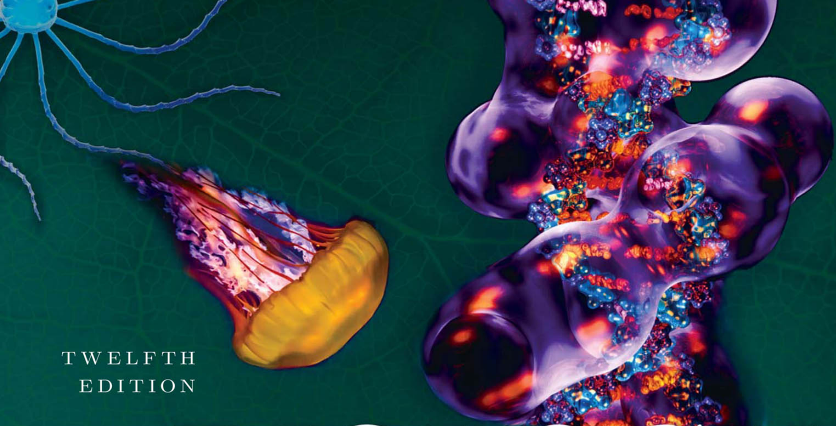

TWELFTH
EDITION

BIOLOGY

Raven
Johnson
Mason
Losos
Duncan

McGraw Hill Education

Twelfth Edition

Biology

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Jonathan B. Losos

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Mc Graw Hill Education

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Brief Contents

About the Authors

©Kenneth Mason

Kenneth Mason maintains an association with the University of Iowa, Department of Biology after having served as a faculty member for eight years. His academic positions, as a teacher and researcher, include the faculty of the University of Kansas, where he designed and established the genetics lab, and taught and published on the genetics of pigmentation in amphibians. At Purdue University, he successfully developed and grew large introductory biology courses and collaborated with other faculty in an innovative biology, chemistry, and physics course supported by the National Science Foundation. At the University of Iowa, where his wife served as president of the university, he taught introductory biology and human genetics. His honor society memberships include Phi Sigma, Alpha Lambda Delta, and, by vote of Purdue pharmacy students, Phi Eta Sigma Freshman Honors Society.

©Jonathan Losos

Jonathan Losos is the William H. Danforth Distinguished University Professor in the Department of Biology at Washington University and Director of the Living Earth Collaborative, a partnership between the university, the Saint Louis Zoo and the Missouri Botanical Garden. Losos's research has focused on studying patterns of adaptive radiation and evolutionary diversification in lizards. He is a member of the National Academy of Sciences, a fellow of the American Academy of Arts and Science, and the recipient of several awards, including the Theodosius Dobzhanksy and David Starr Jordan Prizes, the Edward Osborne Wilson Naturalist Award, and the Daniel Giraud Elliot Medal, as well as receiving fellowships from the John Guggenheim and David and Lucile Packard Foundations. Losos has published more than 200 scientific articles and has written two books, *Lizards in an Evolutionary Tree: Ecology and Adaptive Radiation of Anoles* (University of California Press, 2009) and *Improbable Destinies: Fate, Chance, and the Future of Evolution* (Penguin-Random House, 2017).

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Tod Duncan is a Clinical Assistant Professor at the University of Colorado Denver. He currently teaches first semester general biology and coordinates first and second semester general biology laboratories. Previously, he taught general microbiology, virology, the biology of cancer, medical microbiology, and cell biology. A bachelor's degree in cell biology with an emphasis on plant molecular and cellular biology from the University of East Anglia in England led to doctoral studies in cell cycle control, and postdoctoral research on the molecular and biochemical mechanisms of DNA alkylation damage *in vitro* and in *Drosophila melanogaster*. Currently, he is interested in factors affecting retention and success of incoming first-year students in diverse demographics. He lives in Boulder, Colorado, with his two Great Danes, Eddie and Henry.

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Part VIII Ecology and Behavior

Committed to Excellence

With the new 12th edition, Raven and Johnson's *Biology* continues the momentum built over the last four editions. We continue to provide an unmatched comprehensive text fully integrated with a continually evolving, state-of-the-art digital environment. We have used this revision to recommit ourselves to our roots as the majors biology text that best integrates evolution throughout. We have added material emphasizing the relevance of evolution throughout the ecology section, not only in all four ecology chapters, but also in the chapters on behavior and conservation biology. In the animal form and function section we have done extensive revision to modernize, and to emphasize evolution in the context of physiology. Important contributions to this effort came from Dr. Charles Welsh (Duquesne University), who provided his knowledge and experience to this important section. We have also moved the examples and insights from the chapter devoted to the evolution of development to place them into the appropriate context throughout the book. This emphasizes the importance of evolution and development by continually providing examples rather than gathering them together in a single chapter.

We have also renewed our commitment to the ideas set forth in the Vision and Change report from the AAAS, which provides a framework for modern undergraduate biology education. This report will have been with us for a decade coincident with our 12th edition. One important idea articulated by Vision and Change was an emphasis on core concepts. One of the key differences between the way an expert organizes information in their brain compared to a novice is that the expert has a conceptual framework in place to incorporate new information. We have designed the new Connecting the Concepts feature to address this disparity. We emphasize core concepts in each chapter, then at the end of the chapter show how these can be used to build a conceptual framework, and encourage the student to begin building their own. At the end of each part of the book we expand this to show how core concepts are interrelated and how a much larger conceptual framework is constructed.

One unanticipated consequence of the Vision and Change movement was how publishers chasing new approaches would produce books so "feature-laden" as to be virtually unreadable by the average student. We have not abandoned the idea that narrative flow is important, even in a science textbook. While we include a variety of features to improve student learning, they are integrated into the text and not at the expense of the concise, accessible, and engaging writing style we are known for. We maintain the clear emphasis on evolution and scientific inquiry that have made this a leading textbook of choice for majors biology students.

Faculty want textbooks that emphasize student-centered approaches, and core concepts for the biological sciences. As a team, we continually strive to improve the text by integrating the latest cognitive and best practices research with methods that are known to positively affect learning. We emphasize scientific inquiry, including an increased quantitative emphasis in the Scientific Thinking figures. Our text continues to be a leader with an organization that emphasizes important biological concepts, while keeping the student engaged with learning outcomes that allow assessment of progress in understanding these concepts. An inquiry-based approach with robust, adaptive tools for discovery and assessment in both text and digital resources provides the intellectual challenge needed to promote student critical thinking and ensure academic success.

We continue to use our digital environment in the revision of *Biology*. A major strength of both text and digital resources is assessment across multiple levels of Bloom's taxonomy that develops critical-thinking and problem-solving skills in addition to comprehensive factual knowledge.

McGraw-Hill Education's Connect® platform offers a powerful suite of online tools that are linked to the text and includes new quantitative assessment tools. We now have available interactive exercises that use graphical data, controlled by the student, to engage them in actively exploring quantitative aspects of biology. Our adaptive learning system helps students learn faster, study efficiently, and retain more knowledge of key concepts.

The 12th edition continues to employ the aesthetically stunning art program that the Raven and Johnson *Biology* text is known for. Complex topics are represented clearly and succinctly, helping students to build the mental models needed to understanding biology.

We continue 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. This "heat-mapping" technology is unique in the industry, and allows direct editing of difficult areas, or problem areas for students.

- 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, we edited the probe, rather than the text.

We're excited about the 12th edition of this quality textbook providing a learning path for a new generation of students. All of us have extensive experience teaching undergraduate biology, and we've used this knowledge as a guide in producing a text that is up to date, beautifully illustrated, and pedagogically sound for the student. We are also excited about the continually evolving digital environment that provides unique and engaging learning environment for modern students. We've worked hard to provide clear explicit learning outcomes, and more closely integrate the text with its media support materials to provide instructors with an excellent complement to their teaching.

Ken Mason, Jonathan Losos, Tod Duncan

Cutting Edge Science

Changes to the 12th Edition

Part I: The Molecular Basis of Life

Chapter 1—New section added that elaborates on the core concepts and prepares the student for the use of the Connecting the Concepts feature.

Chapter 2—Edited for clarity, especially regarding atomic structure and the periodic table.

Chapter 3—Edited for clarity especially regarding the structure of nucleotides, the role of ATP in cells, and secondary structure in proteins.

Part II: Biology of the Cell

Chapter 4—The section on the endomembrane system has been completely rewritten. This includes new material on lipid droplets. Material on adhesive junctions has been rewritten to give a more evolutionary perspective.

Chapter 5—New material on proteins that can alter membrane structure has been added. This provides information on how the different cellular membranes can have different structures. Figure on Na^+/K^+ pump was redone to address errors in mechanism. Material on diffusion and facilitated diffusion was rewritten.

Chapter 6—The material on free energy and chemical reactions was completely rewritten, including redoing the figures. These changes significantly improve clarity and accuracy. Material on the role of ATP in cells was rewritten for clarity. Discussions of energy throughout the chapter were rewritten to improve clarity and accuracy of chemical concepts.

