# Principles of Life

THIRD EDITION

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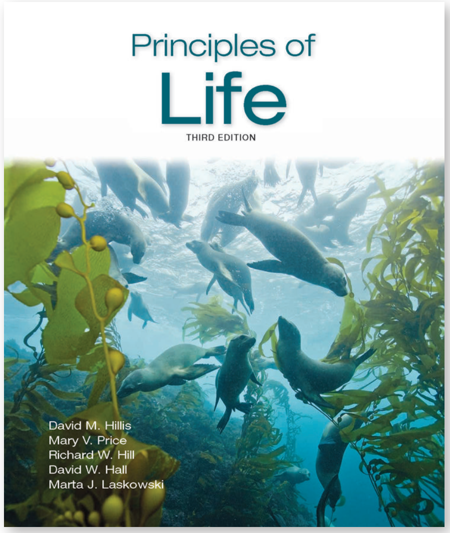

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Principles of Life, Third Edition



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*To all our students. You have taught us, too, and inspired us to write this book.*

# About the Authors

*from left: Mary Price, David Hall, Marta Laskowski, David Hillis, Richard Hill*

**DAVID M. HILLIS** is the Alfred W. Roark Centennial Professor in Integrative Biology at the University of Texas at Austin, where he also has directed the Center for Computational Biology and Bioinformatics, the Biodiversity Center, and the School of Biological Sciences. Dr. Hillis has taught courses in introductory biology, genetics, evolution, systematics, and biodiversity. He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences. He was awarded a John D. and Catherine T. MacArthur Fellowship, and has served as President of the Society for the Study of Evolution and of the Society of Systematic Biologists. He served on the National Research Council committee that wrote the report *BIO 2010: Transforming Undergraduate Biology Education for Research Biologists*, and currently serves on the Executive Committee of the National Academies Scientific Teaching Alliance.

**MARY V. PRICE** is Professor of Biology, Emerita, at the University of California, Riverside, and Adjunct Professor in the School of Natural Resources and the Environment at the University of Arizona. In "retirement" she continues to teach, investigate, and publish. Dr. Price has taught, mentored, and published with students at all levels, and particularly enjoys leading field classes in the arid regions of North America and Australia, and the tropical forests of Central America, Africa, and Madagascar. Her research focuses on understanding not only the ecology of North American deserts and mountains, but also on how science really works.

**RICHARD W. HILL** is Emeritus Professor in the Department of Integrative Biology at Michigan State University and a frequent Guest Investigator at Woods Hole Oceanographic Institution. He is the senior author of the leading textbook on animal physiology. Among the awards he has received are the Outstanding Faculty Award, Meritorious Faculty Award, and election as Fellow of the AAAS. His research interests include: temperature regulation and energetics in birds and mammals, especially neonates; and environmental physiology of marine tertiary sulfonium and quaternary ammonium compounds.

**DAVID W. HALL** is an Associate Professor of Genetics at the University of Georgia, where he was the recipient of the Sandy Beaver Excellence in Teaching Award in 2013. Recent work includes using mathematical models to address the evolution of meiotic drive, the rate and pattern of molecular evolution in social insects, and early sex chromosome evolution. In the lab, he utilizes different yeast species to study spontaneous mutations using a combination of both mutation-accumulation and adaptation experiments. Since high school, he has been captivated by how the living world works. Like many students, he was initially overwhelmed by the diversity of life, but he came to realize that there are fundamental principles that unite organisms. His interest in determining how these principles shape the diversity of life led him into his research and teaching career.

**MARTA J. LASKOWSKI** is a Professor in the Biology Department at Oberlin College. Dr. Laskowski has mentored undergraduate students in research and has taught introductory biology, skills-based first year seminars (Feeding the World), plant physiology, and plant development. She heads an effort at Oberlin, funded by the HHMI Inclusive Excellence program, to enhance the climate for and success of a diverse student population in STEM. One of her numerous journal articles resulted in a *Guinness World Record* for the fastest opening flower (*Cornus canadensis*; bunchberry). A college class in developmental biology so captivated her that she decided to focus her research on discovering the intricate sub-cellular interactions that establish the plant root system.

"All the new enhancements add not just to the learning experience of the students, but also make teaching this material that much more focused and aligned with something that is emerging as an important standard.… A welcome improvement in a biology textbook, designed for both instructors and students, which adopts key pedagogical competencies, wholly aligned with the *Vision and Change* directive."

Kamal Dulai, University of California, Merced

"The new toolbox of active learning opportunities integrated into the Third Edition of *Principles of Life* provides numerous opportunities for students and faculty to master *Vision and Change*'s Core Competencies. If used creatively, this text contains essential tools for mastering biology."

Justen Whittall, Santa Clara University

# *Principles of Life*, Third Edition



*** = New Chapter**

# *Principles of Life*—Tour of the New Edition

## Because success as a biologist means more than just succeeding in the first biology course

If you're concerned that the practical skills of biology will be lost when you move on to the next course or take your first step into the "real world," *Principles of Life*, Third Edition lays a solid foundation for later courses and for your career. Expanding on its pioneering concept-driven approach, experimental data-driven exercises, and active learning focus, the new edition introduces features designed to help you master concepts and become skillful at solving biological problems.

Research shows that when students engage with a course, it leads to better outcomes. *Principles of Life*, Third Edition is a holistic solution that has been designed from the ground up to actively engage you and help develop your skills as a biologist.

With its focus on key competencies foundational to biology education and careers, self-guided adaptive learning, and online resources, *Principles of Life* is the resource you need to succeed.

**THINK** LIKE A **SCIENTIST**

Quantitative Reasoning

Modeling & Simulation

**Changes in Earth's physical environment have affected the evolution of life**

In the experiment shown in Investigation Figure 17.8, body mass of individuals in the experimental populations of *Drosophila* increased (on average) about 2 percent per generation in the high-oxygen environment (although the rate of increase was not constant over the experiment). In the Permian, giant flying insects, such as dragonflies the size of modern hawks, inhabited Earth. Is the rate of increase in body mass

## A FOCUS ON SKILLS AND CORE COMPETENCIES

New to this edition, the AAAS *Vision and Change* report's six "core competencies," related to quantitative reasoning, simulation, and communication, are integrated both implicitly throughout the text and explicitly in a new key feature, Think Like a Scientist. TLAS boxes develop these core competencies, and have been designed specifically to teach you the skills you need to become a functional, practical, effective scientist.

**ANALYZE THE DATA**

After Kashefi and Lovley isolated Strain 121, they examined its growth at various temperatures. The table below shows generation time (time between cell divisions) at nine temperatures.

| Temperature (°C) | Generation time (hr) |
|---|---|
| 85 | 10 |
| 90 | 4 |
| 95 | 3 |
| 100 | 2.5 |
| 105 | 2 |
| 110 | 4 |
| 115 | 6 |
| 120 | 20 |

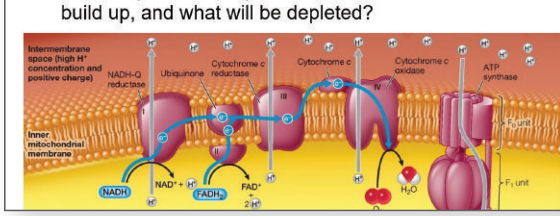
## A FOCUS ON DATA

*Principles of Life* has always emphasized the role of research and experimentation in the introductory biology curriculum. You will learn about the scientific method and experimental design, and understand how real research continues to drive our understanding of life on Earth.

Chemiosmotic Mechanism

**Examining Mitochondrial Poisons: Cyanide**

In your groups, predict what effect HCN would have on the inputs and outputs of these reactions. What will build up, and what will be depleted?




## A FOCUS ON ACTIVE LEARNING

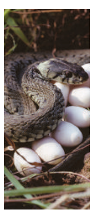
Where other texts give lip service to active learning, *Principles of Life* delivers, with an Active Learning Guide and 30 Active Learning Modules ready for classroom delivery. Built around key concepts, the ALMs provide a road map for pre-class work and in-class activities, including Apply the Data exercises, animations, videos, and quizzing directly mapped to in-text concepts and learning objectives.

# *Principles of Life*, Third Edition Content Updates

**The Third Edition of *Principles of Life* has not only been revised to be a more effective pedagogical tool, but it has also been updated to reflect the latest research and advances in biology.**

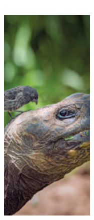
## PART 1: CELLS

- Increased focus on electronegativity to understand chemical bonding, including polarity, and redox reactions
- Clarified the meaning and role of chemical bond energy
- Increased emphasis on structure as it relates to function
- Improved emphasis on similarities across all organisms at the cellular level
- Reorganized treatment of cell metabolism to focus on underlying principles
- Simplified descriptions of cell signaling pathways to focus on general principles



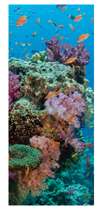
## PART 2: GENETICS

- Increased emphasis of similarities across all organisms for the encoding and expression of genetic information
- Now focused on the differences in initiation, elongation, and termination for replication, transcription, and translation, to prevent common misconceptions
- Focused descriptions of the relationship between genotype and phenotype for clarity
- Clarified coverage of the similarities and differences between meiosis and mitosis
- Updated genomics chapter (Chapter 12) and extended coverage of selfish DNA
- Biotechnology content integrated into other chapters to improve context



## PART 3: EVOLUTION

- Integrated coverage of Evo-Devo (evolution and development) into evolution section
- NEW CHAPTER: Chapter 15, Evolution of Genes and Genomes
- New problems that ask you to make and use phylogenetic trees, assess selection, calculate rates of change, and evaluate reproductive isolation
- Updated information on the history of life on Earth

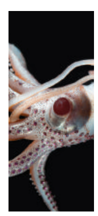


## PART 4: DIVERSITY

- Updated information on classifications and phylogeny of life
- Clarified coverage of the similarities and differences of sexual reproduction across major groups of life
- More problems asking you to apply information about the diversity of life to practical situations
- Simplified terminology in explaining the principles surrounding life's diversity

## PART 5: PLANT FORM AND FUNCTION

- Added explanations of mechanisms that drive plant development including meristem function and cell identity specification
- Updated information as to how temperature-dependent changes in the dark reversion rates of phytochrome allow plants to sense and respond to temperature
- Added connections between plant physiology and real-world issues such as climate change



## PART 6: ANIMAL FORM AND FUNCTION

- NEW CHAPTER: Chapter 29, Animals in Their Environments
- A single unified chapter on breathing and circulation (Chapter 30)
- Twice as many data sets for analysis and discussion
- An emphasis on comparative approaches to ecology throughout these chapters

## PART 7: ECOLOGY

- Expanded and updated treatment of the human microbiome as an ecological system
- Streamlined mathematical treatment of the dynamics of ecological populations
- Updated coverage of biogeochemical cycles with latest research findings

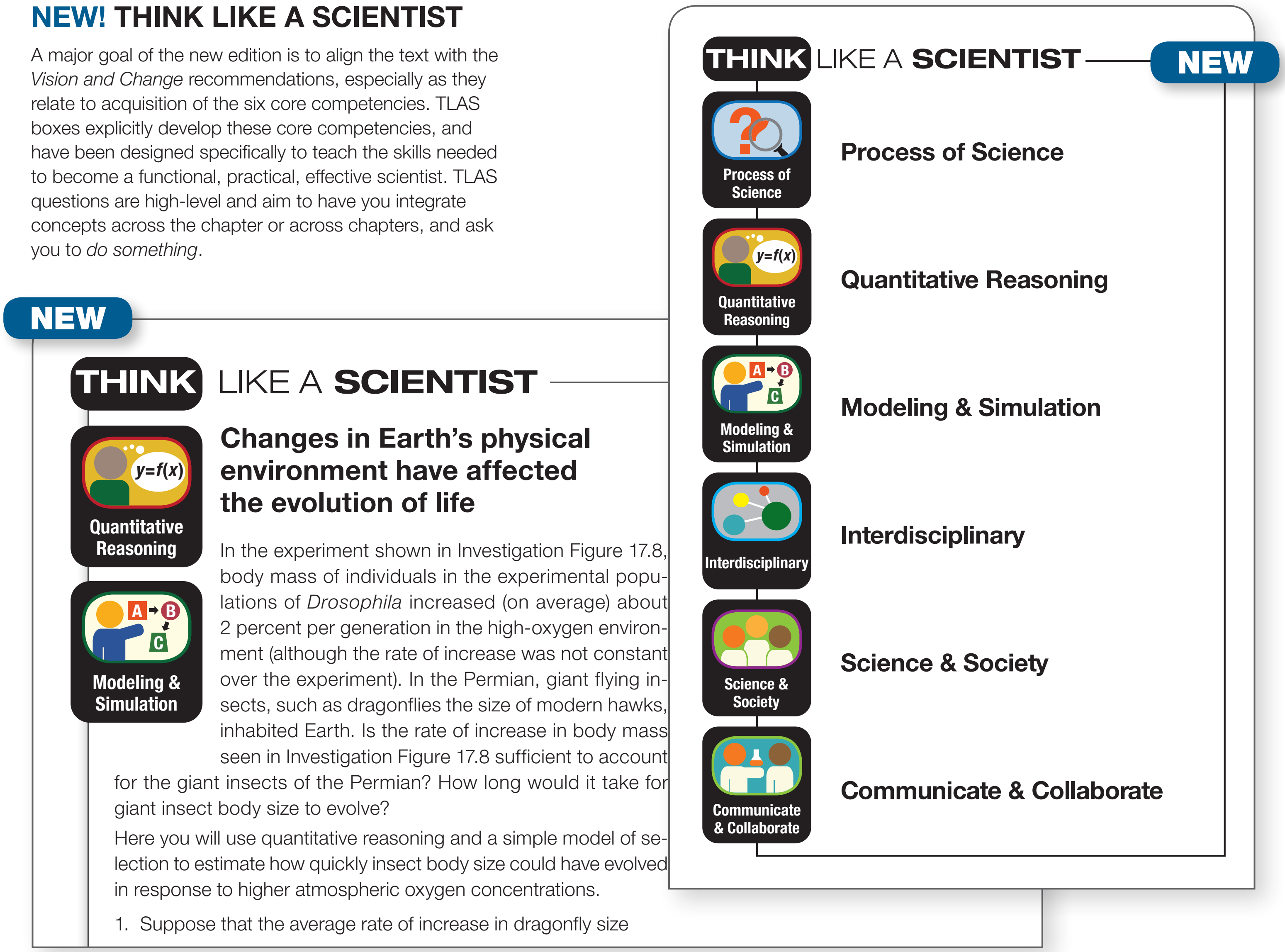
# Core Competencies

***Principles of Life*** **was created to ensure that you gain the knowledge you need from your introductory biology course, and acquire the skills needed to succeed as a life sciences major.**

New to this edition, the AAAS *Vision and Change* report's six "core competencies," related to quantitative reasoning, simulation, and communication, are integrated both implicitly throughout the text and explicitly in a new key feature, **THINK LIKE A SCIENTIST**.

## NEW! THINK LIKE A SCIENTIST

A major goal of the new edition is to align the text with the *Vision and Change* recommendations, especially as they relate to acquisition of the six core competencies. TLAS boxes explicitly develop these core competencies, and have been designed specifically to teach the skills needed to become a functional, practical, effective scientist. TLAS questions are high-level and aim to have you integrate concepts across the chapter or across chapters, and ask you to *do something*.




**Very Effective—Think Like a Scientist** is a great feature and I would assign this as a supplemental assignment. This feature encourages synthesis of material and development of critical-thinking skills around a relevant topic."

Sara E. Lahman, PhD, *University of Mount Olive*

# Core Competencies

"The **TLAS** is great. Wonderful emphasis on critical thinking and application."
Jennifer A. Metzler, *Ball State University*

NEW

## THINK LIKE A SCIENTIST

Science & Society

### Forensic phylogeny

Phylogenetic trees are used throughout biology, but only in recent years have they become important for forensic investigations. Here you will explore the relationship between science and society by applying your knowledge of phylogeny to a criminal court case.

