

Principles of **Life**

THIRD EDITION

DIGITAL UPDATE



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To Our Readers

Welcome to *Principles of Life*. This book is a *concept-centered* introduction to biology. When we ourselves were students, we realized that—six months after a course ended—the concepts were what we remembered. By now, educational research has confirmed that in undergraduate courses, student needs are served best by an emphasis on concepts. With its concept-centered approach, this book is written for you.

With all the rapid advances in information-sharing on the internet, simple facts are easier than ever to look up. This easy accessibility changes our relationship to facts. In particular, it places an ever-increasing premium on our ability to evaluate facts and integrate them into coherent knowledge. This reality helps explain why central organizing frameworks—concepts—are so important.

Some of you intend to go on into science or medicine. For you, *Principles of Life* recognizes that a solid foundation in concepts will be important throughout your career, helping you to assimilate and use ever-enlarging spheres of factual knowledge.

Some of you expect to move on into other interests after completing your introductory courses in science. For you, long-term knowledge will be your pay-off for your study of biology. *Principles of Life* recognizes that you will be most likely to recall concepts, not isolated facts, as years go by.

Believe it or not, scientists and educators occasionally gather together to debate how university and college courses can best serve your needs. A decade ago, a group of about 500 helped formulate a watershed report—*Vision and Change in Undergraduate Biology Education: A Call to Action*.¹

Two questions—both of great importance to you—are stressed in *Vision and Change* (V & C). First, what are the core concepts that students of the twenty-first century need to understand? Second, what competencies—personal abilities—do you need to develop to succeed? *Principles of Life* is focused on helping you master both the core concepts and the competencies.

Principles of Life, as part of its conceptual approach, places central importance on the five **core concepts** pinpointed by V & C:

- evolution
- the relationship between structure and function
- information flow, exchange, and storage
- pathways and transformations of energy and matter
- systems biology

Principles of Life highlights the six V & C **competencies** in every chapter, helping you develop your ability 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

¹*Vision and Change* is published by the American Association for the Advancement of Science. To read the report, go to <https://visionandchange.org/> and upload the 2011 report.

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.



Mark Kirkpatrick

DAVID W. HALL taught a variety of classes at Wake Forest University, the University of Texas, and the University of Georgia during his academic career. He especially enjoyed teaching introductory biology and genetics to undergraduates and received several teaching awards for his efforts in the classroom. Ever since high school, he has been captivated by the living world but was initially overwhelmed by the enormous diversity of life. However, he soon realized that there are fundamental principles that unite all organisms, which greatly facilitates the study of biology. Helping students learn these principles was the foundation of his biological teaching.

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*

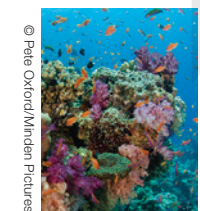


The new toolbox of active learning opportunities integrated into the Third Edition of *Principles of Life* provides numerous opportunities for students and faculty to master *Vision and Change*’s Core Competencies. If used creatively, this text contains essential tools for mastering biology.”

Justen Whittall, *Santa Clara University*

Principles of Life, Third Edition Digital Update

1 Principles of Life



PART 1 CELLS

- 2 Life's Chemistry and the Importance of Water
- 3 Macromolecules
- 4 Cell Structure and Membranes
- 5 Cell Metabolism: Synthesis and Degradation of Biological Molecules
- 6 Cell Signals and Responses

PART 2 GENETICS

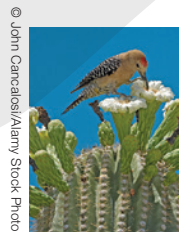
- 7 The Cell Cycle and Cell Division
- 8 Inheritance, Genes, and Chromosomes
- 9 DNA and Its Role in Heredity
- 10 From DNA to Protein: Gene Expression
- 11 Regulation of Gene Expression
- 12 Genomes

PART 3 EVOLUTION

- 13 Processes of Evolution
- 14 Reconstructing and Using Phylogenies
- 15 Evolution of Genes and Genomes
- 16 Speciation
- 17 The History of Life on Earth

PART 4 DIVERSITY

- 18 Bacteria, Archaea, and Viruses
- 19 The Origin and Diversification of Eukaryotes
- 20 The Evolution of Plants
- 21 The Evolution and Diversity of Fungi
- 22 Animal Origins and Diversity



PART 5 PLANT FORM AND FUNCTION

- 23 The Plant Body
- 24 Plant Nutrition and Transport
- 25 Plant Growth and Development
- 26 Reproduction of Flowering Plants
- 27 Plants in the Environment

PART 6 ANIMAL FORM AND FUNCTION

- 28 Transformations of Energy and Matter: Nutrition, Temperature, and Homeostasis
- 29 Animals in Their Environments
- 30 Breathing and Circulation
- 31 Neurons, Sense Organs, and Nervous Systems
- 32 Control by the Endocrine and Nervous Systems
- 33 Muscle and Movement
- 34 Animal Reproduction
- 35 Animal Development
- 36 Immunology: Animal Defense Systems
- 37 Animal Behavior

Water and Salt Balance (Online only)*

PART 7 ECOLOGY

- 38 Ecological Systems in Time and Space
- 39 Populations
- 40 Interactions within and among Species
- 41 Ecological Communities
- 42 The Global Ecosystem

* = New Chapter

Principles of Life—Tour of the Third Edition Digital Update

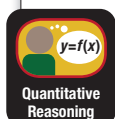
Because success as a biologist means more than just succeeding in the first biology course

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* 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 Third Edition Digital Update includes 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* 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.

