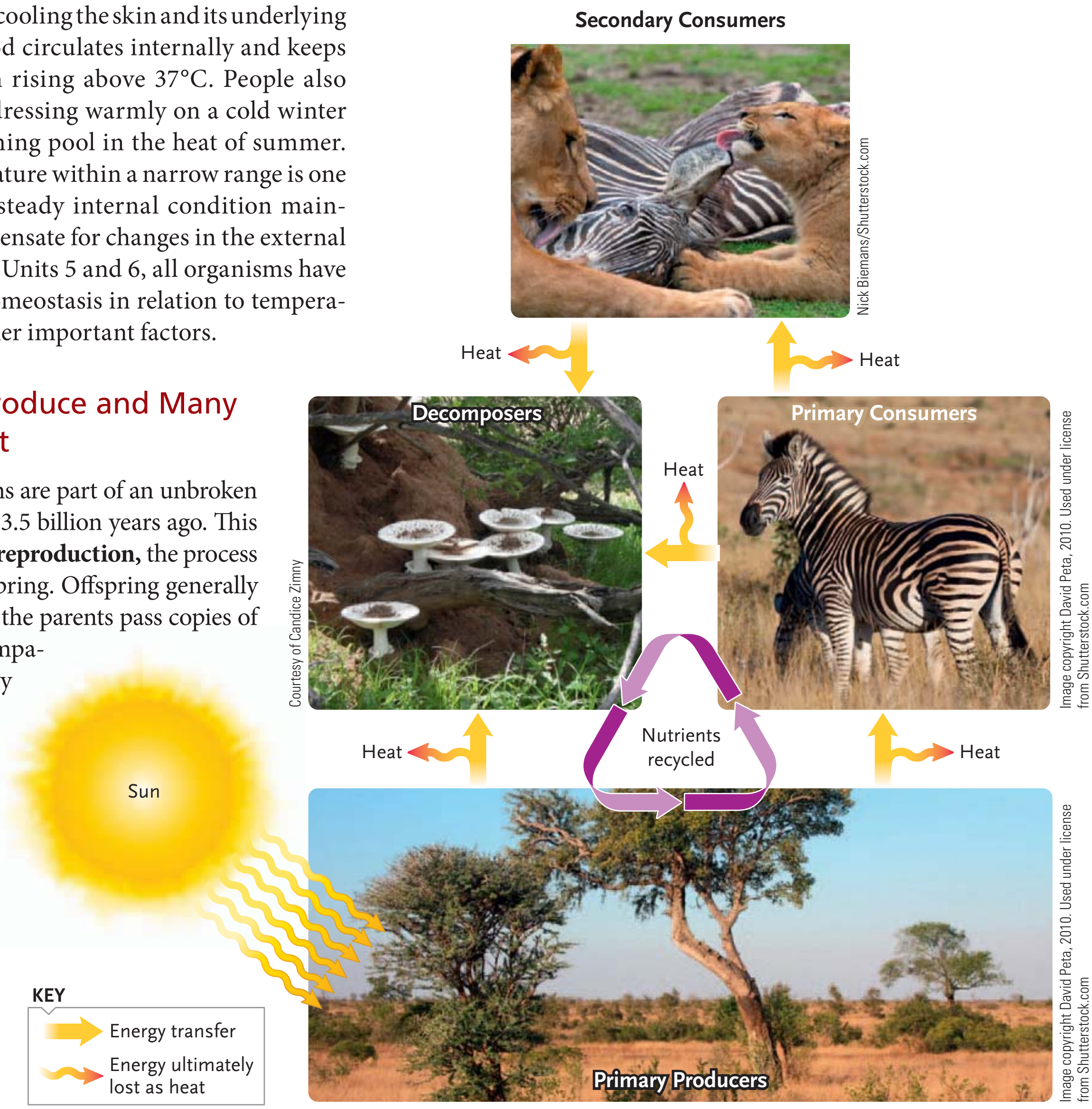



**FIGURE 1.6 Energy flow and nutrient recycling.** In most ecosystems, energy flows from the sun to producers to consumers to decomposers. On the African savanna, the sun provides energy to grasses (producers); zebras (primary consumers) then feed on the grasses before being eaten by lions (secondary consumers); fungi (decomposers) absorb nutrients and energy from the digestive wastes of animals and from the remains of dead animals and plants. All of the energy that enters an ecosystem is ultimately lost from the system as heat. Nutrients move through the same pathways, but they are conserved and recycled.