Chapter 7—The nature and action of cofactors in redox reactions and the role of ATP in cells were improved.

Chapter 8—The nature and structure of photosystems was rewritten for clarity and accuracy.

Chapter 10—The section on chromosome structure was completely rewritten to reflect new data and views of this important topic. The material on cancer was expanded and updated, producing a new section "Genetics of Cancer." This contains significant new information and pulls together material on cancer from this chapter and others.

Part III: Genetic and Molecular Biology

The overall organization of this section remains the same. We have retained the split of transmission genetics into two chapters as it has proved successful for students.

Chapter 11—Edited for clarity and readability for the student, especially regarding the events of meiosis I.

Chapter 12—The material on extensions to Mendel was rewritten for clarity and accuracy.

Chapter 13—The material on analyzing and mapping genetic variation in humans was updated and rewritten. The section on human genetic disorders was completely rewritten to reflect new information, and to make more accessible for the student. A new figure on imprinting in mouse was added to clarify this important and difficult concept.

Chapter 14—The material on eukaryotic DNA replication was rewritten and updated. Particular emphasis was placed on the evolution of DNA replication. The section on DNA repair was rewritten and updated and information on mismatch repair was added.

Chapter 15—Content on process of transcription was rewritten to reflect new data on elongation machinery. New data on alternative splicing was included, along with information on the integration of RNA modification during transcription. The section on the nature of mutations was rewritten and includes latest data on human mutation rates.

Chapter 16—Overview of control of eukaryotic transcription was rewritten to reflect modern views. Continued updating of the material on chromatin structure and the control of gene expression. Material on control of gene expression at the level of transcription was updated.

Chapter 18—New section added on the 1000 Genomes project to illustrate how fast information on genetic diversity is accumulating. The material on the wheat genome was updated, which provides both new information and approaches to complex genomes.

Chapter 19—Added a new section on the evolution of pattern formation using new material and material from chapter 25. This consolidates material on this subject, and provides a clear vision for the student.

Part IV: Evolution

Chapter 20—The topic of sexual selection was moved into this chapter from the Behavioral Biology chapter. Some material on Lamarck was eliminated, natural selection was explicitly defined, information on snp variation in humans and other animals was added. New examples of pleiotropy were added, and new data on how the speed of racehorses has not changed through time were added along with a revised figure. A new section was added on the role of sensory exploitation as a mechanism for traits to evolve under sexual selection.

Chapter 21—A number of points were updated and an example of vestigial traits involving the toenails of manatees was added.

Chapter 23—The figure on the evolution of feathers in dinosaurs was updated to incorporate new paleontological findings. Discussion of HIV evolution and other points were also revised in light of new science.

Chapter 24—Updated material on comparative genomics of vertebrates. New data on Neanderthal and Denisovan genomes have been added. Presentation of genes unique to humans has been updated and edited for clarity.

Note: *Evolution of Development* (chapter 25 in the 11th edition) was eliminated and material moved to other chapters, placing the topic of evolution of development into the appropriate context. This reflects the view that evolution and development are now so clearly intertwined with all of biology that setting off the material in a separate chapter no longer made sense.

Part V: Diversity of Life on Earth

Chapter 26—This chapter has been largely rewritten and now includes material on viral diversity, classification, metagenomics, and taxonomy. The latter part of the chapter now focuses on viruses of medical importance to promote student engagement and interest.

Chapter 27—This chapter has been largely rewritten. In addition to the traditional discussion of prokaryotic structure and function, and taxonomy, there is new emphasis placed on microbial ecology and medical microbiology with relevant examples.

Chapter 31—The chapter has been rewritten for clarity. The chapter has also been reordered to bring material most relevant to society to the front of the chapter. The reorganization includes expanding and moving the fungal ecology up earlier in the chapter, as well as expanding and moving the fungal parasites and pathogens up earlier in the chapter. The chapter now ends with the coverage of fungal classification.

Chapter 32—Aspects of taxonomy and natural history were updated in line with new findings.

Chapter 33—The presentation of taxonomic relationships was revised as a result of new findings based primarily on molecular phylogenetic studies, specifically with regards to Platyhelminthes, lophotrochozoans (formerly Spiralia) and a few others. New natural history information was included.

Chapter 34—The discussion of the evolutionary history of vertebrates was substantially revised, especially the sections on lobe-finned fishes/early tetrapods/early amniotes (emphasizing now those terms, rather than referring to all of the early diverging lineages as amphibians or reptiles). Also, the terminology about human evolution was revised to acknowledge the new meaning of “hominin” and “hominid.” A new paragraph on *Homo naledi* was added to discuss recent discoveries.

Part VI: Plant Form and Function

There have been no major changes in the plant form and function chapters. There has been overall editing for readability and responding to recommendations by reviewers and users of the 11th edition.

Part VII: Animal Form and Function

Charles Welsh of Duquesne University, brought his expertise in animal anatomy and physiology as a Contributor to the Animal Form and Function Part in the 12th edition, placing greater emphasis on evolutionary aspects of animal biology.

Chapter 41—The discussion of the evolution of tissues in invertebrates and vertebrates was expanded, including the addition of a phylogeny and an image of cnidarian tissues.

Chapter 42—The graph of an action potential was revised and improved. Discussions and images of glial cells and cranial nerves were added.

Chapter 43—The chapter was revised and reorganized with regards to the general senses. The evolution of eyes material found in chapter 25 in the 11th edition was moved to this chapter with a revised phylogeny added. The illustration depicting the evolution of the inner ear has been revised to make it more clear, concise, and informative.

Chapter 44—Section 44.2 was formerly organized as action of lipophilic vs. hydrophilic hormones. This has now been reorganized to be a complete overview of how hormones work. This organization should improve clarity for students.

Chapter 45—The chapter was extensively revised. This included the addition of images for the human skeleton, ossification, osteoporosis, invertebrate muscle, comparative anatomy of flying vertebrates, and a new phylogeny that reveals the evolution of various vertebrate skeletal characters.

Chapter 46—The structure of the latter half this chapter was completely reorganized for better conceptual flow.

Chapter 47—The images for the bicarbonate buffering system and the mechanics of breathing have been revised. The discussion of lung volumes and capacities was expanded with the addition of an accompanying figure.

Chapter 48—The chapter was reorganized and extensively revised. Invertebrate circulatory systems is now the first section in the chapter. The sections on Cardiac Cycle, ECG, Electrical Conduction, and Cardiac Output have been reorganized and revised. The discussions of blood vessels and blood pressure are now in the same section. The phylogeny of the evolution of vertebrate hearts has been revised.

Chapter 50—Material on innate immunity was updated and rewritten for clarity. The coverage on effects of AIDS was also updated to reflect new information.

Chapter 51—A discussion of some select invertebrate reproductive strategies has been added, with accompanying images.

Chapter 52—A section detailing the classic experiments regarding pattern formation in chick limb buds has been added. This includes a discussion of AER, ZPA, FGF, *Hox* genes, and Shh. The material on gene regulation from chapter 25 in the 11th edition has also been added.

Part VIII: Ecology and Behavior

Chapter 53—Stronger emphasis on phylogenetic and evolutionary perspectives was added throughout the chapter, including a new section on evolution and behavior.

Chapter 54—Human population trends and other timely data were updated to stay current. An evolutionary perspective on population adaptation was added to the beginning of the chapter.

Chapter 55—An evolutionary perspective was added in several places.

Chapter 56—New material on the impact of anthropogenic changes on nutrient cycling was added. An evolutionary perspective to discussion of the species-area relationship was incorporated.

Chapter 57—Evolution was discussed more thoroughly in the section on microclimate adaptation during adaptive radiation. All of the data on biosphere impacts of humans were updated to stay current.

Chapter 58—The chapter was substantially revised, including much new discussion of the relevance of evolution to conservation biology, including the role of natural selection, the importance of phylogenetic perspectives, and how speciation can lead to biodiversity hotspots.

A Note From the Authors

A revision of this scope relies on the talents and efforts of many people working behind the scenes and we have benefited greatly from their assistance.

Dr. Charles Welsh made significant contributions to the Animal Form and Function section. He updated them to provide a more modern perspective, and added new examples.

Beth Bulger was the copyeditor for this edition. She has labored many hours and always improves the clarity and consistency of the text. She has made significant contributions to the quality of the final product.

We were fortunate to work again with MPS to update the art program and improve the layout of the pages. Our close collaboration resulted in a text that is pedagogically effective as well as more beautiful than any other biology text on the market.

We have the continued support of an excellent team at McGraw-Hill Education. Andrew Urban, preceded by Justin Wyatt, the portfolio managers for *Biology* have been steady leaders during a time of change. Senior Product Developer Liz Sievers, provided support in so many ways it would be impossible to name them all. Kelly Hart, content project manager, and David Hash, designer, ensured our text was on time and elegantly designed. Kelly Brown, senior marketing manager, is always a sounding board for more than just marketing, and many more people behind the scenes have all contributed to the success of our text. This includes the digital team, whom we owe a great deal for their efforts to continue improving our Connect assessment tools.