A criminal case in Texas charged a defendant with knowingly and intentionally infecting a series of women with HIV. A phylogenetic analysis was used to demonstrate that the defendant transmitted HIV to his victims. (Other evidence was needed to prove knowledge and intent.) In this case, sequences of HIV isolated from the victims and the defendant, together with the closest sequences from an HIV database (the outgroup), were compared and used to construct a phylogenetic tree of the viruses (**FIGURE 14.10**). Viruses from each individual in the case are colored alike on the tree to the right. The labels are the codes for the individuals in the case. All of the individuals labeled CC01–CC08 are known to have engaged in sex; they represent an epidemiological cluster. (In forensic cases, samples are "blinded" to the investigators by assigning numbers to each sample, rather than using people's names. Only after the conclusions are finalized do other investigators decode the numbers to reveal the results.)

1. Which of the individuals labeled in the tree is consistent with being the source of this infection cluster? Why?
2. Why is the tree inconsistent with any of the other individuals being the source of infection within this cluster?
3. What was the purpose of including an outgroup made up of individuals who were outside the epidemiological cluster?

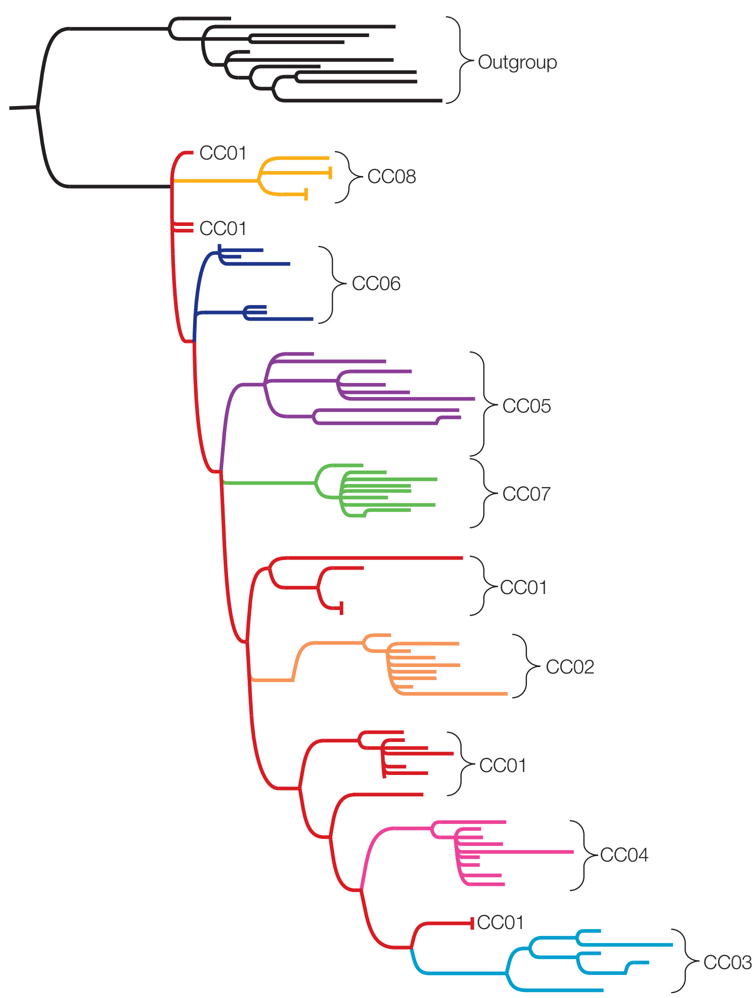



**FIGURE 14.10 Forensic Phylogeny** (After D. I. Scaduto et al. 2010. *Proc Natl Acad Sci USA* 107: 21242–21247.)

A complete list of the **Think Like a Scientist** boxes is shown on the following pages xii and xiii, along with their related **core competencies**.

# Core Competencies

## THINK LIKE A SCIENTIST

| Chapter | Title | Process of Science | Quantitative Reasoning | Modeling & Simulation | Interdisciplinary | Science & Society | Communicate & Collaborate |
|---|---|---|---|---|---|---|---|
| 2 | Climbing the walls | ● | | | | ● | |
| 3 | The origin of the molecules of life on Earth | | | ● | | | |
| 4 | Advances in microscopy have resulted in greater understanding of cell structure and function | | ● | | ● | | |
| 5 | The green Earth | ● | ● | | | | |
| 6 | Identifying and ordering steps in signal transduction pathways | ● | | | | | |
| 7 | Treating cancer | ● | | | | ● | |
| 8 | Coat color inheritance in Labrador retrievers | | ● | | | ● | |
| 9 | How can CODIS be used to identify suspects from a drop of blood? | ● | ● | | | ● | |
| 10 | Evidence for lateral gene transfer in aphids | ● | | | | | |
| 11 | Determining the regulation of the *lac* operon | ● | | | | | |
| 12 | Inactivation of specific genes using CRISPR-Cas9 gene editing | ● | | | | | |
| 13 | Observing and measuring phenotypic evolution | ● | | | | | |
| 14 | Forensic phylogeny | | | | | ● | |
| 15 | Why was the 1918–1919 influenza pandemic so severe? | | | | ● | ● | ● |
| 16 | Reinforcement of reproductive isolation | ● | | | | | |
| 17 | Changes in Earth's physical environment have affected the evolution of life | | ● | ● | | | |
| 18 | Putting bacteria to work | | | | | ● | |
| 19 | Using phylogenies to make predictions | | | | ● | | |
| 20 | Coevolution of plants and their pollinators | ● | | | | | |
| 21 | How dependent are plants on their fungal mutualists? | | ● | | | | |
| 22 | How do biologists estimate how many species are still undiscovered? | | | ● | | | |
| 23 | How can one identify the anatomical parts of a plant if they appear unfamiliar? | ● | | | | | |
| 24 | Testing new analytical methods: Might *Tillandsia* make useful air pollution monitors? | | ● | | | ● | |
| 25 | Correlation and causation | ● | | | | | |
| 26 | Impact of temperature on the bloom time of plants near Walden Pond in Concord, Massachusetts | | ● | | | ● | ● |
| 27 | Modeling Earth's carbon cycle | | ● | ● | | ● | |
| 28 | Using quantitative reasoning to communicate with nonscientists about "burning off" extra food calories | | ● | | | | ● |
| 29 | Is global warming affecting animal life or not? | ● | | | | ● | |

# Core Competencies

## THINK LIKE A SCIENTIST

| Chapter | Title | Process of Science | Quantitative Reasoning | Modeling & Simulation | Interdisciplinary | Science & Society | Communicate & Collaborate |
|---|---|---|---|---|---|---|---|
| 30 | How does a person's maximal rate of $O_2$ consumption vary with elevation in the mountains? | | ● | | | | |
| 31 | Do some moths jam bats' echolocation mechanism? | ● | | | | | |
| 32 | Commercialization of hormones: New choices for people to make | ● | | | | | ● |
| 33 | From the shores of ancient Rome to flashing muscle fibers: Progress in a stunning collaboration across generations of scientists, disciplines, animals, and tissues | ● | | | ● | | ● |
| 34 | The value of manipulative experiments | ● | ● | | ● | | |
| 35 | Differentiation can be due to inhibition of transcription factors | ● | | | | | |
| 36 | Avoiding incompatibilities in blood type: The immune response to the Rh factor | | | | | ● | |
| 37 | How are animals reacting to global warming? | ● | | | | | |
| 38 | Phylogenetic methods contribute to our understanding of biogeography | ● | | | ● | | |
| 39 | Dispersal corridors can "rescue" fragmented populations from extinction | ● | ● | | | | |
| 40 | Intra- and interspecific competition influence the morphology of coexisting species | ● | ● | | | | |
| 41 | Additional predictions of the MacArthur-Wilson theory can be tested | ● | ● | | | | |
| 42 | Computer models of Earth's climate link global warming to human activities | | ● | ● | ● | ● | ● |

**Process of Science**

**Quantitative Reasoning**

**Modeling & Simulation**

**Interdisciplinary**

**Science & Society**

**Communicate & Collaborate**

# Mastering the Key Concepts

**Each chapter of *Principles of Life* is built around a pedagogical framework meant to ensure a mastery of all of the important biological concepts in the introductory course.**

## KEY CONCEPTS

Dividing chapters into sections, every Key Concept explores a single essential concept in light of established facts and relevant experimental evidence, providing the conceptual framework for the chapter, exercises, and questions ahead.


## NEW! LEARNING OBJECTIVES

Learning Objectives are provided at the start of each Key Concept. The goal of Learning Objectives is to help you focus your attention as you read each section. At the end of each section, we reinforce the Learning Objectives with exercises/questions in Review & Apply. Learning Objectives encourage active learning and focus on mastering concepts and skills.

**17.1 Events in Earth's History Can Be Dated** — NEW

**LEARNING OBJECTIVES**

By the end of this key concept you should be able to:

- **17.1.1** Construct a geological map indicating the ages of exposed rocks and use the map to search for fossils of a given age.
- **17.1.2** Select appropriate methods for dating fossils and rocks from different geological time periods.
- **17.1.3** Place important events in biological history onto a time line of Earth's history.

## NEW! REVIEW & APPLY

This new feature is designed to briefly summarize the previous section, and help you master concepts and competencies through questions. R&A questions are concept-specific, aligning with the Learning Objectives. With the exception of introductory concepts, R&A questions tend to be higher-level Bloom's, and when possible, ask you to engage in an activity-based answer.

**REVIEW & APPLY | 17.1** — NEW

**R** The layering of sedimentary rock strata enables geologists to determine the relative ages of fossils. Assigning actual ages to these strata requires analysis of radioactive decay, paleomagnetic dating, and fossil comparisons across strata. Geologists divide the history of life into eons, eras, and periods based on assemblages of fossil organisms found in successive layers of rocks.

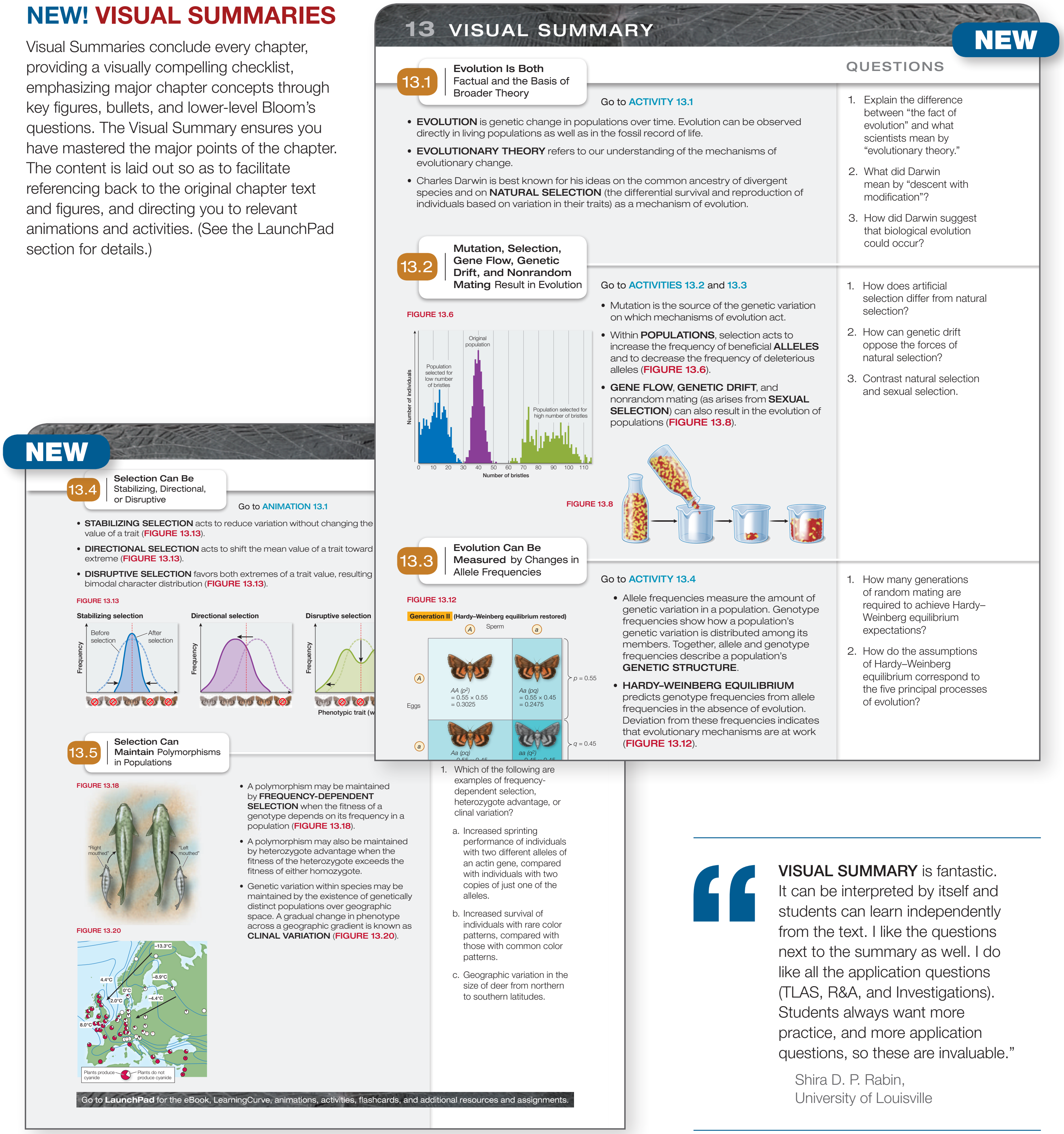
**A** Imagine you have been assigned the job of producing a geological map of rocks that were formed between 600 and 400 million years ago (mya). You collect a sample from each of ten sites (1–10 on the map below), determine the ratio of $^{206}Pb$ to $^{238}U$ for each sample, and use these ratios to estimate the ages of the rock samples, resulting in the table on the following page.


| Site | $^{206}Pb/^{238}U$ ratio | Estimated age (mya) |
|---|---|---|
| 1 | 0.076 | 474 |
| 2 | 0.077 | 479 |
| 3 | 0.069 | 431 |
| 4 | 0.081 | 505 |

# Mastering the Key Concepts

## NEW! VISUAL SUMMARIES

Visual Summaries conclude every chapter, providing a visually compelling checklist, emphasizing major chapter concepts through key figures, bullets, and lower-level Bloom's questions. The Visual Summary ensures you have mastered the major points of the chapter. The content is laid out so as to facilitate referencing back to the original chapter text and figures, and directing you to relevant animations and activities. (See the LaunchPad section for details.)




> **"VISUAL SUMMARY** is fantastic. It can be interpreted by itself and students can learn independently from the text. I like the questions next to the summary as well. I do like all the application questions (TLAS, R&A, and Investigations). Students always want more practice, and more application questions, so these are invaluable."
>
> Shira D. P. Rabin,
> University of Louisville

# Developing Skills and Working with Data

***Principles of Life*** **has always been known for emphasizing the role of experimentation, data, and research in our understanding of biology. The Third Edition includes even more tools to help you understand how we know what we know.**

## INVESTIGATION

**FIGURE 18.14 What Is the Highest Temperature Compatible with Life?** Can any organism thrive at temperatures above 120°C? This is the temperature used for sterilization, known to destroy all previously described organisms. Kazem Kashefi and Derek Lovley isolated an unidentified prokaryote from water samples taken near a hydrothermal vent and found it survived and even multiplied at 121°C. The organism was dubbed "Strain 121," and its gene sequencing results indicate that it is a prokaryotic archaeal species.[a]

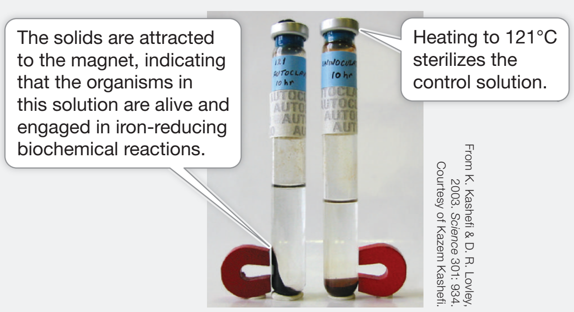
### HYPOTHESIS

Some prokaryotes can survive at temperatures above 120°C.