## Living Organisms Reproduce and Many Undergo Development

Humans and all other organisms are part of an unbroken chain of life that began at least 3.5 billion years ago. This chain continues today through **reproduction,** the process by which parents produce offspring. Offspring generally resemble their parents because the parents pass copies of their DNA—with all the accompanying instructions for virtually every life process—to their offspring. The transmission of DNA (that is, genetic information) from one generation to the next is called **inheritance.** For example, the eggs produced by storks hatch into little storks, not into pelicans, because they inherited stork DNA, which is different from pelican DNA.

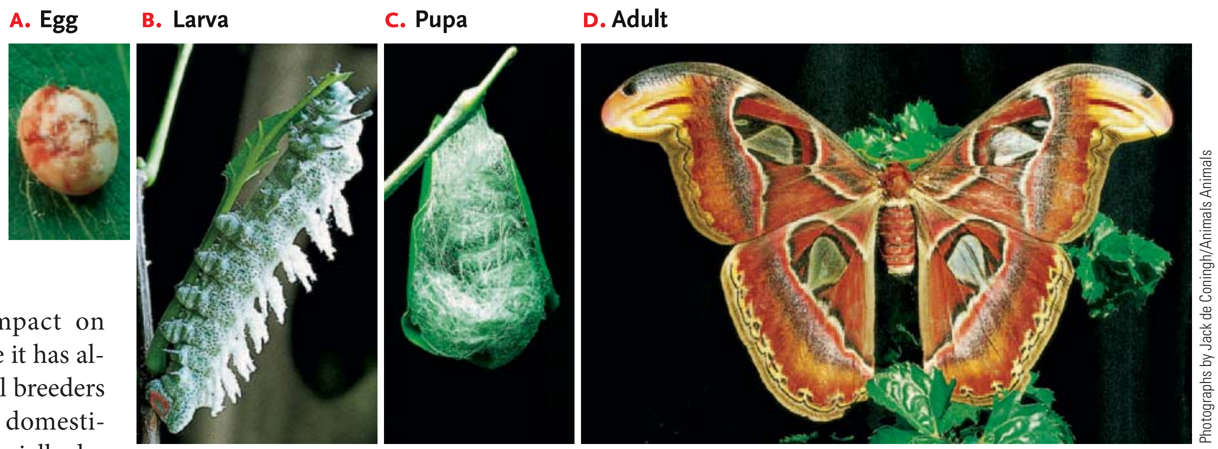
Multicellular organisms also undergo a process of **development,** a series of programmed changes encoded in DNA, through which a fertilized egg divides into many cells that ultimately are transformed into an adult, which is itself capable of reproduction. As an example, consider the development of a moth **(Figure 1.7).** This insect begins its life as a tiny egg that contains all the instructions necessary for its development into an adult moth. Following these instructions, the egg first hatches into a caterpillar, a larval form adapted for feeding and rapid growth. The caterpillar increases in size until internal chemical signals indicate that it is time to spin a cocoon and become a pupa. Inside its cocoon, the pupa undergoes profound developmental changes that remodel its body completely. Some cells die; others multiply and become organized in different patterns. When these transformations are complete, the adult moth emerges from the cocoon. It is equipped with structures and behaviors, quite different from those of the caterpillar, that enable it to reproduce.

The sequential stages through which individuals develop, grow, maintain themselves, and reproduce are known collectively as the **life cycle** of an organism. The moth's life cycle includes egg, larva, pupa, and adult stages. Through reproduction, adult moths continue the cycle by producing the sperm and eggs that unite to form the fertilized egg, which starts the next generation.