Throughout this edition we have had the support of spouses and families, who have seen less of us than they might have liked because of the pressures of getting this revision completed. They have adapted to the many hours this book draws us away from them, and, even more than us, looked forward to its completion.

In the end, the people we owe the most are the generations of students who have used the many editions of this text. They have taught us at least as much as we have taught them, and their questions and suggestions continue to improve the text and supplementary materials.

Finally, we need to thank instructors from across the country who are continually sharing their knowledge and experience with us through market feedback and symposia. The feedback we received shaped this edition. All of these people took time to share their ideas and opinions to help us build a better edition of *Biology* for the next generation of introductory biology students, and they have our heartfelt thanks.

Reviewers for Biology, 12th edition

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D. Alexander Wait *Missouri State University*
Maureen Walter *Florida International University*
Darla Wise *Concord University*

Developing Critical Thinking with the Help of . . .

Scientific Thinking Figures

Key illustrations in every chapter highlight how the frontiers of knowledge are pushed forward by a combination of hypothesis and experimentation. These figures begin with a hypothesis, then show how it makes explicit predictions, tests these by experiment and finally demonstrates what conclusions can be drawn, and where this leads. Scientific Thinking figures provide a consistent framework to guide the student in the logic of scientific inquiry. Each illustration concludes with open-ended questions to promote scientific inquiry.

Data Analysis Questions

It's not enough that students learn concepts and memorize scientific facts, a biologist needs to analyze data and apply that knowledge. Data Analysis questions inserted throughout the text challenge students to analyze data and Interpret experimental results, which shows a deeper level of understanding.

Inquiry Questions

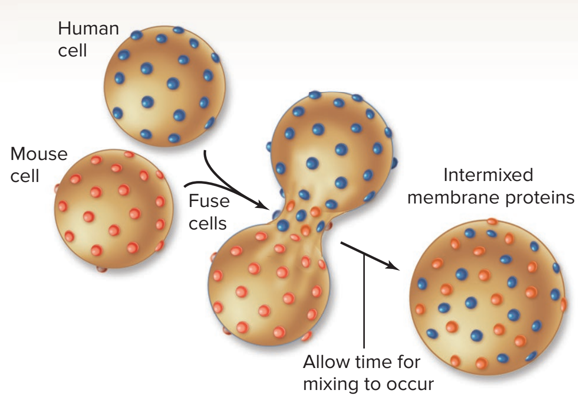
Questions that challenge students to think about and engage in what they are reading at a more sophisticated level.

SCIENTIFIC THINKING

Hypothesis: *The plasma membrane is fluid, not rigid.*

Prediction: *If the membrane is fluid, membrane proteins may diffuse laterally.*

Test: *Fuse mouse and human cells, then observe the distribution of membrane proteins over time by labeling specific mouse and human proteins.*



Result: *Over time, hybrid cells show increasingly intermixed proteins.*

Conclusion: *At least some membrane proteins can diffuse laterally in the membrane.*

Further Experiments: *Can you think of any other explanation for these observations? What if newly synthesized proteins were inserted into the membrane during the experiment? How could you use this basic experimental design to rule out this or other possible explanations?*

Figure 5.5 **Test of membrane fluidity.**

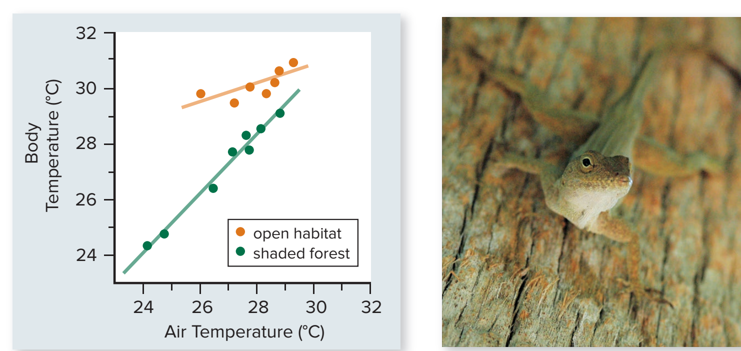


Figure 55.3 **Behavioral adaptation.** In open habitats, the Puerto Rican crested lizard, *Anolis cristatellus,* maintains a relatively constant temperature by seeking out and basking in patches of sunlight; as a result, it can maintain a relatively high temperature even when the air is cool. In contrast, in shaded forests, this behavior is not possible, and the lizard's body temperature conforms to that of its surroundings.

(inset) ©Melissa Losos

? **Inquiry question** When given the opportunity, lizards regulate their body temperature to maintain a temperature optimal for physiological functioning. Would lizards in open habitats exhibit different escape behaviors from those of lizards in shaded forest?

Data analysis Can the slope of the line tell us something about the behavior of the lizard?

Connecting the Concepts

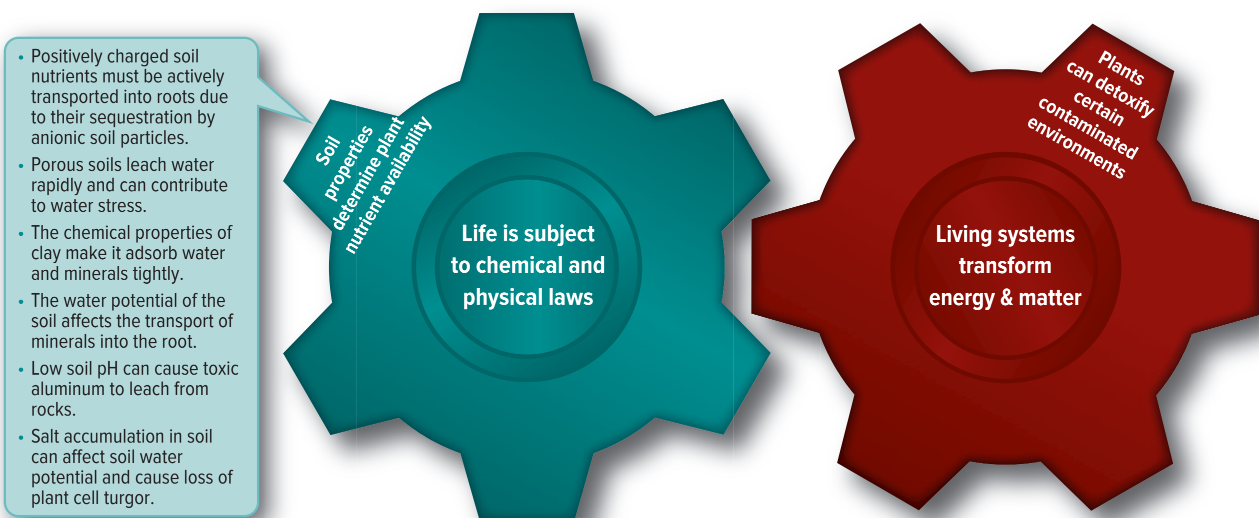
There are two new but related features in *Biology*, 12th edition that help students build a conceptual framework into which they can insert new knowledge. The Connecting the Concepts feature at the end of the chapters identifies core concepts that are related to material in the chapter. The conceptual framework begins with a core concept that is represented by a gear icon. Examples from the chapter that relate to the core concept are secondary concepts that are placed on the cogs. Each cog contains a list of observations from the chapter that connects the secondary concept to the core concept.

At the chapter level:

The Connecting the Concept shows the student a completed concept (core concept, secondary concept, list of observations). A second cog or gear is presented that lacks the list of observations. The student is challenged to identify examples from the chapter that demonstrate how the secondary concept is related to the core concept.

CONNECTING THE CONCEPTS

This feature is intended to give you practice in organizing information using core concepts. We use a metaphor of gears and cogs to represent a conceptual hierarchy with each core concept represented as a gear. Secondary concepts are the cogs, and tertiary concepts, which are particular examples from the chapter, are presented as a list of bulleted points. Using the completed conceptual unit as a guide, build from material in the chapter a list of tertiary concepts that support the open secondary concept.



At the Part level:

As valuable as that exercise is, the full understanding of a conceptual framework and how that helps students see the connections to core concepts is when the chapter-ending Connecting the Concepts are pulled together. This happens at the Part level, which themselves present a higher level to the conceptual framework. When these are built, students see how topics that appear unrelated fit into the conceptual framework of the core concepts. Once students begin to see these connections, the topics and information in biology make more sense.

Connecting the Concepts Part VI Plant Form and Function

Vascular plants are comprised of roots and shoots, which in turn are made of three principal tissue types. Each of these tissues has distinct cell types that express the genes needed to produce the proteins necessary for their specialized functions. Plants move fluids using differences in solute concentration and pressure. Plant form is often an evolutionary compromise between competing needs such as maximizing the surface area of leaves for photosynthesis while minimizing water loss when exchanges gases. The reproductive structures of plants are organized into flowers that have evolved to facilitate the dissemination of genetic information.