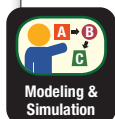
THINK LIKE A SCIENTIST



Quantitative Reasoning

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



Modeling & Simulation

A FOCUS ON SKILLS AND CORE COMPETENCIES

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 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

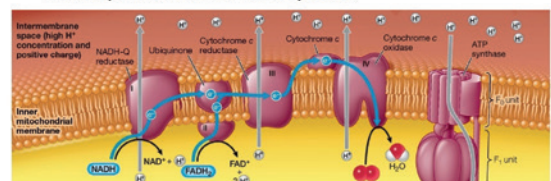
A FOCUS ON DATA

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 Digital Update Content Updates

The Third Edition Digital Update 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.



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CHAPTER 1

- New Section describing how science informs society using COVID-19 as an example

PART 1: CELLS

- Update to Review & Apply 2.1 to clarify terminology
- Updates to Figures throughout to improve illustrations



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PART 2: GENETICS

- Updates to Figures throughout to improve illustrations
- Update to Link to acknowledge in Chapter 13 students will learn that evolution would be impossible without mutation
- Revised content related to silent mutations
- Revisions to “The information for protein synthesis lies in the genetic code” subsection related to DNA mutations that are synonymous and how tRNA interacts with mRNA; throughout section silent is revised to synonymous
- Revisions to “Stability of mRNA can be regulated” subsection to discuss miRNAs and siRNAs
- Revised Table 12.2 title to: Initial Estimates of Protein-Coding Genes in a Strain of Three Species of Bacteria from Genome Sequencing; updated gene numbers in table
- Revisions to “Metagenomics reveals the diversity of viruses and prokaryotic organisms” subsection to include example about sequencing RNA from nasal samples of COVID-19 patients
- Updates to Table 12.3 to update haploid gene sizes and number of protein-coding genes
- Updated numbers in “The human genome sequence held some surprises” subsection



© Tui De Roy/Minden Pictures

PART 3: EVOLUTION

- Revision to introduction to acknowledge COVID-19
- **NEW CHAPTER:** opening art of phylogenetic trees that depict and track COVID-19 evolution
- New answer to chapter opening question about how phylogenetic methods are used to understand the origin, evolution, and spread of new diseases, like COVID-19
- Revisions in “Molecular evolution is used to study and combat diseases” subsection to acknowledge COVID-19



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PART 4: DIVERSITY

- Revisions to subsection “The great majority of prokaryotic species have never been studied” to update numbers of described bacteria and species of prokaryotic archae
- Revisions to include COVID-19 as an example of human diseases caused by positive-sense single-strand RNA viruses; update to Figure 18.23 to include description of coronaviruses



© Chien Lee/Minden Pictures

- Updates to Table 22.1 to update the approximate number of living species for rotifers and relatives and vertebrates
- Revisions to update numbers referenced to known species of amphibians, anurans, reptiles, living mammals, morphologically diverse eutherians; updates to Table 22.3 to update number of described species of marsupials and eutherians

PART 5: PLANT FORM AND FUNCTION

- Updates to Figures throughout to improve illustrations
- Revisions to subsection “Cells that undergo asymmetrical cell division can produce daughter cells with an identity different from that of their parents” to clarify explanation of BASL
- Revisions to “Separation of Male and Female Gametophytes” subsection to clarify how some plant species form two separate types of flowers
- Updates to “Think Like a Scientist: Modeling Earth’s carbon cycle” to update data for mean concentration of CO₂ at Mauna Loa for the indicated month
- Review & Apply 27.1 updated by reordering questions and adding new questions #3 & #4, new graph supports question #3



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PART 6: ANIMAL FORM AND FUNCTION

- Updates to Figures throughout to improve illustrations
- Updates to clarify explanation in chapter opening introduction
- Revisions to “Adaptive immunity has four key features” subsection to clarify explanation of herd immunity
- Revision to Answer to chapter opening question “Do people who refuse vaccination for themselves put others at risk” to address COVID-19 vaccinations
- Added online chapter **Water and Salt Balance**



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PART 7: ECOLOGY

- Added Media Clip to subsection “Climate is not the only factor that molds terrestrial biomes” and Figure 38.12 entitled Grasslands and Fire
- Revisions to “Life histories are diverse” subsection to update life expectancy in light of COVID-19
- Revisions to “Knowledge of metapopulation dynamics helps us conserve species and control epidemics” to acknowledge epidemics; added Activity 39.6 COVID-19 Simulation
- Revisions to placement of media Activity 40.5 to appear with Figure 40.10; renamed Evolutionary Arms Race Simulation
- Updates to climate change key term definition
- Updates to Figure 42.12 to use most recent data on greenhouse gas concentrations
- Revisions to “Recent increases in greenhouse gases are warming Earth’s surface” subsection to address latest trends and data of extreme weather events

Core Competencies

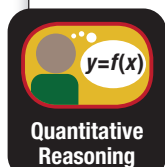
Principles of Life was created to ensure that you gain the knowledge you need from your introductory biology course and acquire the skills needed to succeed as a life sciences major.

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 key feature, **THINK LIKE A SCIENTIST**.

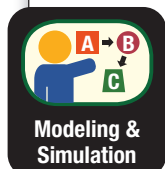
THINK LIKE A SCIENTIST

A major goal 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*.

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 seen in Investigation Figure 17.8 sufficient to account

for the giant insects of the Permian? How long would it take for giant insect body size to evolve?