## Populations of Living Organisms Change from One Generation to the Next

Although offspring generally resemble their parents, individuals with unusual characteristics sometimes suddenly appear in a population. Moreover, the features that distinguish these oddballs are

**FIGURE 1.7** Life cycle of an atlas moth *(Attacus atlas).*




often inherited by their offspring. Our awareness of the inheritance of unusual characteristics has had an enormous impact on human history because it has allowed plant and animal breeders to produce crops and domesticated animals with especially desirable characteristics.

Biologists have observed that similar changes also take place under natural conditions. In other words, populations of all organisms change from one generation to the next, because some individuals experience changes in their DNA and they pass those modified instructions along to their offspring. We introduce this fundamental process, **biological evolution,** in the next section. Although we explore biological evolution in great detail in Unit 3, every chapter in this book—indeed, every idea in biology—references our understanding that all biological systems are the products of evolutionary change.

**STUDY BREAK 1.1**

1. List the major levels in the hierarchy of life, and identify one emergent property of each level.
2. What do living organisms do with the energy they collect from the external environment?
3. What is a life cycle?

## 1.2 Biological Evolution

All research in biology—ranging from analyses of the precise structure of biological molecules to energy flow through the biosphere—is undertaken with the knowledge that biological evolution has shaped life on Earth. Our understanding of the evolutionary process reveals several truths about the living world: (1) all populations change through time, (2) all organisms are descended from a common ancestor that lived in the distant past, and (3) evolution has produced the spectacular diversity of life that we see around us. Evolution is the unifying theme that links all the subfields of the biological sciences, and it provides cohesion to our treatment of the many topics discussed in this book.

### Darwin and Wallace Explained How Organisms Change through Time

How do evolutionary changes take place? One important mechanism was first explained in the mid-nineteenth century by two British naturalists, Charles Darwin and Alfred Russel Wallace. On a five-year voyage around the world, Darwin observed many "strange and wondrous" organisms. He also found fossils of species that are now extinct (that is, all members of the species are dead). The extinct forms often resembled living species in some traits but differed in others. Darwin originally believed in special creation—the idea that living organisms were placed on Earth in their present numbers and kinds and have not changed since their creation. But he became convinced that species do not remain constant with the passage of time: instead, they change from one form to another over generations. Wallace came to the same conclusion through his observations of the great variety of plants and animals in the jungles of South America and Southeast Asia.

Darwin also studied the process of evolution through observations and experiments on domesticated animals. Pigeons were among his favorite experimental subjects. Domesticated pigeons exist in a variety of sizes, colors, and shapes, but all of them are descended from the wild rock dove **(Figure 1.8).** Darwin noted that pigeon breeders who wished to promote a certain characteristic, such as elaborately curled tail feathers, selected individuals with the most curl in their feathers as parents for the next generation. By permitting only these birds to mate, the breeders fostered the desired characteristic and gradually eliminated or reduced other traits. The same practice is still used today to increase the frequency of desirable traits in tomatoes, dogs, and other domesticated plants and animals. Darwin called this practice **artificial selection.** He termed the equivalent process that occurs in nature **natural selection.**