Each Connecting the Concept unit (a Core concept, secondary concept, and bulleted list) is picked up from the end-of-chapter features. This reinforces the overarching hierarchy of the Core concepts, tying together seemingly unrelated material.

Students will see how the same Core concepts are found throughout the book, establishing the conceptual framework into which they can insert new knowledge.

Strengthen Problem-Solving Skills with Connect®

Detailed Feedback in Connect®

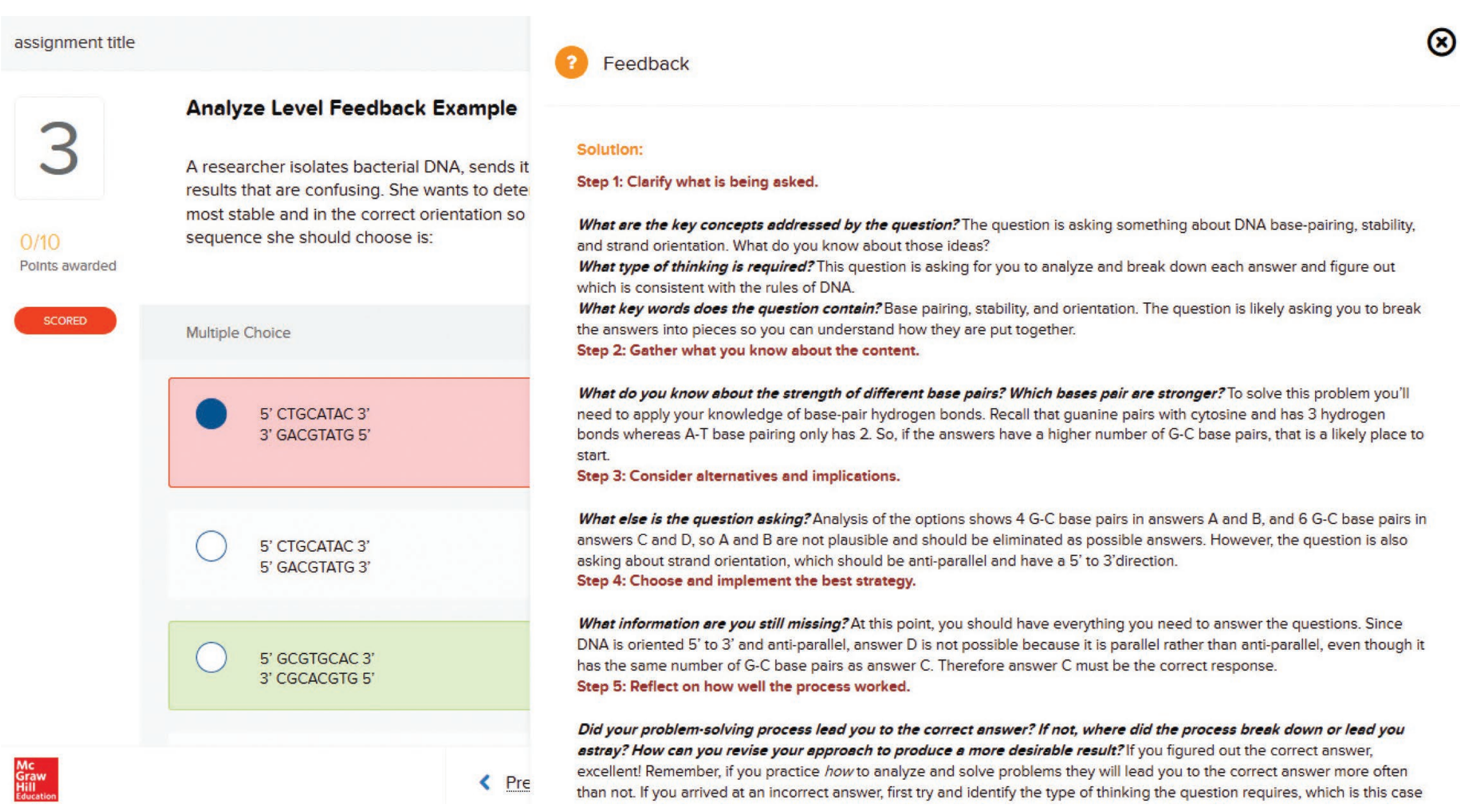
Learning is a process of iterative development, of making mistakes, reflecting, and adjusting over time. The question and test banks in Connect® for *Biology*, 12th edition, are more than direct assessments; they are self-contained learning experiences that systematically build student learning over time.

For many students, choosing the right answer is not necessarily based on applying content correctly; it is more a matter of increasing their statistical odds of guessing. A major fault with this approach is students don't learn how to process the questions correctly, mostly because they are repeating and reinforcing their mistakes rather than reflecting and learning from them. To help students develop problem-solving skills, all higher level Blooms questions in Connect are supported with hints, to help students focus on important information for answering the questions, and detailed feedback that walks students through the problem-solving process, using Socratic questions in a decision-tree-style framework to scaffold learning, where each step models and reinforces the learning process.

The feedback for each higher level Blooms question (Apply, Analyze, Evaluate) follows a similar process: Clarify Question, Gather Content, Choose Answer, Reflect on Process.

Unpacking the Concepts

We've taken problem solving a step further. In each chapter, three to five higher level Blooms questions in the question and test banks are broken out by the steps of the detailed feedback. Rather than leaving it up to the student to work through the detailed feedback, a second version of the question is presented in a stepwise format. Following the problem-solving steps, students need to answer questions about earlier steps, such as "What is the key concept addressed by the question?" before proceeding to answer the question. A professor can choose which version of the question to include in the assignment based on the problem-solving skills of the students.

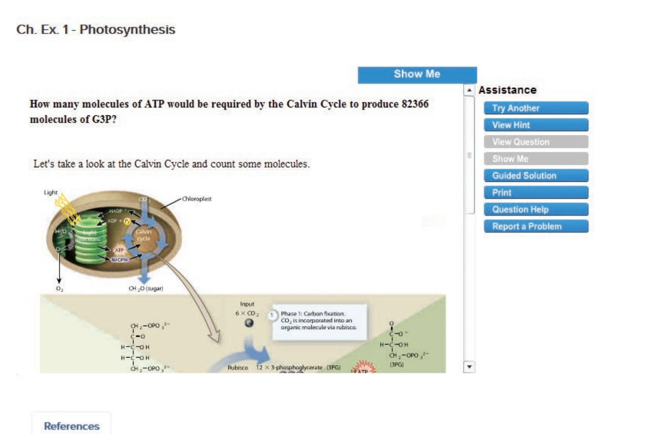


Graphing Interactives

To help students develop analytical skills, Connect® for *Biology*, 12th edition, is enhanced with interactive graphing questions. Students are presented with a scientific problem and the opportunity to manipulate variables, producing different results on a graph. A series of questions follows the graphing activity to assess if the student understands and is able to interpret the data and results.

Quantitative Question Bank

Many chapters also contain a **Quantitative Question Bank.** These are more challenging algorithmic questions, intended to help your students practice their quantitative reasoning skills. Hints and guided solution options step students through a problem.



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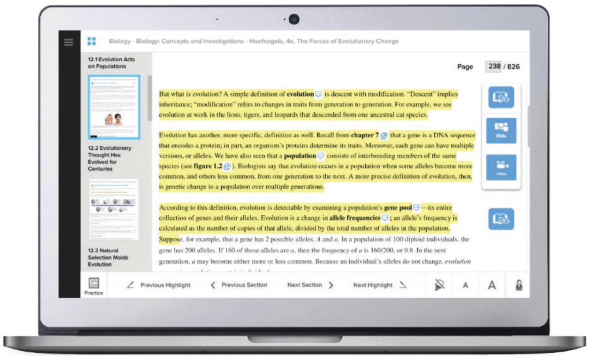

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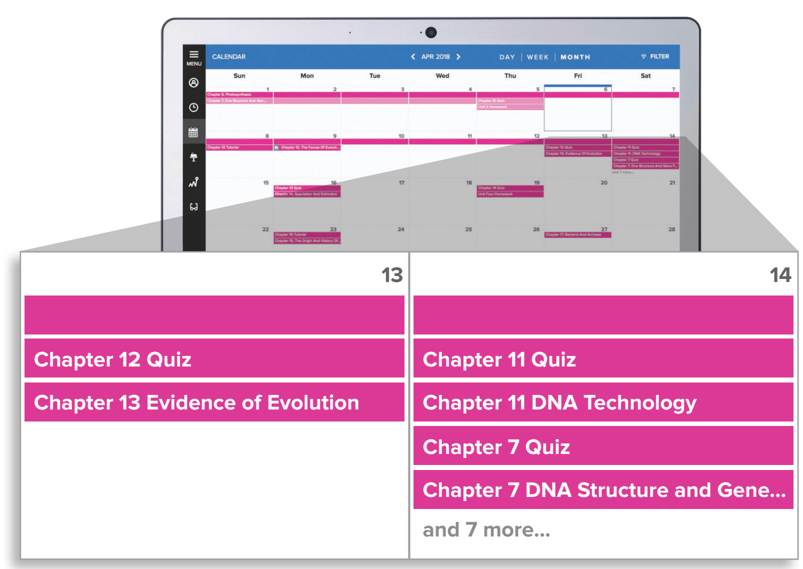