### METHOD

1. Seal samples of unidentified, iron-reducing, thermal vent prokaryotes in tubes with a medium containing $Fe^{3+}$ as an electron acceptor. Control tubes contain $Fe^{3+}$ but no organisms.
2. Hold both tubes in a sterilizer at 121°C for 10 hours. If the iron-reducing organisms are metabolically active, they will reduce the $Fe^{3+}$ to $Fe^{2+}$ (as magnetite, which can be detected with a magnet).

### RESULTS




From K. Kashefi & D. R. Lovley, 2003. Science 301: 934. Courtesy of Kazem Kashefi.

### CONCLUSION

Prokaryotic archaea of Strain 121 can survive at temperatures above the previously defined sterilization limit.

### ANALYZE THE DATA

After Kashefi and Lovley isolated Strain 121, they examined its growth at various temperatures. The table below shows generation time (time between cell divisions) at nine temperatures.

| Temperature (°C) | Generation time (hr) |
|---|---|
| 85 | 10 |
| 90 | 4 |
| 95 | 3 |
| 100 | 2.5 |
| 105 | 2 |
| 110 | 4 |
| 115 | 6 |
| 120 | 20 |
| 130 | No growth, but cells not killed |

## INVESTIGATIONS WITH ANALYZE THE DATA QUESTIONS

Highly acclaimed by adopters, Investigations and Analyze the Data return in the Third Edition. The goal of the Investigations is to help you master both big concepts in biology and *Vision and Change* competencies. This is done by illustrating a real study and having you analyze the resulting real data. Investigations with Analyze the Data questions are higher-level Bloom's, integrating concepts within the chapter or across chapters, and encouraging activity-based answers. In addition, LaunchPad includes online companions to the Analyze the Data exercises. (See the LaunchPad section for details.)

## RESEARCH TOOLS

Throughout *Principles of Life*, this feature focuses on techniques and quantitative methods scientists use to investigate biological systems.

### RESEARCH TOOLS

**FIGURE 13.11 Calculating Allele and Genotype Frequencies** Allele and genotype frequencies for a gene locus with two alleles in the population can be calculated using the equations in panel 1. When the equations are applied to two populations (panel 2), we find that the frequencies of alleles *A* and *a* in the two populations are the same, but the alleles are distributed differently between heterozygous and homozygous genotypes.

**1** In any population, where *N* is the total number of individuals in the population:

**Frequency of allele *A*** $= p = \frac{2N_{AA} + N_{Aa}}{2N}$ **Frequency of allele *a*** $= q = \frac{2N_{aa} + N_{Aa}}{2N}$

Frequency of genotype *AA* $= N_{AA}/N$
Frequency of genotype *Aa* $= N_{Aa}/N$
Frequency of genotype *aa* $= N_{aa}/N$

**2** Compute the allele and genotype frequencies for two separate populations of $N = 200$:

| Population 1 (mostly homozygotes) | Population 2 (mostly heterozygotes) |
|---|---|
| $N_{AA} = 90$, $N_{Aa} = 40$, and $N_{aa} = 70$ | $N_{AA} = 45$, $N_{Aa} = 130$, and $N_{aa} = 25$ |

# Developing Skills and Working with Data

> I think this **(REVIEW & APPLY)** is a great feature. Applying what they've just read in a slightly new way will improve understanding and retention. . . ."
>
> Jennifer Butler, Willamette University

## MAKING SENSE OF DATA: A STATISTICS PRIMER

This primer (an appendix in the text and also in LaunchPad) lays the proper groundwork for understanding statistics and data, providing helpful support for all of the quantitative exercises in the new edition.

*How Does Statistics Help Us Understand the Natural World?*

Statistics is essential to scientific discovery. Most biological studies involve five basic steps, each of which requires statistics:

- **Step 1: Choose an Experimental Design**
  Clearly define the scientific question and the methods necessary to tackle the question.
- **Step 2: Collect Data**
  Gather information about the natural world through observations and experiments.
- **Step 3: Organize and Visualize the Data**
  Use tables, graphs, and other useful representations to gain intuition about the data.

### REVIEW & APPLY | 16.3

NEW

**R** Allopatric speciation results from the separation of populations by geographic barriers; it is the dominant mode of speciation among most groups of organisms. Sympatric speciation may result from disruptive selection that results in ecological isolation, but polyploidy is the most common cause of sympatric speciation among plants.

**A**

1. Explain how speciation via polyploidy can happen in only two generations.
2. If allopatric speciation is the most prevalent mode of speciation, what do you predict about the geographic distributions of many closely related species? Does your answer differ for species that are sedentary versus highly mobile?
3. The species of Darwin's finches shown in the phylogeny in Figure 16.8 have all evolved on islands of the Galápagos archipelago within the past 3 million years. Molecular clock analysis (see Key Concept 14.3) has been used to determine the dates of the various speciation events in that phylogeny. Geological techniques for dating rock samples (see Key Concept 17.1) have been used to determine the ages of the various Galápagos islands. The table shows the number of species of Darwin's finches and the number of islands that have existed in the archipelago at several times during the past 4 million years (data from P. R. Grant. 2001. *Oikos* 92: 385–403).

| Time (millions of years ago) | Number of islands | Number of finch species |
|---|---|---|
| 0.25 | 18 | 14 |
| 0.50 | 18 | 9 |
| 0.75 | 9 | 7 |
| 1.00 | 6 | 5 |
| 2.00 | 4 | 3 |
| 3.00 | 4 | 1 |
| 4.00 | 3 | 0 |

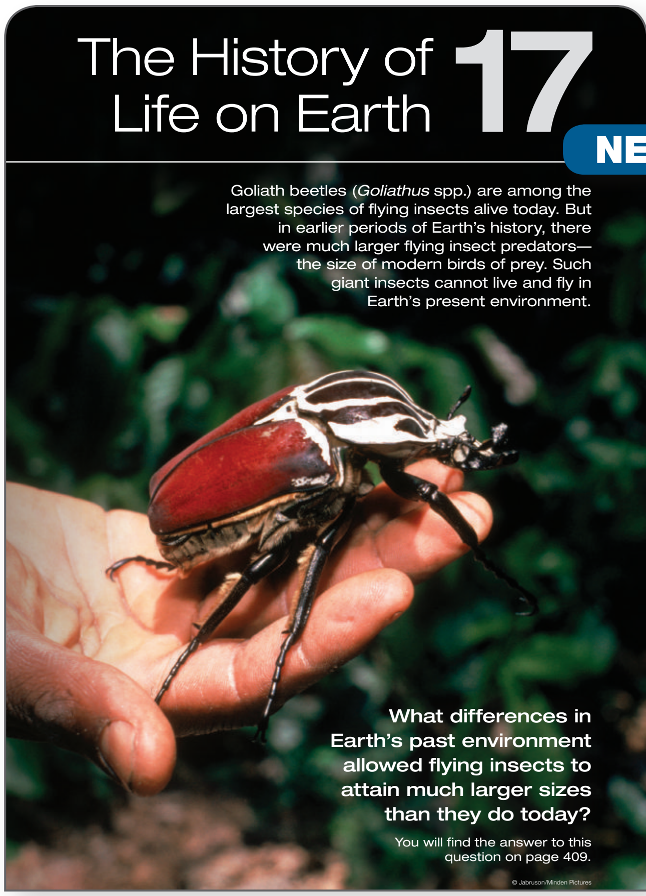
   a. Plot the number of species of Darwin's finches and the number of islands in the Galápagos archipelago (dependent variables) against time (independent variable).
   b. Are the data consistent with the hypothesis that isolation of populations on newly formed islands is related to speciation in this group of birds? Why or why not?
4. If no more islands form in the Galápagos archipelago, do you think that speciation by geographic isolation will continue to occur among Darwin's finches? Why or why not? What additional data could you collect to test your hypothesis (without waiting to see if speciation occurs)?

# Active Learning

**Active learning continues to be central to the mission of *Principles of Life*. New features both in the text and online present you with an even more engaging experience.**

## NEW! CHAPTER OPENER WITH QUESTION

A short introduction with an attention-grabbing photo and compelling question gives you something to ponder while reading and studying the chapter. The chapter ends with a return to the question and some discussion of the answer.




## LINKS

Links point you to additional discussion of a concept or key term elsewhere in the book, providing an opportunity for integration across chapters.

**LINK** **Key Concept 14.3** describes how biologists reconstruct the gene sequences of extinct organisms.

## NEW! IN-FIGURE QUESTIONS

Incorporated into figures, these questions are designed to engage you and help you think about the implications of the figure/diagram. In-figure questions tend to be lower-level Bloom's, and are often amenable to in-class discussion.

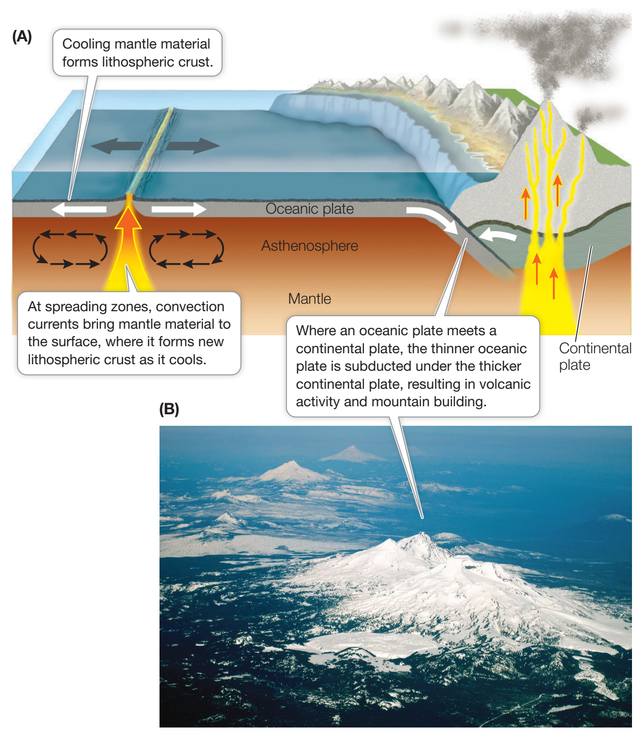



**FIGURE 17.2 Plate Tectonics and Continental Drift** **(A)** The heat of Earth's core generates convection currents in the viscous mantle material underlying the oceanic and continental plates. Those currents push the continental plates, along with the land masses they carry, together or apart. Where plates collide, one may slide under the other, creating mountain ranges and often volcanoes. **(B)** The Cascade Range of the Pacific Northwest of North America is an example of a mountain chain produced by subduction of an oceanic plate under a continental plate.

**Why** are both shores of the Pacific Ocean ringed with volcanic mountain ranges?
**Media Clip 17.2** Lava Flows and Magma Explosions
**PoL3e.com/mc17.2**

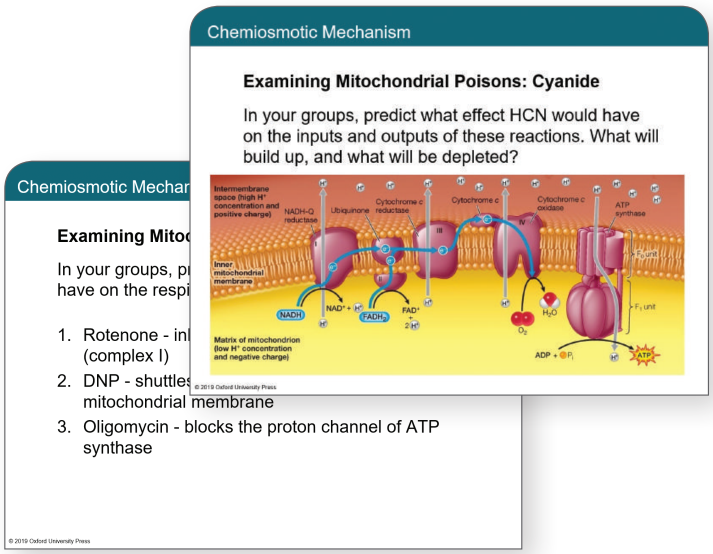
NEW

**Why** are both shores of the Pacific Ocean ringed with volcanic mountain ranges?
**Media Clip 17.2** Lava Flows and Magma Explosions
**PoL3e.com/mc17.2**

# Active Learning

Encouraging you to be more involved while reading the textbook is just the beginning of the Active Learning approach in *Principles of Life*. For instructors who have been teaching actively for years, or those who are just beginning to use these techniques, we've created an Active Learning Guide and an accompanying set of Active Learning Modules to engage you before, during, and after class.

## EXPANDED! ACTIVE LEARNING MODULES

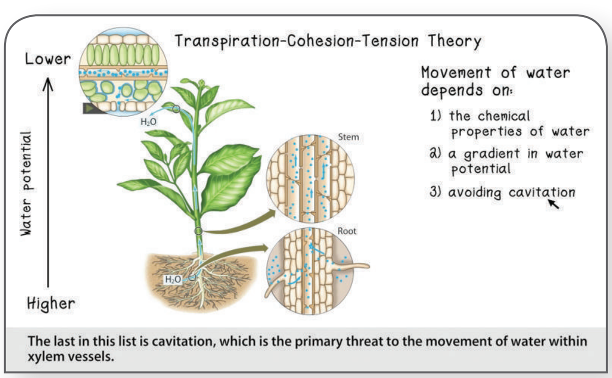



Active Learning Module In-Class Exercise Slides

The expanded Active Learning Modules provide everything instructors need to successfully implement an active approach to teaching key topics. Each module's many resources include:

- Pre-class video specifically created for the module
- Pre-quiz and post-quiz
- Handout for in-class work
- Detailed in-class exercise
- Detailed instructor's guide

These modules are easy to implement and are a great way to add more active learning to the classroom.




Active Learning Module In-Class Video

## NEW! ACTIVE LEARNING GUIDE

The Active Learning Guide provides extensive resources and support for implementing active learning techniques in any classroom, large or small. This all-new guide provides instructors with a thorough introduction to the concepts, techniques, and benefits of active learning. Chapter-by-chapter guidance provides strategies for how to best utilize learning resources in *Principles of Life* to teach in a more active format.

### Part 1: Introduction to Active Learning

Chapter 1: What Is Active Learning?