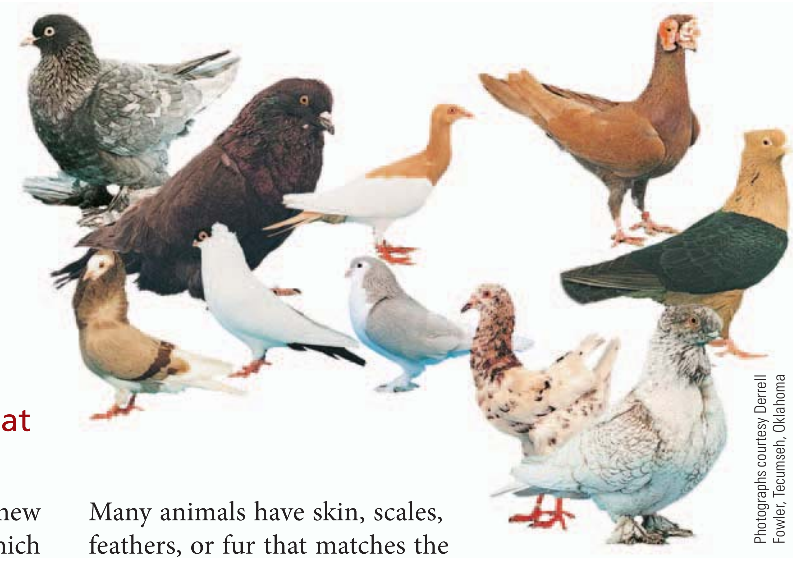
In 1858, Darwin and Wallace formally summarized their observations and conclusions explaining biological evolution. (1) Most organisms can produce numerous offspring, but environmental factors limit the number that actually survive and reproduce. (2) Heritable variations allow some individuals to compete more successfully for space, food, and mates. (3) These successful individuals somehow pass the favorable characteristics to their offspring. (4) As a result, the favorable traits become more common in the next generation, and less successful traits become less common. This process of natural selection results in evolutionary change. Today, evolutionary biologists recognize that natural selection is just one of several potent evolutionary processes, as described in Chapter 21.

Over many generations, the evolutionary changes in a population may become extensive enough to produce a population of organisms that is distinct from its ancestors. Nevertheless, parental and descendant species often share many characteristics, allowing researchers to understand their relationships and reconstruct their shared evolutionary history, as described below and in Chapter 24. Starting with the first organized cells, this aspect of evolutionary change has contributed to the diversity of life that exists today.

Darwin and Wallace described evolutionary change largely in terms of how natural selection changes the commonness or rarity of particular variations over time. Their intellectual achievement was remarkable for its time. Although Darwin and Wallace understood the central importance of variability among organisms to the process of evolution, they could not explain how new variations arose or how they were passed to the next generation.

Wild rock dove

**FIGURE 1.8 Artificial selection.** Using artificial selection, pigeon breeders have produced more than 300 varieties of domesticated pigeons from ancestral wild rock doves *(Columba livia)*.



Photographs courtesy Derrell Fowler, Tecumseh, Oklahoma

## Mutations in DNA Are the Raw Materials That Allow Evolutionary Change

Today, we know that both the origin and the inheritance of new variations arise from the structure and variability of DNA, which is organized into functional units called **genes.** Each gene contains the code (that is, the instructions for building) for a protein molecule or one of its parts. Proteins are the molecules that establish the structures and perform important biological functions within organisms.

Variability among individuals—the raw material molded by evolutionary processes—arises ultimately through **mutations,** random changes in the structure, number, or arrangement of DNA molecules. Mutations in the DNA of reproductive cells (that is, sperm and eggs) may change the instructions for the development of offspring that the reproductive cells produce. Many mutations are of no particular value to individuals bearing them, and some turn out to be harmful. On rare occasions, however, a mutation is beneficial under the prevailing environmental conditions. Beneficial mutations increase the likelihood that individuals carrying the mutation will survive and reproduce. Thus, through the persistence and spread of beneficial mutations among individuals and their descendants, the genetic makeup of a population will change from one generation to the next.

## Adaptations Enable Organisms to Survive and Reproduce in the Environments Where They Live

Favorable mutations may produce **adaptations,** characteristics that help an organism survive longer or reproduce more under a particular set of environmental conditions. To understand how organisms benefit from adaptations, consider an example from the recent literature on *cryptic coloration* (camouflage) in animals. Many animals have skin, scales, feathers, or fur that matches the color and appearance of the background in their environment, enabling them to blend into their surroundings. Camouflage makes it harder for predators to identify and then catch them—an obvious advantage to survival. Animals that are not camouflaged are often just sitting ducks.