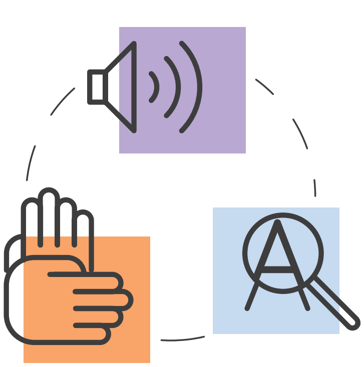

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CHAPTER 1

The Science of Biology

Chapter Contents

Introduction

You are about to embark on a journey—a journey of discovery about the nature of life. More than 180 years ago, a young English naturalist named Charles Darwin set sail on a similar journey on board H.M.S. *Beagle*; a replica of this ship is pictured here. What Darwin learned on his five-year voyage led directly to his development of the theory of evolution by natural selection, a theory that has become the core of the science of biology. Darwin's voyage seems a fitting place to begin our exploration of biology—the scientific study of living organisms and how they have evolved. Before we begin, however, let's take a moment to think about what biology is and why it's important.

1.1 The Science of Life

Learning Outcomes

1. *Compare biology to other natural sciences.*
2. *Describe the characteristics of living systems.*
3. *Characterize the hierarchical organization of living systems.*

This is the most exciting time to be studying biology in the history of the field. The amount of information available about the natural world has exploded in the last 42 years, since the construction of the first recombinant DNA molecule. We are now in a position to ask and answer questions that previously were only dreamed of.

The 21st century began with the completion of the sequence of the human genome. The largest single project in the history of biology took about 20 years. Yet less than 15 years later, we can sequence an entire genome in a matter of days. This flood of sequence data and genomic analysis are altering the landscape of biology. These and other discoveries are also moving into the clinic as never before, with new tools for diagnostics and treatment. With robotics, next-generation DNA sequencing technologies, advanced imaging, and analytical techniques, we have tools available that were formerly the stuff of science fiction.

In this text, we attempt to draw a contemporary picture of the science of biology, as well as provide some history and experimental perspective on this exciting time in the discipline. In this introductory chapter, we examine the nature of biology and the foundations of science in general to put into context the information presented in the rest of the text.

Biology unifies much of natural science

The study of biology is a point of convergence for the information and tools from all of the natural sciences. Biological systems are the most complex chemical systems on Earth, and their many functions are both determined and constrained by the principles of chemistry and physics. Put another way, no new laws of nature can be gleaned from the study of biology—but that study does illuminate and illustrate the workings of those natural laws.

The intricate chemical workings of cells can be understood using the tools and principles of chemistry. And every level of biological organization is governed by the nature of energy transactions first studied by thermodynamics. Biological systems do not represent any new forms of matter, and yet they are the most complex organization of matter known. The complexity of living systems is made possible by a constant source of energy—the Sun. The conversion of this radiant energy into organic molecules by photosynthesis is one of the most beautiful and complex reactions known in chemistry and physics.

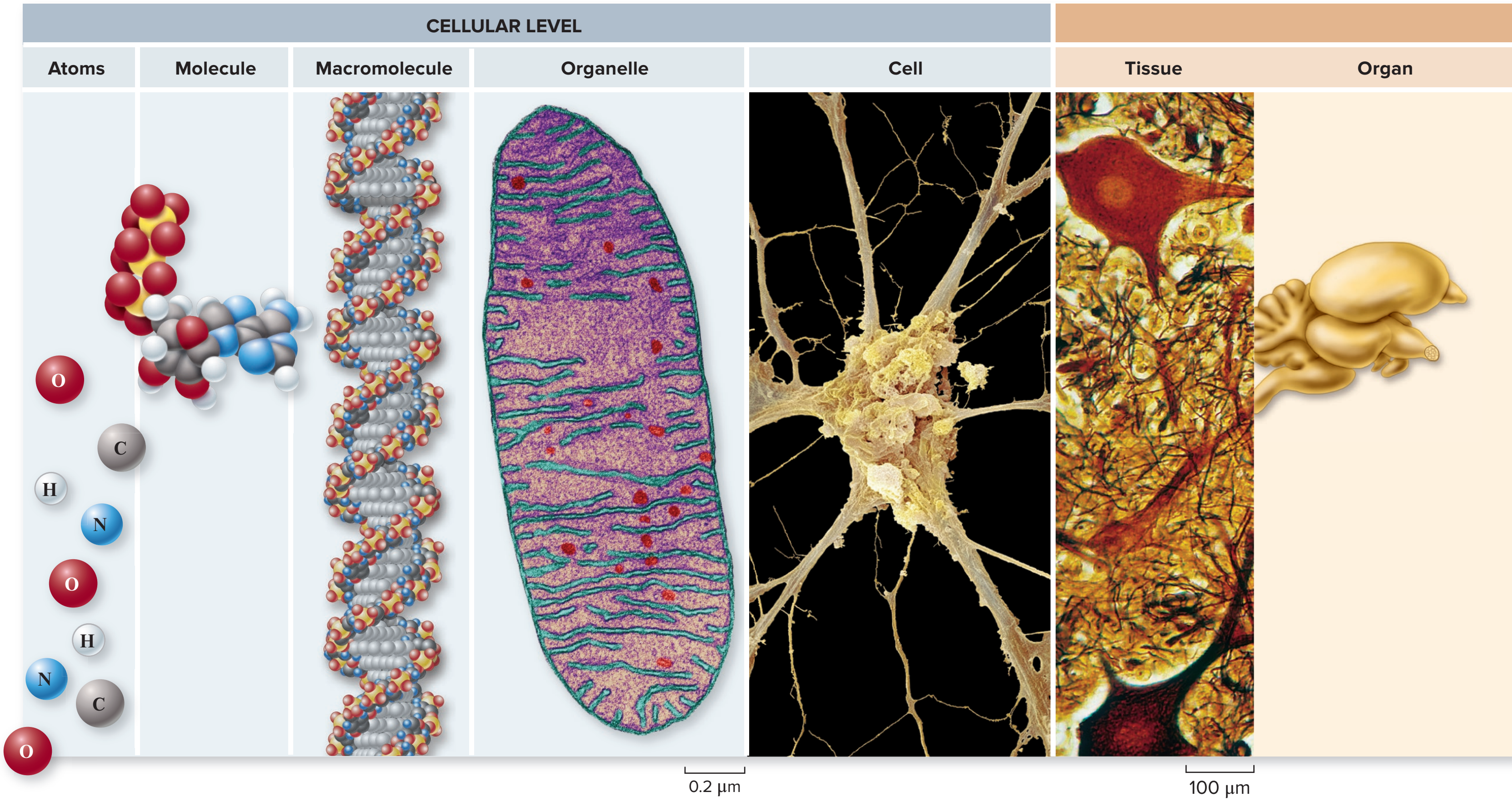
The way we do science is changing to grapple with increasingly difficult modern problems. Science is becoming more interdisciplinary, combining the expertise from a variety of traditional disciplines and emerging fields such as nanotechnology. Biology is at the heart of this multidisciplinary approach because biological problems often require many different approaches to arrive at solutions.

Life defies simple definition

In its broadest sense, biology is the study of living things—*the science of life*. Living things come in an astounding variety of shapes and forms, and biologists study life in many different ways. They live with gorillas, collect fossils, and listen to whales. They read the messages encoded in the long molecules of heredity and count how many times a hummingbird's wings beat each second.

What makes something "alive"? Anyone could deduce that a galloping horse is alive and a car is not, but why? We cannot say, "If it moves, it's alive," because a car can move, and gelatin can wiggle in a bowl. They certainly are not alive. Although we cannot define life with a single simple sentence, we can come up with a series of seven characteristics shared by living systems:

- **Cellular organization.** All organisms consist of one or more cells. Often too tiny to see, cells carry out the basic activities of living. Each cell is bounded by a membrane that separates it from its surroundings.
- **Ordered complexity.** All living things are both complex and highly ordered. Your body is composed of many different kinds of cells, each containing many complex molecular structures. Many nonliving things may also be complex, but they do not exhibit this degree of ordered complexity.