Chapter 2: Designing Your Course for Active Learning

Chapter 3: Using Active Learning in the Classroom

Chapter 4: How to Implement *Principles of Life* Resources

### Part 2: Active Learning Resources and Suggestions by Chapter

Each chapter in Part 2 of the Active Learning Guide corresponds to a textbook chapter and includes the following:

- An overview of the textbook chapter
- References to all of the student media resources, listed by Key Concept
- References to and descriptions of each Active Learning Module
- Detailed suggestions for active learning activities and exercises for each Key Concept, including "draw," "video," and "compare" exercises, think-pair-share activities, spider maps, minute papers, clicker questions, and more
- Suggestions for incorporating the in-text Links and Analyze the Data features into in-class activities

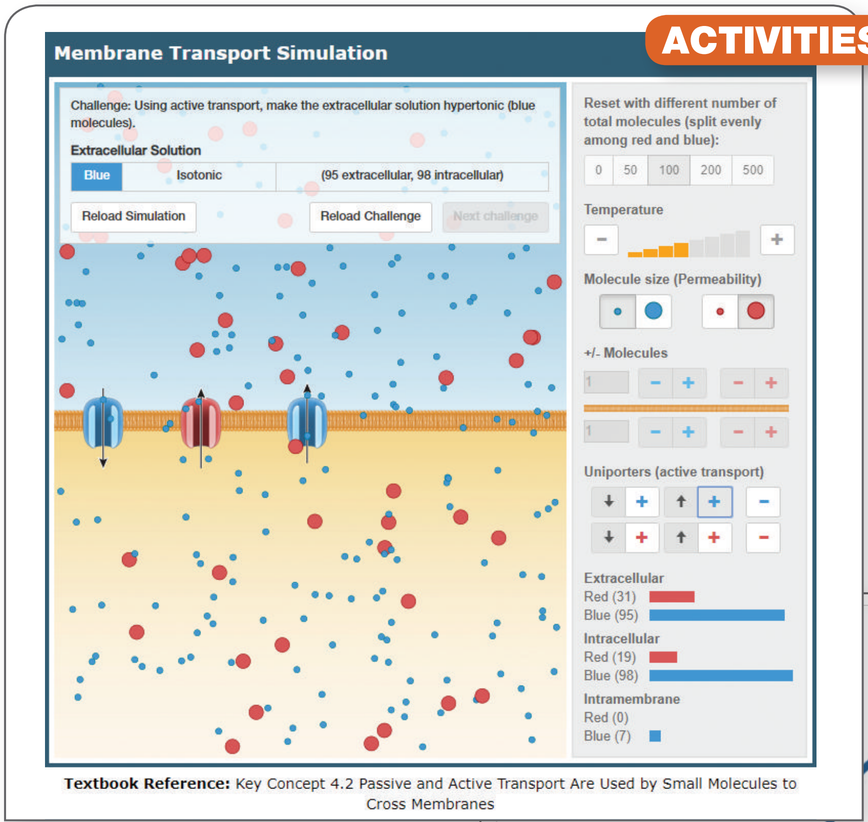
### Part 3: Appendices

- Appendix A: An Overview of Bloom's Taxonomy
- Appendix B: A Guide to Using the *Principles of Life*, Third Edition Learning Objectives
- Appendix C: Learning Objectives for *Principles of Life*, Third Edition

# LaunchPad

## The complete experience of *Principles of Life* is delivered through LaunchPad, our online learning platform.

Built to address the most challenging classroom issues instructors face, LaunchPad gives you everything you need to prepare for class and exams. At the same time, LaunchPad gives instructors the tools *they* need to quickly set up a course, shape the content to their syllabus, craft presentations and lectures, assign and assess homework, and guide the progress of individual students and the class as a whole.

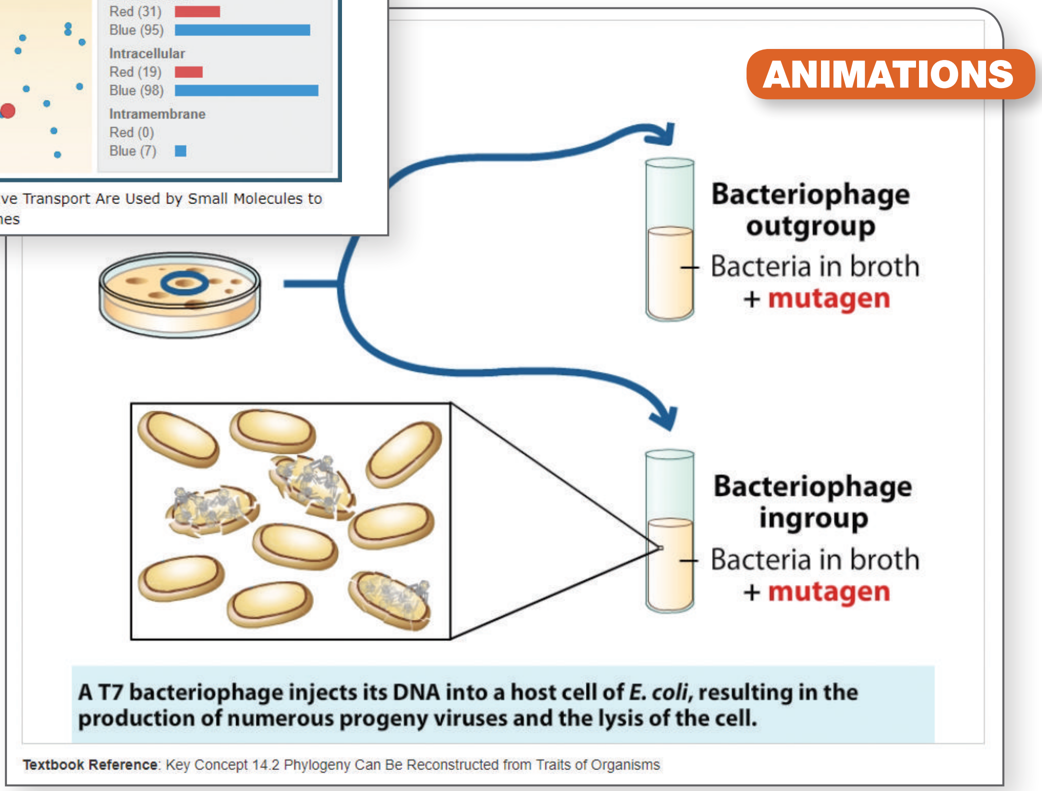



Activity 4.3: Membrane Transport Simulation

LaunchPad is organized into units that mirror the textbook's chapters. Each unit includes the e-Book chapter, organized by Key Concept, with integrated media resources, chapter-specific assessment, and other resources.

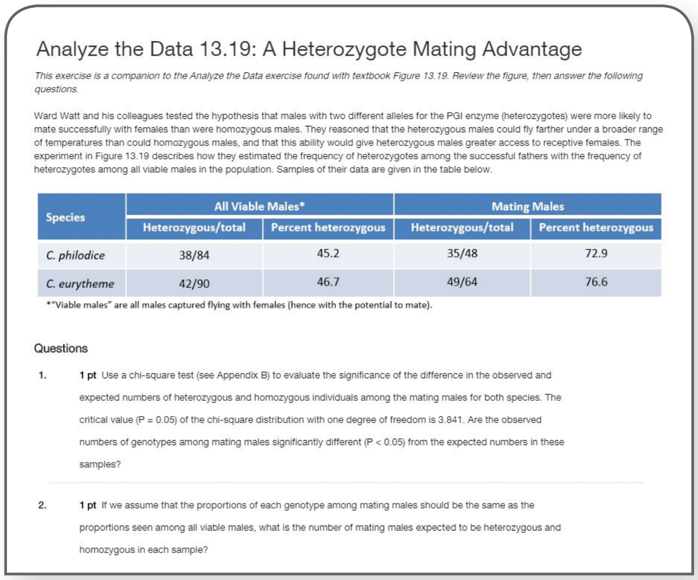
All of LaunchPad's resources directly support *Principles of Life*, Third Edition. Assessment, media resources, exercises, and other components are aligned clearly to the textbook's Key Concepts.

Substantial new active learning resources—such as the activity and animation shown here—support the use of the book in an active learning context.




Animation 14.1: Using Phylogenetic Analysis to Reconstruct Evolutionary History

# LearningCurve



## Analyze the Data 13.19: A Heterozygote Mating Advantage

*This exercise is a companion to the Analyze the Data exercise found with textbook Figure 13.19. Review the figure, then answer the following questions.*

Ward Watt and his colleagues tested the hypothesis that males with two different alleles for the PGI enzyme (heterozygotes) were more likely to mate successfully with females than were homozygous males. They reasoned that the heterozygous males could fly farther under a broader range of temperatures than could homozygous males, and that this ability would give heterozygous males greater access to receptive females. The experiment in Figure 13.19 describes how they estimated the frequency of heterozygotes among the successful fathers with the frequency of heterozygotes among all viable males in the population. Samples of their data are given in the table below.

| Species | All Viable Males* | | Mating Males | |
|---|---|---|---|---|
| | Heterozygous/total | Percent heterozygous | Heterozygous/total | Percent heterozygous |
| *C. philodice* | 38/84 | 45.2 | 35/48 | 72.9 |
| *C. eurytheme* | 42/90 | 46.7 | 49/64 | 76.6 |

*"Viable males" are all males captured flying with females (hence with the potential to mate).

Questions

1. **1 pt** Use a chi-square test (see Appendix B) to evaluate the significance of the difference in the observed and expected numbers of heterozygous and homozygous individuals among the mating males for both species. The critical value ($P = 0.05$) of the chi-square distribution with one degree of freedom is 3.841. Are the observed numbers of genotypes among mating males significantly different ($P < 0.05$) from the expected numbers in these samples?

2. **1 pt** If we assume that the proportions of each genotype among mating males should be the same as the proportions seen among all viable males, what is the number of mating males expected to be heterozygous and homozygous in each sample?

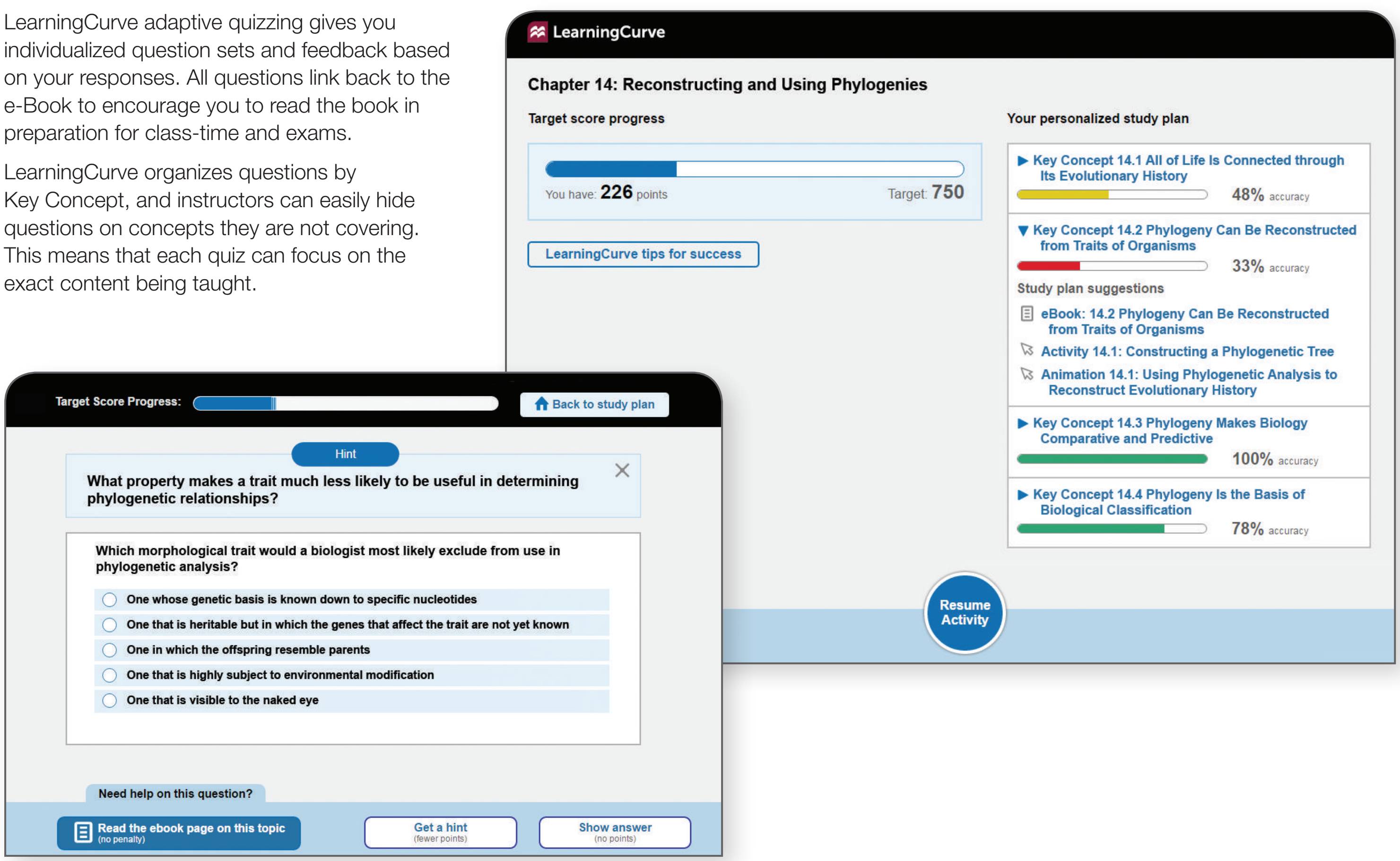
Online companion to in-text Analyze the Data exercise

Each in-text Analyze the Data exercise is accompanied by an online companion exercise in LaunchPad. The online companion exercise gives you additional practice with the same skills addressed by the in-text exercise, and can be assigned by your instructor.

> "The **LAUNCHPAD** program is amazing, I wish all my classes used similar programs. I really liked how each chapter is broken into sections, and those sections broken into smaller subsections. This not only made reading the chapters extremely easy, but also helped me stay organized with note taking. The LearningCurve exercises were my favorite part of LaunchPad. They really helped me memorize information, and if I happened to forget something it was easy to go back and re-read the section of the book it was in."
>
> Student User

LearningCurve adaptive quizzing gives you individualized question sets and feedback based on your responses. All questions link back to the e-Book to encourage you to read the book in preparation for class-time and exams.

LearningCurve organizes questions by Key Concept, and instructors can easily hide questions on concepts they are not covering. This means that each quiz can focus on the exact content being taught.




Learning Curve instructor and student views

# Assessment

*Principles of Life's* assessment resources give instructors a range of tools for assessing your progress before class, after class, and on exams. Along with updating and revising all question banks and adding new questions at higher cognitive levels, we have fully aligned all in-book and online content to the new Third Edition.

Third-Edition assessment questions and resources are aligned to the new Learning Objectives featured in each Key Concept. This provides instructors with a concrete way of assessing you on your mastery of the most important material in each chapter.

## SEARCHABLE QUESTION BANK

LaunchPad's enhanced question bank functionality makes it easy to search for and select questions from any of the *Principles of Life* question banks (Test Bank, LearningCurve, Summative Quizzes). With the new filtering functionality, instructors can get the precise mix of questions they want by filtering for:

- Learning Objective
- Key Concept/Textbook Section
- Bloom's Taxonomy Level
- Difficulty (for LearningCurve questions)
- Source

## SUMMATIVE QUIZZES

In LaunchPad, each chapter includes a Summative Quiz composed of 20 questions spanning the chapter's Key Concepts. Quizzes are pre-built and ready to assign. At the same time, they are completely customizable; instructors can add, revise, or remove questions to match their course content.

## LEARNINGCURVE

For each chapter, LearningCurve offers an extensive set of questions that are distinct from those in the Test Bank and Summative Quizzes. Questions are organized by Key Concepts and ranked by difficulty. Thus, you can master the material at a manageable pace, facing more difficult questions after answering easy and moderate questions correctly.

## TEST BANK

The *Principles of Life* Test Bank has been significantly revised for the Third Edition. Questions have been updated to match the revised textbook chapters and aligned to the new Learning Objectives. In addition, the number of questions at higher cognitive (Bloom's) levels has been increased. All questions are available in LaunchPad and are easily searchable by chapter, Key Concept, Learning Objective, and Bloom's Level using LaunchPad's new question bank tools.

| FEATURE | LAUNCHPAD ASSESSMENT RESOURCES |
|---|---|
| Active Learning Modules | The expanded set of Active Learning Modules includes pre- and post-quizzes in LaunchPad, plus additional assessment questions. |
| Activities & Simulations | All activities, including simulations, are assignable in LaunchPad and report to the LaunchPad gradebook upon completion. |
| Analyze the Data | For each in-text Analyze the Data exercise, a companion exercise is available in LaunchPad. |
| Animations | Pre-built quizzes accompany each Animation in LaunchPad. |
| Key Concepts | • All quiz and test questions are tagged by Key Concept and searchable in LaunchPad.<br>• LearningCurve study plans and instructor reports are organized around the Key Concepts. |
| Learning Objectives | Learning Curve, Summative Quiz, and test questions align with the new Learning Objectives and are searchable in LaunchPad. |
| Summative Quizzes | Each chapter includes a pre-built Summative Quiz in LaunchPad. |
| Test Bank | An extensive Test Bank is provided for each chapter in a variety of formats: LaunchPad question banks, Word documents, and Respondus format. |

# Preface

We are standing at an important crossroad in biology education, with an opportunity for lasting change in the way we teach introductory biology. Numerous reports and studies published by education agencies and national study groups since the turn of the millennium have advocated a shift away from an emphasis on facts and memorization. Two major reports in particular have encouraged this change: *Vision and Change in Undergraduate Biology Education: A Call to Action*, published by the American Association for the Advancement of Science (supported by the National Science Foundation) at the time of the First Edition of *Principles of Life*; and *BIO2010: Transforming Undergraduate Education for Future Research Biologists*, sponsored by the National Institutes of Health and the Howard Hughes Medical Institute. These reports recommend focusing on core concepts and competencies, teaching students through active learning rather than memorization, and improving the integration of statistical and computational approaches. From the First Edition of *Principles of Life*, we have used our experience as authors and educators to implement these recommendations for a new approach to teaching introductory biology.