The rock pocket mouse *(Chaetodipus intermedius),* which lives in the deserts of the southwestern United States, is mostly nocturnal (that is, active at night). At most desert localities, the rocks are pale brown, and rock pocket mice have sandy-colored fur on their backs. However, at several sites, the rocks—remnants of lava flows from now-extinct volcanoes—are black; here, the rock pocket mice have black fur on their backs. Thus, like the sandy-colored mice in other areas, they are camouflaged in their habitats, the types of areas in which they live **(Figure 1.9A).** Camouflage appears to be important to these mice because owls, which locate prey using their exceptionally keen eyesight, frequently eat nocturnal desert mice.

Examples of cryptic coloration are well documented in scientific literature, and biologists generally interpret them as adaptations that reduce the likelihood of being captured by a predator. Michael W. Nachman, Hopi E. Hoekstra, and their colleagues at the University of Arizona explored the genetic and evolutionary basis for the color difference between rock pocket mice that live on light and dark backgrounds. In an article published in 2003, they reported the results of an analysis of mice sampled at six sites in southern Arizona and New Mexico. In two regions (Pinacate, AZ, and Armendaris, NM), both light and dark rocks were present, allowing the researchers to compare mice that lived on differently colored backgrounds. Two other sites had only light rocks and sandy-colored mice.

**A. Camouflage in rock pocket mice *(Chaetodipus intermedius)***

Sandy-colored mice are well camouflaged on pale rocks, and black mice are well camouflaged on dark rocks (top); but mice with fur that does not match their backgrounds (bottom) are easy to see.

Photographs courtesy of Hopi Hoekstra, Harvard University

**B. Distributions of rock pocket mice with light and dark fur**

At sites in Arizona and New Mexico, mouse fur color closely matched the color of the rocks where they lived. The pie charts show the proportion of mice with sandy-colored or black fur, N = the number of mice sampled at each site. The bars beneath the pie charts indicate the rock color.

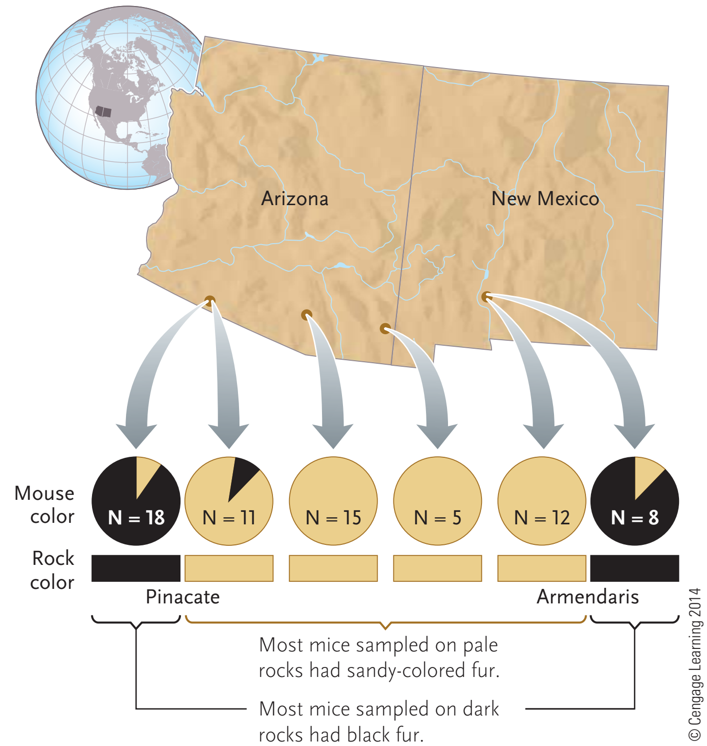





**FIGURE 1.9** **Adaptive coloration in rock pocket mice *(Chaetodipus intermedius)*.**

Nachman and his colleagues found that nearly all of the mice they captured on dark rocks had dark fur and that nearly all of the mice they captured on light rocks had light fur **(Figure 1.9B).** The researchers then studied the structure of *Mc1r,* a gene known to influence fur color in laboratory mice; random mutations in this gene can produce fur colors ranging from light to dark in any population of mice, regardless of the habitat it occupies. The 17 black mice from Pinacate all shared certain mutations in their *Mc1r* gene, which established four specific changes in the structure of the Mc1r protein. However, none of the 12 sandy-colored mice from Pinacate carried these mutations. The exact match between the presence of the mutations and the color of the mouse strongly suggests that these mutations in the *Mc1r* gene are responsible for the dark fur in the mice from Pinacate. These data on the distributions of light and dark mice coupled with analyses of their DNA suggest that the color difference is the product of specific mutations that were favored by natural selection. In other words, natural selection *conserved* random mutations that produced black fur in mice that live on black rocks.