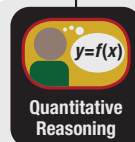
Here you will use quantitative reasoning and a simple model of selection to estimate how quickly insect body size could have evolved in response to higher atmospheric oxygen concentrations.

1. Suppose that the average rate of increase in dragonfly size

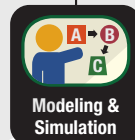
THINK LIKE A SCIENTIST



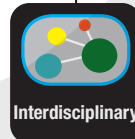
Process of Science



Quantitative Reasoning



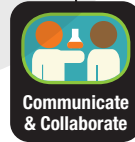
Modeling & Simulation



Interdisciplinary



Science & Society



Communicate & Collaborate

Process of Science

Quantitative Reasoning

Modeling & Simulation

Interdisciplinary

Science & Society

Communicate & Collaborate



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*

THINK LIKE A SCIENTIST



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?

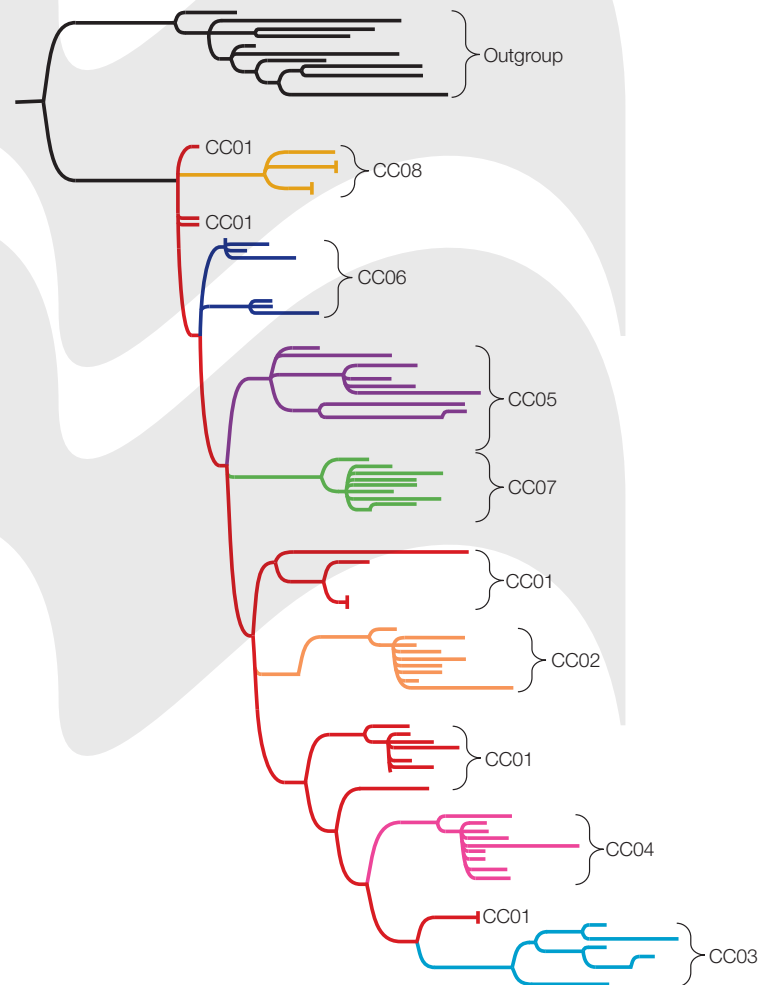


FIGURE 14.10 Forensic Phylogeny (After D. I. Scaduto et al. 2010. *Proc Natl Acad Sci USA* 107: 21242–21247.)

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 <i>lac</i> 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 <i>Tillandsia</i> 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?	•				•	

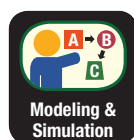
Core Competencies

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		•	•	•	•	•



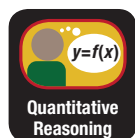
Process of Science



Modeling & Simulation



Science & Society



Quantitative Reasoning



Interdisciplinary



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.

KEY CONCEPTS

17.1

Events in Earth's History Can Be Dated

17.2

Changes in Earth's Physical Environment Have Affected the Evolution of Life

17.3

Major Events in the Evolution of Life Can Be Read in the Fossil Record

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

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.

REVIEW & APPLY

This 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

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

Mastering the Key Concepts

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.

13.4 Selection Can Be Stabilizing, Directional, or Disruptive

Go to [ANIMATION 13.1](#)

- STABILIZING SELECTION** acts to reduce variation without changing the value of a trait ([FIGURE 13.13](#)).
- DIRECTIONAL SELECTION** acts to shift the mean value of a trait toward an extreme ([FIGURE 13.13](#)).
- DISRUPTIVE SELECTION** favors both extremes of a trait value, resulting in a bimodal character distribution ([FIGURE 13.13](#)).

FIGURE 13.13

13.5 Selection Can Maintain Polymorphisms in Populations

Go to [ACTIVITY 13.5](#)

- A polymorphism may be maintained by **FREQUENCY-DEPENDENT SELECTION** when the fitness of a genotype depends on its frequency in a population ([FIGURE 13.18](#)).
- A polymorphism may also be maintained by heterozygote advantage when the fitness of the heterozygote exceeds the fitness of either homozygote.
- Genetic variation within species may be maintained by the existence of genetically distinct populations over geographic space. A gradual change in phenotype across a geographic gradient is known as **CLINAL VARIATION** ([FIGURE 13.20](#)).

FIGURE 13.18

FIGURE 13.20

Go to [Achieve](#) for the e-book, animations, activities, and additional resources and assignments.