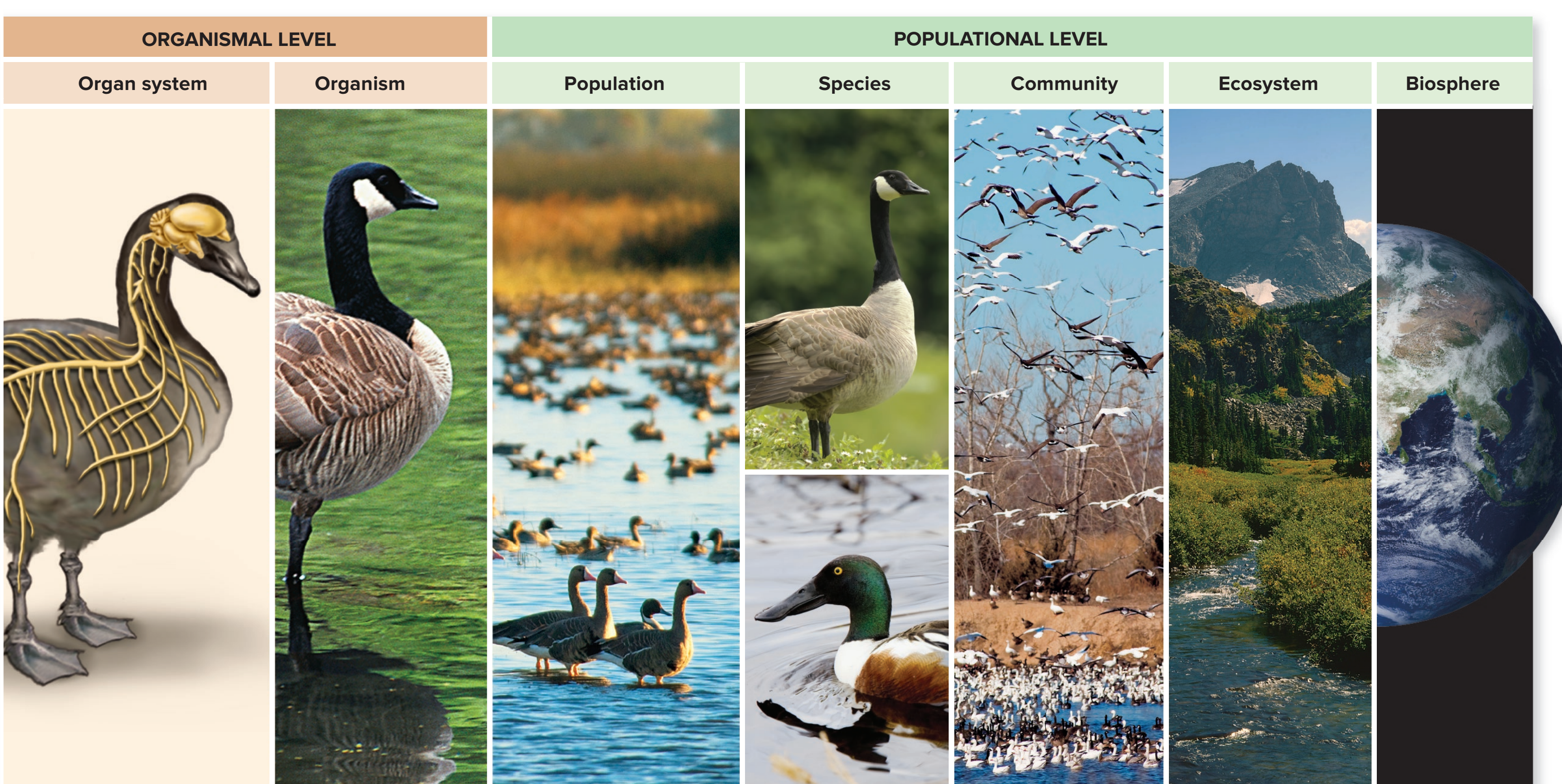
- **Sensitivity.** All organisms respond to stimuli. Plants grow toward a source of light, and the pupils of your eyes dilate when you walk into a dark room.
- **Growth, development, and reproduction.** All organisms are capable of growing and reproducing, and they all possess hereditary molecules that are passed to their offspring, ensuring that the offspring are of the same species.
- **Energy utilization.** All organisms take in energy and use it to perform many kinds of work. Every muscle in your body is powered with energy you obtain from your diet.
- **Homeostasis.** All organisms maintain relatively constant internal conditions that are different from their environment, a process called **homeostasis.** For example, your body temperature remains stable despite changes in outside temperatures.
- **Evolutionary adaptation.** All organisms interact with other organisms and the nonliving environment in ways that influence their survival, and as a consequence, organisms evolve adaptations to their environments.

Living systems show hierarchical organization

The organization of the biological world is hierarchical—that is, each level builds on the level below it:

1. **The cellular level.** At the cellular level (figure 1.1), **atoms,** the fundamental elements of matter, are joined together into clusters called **molecules.** Complex biological molecules are assembled into tiny structures called **organelles** within membrane-bounded units we call **cells.** The cell is the basic unit of life. Many independent organisms are composed only of single cells. Bacteria are single cells, for example. All animals and plants, as well as most fungi and algae, are multicellular—composed of more than one cell.
2. **The organismal level.** Cells in complex multicellular organisms exhibit three levels of organization. The most basic level is that of **tissues,** which are groups of similar cells that act as a functional unit. Tissues, in turn, are grouped into **organs—**body structures composed of several different tissues that act as a structural and functional unit. Your brain is an organ composed of nerve cells and a variety of associated tissues that form protective coverings and contribute blood. At the third level of organization, organs are grouped into **organ systems.** The nervous system, for example, consists of sensory organs, the brain and spinal cord, and neurons that convey signals.

Figure 1.1 Hierarchical organization of living systems. Life forms a hierarchy of organization from atoms to complex multicellular organisms. Atoms are joined together to form molecules, which are assembled into more complex structures such as organelles. These in turn form subsystems that provide different functions. Cells can be organized into tissues, then into organs and organ systems such as the goose's nervous system pictured. This organization then extends beyond individual organisms to populations, communities, ecosystems, and finally the biosphere. (Organelle): ©Keith R. Porter/Science Source; (Cell): ©STEVE GSCHMEISSNER/Getty Images; (Tissue): ©Ed Reschke; (Organism): ©Russell Illig/Getty Images; (Population): ©George Ostertag/age fotostock; (Species): ©iStockphoto/Getty Images; ©Pictureguy/Shutterstock; (Community): ©Ryan McGinnis/Alamy; (Ecosystem): ©Robert and Jean Pollock; (Biosphere): Source: NASA



3. **The populational level.** Individual organisms can be categorized into several hierarchical levels within the living world. The most basic of these is the **population—**a group of organisms of the same species living in the same place. All populations of a particular kind of organism together form a **species,** its members similar in appearance and able to interbreed. At a higher level of biological organization, a **biological community** consists of all the populations of different species living together in one place.
4. **The ecosystem level.** At the highest tier of biological organization, populations of organisms interact with each other and their physical environment. Together populations and their environment constitute an ecological system, or **ecosystem.** For example, the biological community of a mountain meadow interacts with the soil, water, and atmosphere of a mountain ecosystem in many important ways.
5. **The biosphere.** The entire planet can be thought of as an ecosystem that we call the biosphere.

As you move up this hierarchy, the many interactions occurring at lower levels can produce novel properties. These so-called **emergent properties** may not be predictable. Examining individual cells, for example, gives little hint about the whole animal. Many weather phenomena, such as hurricanes, are actually emergent properties of many interacting meteorological variables. It is because the living world exhibits many emergent properties that it is difficult to define "life."

This description of the common features and organization of living systems provides an introduction for our exploration of biology. Before we continue, we will consider the broader question of the nature of science itself.

Learning Outcomes Review 1.1

Biology as a science brings together other natural sciences, such as chemistry and physics, to study living systems. Life does not have a simple definition, but living systems share a number of properties that together describe life. Living systems can be organized hierarchically, from the cellular level to the entire biosphere, with emergent properties that may exceed the sum of the parts.

- ***Can you study biology without studying other sciences?***

1.2 The Nature of Science

Learning Outcomes

1. *Compare the different types of reasoning used by biologists.*
2. *Demonstrate how to formulate and test a hypothesis.*

Much like life itself, the nature of science defies simple description. For many years scientists have written about the "scientific method" as though there is a single way of doing science. This oversimplification has contributed to confusion on the part of nonscientists about the nature of science.

At its core, science is concerned with developing an increasingly accurate understanding of the world around us using observation and reasoning. To begin with, we assume that natural forces acting now have always acted, that the fundamental nature of the universe has not changed since its inception, and that it is not changing now. A number of complementary approaches allow understanding of natural phenomena—there is no one "scientific method."

Scientists also attempt to be as objective as possible in the interpretation of the data and observations they have collected. Because scientists themselves are human, this is not completely possible, but because science is a collective endeavor subject to scrutiny, it is self-correcting. One person's results are verified by others, and if the results cannot be repeated, they are rejected.

Much of science is descriptive

The classic vision of the scientific method is that observations lead to hypotheses that in turn make experimentally testable predictions. In this way, we dispassionately evaluate new ideas to arrive at an increasingly accurate view of nature. We discuss this way of doing science later in this section but it is important to understand that much of science is purely descriptive: In order to understand anything, the first step is to describe it completely. Much of biology is concerned with arriving at an increasingly accurate description of nature.