Nachman's team then analyzed the *Mc1r* gene in the dark and light mice from Armendaris and in the light mice at two intermediate sites. Because the mice in these regions also closely matched the color of their environments, the researchers expected to find the *Mc1r* mutations in the dark mice but not in the light mice. However, none of the mice from Armendaris shared any of the mutations that apparently contribute to the dark color of mice from Pinacate. Thus, mutations in some other gene or genes, which the researchers have not yet identified, must be responsible for the camouflaging black coloration of mice that live on black rocks in Armendaris.

The example of an adaptation provided by the rock pocket mice illustrates the observation that genetic differences often develop between populations. Sometimes these differences become so great that the organisms develop different appearances and adopt different ways of life. If they become different enough, biologists may regard them as distinct types, as described in Chapter 22. Over immense spans of time, evolutionary processes have produced many types of organisms, which constitute the diversity of life on Earth. In the next section, we survey this diversity and consider how it is studied.

### STUDY BREAK 1.2

1. **What is the difference between artificial selection and natural selection?**
2. **How do random changes in the structure of DNA affect the characteristics of organisms?**
3. **What is the usefulness of being camouflaged in natural environments?**

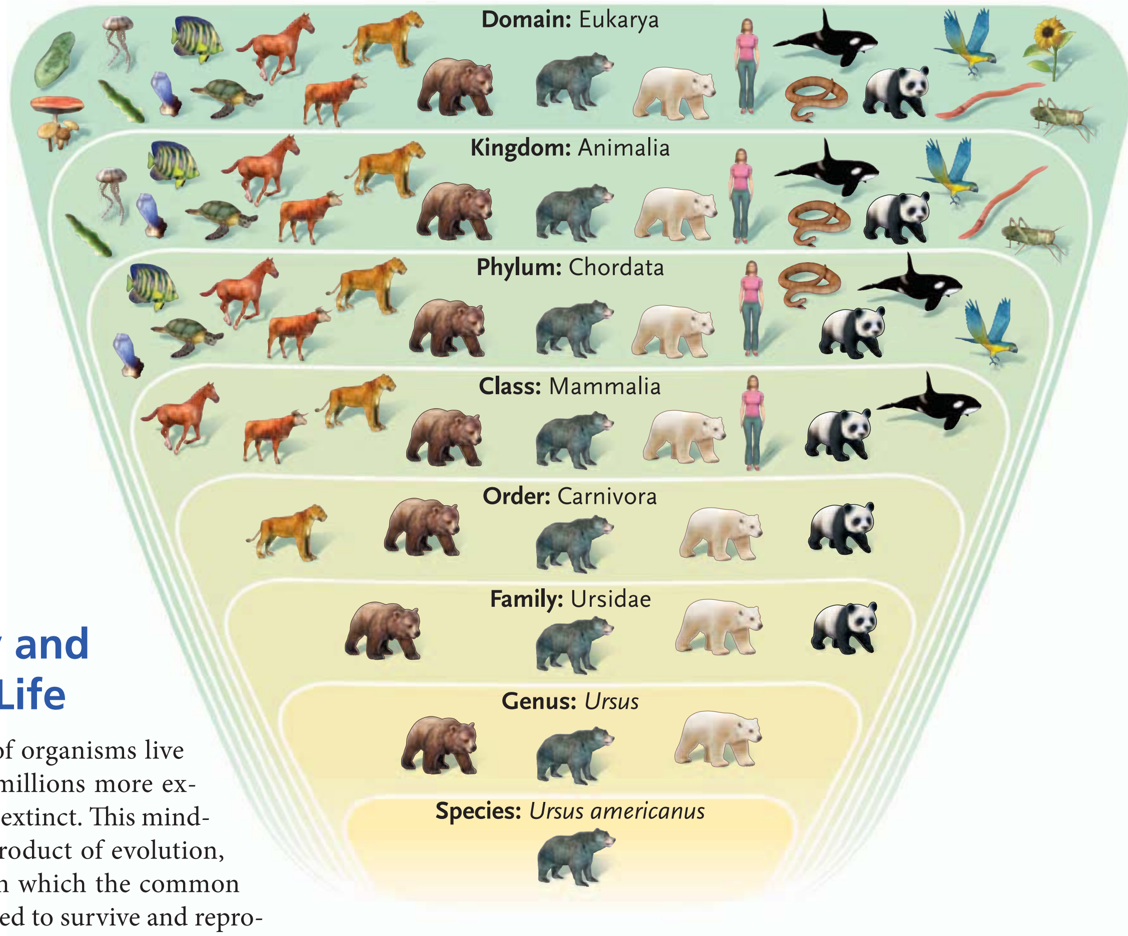



**FIGURE 1.10 Traditional hierarchical classification.** The classification of the American black bear *(Ursus americanus)* illustrates how each species fits into a nested hierarchy of ever-more inclusive categories. The following sentence can help you remember the order of categories in a classification, from *Domain* to *Species:* Diligent Kindly Professors Cannot Often Fail Good Students.



## 1.3 Biodiversity and the Tree of Life

Millions of different kinds of organisms live on Earth today, and many millions more existed in the past and became extinct. This mind-boggling biodiversity, the product of evolution, represents the many ways in which the common elements of life have combined to survive and reproduce. To make sense of the past and present diversity of life on Earth, biologists analyze the evolutionary relationships of these organisms and use classification systems to keep track of them. As described in Chapter 24, the task is daunting, and there is no clear consensus on the numbers and kinds of divisions and categories to use. Moreover, our understanding of evolutionary relationships is constantly changing as researchers develop new analytical techniques and learn more about extinct and living organisms.