13 VISUAL SUMMARY

13.1 Evolution Is Both Factual and the Basis of Broader Theory

Go to [ACTIVITY 13.1](#)

- EVOLUTION** is genetic change in populations over time. Evolution can be observed directly in living populations as well as in the fossil record of life.
- EVOLUTIONARY THEORY** refers to our understanding of the mechanisms of evolutionary change.
- Charles Darwin is best known for his ideas on the common ancestry of divergent species and on **NATURAL SELECTION** (the differential survival and reproduction of individuals based on variation in their traits) as a mechanism of evolution.

13.2 Mutation, Selection, Gene Flow, Genetic Drift, and Nonrandom Mating Result in Evolution

Go to [ACTIVITIES 13.2 and 13.3](#)

- Mutation is the source of the genetic variation on which mechanisms of evolution act.
- Within **POPULATIONS**, selection acts to increase the frequency of beneficial **ALLELES** and to decrease the frequency of deleterious alleles ([FIGURE 13.6](#)).
- GENE FLOW, GENETIC DRIFT**, and nonrandom mating (as arises from **SEXUAL SELECTION**) can also result in the evolution of populations ([FIGURE 13.8](#)).

FIGURE 13.6

FIGURE 13.8

13.3 Evolution Can Be Measured by Changes in Allele Frequencies

Go to [ACTIVITY 13.4](#)

FIGURE 13.12

Generation II (Hardy-Weinberg equilibrium restored)

Genotype	Frequency
AA (p ²)	0.55 × 0.55 = 0.3025
Aa (pq)	0.55 × 0.45 = 0.2475
aA (pq)	0.45 × 0.55 = 0.2475
aa (q ²)	0.45 × 0.45 = 0.2025

p = 0.55, q = 0.45

- Allele frequencies measure the amount of genetic variation in a population. Genotype frequencies show how a population's genetic variation is distributed among its members. Together, allele and genotype frequencies describe a population's **GENETIC STRUCTURE**.
- HARDY-WEINBERG EQUILIBRIUM** predicts genotype frequencies from allele frequencies in the absence of evolution. Deviation from these frequencies indicates that evolutionary mechanisms are at work ([FIGURE 13.12](#)).

QUESTIONS

1. Explain the difference between “the fact of evolution” and what scientists mean by “evolutionary theory.”
2. What did Darwin mean by “descent with modification”?
3. How did Darwin suggest that biological evolution could occur?
1. How does artificial selection differ from natural selection?
2. How can genetic drift oppose the forces of natural selection?
3. Contrast natural selection and sexual selection.
1. How many generations of random mating are required to achieve Hardy-Weinberg equilibrium expectations?
2. How do the assumptions of Hardy-Weinberg equilibrium correspond to the five principal processes of evolution?



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 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

The solids are attracted to the magnet, indicating that the organisms in this solution are alive and engaged in iron-reducing biochemical reactions.



Heating to 121°C sterilizes the control solution.

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, Achieve includes online companions to the Analyze the Data exercises. (See the Achieve 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:

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

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 Achieve) lays the proper groundwork for understanding statistics and data, providing helpful support for all of the quantitative exercises.

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

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*. Features both in the text and online present you with an even more engaging experience.

CHAPTER OPENER WITH QUESTION

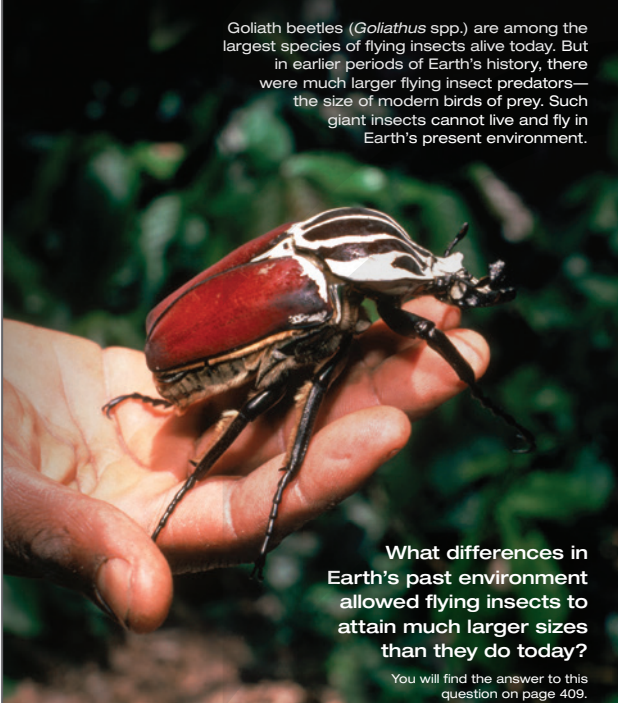
A short introduction with an attention-grabbing photo and compelling question gives you something to ponder while reading and studying the chapter. The chapter ends with a return to the question and some discussion of the answer.

The History of Life on Earth 17

Goliath beetles (*Goliathus* spp.) are among the largest species of flying insects alive today. But in earlier periods of Earth's history, there were much larger flying insect predators—the size of modern birds of prey. Such giant insects cannot live and fly in Earth's present environment.

What differences in Earth's past environment allowed flying insects to attain much larger sizes than they do today?

You will find the answer to this question on page 409.