The study of biodiversity is an example of descriptive science that has implications for other aspects of biology in addition to societal implications. Efforts are currently under way to classify all life on Earth. This ambitious project is purely descriptive, but it will lead to a much greater understanding of biodiversity as well as the effect our species has on biodiversity.

One of the most important accomplishments of molecular biology at the dawn of the 21st century was the completion of the sequence of the human genome. Many new hypotheses about human biology will be generated by this knowledge, and many experiments will be needed to test these hypotheses, but the determination of the sequence itself was descriptive science.

Science uses both deductive and inductive reasoning

The study of logic recognizes two opposite ways of arriving at logical conclusions: deductive and inductive reasoning. Science makes use of both of these methods, although induction is the primary way of reasoning in hypothesis-driven science.

Deductive reasoning

Deductive reasoning applies general principles to predict specific results. More than 2200 years ago, the Greek scientist Eratosthenes used Euclidean geometry and deductive reasoning to accurately estimate the circumference of the Earth (figure 1.2). Deductive reasoning is the reasoning of mathematics and philosophy, and it is used to test the validity of general ideas in all

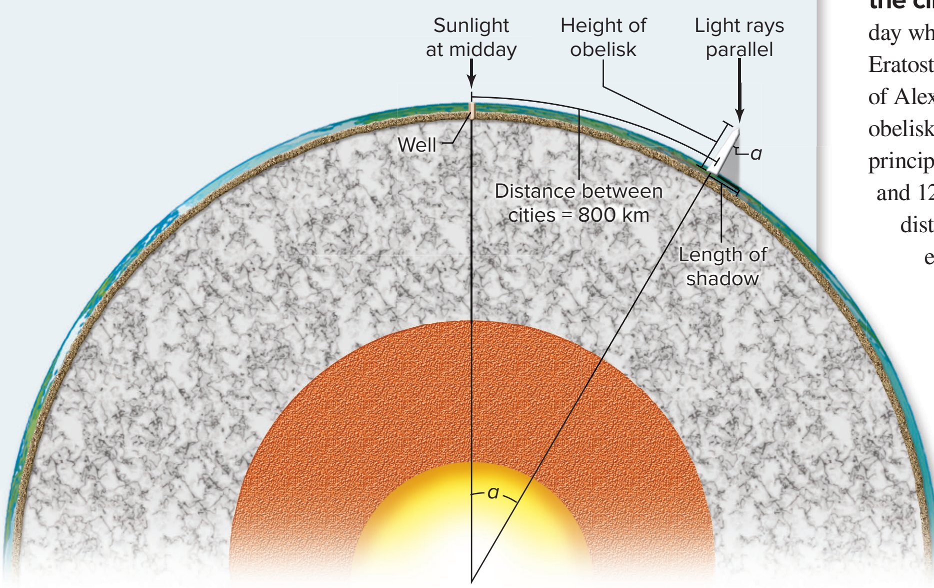


Figure 1.2 Deductive reasoning: How Eratosthenes estimated the circumference of the Earth using deductive reasoning. ***1.*** On a day when sunlight shone straight down a deep well at Syene in Egypt, Eratosthenes measured the length of the shadow cast by a tall obelisk in the city of Alexandria, about 800 kilometers (km) away. ***2.*** The shadow's length and the obelisk's height formed two sides of a triangle. Using the recently developed principles of Euclidean geometry, Eratosthenes calculated the angle, *a,* to be 7° and 12′, exactly 1/50 of a circle (360°). ***3.*** If angle *a* is 1/50 of a circle, then the distance between the obelisk (in Alexandria) and the well (in Syene) must be equal to 1/50 the circumference of the Earth. ***4.*** Eratosthenes had heard that it was a 50-day camel trip from Alexandria to Syene. Assuming a camel travels about 18.5 km per day, he estimated the distance between obelisk and well as 925 km (using different units of measure, of course). ***5.*** Eratosthenes thus deduced the circumference of the Earth to be 50 × 925 = 46,250 km. Modern measurements put the distance from the well to the obelisk at just over 800 km. Using this distance Eratosthenes's value would have been 50 × 800 = 40,000 km. The actual circumference is 40,075 km.

branches of knowledge. For example, if all mammals by definition have hair, and you find an animal that does not have hair, then you may conclude that this animal is not a mammal. A biologist uses deductive reasoning to infer the species of a specimen from its characteristics.

Inductive reasoning

In **inductive reasoning,** the logic flows in the opposite direction, from the specific to the general. Inductive reasoning uses specific observations to construct general scientific principles. For example, if poodles have hair, and terriers have hair, and every dog that you observe has hair, then you may conclude that all dogs have hair. Inductive reasoning leads to generalizations that can then be tested. Inductive reasoning first became important to science in the 1600s in Europe, when Francis Bacon, Isaac Newton, and others began to use the results of particular experiments to infer general principles about how the world operates.

An example from modern biology is the role of homeobox genes in development. Studies in the fruit fly, *Drosophila melanogaster,* identified genes that could cause dramatic changes in developmental fate, such as a leg appearing in the place of an antenna. These genes have since been found in essentially all multicellular animals analyzed. This led to the general idea that homeobox genes control developmental fate in animals.

Hypothesis-driven science makes and tests predictions

Scientists establish which general principles are true from among the many that might be true through the process of systematically testing alternative proposals. If these proposals prove inconsistent with experimental observations, they are rejected as untrue. Figure 1.3 illustrates the process.

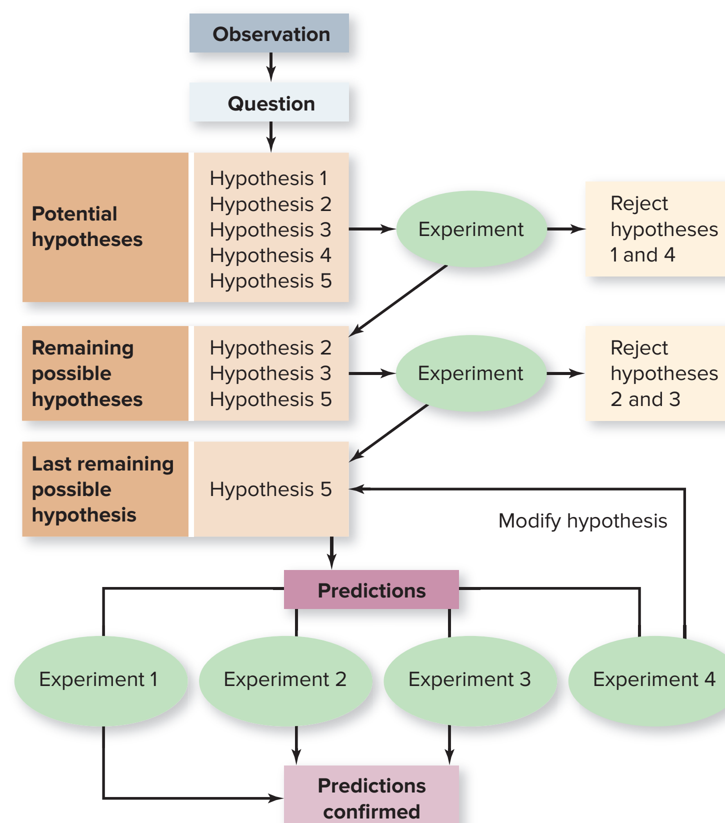


Figure 1.3 How science is done. This diagram illustrates how scientific investigations proceed. First, scientists make observations that raise a particular question. They develop a number of potential explanations (hypotheses) to answer the question. Next, they carry out experiments in an attempt to eliminate one or more of these hypotheses. Then, predictions are made based on the remaining hypotheses, and further experiments are carried out to test these predictions. The process can also be iterative. As experimental results are performed, the information can be used to modify the original hypothesis to fit each new observation.

After making careful observations, scientists construct a **hypothesis,** which is a suggested explanation that accounts for those observations. A hypothesis is a proposition that might be true. Those hypotheses that have not yet been disproved are retained. They are useful because they fit the known facts, but they are always subject to future rejection if, in the light of new information, they are found to be incorrect.

This is usually an ongoing process with a hypothesis changing and being refined with new data. For instance, geneticists George Beadle and Edward Tatum studied the nature of genetic information to arrive at their "one-gene/one-enzyme" hypothesis (see chapter 15). This hypothesis states that a gene represents the genetic information necessary to make a single enzyme. As investigators learned more about the molecular nature of genetic information, the hypothesis was refined to "one gene/one polypeptide" because enzymes can be made up of more than one polypeptide. With still more information about the nature of genetic information, other investigators found that a single gene can specify more than one polypeptide, and the hypothesis was refined again.