### Researchers Traditionally Defined Species and Grouped Them into Successively More Inclusive Hierarchical Categories

Biologists generally consider the species to be the most fundamental grouping in the diversity of life. As described in Chapter 22, a **species** is a group of populations in which the individuals are so similar in structure, biochemistry, and behavior that they can successfully interbreed. Biologists recognize a **genus** (plural, *genera*) as a group of similar species that share recent common ancestry. Species in the same genus usually also share many characteristics. For example, a group of closely related animals that have large bodies, four stocky legs, long snouts, shaggy hair, nonretractable claws, and short tails are classified together in the genus *Ursus,* commonly known as bears.

Each species is assigned a two-part **scientific name:** the first part identifies the genus to which it belongs, and the second part designates a particular species within that genus. In the genus *Ursus,* for example, *Ursus americanus* is the scientific name of the American black bear; *Ursus maritimus,* the polar bear, and *Ursus arctos,* the brown bear, are two other species in the same genus. Scientific names are always written in italics, and only the genus name is capitalized. After its first mention in a discussion, the genus name is frequently abbreviated to its first letter, as in *U. americanus.*

In a traditional classification, biologists first identified species and then grouped them into successively more inclusive categories **(Figure 1.10):** related genera are placed in the same **family,** related families in the same **order,** and related orders in the same **class.** Related classes are grouped into a **phylum** (plural, *phyla*), and related phyla are assigned to a **kingdom.** In recent years, biologists have added the **domain** as the most inclusive group.

### Today Biologists Identify the Trunks, Branches, and Twigs on the Tree of Life

For hundreds of years, biologists classified biodiversity within the hierarchical scheme described above, mostly using structural similarities and differences as clues to evolutionary relationships. With the development of new techniques late in the twentieth century, biologists began to use the precise structure of DNA and other biological molecules to trace the evolutionary pathways