LINKS

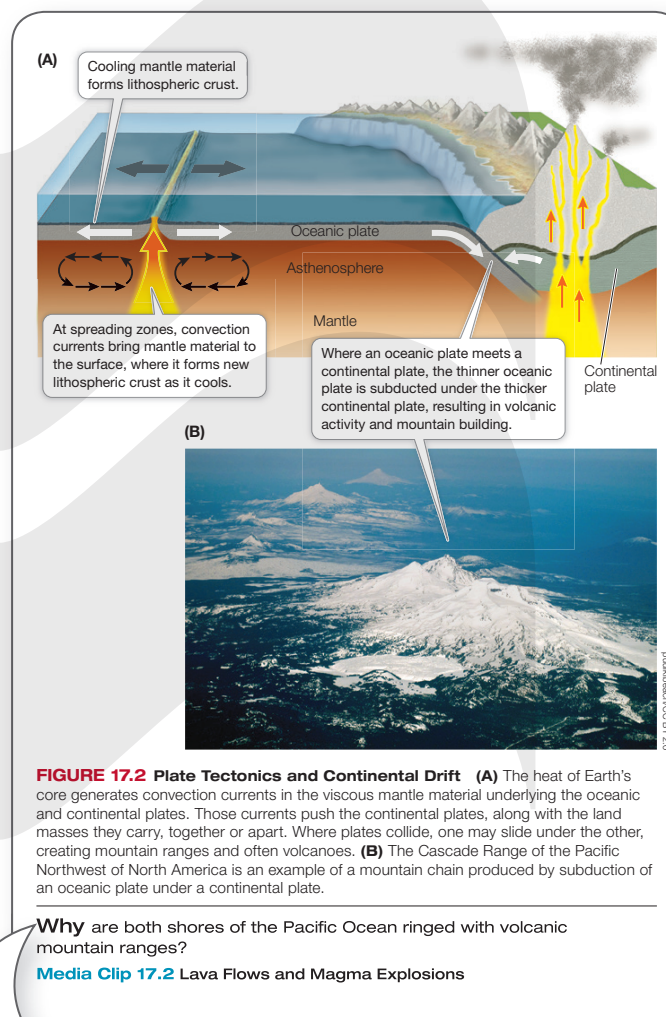
Links point you to additional discussion of a concept or key term elsewhere in the book, providing an opportunity for integration across chapters.

LINK

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

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.



Why are both shores of the Pacific Ocean ringed with volcanic mountain ranges?

Media Clip 17.2 Lava Flows and Magma Explosions

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.

ACTIVE LEARNING MODULES

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?

Chemiosmotic Mechanism

Examining Mitochondrial Poisons

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?

1. Rotenone - inhibits (complex I)
2. DNP - shuttles protons across the mitochondrial membrane
3. Oligomycin - blocks the proton channel of ATP synthase

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.

Transpiration-Cohesion-Tension Theory

Movement of water depends on:

- 1) the chemical properties of water
- 2) a gradient in water potential
- 3) avoiding cavitation

The last in this list is cavitation, which is the primary threat to the movement of water within xylem vessels.

Active Learning Module In-Class Video

ACTIVE LEARNING GUIDE

The Active Learning Guide provides extensive resources and support for implementing active learning techniques in any classroom, large or small. This 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

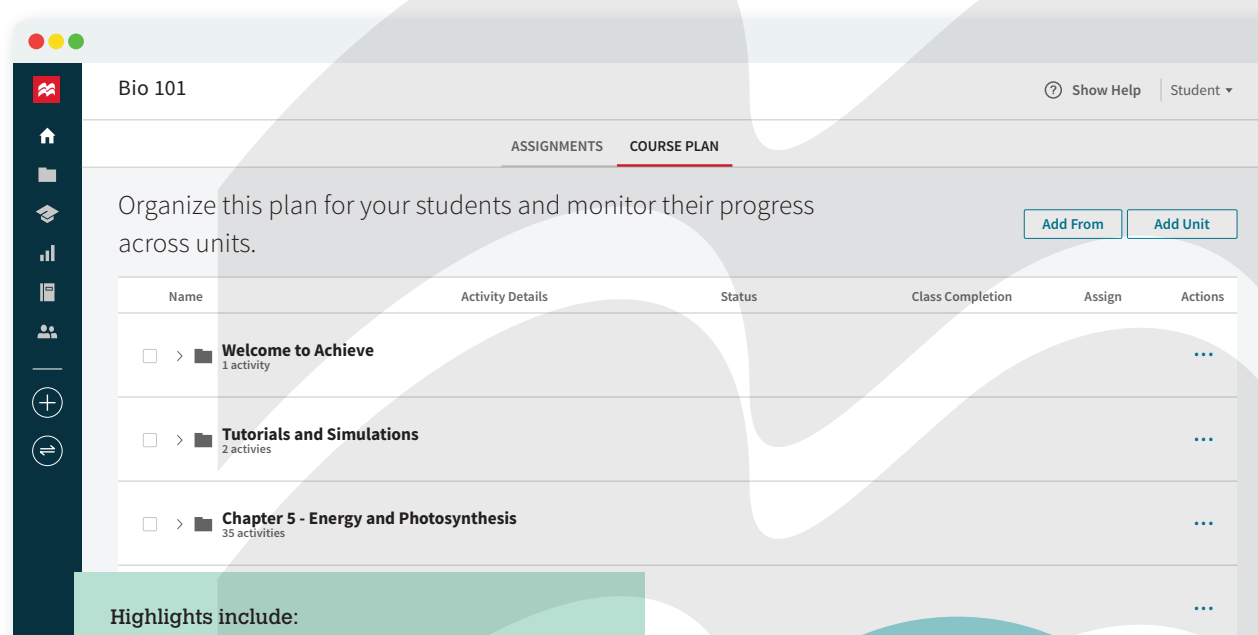
Part 3: Appendices

- 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

Principles of Life, now available with Achieve

Achieve is the culmination of years of development work put toward creating the most powerful online learning tool for biology students. It houses all of our renowned assessments, multimedia assets, e-books, and instructor resources in a powerful new platform.