In this, the Third Edition of *Principles of Life*, we continue to stress the five core themes identified in *Vision and Change*:

- Evolution
- The relationship between structure and function
- Information flow, exchange, and storage
- Pathways and transformations of energy and matter
- Biological systems

As we develop these themes, we keep a steady focus on the needs of beginning students at the university level. In preparing each chapter, our central question has been, "What does a beginning student need to know?" We have then met the needs of the beginning student with a concept-centered approach that introduces facts and terms as they are needed to develop concepts, avoiding the inclusion of terms and facts for their own sake. For students who go on in biological science, *Principles of Life*, Third Edition, provides the conceptual foundation they will need to succeed in upper-level courses. For the many students who complete their study of biology at the introductory level, *Principles of Life* recognizes that—long after a year of study—people remember concepts, not isolated facts.

In writing *Principles of Life*, Third Edition, we have doubled our emphasis on active learning. Each section within each chapter starts with carefully worded *Learning Objectives* so that students can clearly see the goals they will achieve in their studies. Chapter openers have been completely revised with active learning in mind. Each chapter begins with a brief statement focused on major themes, accompanied by a dramatic photograph and interpretive questions for students to consider. These opening questions are designed so that students will be able to offer tentative answers as they start a chapter but will be able to offer far more thorough answers as they finish. At the end of each chapter, we reprise the opening photograph with an answer of our own.

Also, to promote active learning, each section in each chapter ends with a *Review & Apply*, in which we present a concise summary and a set of study questions. Many of these questions encourage students to go beyond memorization and engage more thoroughly in the process of science. As with all study questions in the book, we provide answers in LaunchPad, our online companion site.

Each chapter includes an *Investigation*, in which we unpack the logic of real, important research using actual data sets from the scientific literature. The *Investigation* often includes an *Analyze the Data* feature that presents questions that guide students through the interpretation of results, often tying in with our *Making Sense of Data: A Statistics Primer* (Appendix B). As students read a chapter, they will also encounter occasional questions tied to illustrations: questions that highlight what can be learned from the illustrations and associated text.

Each chapter ends with a dramatic new feature: a *Visual Summary* that helps students review the content of the chapter. To help students recall what they have learned, the *Visual Summary* includes both illustrations (especially helpful for visual learners) and bulleted points. The *Visual Summary* also includes additional study questions about each section in the chapter. Again, answers to all questions are provided online.

Another new feature found in each chapter—*Think Like a Scientist*—provides additional opportunities for active learning focused on the core competencies recommended by *Vision and Change*. *Vision and Change* argues that students need to cultivate six core competencies to become biologically literate. Students should be able to

- apply the process of science;
- use quantitative reasoning;
- use modeling and simulation;
- tap into the interdisciplinary nature of science;
- communicate and collaborate with other disciplines;
- understand the relationship between science and society.

The *Think Like a Scientist* feature in each chapter emphasizes one or more of these core competencies (using icons to highlight the particular competencies). Topics such as manipulative experiments, proper choice of controls, meta-analysis, and communicating science to the public are presented in ways that (true to the name of the feature) will help each student learn more about the ways that scientists think. Questions (with online answers) are often provided to stimulate student engagement.

The art program in *Principles of Life*, Third Edition, plays an essential role in our concept-centered approach. It has been entirely revised using new color palettes that are more attractive and ensure all readers can learn from the illustrations regardless of their color vision. New conceptual diagrams have been added in many places, and text–art coordination has been emphasized. To be certain students know the organisms being discussed, the pages of the book are profusely illustrated with photographs and drawings of the animals, plants, and other organisms cited. When diagrams or data sets from the scientific literature are presented, readers will now be able to find those diagrams or data sets in the literature with our new referencing system. Unlike in previous editions, all figures now have figure numbers, enhancing the ability of both students and instructors to find and use figures.

To help students deepen their understanding, we provide *Links* that allow students to see interconnections among such topics as molecular or cell biology, evolution, biological diversity, physiology, and ecology. With this edition, the *Links* are not merely cross-references but include brief statements of pertinence, helping readers see why they might want to follow a *Link*. We have also added more online *Animations* and *Activities*, which include opportunities for students to use modeling and simulation modules to further reinforce their understanding of concepts.

## The *Principles of Life* Story

Prior to our launch of the First Edition of *Principles of Life*, introductory biology textbooks for science majors presented encyclopedic summaries of biological knowledge. We believe that students who spend their time diligently memorizing myriad details and vast terminology actually retain fewer of the concepts that are the foundation for further study in advanced courses. In *Principles of Life*, we take the opposite approach: we promote understanding over memorization. Details are important, but no modern biology textbook can begin to cover all the information biologists have learned to date, and students today have many other ways to access the details as they need them.

To help us create this new breed of biology textbook, in 2009 our publishers—Sinauer Associates (now an imprint of Oxford University Press) and W. H. Freeman (now Macmillan Learning)—brought together an Advisory Board of twenty leading biology educators and instructors in introductory biology from throughout North America. During an intensive meeting of the authors and the Board, dynamic discussions led to the solidification of the core concepts we believe are essential for teaching introductory biology. The book took shape, and the Advisory Board members then reviewed the emerging chapters and provided considerable feedback at every stage of the book's development.

For the Third Edition, all chapters have undergone extensive between-edition review by experts in each respective discipline, and the chapters have been revised both to respond to reviewer input and to incorporate new pedagogical features. Active learning has always been a priority in *Principles of Life*. With the Third Edition, the emphasis on active learning has been dramatically enhanced—to the point that active-learning features permeate the book. We have expanded opportunities for students to apply what they have learned by using real data and examples—and have better integrated and explained the concepts of statistical analysis of data. Our coverage and application of biological systems are expanded. With the new *Think Like a Scientist* feature, we have developed opportunities for students to practice the core competencies that have become critical for modern biology. With our *Visual Summaries*, we believe we provide a review feature so enticing that students will be drawn to it and thus experience important reinforcement.

## Features of the Third Edition

Each chapter is organized into a series of *Key Concepts*, each with its own *Learning Objectives*. Our focus in each *Key Concept* is to identify and explain the concepts that beginning university students need to know. *Principles of Life* is focused on these concepts; it is not meant to be encyclopedic. At the end of each *Key Concept*, a *Review & Apply* concisely recaps the main points and presents questions related to the *Learning Objectives* for students to ponder. At the end of the chapter, the *Visual Summary* follows up with a visual and narrative review of major concepts throughout the chapter—and provides further questions related to the *Learning Objectives*. Throughout, questions are deliberately designed to span the incremental levels of Bloom's Taxonomy of Cognitive Domains: factual knowledge, comprehension, application, analysis, synthesis, and evaluation. As already stressed, we provide answers to all questions in LaunchPad, *Principles of Life*'s online platform.

Each chapter includes additional features in several places, including an *Investigation*, a *Think Like a Scientist* feature, and often an *Analyze the Data* feature. Each of these features reinforces a concept that is central to the chapter and develops a core competency. The features hone in on specific questions, points of view, and types of data of importance to the chapter. Because science students need to understand basic methods for data presentation and analysis, many of the features ask students about interpretation of results, especially statistical significance. To help students understand issues in data presentation and interpretation, we provide a short introduction to the reasoning behind biological statistics in our Appendix B: *Making Sense of Data: A Statistics Primer*. Although this appendix is not meant to replace a more formal introduction to statistics, we believe that data interpretation and statistical thinking are essential skills that should be integral to all introductory science courses.

The *Investigations* help students learn the process of science by being organized into sections on Hypothesis, Method, Results, and Conclusion. Most include a section (*Analyze the Data*) in which we present a subset of original data from the published experiment. Students are asked to analyze these data and to make connections between observations, analyses, hypotheses, and conclusions.

Another important element for achieving student success is reinforcement and application of concepts through three types of online features in LaunchPad: *Animations*, *Activities*, and *Media Clips*. For many concepts, in the *Animations* and *Activities* students can conduct their own simulations, explore a concept in greater depth, and understand concepts through active discovery. Using the *Media Clips*, they can also watch videos that help explain concepts or introduce them to the wonders of biological diversity.

Students need to learn about some of the major research tools that are used in biology, including major laboratory, computational, and field methods. At key places, we provide *Research Tools* figures that explain these tools and explain the contexts in which they are used by biologists. With the Third Edition, we have also added a new appendix on *Working with DNA* (Appendix D) so that students have an easy place to review and understand the major methods of molecular genetics.

Our art program for *Principles of Life* continues to build on our success in *Life: The Science of Biology*. We pioneered the use of balloon captions to help students understand and interpret the biological processes illustrated in figures without repeatedly going back and forth between a figure, its legend, and the text. These guides play an invaluable role in text–art coordination, helping students connect critical points of figures to the concepts that are developed in the text.

## Special Contributions

Many people contributed to the creation of the Third Edition of *Principles of Life* (see below). However, three individuals deserve special mention and thanks for their contributions. Susan D. Hill did a masterful job in writing Chapter 35 on Animal Development. Nickolas Waser worked extensively with Mary Price on the Ecology section (Part 7) and was otherwise intimately involved in discussions of the book's planning and execution. David Sadava reprised his Chapter 36 on Immunology and provided expert editorial support on the Cells and Genetics sections (Parts 1 and 2) in the closing months of the project.

## Many People to Thank

Our publisher, Andy Sinauer, embraced the need for change in introductory biology textbooks and has helped make our vision a reality. Also at Sinauer Associates, Dean Scudder played a key leadership role in every stage of the book's development. We extend special thanks to both of them. Bill Purves, Gordon Orians, and Craig Heller, our coauthors on earlier editions of *Life: The Science of Biology* and/or *Principles of Life*, were instrumental in articulating the concepts developed in all editions of *Principles of Life*, and many aspects of this book can be traced back to their critical contributions.

In addition to the many biologists listed on the next page who provided formal reviews, each of us benefitted enormously from personal contacts with colleagues who helped us resolve dilemmas and made critical suggestions for new material. Colleagues deserving particular thanks are Walter Arnold, University of Veterinary Medicine (Vienna); Tobias Baskin, University of Massachusetts, Amherst; John Dacey, Woods Hole Oceanographic Institution; Larry Gilbert, University of Texas, Austin; Harry Greene, Cornell University; Hugo Hofhuis, Wageningen University Research (the Netherlands); Matthew Kayser, University of Pennsylvania; Edward McCabe, University of Colorado and the March of Dimes Foundation; Will Petry, University of California, Irvine; Frank Price, Utica College; Thomas Ruf, University of Veterinary Medicine (Vienna); David Sleboda, Brown University; Viola Willemsen, Wageningen University Research (the Netherlands); and Andrew Zanella, The Claremont Colleges. Richard Shingles, Johns Hopkins University, worked with each of us to develop a coherent and effective set of Learning Objectives for each chapter and Key Concept. In this way he helped provide a pedagogical framework for the book, including all of the assessment material.

For this edition, Sinauer Associates assembled a talented team of editors. Danna Niedzwiecki Lockwood coordinated the editorial team and organized the multitude of project pieces, along with being the primary editor for Parts 1–4 and 7. Laura Green was the primary editor for Parts 5 and 6. Mara Silver rounded off the editorial team, assisting with the many pieces of the production process. Carol Pritchard-Martinez, our developmental editor, provided important guidance for new authors on the team, and ensured consistency in style and level in text and features throughout the text. Liz Pierson applied her outstanding copyediting skills to our manuscript. Dragonfly Studios worked with each of us to revise and create effective and beautiful line art. Mark Siddall rose to the challenge of finding new, even better photographs, while Michele Beckta managed the permissions process and was ever vigilant in prompting us to track down data sources. Designer Joanne Delphia brought a fresh look to the book, and Donna DiCarlo did a fine job of assembling all of the book's elements into clear and attractive pages. Chris Small and Joan Gemme coordinated production and imposed their exacting standards on keeping the myriad components consistent. Johannah Walkowicz organized and commissioned the many expert academic reviews. Suzanne Carter coordinated the team, including Carrie Mailler and Peter Lacey, that created the vast array of online media and supplements with help from Tom Friedmann and Jason Dirks in building LaunchPad. Kathaleen Emerson monitored the editorial process from behind the scenes. Rachel Meyers watched over the publication process and was Sinauer Associates' liaison with Macmillan Learning. At Oxford University Press, we appreciate the ongoing support of John Challice and Petra Recter. At Macmillan, we continue to benefit from the long-term editorial support of Sandy Lindelof, and the marketing expertise of Will Moore, in collaboration with the regional specialists and the regional sales managers. They coordinated all the stages of informing Macmillan's skilled sales force of our book's story. We also thank the Macmillan media group for their expertise in producing LaunchPad.

## Media and Supplements

The Third Edition of *Principles of Life* features an expanded collection of online resources to support and reinforce the material covered in the textbook. All the Activities, Animations, and Media Clips referenced throughout the book include direct Web addresses, allowing students to link instantly to these resources from any device—computer, smartphone, or tablet—while reading the book.

The *LaunchPad* online platform integrates all the student resources, instructor resources, the complete e-Book, and all assessment tools within a streamlined interface that groups essential content into easily assignable learning units. LaunchPad features a range of assessment tools, including the *LearningCurve* adaptive quizzing engine and pre-built summative quizzes for each chapter. To support course preparation, classroom sessions, and assessment programs, there is a wide range of instructor resources available, including multiple versions of all textbook figures, a wealth of PowerPoint presentations, multiple banks of assessment questions, and a large collection of videos. New for this edition is the *Active Learning Guide & Instructor's Manual*, providing extensive resources and support for integrating active learning into the classroom.

For a complete list of all the media and supplements available for *Principles of Life*, please refer to "Media and Supplements to accompany *Principles of Life,* Third Edition" following this Preface.