Testing hypotheses

We call the test of a hypothesis an **experiment.** Suppose you enter a dark room. To understand why it is dark, you propose several hypotheses. The first might be, "There is no light in the room because the light switch is turned off." An alternative hypothesis might be, "There is no light in the room because the lightbulb is burned out." And yet another hypothesis might be, "I am going blind." To evaluate these hypotheses, you would conduct an experiment designed to eliminate one or more of the hypotheses.

For example, you might test your hypotheses by flipping the light switch. If you do so and the room is still dark, you have disproved the first hypothesis: Something other than the setting of the light switch must be the reason for the darkness. Note that a test such as this does not prove that any of the other hypotheses are true; it merely demonstrates that the one being tested is not. A successful experiment is one in which one or more of the alternative hypotheses is demonstrated to be inconsistent with the results and is thus rejected.

As you proceed through this text, you will encounter many hypotheses that have withstood the test of experiment. Many will continue to do so; others will be revised as new observations are made by biologists. Biology, like all science, is in a constant state of change, with new ideas appearing and replacing or refining old ones.

Establishing controls

Often scientists are interested in learning about processes that are influenced by many factors, or **variables.** To evaluate alternative hypotheses about one variable, all other variables must be kept constant. This is done by carrying out two experiments in parallel: an **experimental treatment** or **group** and a **control treatment** or **group**. In the experimental treatment, one variable is altered in a known way to test a particular hypothesis. In the control treatment, that variable is left unaltered. In all other respects the two experiments are identical, so any difference in the outcomes of the two experiments must result from the influence of the variable that was changed.

Much of the challenge of experimental science lies in designing control experiments that isolate a particular variable from other factors that might influence a process.

Using predictions

A successful scientific hypothesis needs to be not only valid but also useful—it needs to tell us something we want to know. A hypothesis is most useful when it makes predictions because those predictions provide a way to test the validity of the hypothesis. If an experiment produces results inconsistent with the predictions, the hypothesis must be rejected or modified. In contrast, if the predictions are supported by experimental testing, the hypothesis is supported. The more experimentally supported predictions a hypothesis makes, the more valid the hypothesis is.

As an example, in the early history of microbiology it was known that nutrient broth left sitting exposed to air becomes contaminated. Two hypotheses were proposed to explain this observation: spontaneous generation and the germ hypothesis. Spontaneous generation held that there was an inherent property in organic molecules that could lead to the spontaneous generation of life. The germ hypothesis proposed that preexisting microorganisms that were present in the air could contaminate the nutrient broth.

These competing hypotheses were tested by a number of experiments that involved filtering air and boiling the broth to kill any contaminating germs. The definitive experiment was performed by Louis Pasteur, who constructed flasks with curved necks that could be exposed to air, but that would trap any contaminating germs. When such flasks were boiled to sterilize them, they remained sterile, but if the curved neck was broken off, they became contaminated (figure 1.4).

SCIENTIFIC THINKING

Question: *What is the source of contamination that occurs in a flask of nutrient broth left exposed to the air?*

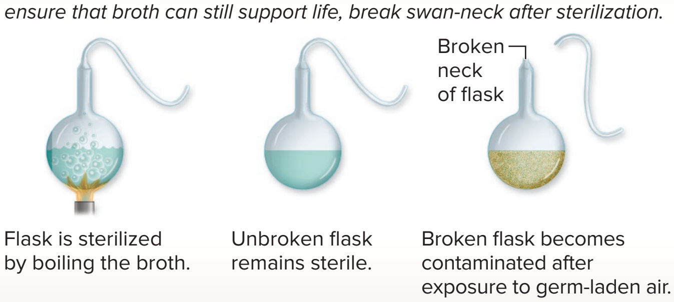
Germ Hypothesis: *Preexisting microorganisms present in the air contaminate nutrient broth.*

Prediction: *Sterilized broth will remain sterile if microorganisms are prevented from entering flask.*

Spontaneous Generation Hypothesis: *Living organisms will spontaneously generate from nonliving organic molecules in broth.*

Prediction: *Organisms will spontaneously generate from organic molecules in broth after sterilization.*

Test: *Use swan-necked flasks to prevent entry of microorganisms. To ensure that broth can still support life, break swan-neck after sterilization.*



Result: *No growth occurs in sterile swan-necked flasks. When the neck is broken off, and the broth is exposed to air, growth occurs.*

Conclusion: *Growth in broth is of preexisting microorganisms.*

Figure 1.4 **Experiment to test spontaneous generation versus germ hypothesis.**

This result was predicted by the germ hypothesis—that when the sterile flask is exposed to air, airborne germs are deposited in the broth and grow. The spontaneous generation hypothesis predicted no difference in results with exposure to air. This experiment disproved the hypothesis of spontaneous generation and supported the hypothesis of airborne germs under the conditions tested.

Reductionism breaks larger systems into their component parts

Scientists use the philosophical approach of **reductionism** to understand a complex system by reducing it to its working parts. Reductionism has been the general approach of biochemistry, which has been enormously successful at unraveling the complexity of cellular metabolism by concentrating on individual pathways and specific enzymes. By analyzing all of the pathways and their components, scientists now have an overall picture of the metabolism of cells.

Reductionism has limits when applied to living systems, however—one of which is that enzymes do not always behave exactly the same in isolation as they do in their normal cellular context. A larger problem is that the complex interworking of many interconnected functions leads to emergent properties that cannot be predicted based on the workings of the parts. For example, ribosomes are the cellular factories that synthesize proteins, but this function could not be predicted based on analysis of the individual proteins and RNA that make up the structure. On a higher level, understanding the physiology of a single Canada goose would not lead to predictions about flocking behavior. The emerging field of systems biology uses mathematical and computational models to deal with the whole as well as understanding the interacting parts.

Biologists construct models to explain living systems

Biologists construct models in many different ways for a variety of uses. Geneticists construct models of interacting networks of proteins that control gene expression, often even drawing cartoon figures to represent that which we cannot see. Population biologists build models of how evolutionary change occurs. Cell biologists build models of signal transduction pathways and the events leading from an external signal to internal events. Structural biologists build actual models of the structure of proteins and macromolecular complexes in cells.

Models provide a way to organize how we think about a problem. Models can also get us closer to the larger picture and away from the extreme reductionist approach. The working parts are provided by the reductionist analysis, but the model shows how they fit together. Often these models suggest other experiments that can be performed to refine or test the model.

As researchers gain more knowledge about the actual flow of molecules in living systems, more sophisticated kinetic models can be used to apply information about isolated enzymes to their cellular context. In systems biology, this modeling is being applied on a large scale to regulatory networks during development, and even to modeling an entire bacterial cell.

The nature of scientific theories

Scientists use the word **theory** in two main ways. The first meaning of theory is a proposed explanation for some natural phenomenon, often based on some general principle. Thus, we speak of the principle first proposed by Newton as the "theory of gravity." Such theories often bring together concepts that were previously thought to be unrelated.

The second meaning of theory is the body of interconnected concepts, supported by scientific reasoning and experimental evidence, that explains the facts in some area of study. Such a theory provides an indispensable framework for organizing a body of knowledge. For example, quantum theory in physics brings together a set of ideas about the nature of the universe, explains experimental facts, and serves as a guide to further questions and experiments.

To a scientist, theories are the solid ground of science, expressing ideas of which we are most certain. In contrast, to the general public, the word theory usually implies the opposite—a *lack* of knowledge, or a guess. Not surprisingly, this difference often results in confusion. In this text, theory will always be used in its scientific sense, in reference to an accepted general principle or body of knowledge.

Some critics outside of science attempt to discredit evolution by saying it is "just a theory." The hypothesis that evolution has occurred, however, is an accepted scientific fact—it is supported by overwhelming evidence. Modern evolutionary theory is a complex body of ideas, the importance of which spreads far beyond explaining evolution. Its ramifications permeate all areas of biology, and it provides the conceptual framework that unifies biology as a science. Again, the key is how well a hypothesis fits the observations. Evolutionary theory fits the observations very well.

Research can be basic or applied

In the past it was fashionable to speak of the "scientific method" as consisting of an orderly sequence of logical, either–or steps. Each step would reject one of two mutually incompatible alternatives, as though trial-and-error testing would inevitably lead a researcher through the maze of uncertainty to the ultimate scientific answer. If this were the case, a computer would make a good scientist. But science is not done this way.

As the British philosopher Karl Popper has pointed out, successful scientists without exception design their experiments with a pretty fair idea of how the results are going to come out. They have what Popper calls an "imaginative preconception" of what the truth might be. Because insight and imagination play such a large role in scientific progress, some scientists are better at science than others—just as Bruce Springsteen stands out among songwriters or Claude Monet stands out among Impressionist painters.

Some scientists perform *basic research,* which is intended to extend the boundaries of what we know. These individuals typically work at universities, and their research is usually supported by grants from various agencies and foundations.

The information generated by basic research contributes to the growing body of scientific knowledge, and it provides the scientific foundation utilized by *applied research.* Scientists who conduct applied research are often employed in some kind of industry. Their work may involve the manufacture of food additives, the creation of new drugs, or the testing of environmental quality.