Achieve supports educators and students throughout the full range of instruction, including assets suitable for pre-class preparation, in-class active learning, and post-class study and assessment. The pairing of a powerful new platform with outstanding biology content provides an unrivaled learning experience.



Highlights include:

- **A design guided by learning science research.** Co-designed through extensive collaboration and testing by both students and faculty including two levels of Institutional Review Board approval for every study of Achieve.
- **A learning path of powerful content** including pre-class, in-class, and post-class activities and assessments. A detailed Gradebook with insights for just-in-time teaching and reporting on student achievement by learning objective.
- **Easy integration and Gradebook sync** with iClicker classroom engagement solutions.
- **Simple integration** with your campus LMS and availability through **Inclusive Access** programs.



For more information or to sign up for a demonstration of Achieve, contact your local Macmillan representative or visit macmillanlearning.com/achieve.

Achieve: Media and Assessment Resources

Principles of Life's assessment and media resources give instructors a range of tools for assessing student's progress before class, in class, after class, and on exams.

Assessment questions and resources are aligned to the Learning Objectives associated with each Key Concept. This provides instructors with a concrete way of assessing students on mastery of the most important material in each chapter.

FEATURE	ASSESSMENT AND MEDIA RESOURCES
Active Learning Modules	Active Learning modules include everything needed to conduct in-class activities. Resources include pre- and post-class quizzes, videos, student handouts, and instructor activity guides.
Learning Curve	<p>LearningCurve adaptive quizzing gives students individualized question sets and feedback based on responses. All questions link back to the e-book to encourage students to read the book in preparation for class and exams.</p> <p>LearningCurve organizes questions by Key Concept, and instructors can easily hide questions on concepts they are not covering.</p> <p>New questions have been added to Learning Curve for the Third Edition Digital Update.</p>
Activities & Simulations	Interactive activities, including simulations, are assignable and include assessment questions for students to check their understanding.
Analyze the Data	Each in-text Analyze the Data exercise is accompanied by an online companion exercise. The online companion exercise gives additional practice with the same skills addressed by the in-text exercise.
Animations	Animations with associated questions to help students visualize important concepts.
Summative Quizzes	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.
Test Bank	The <i>Principles of Life</i> Test Bank available in Cognition includes new questions added for the Third Edition Digital Update. Questions are offered at a variety of Bloom's levels and cover all key concepts in the text.
Achieve Item Library	The Achieve item library allows instructors to create their own assignments and author their own questions. Easily search for questions and filter by difficulty level, Bloom's level, grading, or question type or topic. <i>Principles of Life</i> , Third Edition Digital Update, includes many new questions, including kinesthetic type questions.

Preface

Principles of Life, Third Edition Digital Update

Principles of Life, Third Edition, is updated and now available with Achieve! Achieve supports students and educators throughout the full range of instruction, including assets suitable for pre-class preparation, in-class active learning, post-class study and assessment. The pairing of a powerful new platform with outstanding biology content provides an unrivaled learning experience.

Features of Achieve Include

- A design guided by learning science research. Developed with extensive collaboration and testing by students and faculty, including two levels of Institutional Review Board approval for every efficacy study of Achieve.
- A learning path of powerful content including pre-class, in-class, and post-class activities and assessments.
- A detailed Gradebook with insights for just-in-time teaching and reporting on student achievement by learning concept.
- Easy integration and Gradebook synchronization with iClicker classroom engagement solutions.
- Simple integration with your campus LMS and availability through Inclusive Access programs.

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 a 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.

The conception of *Principles of Life* coincided with two major reports that supported the change to a conceptual approach; *Vision and Change in Undergraduate Biology Education: A Call to Action*, published in 2011 by the American Association for the Advancement of Science (supported by the National Science Foundation) 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.

With the astute guidance of Andy Sinauer—we convened an advisory group of twenty leading biology educators and instructors in introductory biology from throughout North America. During an intensive meeting of the authors and this group, dynamic discussions led to the solidification of the core concepts we believe are essential for teaching introductory biology. The book took shape, and members of the advisory group reviewed the emerging chapters, providing feedback at every stage of the book's development.

All chapters have undergone extensive between-edition review by experts in each respective discipline, and the chapters have been revised accordingly. Active learning has always been a priority in *Principles of Life*. With the Third Edition revised, 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 systems concepts is expanded. With the *Think Like a Scientist* feature, we have developed opportunities for students to practice the core competencies that have become critical for modern biologists.

Principles of Life stresses the five core concepts (themes) identified in *Vision and Change* as being essential for all undergraduates to understand:

- 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 concepts, 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* 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.

Vision and Change, in addition, identified six core competencies that undergraduates must develop to succeed in science in the twenty-first century. *Principles of Life* and Achieve support students in developing these skills. *Vision and Change* argues 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, and
- understand the relationship between science and society.

Our art program for *Principles of Life* continues to build on our success from *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 help students connect critical points of figures to the concepts that are developed in the text. Conceptual diagrams are used in many places, and text-art coordination has been emphasized. 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.

Features of *Principles of Life*

Focus on Concepts: Each chapter is organized into a series of *Key Concepts*, each with its own *Learning Objectives*. Our focus in each Key Concept section is to identify and explain the concepts that beginning university students need to know. At the end of each Key Concept, a *Review & Apply* 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 further questions related to the Learning Objectives. Throughout, the questions we raise are deliberately designed to span the incremental levels of Bloom's Taxonomy of Cognitive Domains. Answers to all questions are included in Achieve, *Principles of Life's* online platform.