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to accompany *Principles of Life*, Third Edition

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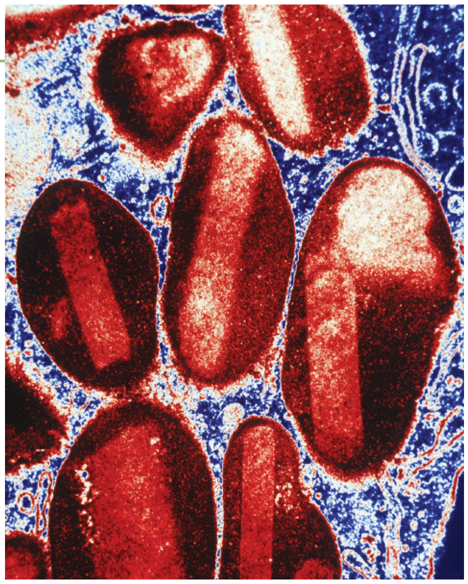

# Part 3 Evolution

# Part 4 Diversity

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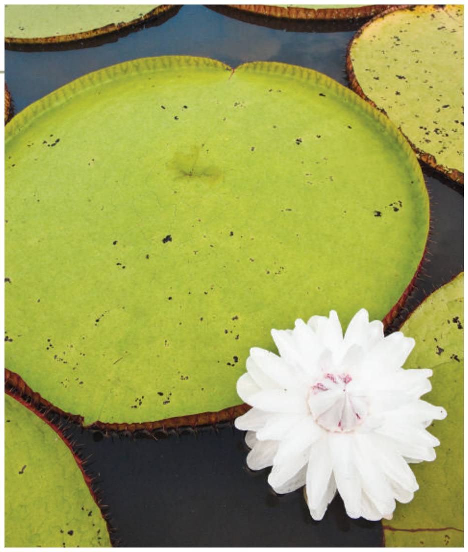
# Part 5 Plant Form and Function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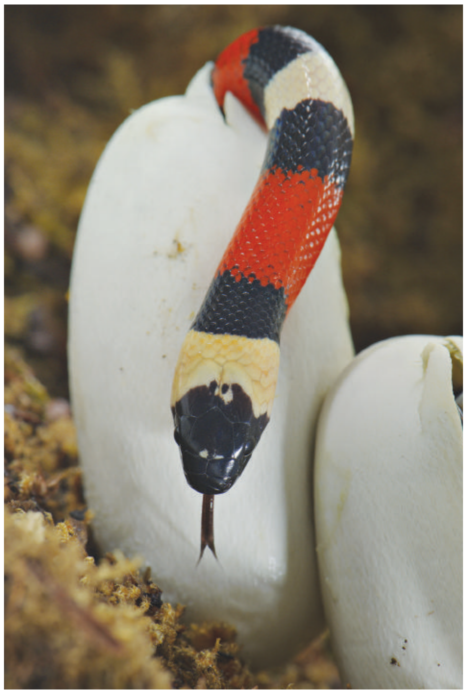

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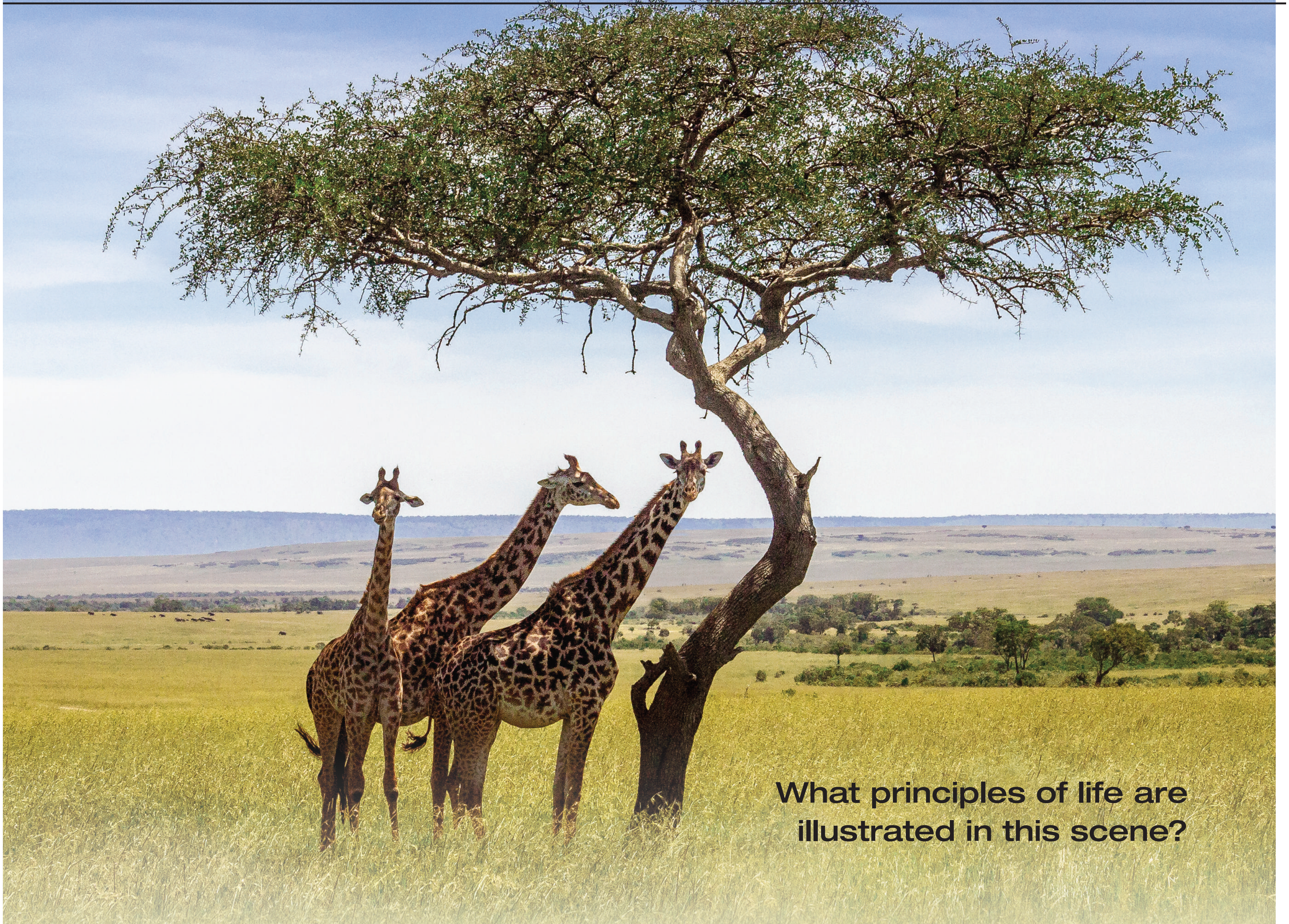
# 1 Principles of Life



## What principles of life are illustrated in this scene?

You have probably seen the African savannas in photographs or films. What did you notice? Like most people, you probably saw the vivid sunlit grasslands and the exotic animals such as giraffes. However, if you have not done so before, take a little time now to think about how these living things survive, reproduce, interact with one another, and influence their environment. With the introduction to biology in this book, we would like to inspire you to ask questions about what life is, how living systems work, and how the living world came to be as we observe it today.

Biologists have amassed a huge amount of information about the living world, and some introductory biology classes focus on memorizing details. In this book we take a different approach, focusing on the major principles of life that underlie everything in biology.

What do we mean by "principles of life"? Look at the photograph. Why is the view mostly of plants, with just a few animals? Why does the tree have the shape it does? Why have the giraffes evolved such long necks? A fundamental principle of life, namely that all living organisms require energy to grow, move, reproduce, and maintain their bodies, can explain the prevalence of plants. Ultimately, most of the needed energy comes from the Sun. The leaves of the grasses and trees contain chlorophyll, a green pigment that absorbs the light energy from the Sun. In fact, some of the plants, such as the acacia tree in the photograph, have evolved shapes whereby they present great numbers of leaves directly to the Sun's light, maximizing solar energy absorption, while also evading the reach of leaf-eating mammals. By the process of photosynthesis, the green leaves of the plants transform water and carbon dioxide into sugar and oxygen, and in this process some of the energy from the Sun is stored in the sugar. The plants then use this sugar as a source of energy to build their tissues and grow. In turn, giraffes and other animals eat the plants to obtain energy from their tissues. A giraffe is ultimately solar-powered, as is the person who took the photograph.

The photograph also illustrates other principles of biology in addition to the flow of energy. One is that living organisms often survive and thrive by interacting with one another in complex ways. Another is that evolution has often modified organisms based on the demands of their interactions. The long neck of the giraffes, which has evolved over millions of years, permits them to reach the high leaves on the trees in their ecological community. After reading this book, you will better understand the main principles of life. You'll be able to describe how organisms capture and transform energy; pass genetic information to their offspring in reproduction; grow, develop, and behave; and interact with other organisms and with their physical environment. You will also have learned how the system of life on Earth evolved, and how it continues to change. May you always view the natural world with new insight and understanding!

## KEY CONCEPTS

- **1.1** Living Organisms Share Common Aspects of Structure, Function, and Energy Flow
- **1.2** Life Depends on Organization and Energy
- **1.3** Genetic Systems Control the Flow, Exchange, Storage, and Use of Information
- **1.4** Evolution Explains the Diversity as Well as the Unity of Life
- **1.5** Science Is Based on Quantitative Observations, Experiments, and Reasoning

## 1.1 Living Organisms Share Common Aspects of Structure, Function, and Energy Flow

Biology is the scientific study of life, which encompasses all living things, or **organisms**. The living things we know about are all descended from a single-celled ancestor that lived on Earth almost 4 billion years ago. We can imagine that something with some similarities to life as we know it might have originated differently, perhaps on other planets. But the evidence suggests that all of life on Earth today has a single origin—a single common ancestor—and we consider all the organisms that descended from that common ancestor to be a part of life.

### Life as we know it had a single origin

The overwhelming evidence for the common ancestry of life lies in the many characteristics that are shared among living organisms. Typically, living organisms

- are composed of a common set of chemical parts, such as nucleic acids (including DNA, which carries our genetic information) and amino acids (the chemical building blocks that make up proteins)
- are composed at a microscopic level of similar structures, such as cells enclosed within membranes
- depend on intricate interactions among structurally complex parts to maintain the living state
- contain genetic information that uses a nearly universal code to specify how proteins are assembled
- convert molecules obtained from their environment into new biological molecules
- extract energy from the environment and use it to carry out life functions
- replicate their genetic information in the same manner when reproducing themselves
- have a fundamental set of genes that share structural similarities
- evolve through gradual changes in their genetic information

Taken together, these shared characteristics logically lead to the conclusion that all life has a common ancestry, and that the diverse organisms that exist today originated from one life form. If life had multiple origins, there would be little reason to expect a nearly universal genetic code, or the structural similarities among many genes, or a common set of amino acids. If we were to discover something similar to life that had originated independently, such as a self-replicating system on another planet, we would expect it to be fundamentally different in these aspects. It might be similar in some ways to life on Earth, such as using genetic information to reproduce. But we would not expect the details of its genetic code, for example, to be like ours.

The simple list of shared characteristics above, however, does not describe the incredible complexity and diversity of life. Just think, for example, of the many different kinds of birds you see each month, or the many different kinds of trees. One of the major questions that biologists address today is how the great diversity of life on Earth has evolved. It is fascinating and important that all these life forms share fundamental characteristics, but the enormous diversity of life forms is also an important theme and question in biology.

A final introductory point of great significance concerns the boundaries between "living" and "nonliving." When biologists say that biology is the study of life, they generally have little difficulty distinguishing organisms that are alive from other systems that are not alive. Yet the boundaries are not always clear. One important case for debate is the viruses, which are not composed of cells and cannot carry out most functions on their own. Instead viruses use the cells they invade to perform most functions for them. Yet viruses contain genetic information, and they mutate and evolve. So even though viruses are not independent cellular organisms, their existence depends on cells, and there is strong evidence that viruses evolved from cellular life forms. For these reasons, most biologists consider viruses to be a part of life. But as viruses illustrate, the boundaries between "living" and "nonliving" are not always clear, and all biologists do not agree on exactly where we should draw the lines.

### Major steps in the history of life are compatible with known physical and chemical processes

Geologists estimate that Earth formed between 4.6 and 4.5 billion years ago. At first the planet was not a very hospitable place. It was some 600 million years or more before the earliest life evolved. If we picture the history of Earth as a 30-day month, with each day representing about 150 million years, life first appeared somewhere toward the end of the first week (**FIGURE 1.1**).

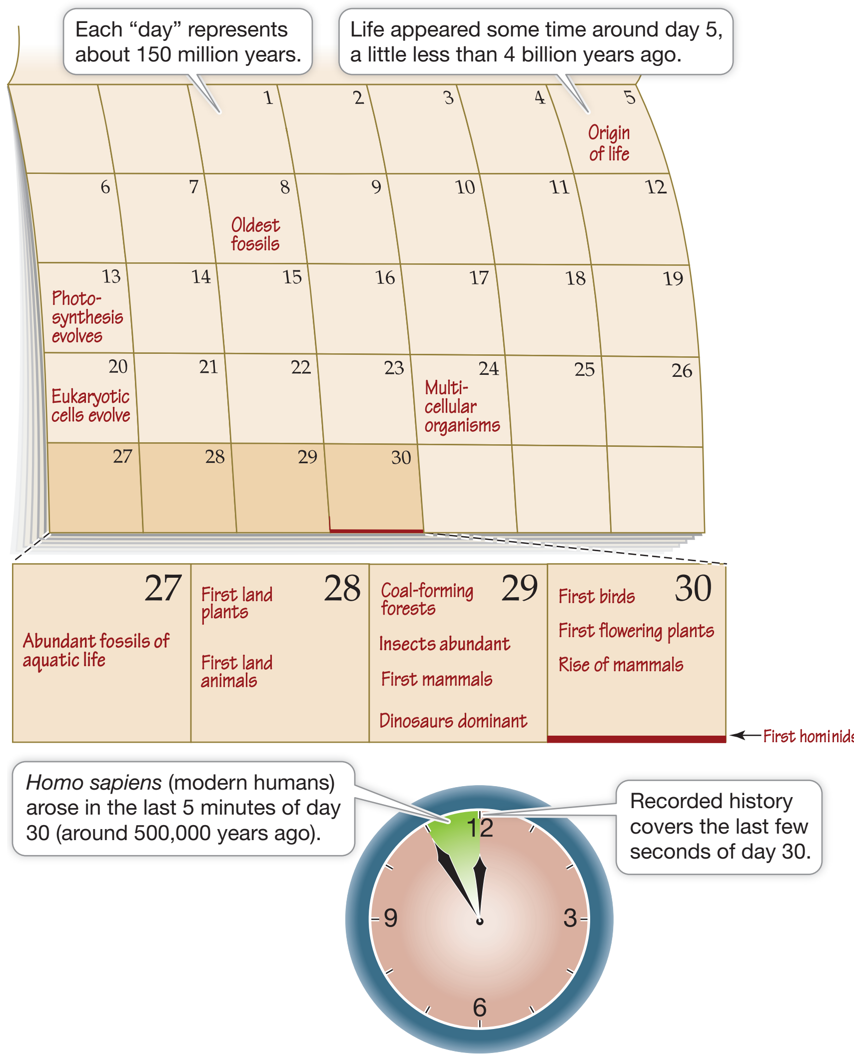



**FIGURE 1.1 Life's Calendar** Depicting Earth's history on the scale of a 30-day month provides a sense of the immensity of evolutionary time.

How might life have arisen from nonliving matter? In thinking about this question, we must take into account that the young Earth's atmosphere, oceans, and climate all were very different than they are today. Biologists have conducted many experiments that simulate the conditions on early Earth. These experiments have confirmed that the formation of complex organic molecules under such conditions is possible, even probable.

The critical step for the evolution of life, however, was the appearance of **nucleic acids**—molecules that could reproduce themselves and also contain the information for the synthesis, or manufacture, of other large molecules with complex but stable shapes. These large, complex molecules were proteins. Their shapes varied enough to enable them to participate in increasing numbers and kinds of chemical reactions with other molecules.

CELLULAR STRUCTURE EVOLVED IN THE COMMON ANCESTOR OF LIFE In the next big step in the origin of life, a membrane surrounded and enclosed complex proteins and other biological molecules, forming a tiny **cell**. This membrane kept the enclosed components separate from the surrounding external environment. Molecules called fatty acids played a critical role because these molecules form membrane-like films instead of dissolving in water. When agitated, these films can form hollow spheres, which could have enveloped assemblages of biological molecules. The creation of a cell interior, separate from the external environment, allowed the reactants and products of chemical reactions to be concentrated, opening up the possibility that those reactions could be integrated and controlled. This natural process of membrane formation likely resulted in the first cells with the ability to reproduce—the evolution of the first cellular organisms.

For more than 2 billion years after cells originated, every organism consisted of only one cell. These first organisms were **prokaryotes**, which are made up of single cells containing genetic material and other biochemical structures enclosed in a membrane

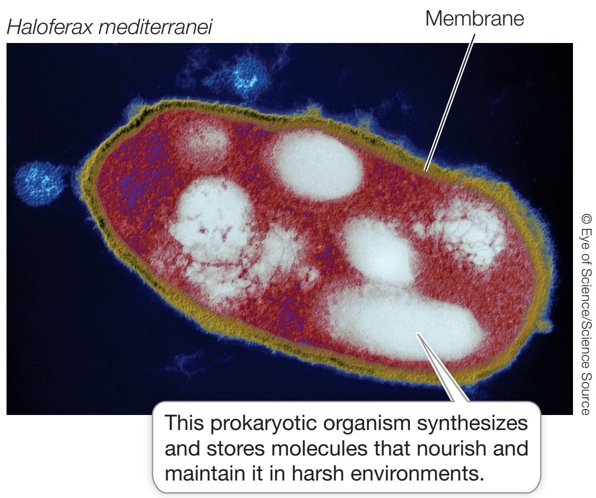



**FIGURE 1.2 The Basic Unit of Life Is the Cell** The concentration of reactions within the enclosing membrane of a cell allowed the evolution of integrated organisms. Today all organisms, even the largest and most complex, are made up of cells. Single-celled organisms such as this one, however, remain the most abundant living organisms (in absolute numbers) on Earth.

(**FIGURE 1.2**). Vast numbers of their descendants, such as bacteria, exist in similar form today. Early prokaryotes were confined to the oceans, which had an abundance of complex molecules they could use as raw materials and sources of energy. The water of the oceans also shielded them from the damaging effects of ultraviolet (UV) light, which was intense at that time because there was little or no oxygen ($O_2$) in the atmosphere, and for that reason, no protective ozone ($O_3$) layer in the upper atmosphere.

PHOTOSYNTHESIS ALLOWED LIVING ORGANISMS TO CAPTURE THE SUN'S ENERGY To fuel the chemical reactions inside them, the earliest prokaryotes took in molecules directly from their environment and broke down these small molecules to release and use the energy contained in their chemical bonds. Many modern prokaryotes still function this way, and very successfully.

About 2.5 billion years ago, or on day 13 of our imaginary month-long calendar of life, the emergence of photosynthesis in some prokaryotes changed the nature of life on Earth (see Figure 1.1). **Photosynthesis** is a set of chemical reactions that transforms the energy of sunlight into chemical-bond energy of the sugar glucose and other relatively small biological molecules. In turn, the chemical-bond energy of these small molecules can be tapped to power other chemical reactions inside cells, including the synthesis of large molecules, such as proteins, that are the building blocks of cells.

Photosynthesis is the basis of much of life on Earth today because its energy-capturing processes provide food not only for photosynthetic organisms themselves, but also for other organisms that eat the photosynthetic ones. Photosynthetic organisms—such as the grasses and trees in our opening photograph—use solar energy to build their tissues, and then other organisms (such as the giraffes) use those tissues as food. Early photosynthetic cells were probably similar to the present-day prokaryotes called cyanobacteria (**FIGURE 1.3**). Over time, the early photosynthetic prokaryotes became so abundant that they produced vast quantities of $O_2$ as a by-product of photosynthesis.

**LINK** The pathways that harvest chemical energy to all the kinds of biological work necessary to support metabolism are presented in **Chapter 5**.

During the early eons of life on Earth, there was no $O_2$ in the atmosphere. In fact, $O_2$ was poisonous to many of the prokaryotes that lived at that time. But organisms that tolerated $O_2$ were able to proliferate as $O_2$ slowly began to accumulate in the atmosphere. The presence of $O_2$ opened up vast new avenues of evolution. **Aerobic metabolism**, a set of chemical reactions that releases energy from life's molecules by using $O_2$, proved to be more efficient than **anaerobic metabolism**, a set of reactions that extracts energy without using $O_2$. For this reason, $O_2$ allowed organisms to live more intensely and grow larger. The majority of living organisms today use $O_2$ in extracting energy from molecules.

Oxygen in the atmosphere also made it possible for life to move onto land. For most of life's history, UV radiation falling


**FIGURE 1.3 Photosynthetic Organisms Changed Earth's Atmosphere** Cyanobacteria were the first photosynthetic organisms on Earth. **(A)** Colonies of cyanobacteria called stromatolites are known from the ancient fossil record. **(B)** Living stromatolites are still found in suitable environments on Earth today.

on Earth's surface was so intense that it destroyed any living cell that was not well shielded by water. But as a result of photosynthesis, $O_2$ accumulated in the atmosphere for more than 2 billion years and gradually resulted in a layer of ozone ($O_3$) in the upper atmosphere. By about 500 million years ago, or about day 28 on our imaginary calendar of life, the ozone layer was sufficiently dense—and absorbed enough of the Sun's UV radiation—to make it possible for organisms to leave the protection of the water and live on land (see Figure 1.1).

EUKARYOTIC CELLS AROSE THROUGH ENDOSYMBIOSIS Another important, earlier step in the history of life was the evolution of cells that are composed internally of membrane-enclosed compartments called **organelles**. Organelles were—and are—important because specialized cellular functions could be performed inside them, separated from the rest of the cell. The first organelles probably appeared about 2.5 billion years after life first appeared on Earth, or on about day 20 in Figure 1.1.

One of these organelles, the **nucleus**, came to contain the cell's genetic information. The nucleus (Latin *nux*, "nut" or "core") gives these cells their name: **eukaryotes** (Greek *eu*, "true," + *karyon*, "kernel" or "core"). The eukaryotic cell is distinct from the cells of prokaryotes (*pro*, "before"), which lack nuclei.

Some organelles are hypothesized to have originated by **endosymbiosis**, which means "living inside another" and may have occurred as a complicated consequence of the ingestion of smaller cells by larger cells. The **mitochondria** that release energy for use by a eukaryotic cell probably evolved from engulfed prokaryotic organisms. And **chloroplasts**—the organelles specialized to conduct photosynthesis in eukaryotic photosynthetic organisms—could have originated when larger eukaryotes ingested photosynthetic prokaryotes. When large cells ingested smaller ones, the two cells could then at times evolve a stable partnership (instead of the large cells always using the smaller ones as food). In this way, ingested prokaryotes could provide the large cells with sugars from photosynthesis, or perform other functions for the large cells. In return, the host cells provided a good environment for their smaller partners.

MULTICELLULARITY ALLOWED SPECIALIZATION OF TISSUES AND FUNCTIONS For the first few billion years of life, all organisms—whether prokaryotic or eukaryotic—were single-celled. At some point, the cells of some eukaryotes failed to separate after cell division and remained attached to each other. In these groupings of cells it was possible for some cells in the group to specialize in certain functions, such as reproduction, while other cells specialized in other functions, such as absorbing nutrients. **Cellular specialization** enabled multicellular eukaryotes to increase in size and become more efficient at gathering resources and living in specific environments.

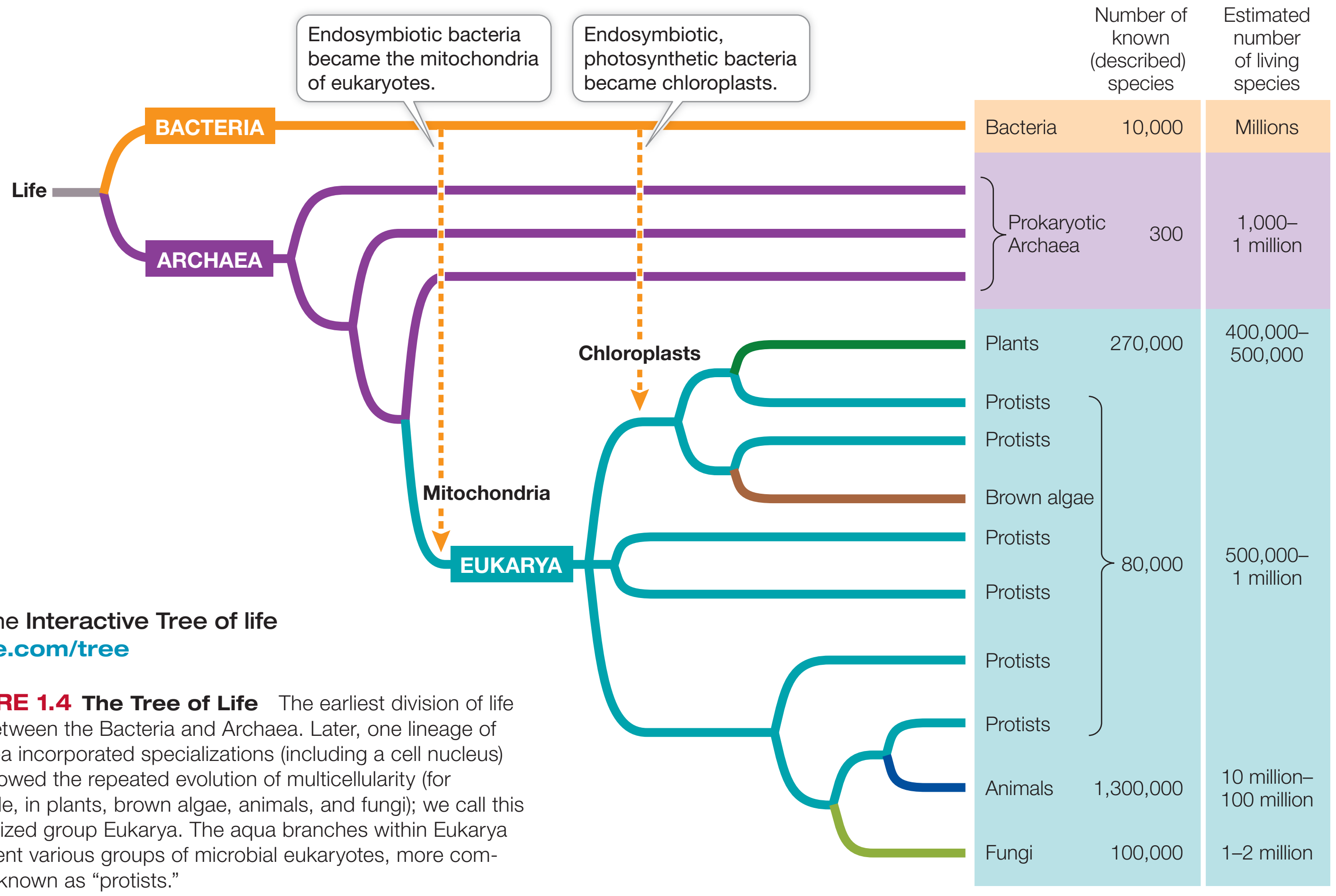
## Biologists can trace the evolutionary tree of life

If all the organisms on Earth today are the descendants of a single kind of unicellular organism that lived almost 4 billion years ago, how have they become so different? An organism reproduces by replicating its **genome**, which is the sum total of its genetic material, as we will discuss shortly. This replication process is not perfect, however, and changes, called **mutations**, are introduced almost every time a genome is replicated. Some mutations give rise to structural and functional changes in organisms. Within a population of organisms, as individuals mate with one another, these changes can spread while the population continues to be made up of one kind, or species, of organism. However, if something happens to isolate some members of a population from the others, structural and functional differences between the two groups will accumulate over time. The two groups may eventually differ enough that their members no longer regularly reproduce with one another. In this way the two populations become two different species.

Tens of millions of species exist on Earth today. Many times that number lived in the past but are now extinct. As biologists discover species, they give each one a scientific name called a **binomial** (because it is made up of two Latinized words). The first word identifies the species' genus—a group of species that share a recent common ancestor. The second word indicates the species. For example, the scientific name for the human species is *Homo sapiens*: *Homo* is our genus and *sapiens* our species. *Homo* is Latin for "man," and *sapiens* is from the Latin word for "wise" or "rational." These scientific names are italicized, and unlike common names, are the same in every language. This allows biologists writing in any language to refer to the same species in the same way.

Much of biology is based on comparisons among species. Our ability to make relevant comparisons has improved greatly in recent decades as a result of our relatively newfound ability to study and compare the genomes of different species. We do this by sequencing a genome (in whole or in part), which means we can determine the order of the nucleotides that serve as the building blocks of the organism's DNA. Genome sequencing and other molecular techniques have allowed biologists to add a vast array of molecular evidence to existing evolutionary knowledge based on the fossil record. The result is the ongoing compilation of **phylogenetic trees** that document and diagram evolutionary relationships as part of an overarching **tree of life**. The broadest categories of this tree are shown in **FIGURE 1.4**. (The tree is expanded in Appendix A, and you can also explore the tree interactively online.)

Although many details remain to be clarified, the broad outlines of the tree of life have been determined. Its branching patterns are based on a rich array of evidence from fossils, structures, chemical processes, behavior, and molecular analyses of genomes. Molecular data in particular have been used to separate the tree into two major branches of life: **Bacteria** and **Archaea**. One specialized group of organisms arose and diversified among the archaea, but with contributions of mitochondria and chloroplasts from endosymbiotic bacteria. We call these specialized organisms **eukaryotes** (or formally, **Eukarya**). Eukaryotes have a distinct cellular structure called a nucleus that contains most of their genetic information. Because eukaryotes have many other distinctive features as well, some of which came from bacteria and some from archaea, most biologists recognize three **domains** of life: Bacteria, Archaea, and Eukarya.




See the **Interactive Tree of life**
**Pol3e.com/tree**

**FIGURE 1.4 The Tree of Life** The earliest division of life was between the Bacteria and Archaea. Later, one lineage of Archaea incorporated specializations (including a cell nucleus) that allowed the repeated evolution of multicellularity (for example, in plants, brown algae, animals, and fungi); we call this specialized group Eukarya. The aqua branches within Eukarya represent various groups of microbial eukaryotes, more commonly known as "protists."

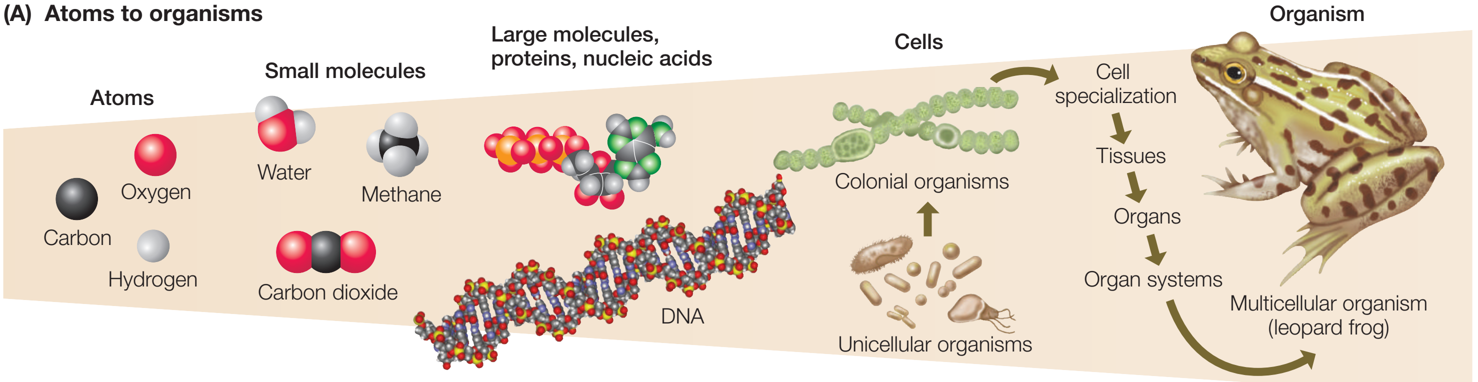
Many (but not all) eukaryotes are multicellular. Plants, brown algae (such as kelp), fungi, and animals are examples of familiar multicellular eukaryotes. We know that multicellularity arose independently in each of these four familiar multicellular groups (as well as in several others that you will learn about) because they are each most closely related to different groups of unicellular eukaryotes (commonly called protists), as you can see from the branching pattern of Figure 1.4.

### Life's unity allows discoveries in biology to be generalized

Knowledge gained from investigations of one kind of organism can, with care, be generalized to other organisms because all life is related by descent from a common ancestor, shares a genetic code, and consists of similar molecular building blocks. Biologists use certain species as **model systems** for research, knowing they can often extend their findings to other organisms, including humans.

Our basic understanding of the chemical reactions in cells came from research on bacteria but is applicable to all cells, including

**(A) Atoms to organisms**



those of humans. Similarly, the biochemistry of photosynthesis—the process by which plants use sunlight to produce sugars—was largely worked out from experiments on *Chlorella*, a unicellular green alga. Much of what we know about the genes that control plant development is the result of work on *Arabidopsis thaliana*, a member of the mustard family. Knowledge about how animals develop has come from work on sea urchins, frogs, chickens, roundworms, and fruit flies. And recently, the discovery of a major gene controlling human skin color came from work on zebrafish. Being able to generalize from model systems is a powerful tool in biology.