Chapter Opener: Each chapter starts with carefully worded, professionally vetted *Learning Objectives*, which are then reinforced with each Key Concept section in the chapter, so that students can clearly see the goals they will achieve in their studies. Chapter openers have been designed with active learning in mind. Each chapter begins with a brief statement focused on major themes accompanied by a dramatic photograph and interpretive question 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.

Think Like a Scientist: The *Think Like a Scientist* entry in each chapter emphasizes one or more of the six core competencies, using a system of 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 will help each student learn more about the ways that scientists think. Questions—with answers at our online companion site, Achieve—are often provided to stimulate engagement.

Investigations: *Investigations* help students learn the process of science by being organized into sections on Hypothesis, Method, Results, and Conclusion. Most include a section (titled *Analyze the Data*) in which we present a subset of actual data from the published experiment. Students are asked to analyze these data and to make connections between observations, analyses, hypotheses, and conclusions. Extensive online resources are provided to expand the content on many Investigations. These resources include expanded discussions of the original research, links to the original publications, and discussion and links for any follow-up investigations that have been published. We have also included a *Making Sense of Data: A Statistics Primer* (Appendix B) to help students in developing this important skill.

Review and Apply: Each section concludes with 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 online in Achieve.

Visual Summary: 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 in Achieve.

Media Links: 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. The *Links* are not merely cross-references but include brief statements of pertinence, helping readers to see why they might want to follow a *Link*. We also feature *Animated Tutorials* and *Activities*, which include opportunities for students to use modeling and simulation modules to further reinforce their understanding of concepts.

Research Tools: Students need to learn about some of the major research tools that are used in biology, including major laboratory, computational, and field methods. Our *Research Tools* figures explain these tools and provide a context for how they are used by biologists. We have also included a *Working with DNA* so that students have an easy place to review and understand the major methods of molecular biology.

Active Learning: Active learning is a key component of *Principles of life*. We have implemented opportunities for active learning throughout the text and online in Achieve. In-text active learning opportunities include chapter opening questions, which give students something to ponder when reading and studying the chapter. Figure questions are designed to engage students and help them think about the implications of the figure or diagram. Active Learning modules include resources for classwork, as well as an instructor guide to support instructors in implementation of active learning.

Special Contributions

Many people contributed to the creation of the Third Edition Digital Update of *Principles of Life* (see below). However, three individuals deserve special mention 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).

Many People to Thank

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 issues and made critical suggestions for new material. They are: Walter Arnold, University of Veterinary Medicine (Vienna); Tobias Baskin, University of Massachusetts; Larry Gilbert, University of Texas, Austin; Harry Greene, Cornell University; Hugo Hofhuis, Wageningen University; 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); Richard Shingles, Johns Hopkins University; David Sleboda, Brown University; Viola Willemsen, Wageningen University; and Andrew Zanella, The Claremont Colleges.

Special thanks go to our editors who have guided us and the book through to the completion of the Third Edition Digital Update: Lisa Lockwood, Debbie Hardin, Marita Bley, Andy

Sinauer, Danna Niedzwiecki, and Laura Green. 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. We also wish to thank the entire team at Macmillan, including the Macmillan media group for their expertise in producing Achieve, the Regional Specialists, and the Regional Sales Managers.

Digital Content and Supplements

Principles of Life features a wide array of online resources to support and reinforce the material covered in the textbook. The activities, animations, and media clips referenced throughout the book are linked directly in the e-book, allowing students to instantly reference these resources from any device.

There is a wide array of instructor resources available, including multiple versions of all textbook figures, PowerPoint presentations, and a computerized test bank. PowerPoints and images are available from within Achieve, as well as the Active Learning Guide and Instructor's Manual. The computerized Test Bank can be accessed from the Instructor's Companion site.

We have enjoyed writing *Principles of Life* and wish you success. We hope that this book will serve you well.

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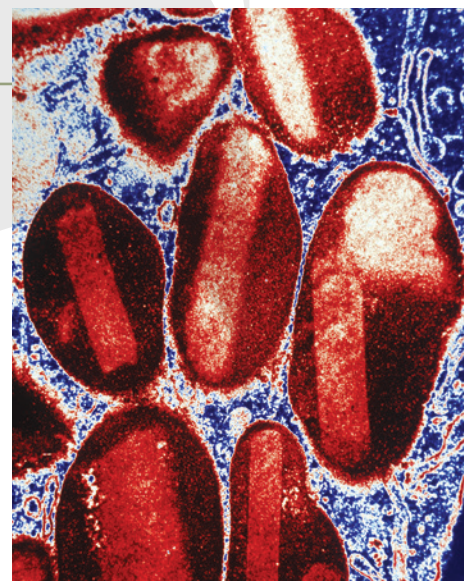
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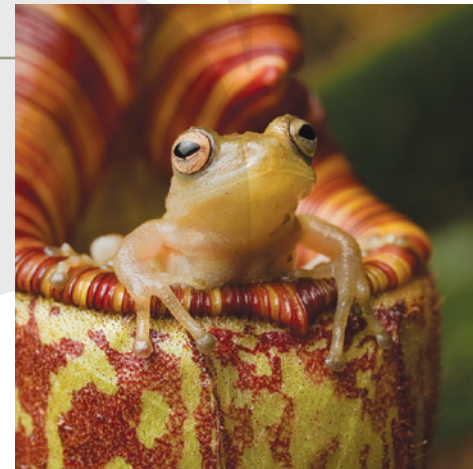
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Some protist life cycles feature alternation of generations 456