## 1.2 Life Depends on Organization and Energy

All of life depends on organization. Physics gives us the second law of thermodynamics, which states that, left to themselves, organized entities tend to become more random. Any loss of organization threatens the well-being of organisms. Cells, for example, must combat the thermodynamic tendency for their molecules, structures, and systems to fall apart—to become disorganized. Energy is required to maintain organization. For this reason, cells require energy throughout their lives.

### Organization is apparent in a hierarchy of levels, from molecules to ecosystems

Cells synthesize, or manufacture, proteins and other complex molecules by assembling atoms into new, highly organized configurations. Such complex molecules give cells their structure and enable them to function. For example, a fatty acid molecule that the cell synthesizes may become part of a membrane that organizes the inside of the cell by dividing it into compartments. Or a protein made by a cell may enable a specific chemical reaction to take place in the cell by helping speed up the reaction—that is, by acting as a catalyst for the reaction.

Organization is also essential for many cells to function together in a multicellular organism. As we have seen, multicellularity allows individual cells to specialize and depend on other cells for functions they themselves do not perform. But the different specialized cells also work together. For example, division of labor in a multicellular organism usually requires a circulatory system so that the functions of specialized cells in one part of the body are of use to cells in other, distant parts of the body.

Overall, a multicellular organism exhibits many hierarchical levels of organization (**FIGURE 1.5A**). Small molecules are organized into larger ones, such as DNA and proteins. Large molecules are organized into cells, and assemblages of differentiated cells are organized into **tissues**. For example, a single muscle cell cannot generate much force, but when many cells combine to form the tissue of a working muscle, considerable force and movement can be generated. Different tissue types are organized to form **organs** that accomplish specific functions. The heart, brain, and stomach are each constructed of several types of tissues, as are the roots, stems, and leaves of plants. Organs whose functions are interrelated can be grouped into **organ systems**; the esophagus, stomach, and intestines, for example, are all part of the digestive system. Because all these levels of organization are subject to the second law of thermodynamics, they all tend to degrade unless

**FIGURE 1.5 Life Consists of Organized Systems at a Hierarchy of Scales (A)** The hierarchy of systems within a multicellular organism. DNA—a molecule—encodes the information for cells—a higher level of organization. Cells, in turn, are the components of still higher levels of organization: tissues, organs, and the organism itself. **(B)** Organisms interacting with their external environment form ecological systems on a hierarchy of scales. Individual organisms form the smallest ecological system. Individuals of a species form populations, which interact with other populations to form communities. Multiple communities in turn interact within landscapes at progressively larger scales until they include all the landscapes and organisms of Earth: the entire biosphere. (NASA image of Biosphere by Reto Stöckli, based on data from NASA and NOAA.)

**Activity 1.1 The Hierarchy of Life**
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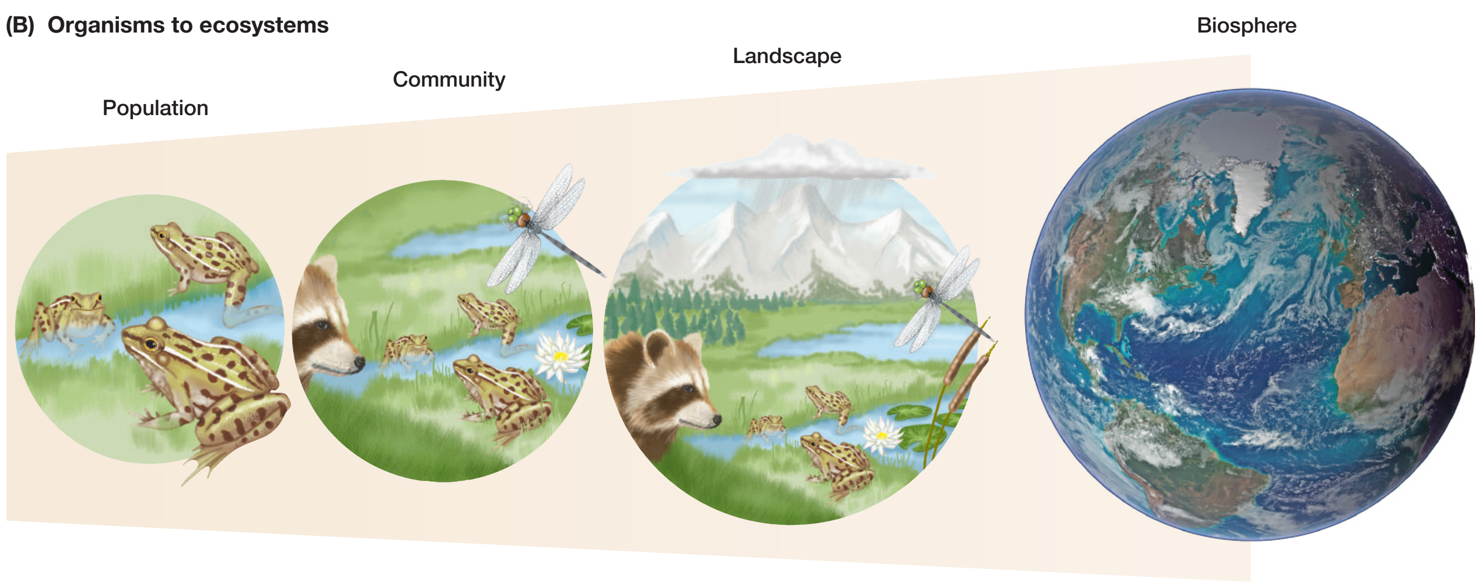

energy is applied to the system. This is why an organism must use energy to maintain its functions.

In addition to the internal hierarchy of an individual organism, there is an external hierarchy in the larger biological world where organisms interact with each other and their physical environment—forming **ecological systems**, often shortened to **ecosystems** (**FIGURE 1.5B**). Individual organisms interacting with their immediate environment form the smallest ecological system. Groups of individuals of any one species live together in **populations**, and populations of multiple species interact in ecological **communities**. Multiple communities interact within **landscapes**. The landscape of the entire Earth and all its life is known as the **biosphere**.

Now that we have recognized the internal hierarchy of organization within an individual organism and the external hierarchy in the ecosystem, we must recognize a highly important distinction between the internal and external hierarchies. All the hierarchical levels of organization within an individual organism are encoded by its single genome, so that these levels generally interact harmoniously. By contrast, the external ecological hierarchy of populations, communities, and landscapes involves interactions among multiple species with multiple genomes, so that interactions are not always harmonious. For example, individuals may prevent others of their own species from exploiting a necessary resource such as food, or they may exploit members of other species as food.

## Each level of biological organization consists of systems

We have already discussed within-organism systems and ecological systems. More generally, a **system** is a set of interacting parts in which neither the parts nor the whole can be fully understood without taking into account the interactions. A simple biological system might consist of a few **components** (e.g., proteins, pools of nutrients, or organisms) and the **processes** by which the components interact (e.g., protein synthesis, nutrient metabolism, or grazing) (**FIGURE 1.6**).

Consider, for example, the system within a cell that synthesizes and controls the quantity of a particular protein, which we'll call Protein T (**FIGURE 1.7A**). The components of the system are the amino acids from which Protein T is made, Protein T, and the breakdown products of Protein T. The processes are the biochemical pathways that synthesize and break down Protein T. To understand how the cell controls the amount of Protein T, we must understand how all the components and processes in this system function.

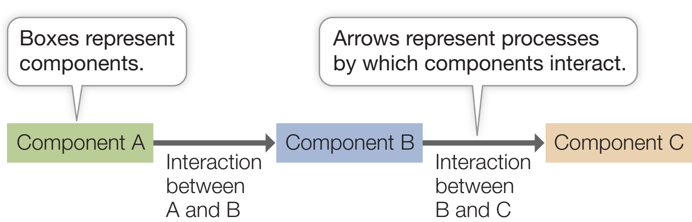


**FIGURE 1.6 A Generalized System** Systems in cells, whole organisms, and ecosystems can be represented with boxes and arrows.

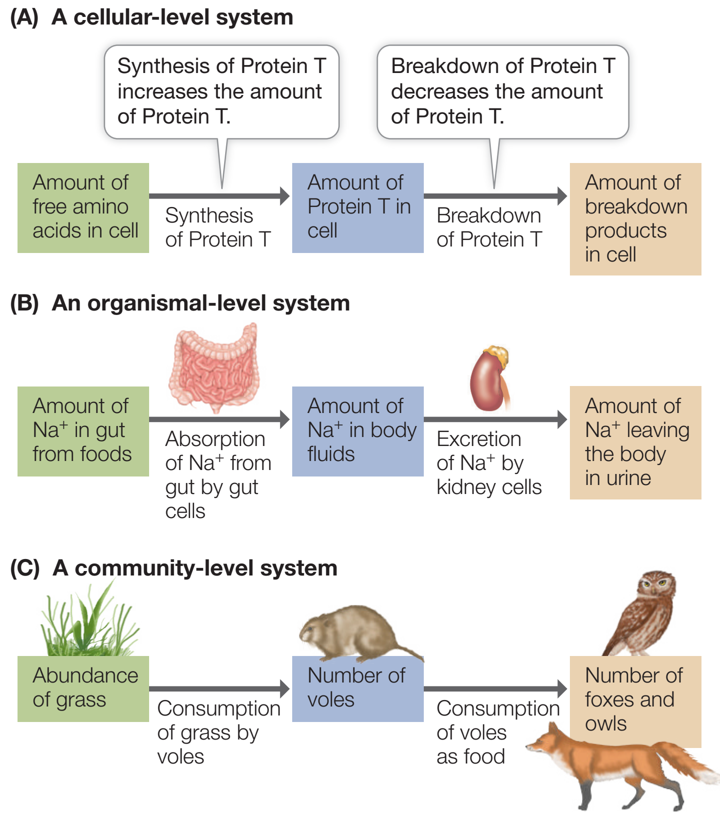


**FIGURE 1.7 Organized Systems Exist at Many Levels** **(A)** This cellular-level system synthesizes and breaks down a cell protein called Protein T. **(B)** This organismal-level system determines the amount (and thus the concentration) of sodium ($Na^+$) in the blood plasma and other extracellular body fluids of a human. **(C)** This community-level system helps determine the number of meadow voles (*Microtus pennsylvanicus*) in a field in the spring.

Systems are found at every level of biological organization. For example, our bodies have a physiological system that controls the amount of sodium ($Na^+$) in our body fluids (**FIGURE 1.7B**). Grass, voles, and predators (e.g., foxes and owls) are components of a community-level system (**FIGURE 1.7C**).

## Biological systems are highly dynamic even as they maintain their essential organization

Given the central importance of organization, you might think that biological systems are inflexible and static. Actually, they are often incredibly **dynamic**—characterized by rapid flows of matter and energy. On average, for example, a cell in your body breaks down and rebuilds 2–3 percent of its protein molecules per day. Each day it also makes and uses more than 100,000 trillion ($10^{14}$) molecules of adenosine triphosphate (ATP), the molecule responsible for shuttling energy from sources to uses. Collectively, all the cells in your body liberate more than 90 grams of hydrogen every day from the foods they break down to obtain energy. Your cells also combine that hydrogen with oxygen ($O_2$) to make almost a liter of water every day.

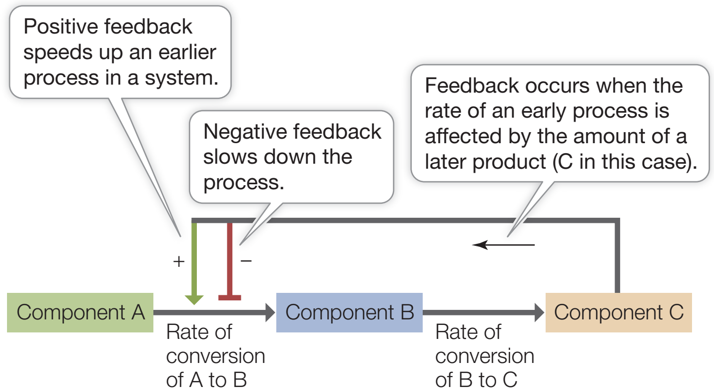


**FIGURE 1.8 Feedback Can Be Positive or Negative** Positive feedback tends to destabilize a system, whereas negative feedback typically stabilizes a system.

This dynamic aspect of biological systems means that they constantly exchange energy and matter with their surroundings. For example, even after a single-celled or multicellular organism has reached maturity, most of its molecules are steadily replaced as time passes. In this ceaseless, dynamic process, atoms are lost from the organism to the surrounding soil, air, or water, and they are replaced with atoms from the soil, air, or water. Yet as the atomic building blocks of any particular organism come and go, the organization of the molecules, structures, and systems in the organism persists. This fact emphasizes the central importance of organization.

## Positive and negative feedback are common in biological systems

Often, the amount of one of the components of a system, such as component C in **FIGURE 1.8**, affects the rate of one of the earlier processes in the system. This effect is called **feedback** and may be described as positive or negative. Feedback is often diagrammed simply with a line and symbol, but its actual mechanism may be complex.

**Positive feedback** occurs in a system when a product of the system *speeds up* an earlier process. The effect of positive feedback is to cause the product to be produced faster and faster. To return to one of our earlier examples, if the breakdown products of Protein T sped up synthesis of Protein T, this would lead to more breakdown products, then even more Protein T, then even more breakdown products, and so on. Positive feedback tends to destabilize a system, but destabilization can sometimes be advantageous, provided it is ultimately brought under control.

**Negative feedback** occurs when a product of a system *slows down* an earlier process in the system. Often, as the product increases in amount or concentration, it exerts more and more of a slowing effect. Negative feedback stabilizes the amount of the product in this way: as a high amount of the product accumulates, that accumulation tends to reduce further production of the product. For example, if an increase in the amount of breakdown products of Protein T slowed down synthesis of Protein T, this would lead to a decreased amount of breakdown products and a return to the previous rate of Protein T synthesis. Negative feedback is very common in **regulatory systems**, which are systems that tend to stabilize amounts or concentrations.

## Systems analysis is a conceptual tool for understanding all levels of organization

Biologists today employ an approach known as **systems analysis** to understand how biological systems function. In systems analysis, we identify the parts or components of a biological system and specify the processes by which the components interact (see Figure 1.6). We may also be able to specify the *rates* of these interactions and how the rates are affected by feedback. What we can do then is analyze how the system will change through time. Will the amounts of different components increase or decrease, and how quickly? Will there be any state of stable balance, or **equilibrium**, that the system eventually reaches? With a detailed systems analysis, we can analyze all these features.

To do the analysis, we write out mathematical equations that express the amounts of the different components and that include the processes and their rates. Expressed in words, such an equation for component B in Figure 1.6 has the following form:

The amount of B present at some time in the future =
the amount of B now + the amount of A converted into B
– the amount of B converted into C

We write out a similar equation for each component in the system.

We can analyze the relatively simple biological systems in Figure 1.7 by hand, but the analysis of larger systems quickly becomes very complicated and is typically carried out using computers. The approach, however, is the same: we express the rates of all processes as mathematical equations (**FIGURE 1.9**). After this analysis is done, we have a **computational model** of the biological system. If the computational model is well grounded in factual knowledge of the biological system, the model will mimic the biological system.

An important use of computational models is prediction. For instance, if atmospheric temperature affects a biological system, we can use a computational model to develop a hypothetical prediction of the future behavior of the system in a warming world by adjusting the model to take into account the expected increase in atmospheric temperature.

**Activity 1.2 System Simulation**
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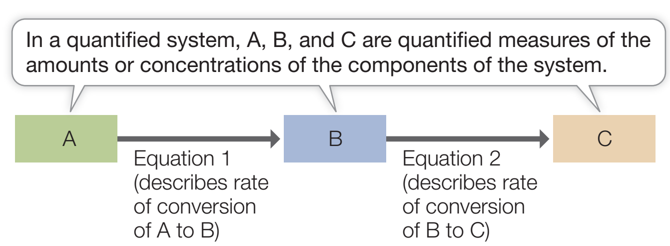


**FIGURE 1.9 Mathematical Equations Allow Us to Quantify Systems** The components of a system can be related through the use of mathematical equations.