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Some microbial eukaryotes are deadly 456
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Tissues are composed of cells 581

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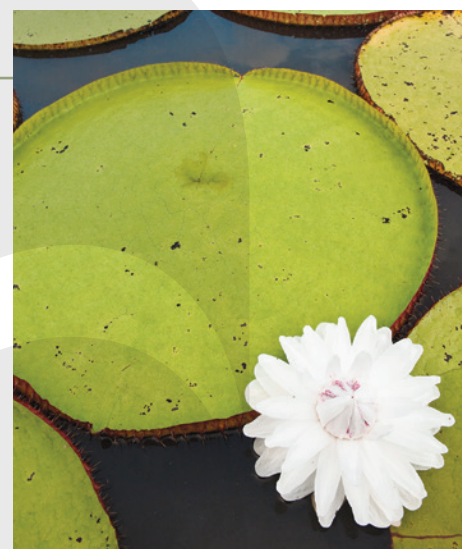
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Part 6 Animal Form and Function

28 Transformations of Energy and Matter: Nutrition, Temperature, and Homeostasis 678

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Animals need chemical building blocks to grow and to replace chemical constituents throughout life 679

Animals need chemical-bond energy to maintain the organization of their body 679

Food provides a great variety of nutrients, some of which are essential 680

Food provides energy 682

Concept 28.2 An Animal's Energy Needs Can Be Quantified 685

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Physical activity increases an animal's metabolic rate 686

Among related animals, metabolic rate usually varies in a regular way with body size 687



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Among animals of a single body size, metabolic rate depends on the ways animals relate to their environments 688

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Animals are classed as homeotherms or poikilotherms based on their thermal relationships with their external environments 690
 Homeotherms have evolved thermoregulatory mechanisms 692
 Thermoregulation illustrates that homeostasis requires a control system 694
 Thermoregulation exemplifies negative-feedback control 694

Concept 28.4 Animal Bodies Exhibit Division of Labor, but Each Cell Must Make Its Own ATP 695

Fluid compartments are separated from one another by epithelia and cell membranes 695
 Animals exhibit a high degree of division of labor 696
 The nutritional value of a food depends on whether an animal can digest it 698
 Division of labor requires a rapid transport system: the circulatory system 699
 Chemical-bond energy is transported by the blood in the form of glucose, other small carbohydrates, and fatty acids 699
 Each cell must make its own ATP 700

29 | Animals in Their Environments 704

Concept 29.1 Animals Prosper in Diverse Thermal Environments 705

Small- and large-bodied animals differ in behavioral options 705
 Large mammals in the Arctic have evolved specialized physiological defenses against cold 706
 Regional hypothermia is achieved by the circulatory system and its controls 707
 In hot deserts and other similar habitats, small- and large-bodied mammals again differ 707
 Lizards and insects prosper in hot deserts 709
 In cold climates, many small mammals hibernate in winter, and insects tolerate freezing or supercooling 710
 Fishes are models of molecular adaptation to temperature 711

Concept 29.2 Animals Live in the Ocean, Fresh Water, and Intermediate Salinities 713

All aqueous solutions are characterized by osmotic pressure, ionic composition, and volume 713
 The fluxes of water and ions between a freshwater animal and its environment are often highly dynamic 714
 Most ocean invertebrates are isosmotic to seawater 715
 Ocean bony fishes are strongly hyposmotic to seawater 716
 Evolutionary history explains why body fluid concentrations vary among animals 716
 Some aquatic animals experience varying environmental salinities 717

Concept 29.3 The Phenotypes of Individual Animals Can Change in Response to Environmental Change 719

Phenotypic plasticity is common at the biochemical level 719
 Phenotypic plasticity also occurs at the scale of tissues and organs 720

Concept 29.4 Animals Have Biological Clocks Tuned to Cycles in Their Environment 720

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 Biological clocks permit anticipation 724
 Biological clocks permit some animals to have a sun compass 724

30 | Breathing and Circulation 728

Concept 30.1 The Pathway for Oxygen: Oxygen Must Travel from Environment to Mitochondria 729

O₂ and CO₂ are transported by diffusion and bulk flow 730
 The diffusion of gases can be highly effective if distances are very short, but it has important limitations 730
 The pathway for oxygen often consists of alternation of bulk flow and diffusion 731
 Partial pressures are often used to study gas diffusion 731

Concept 30.2 Animals Have Evolved Diverse Types of Breathing Organs 732

Animals have evolved specialized breathing organs 732
 Air and water are very different respiratory environments 733
 Fishes have elaborate gills in which gas exchange occurs across secondary lamellae 735
 The directions of ventilation and perfusion can greatly affect the efficiency of gas exchange 735
 Most terrestrial vertebrates have tidally ventilated lungs 736
 Birds have rigid lungs ventilated unidirectionally by air sacs 737
 Insects have airways throughout their bodies 738
 Some animals lack specialized breathing organs 739

Concept 30.3 The Mammalian Breathing System Is Anatomically and Functionally Elaborate 740

Ventilation is adjusted over a wide range to meet needs of rest and exercise 742
 The lungs are ventilated by expansion and contraction of the thoracic cavity 742
 The breathing rhythm depends on nervous stimulation of the breathing muscles 743
 Breathing is under negative-feedback control by CO₂ 743
 Breathing is also controlled in part by body motion and blood O₂ 744

Concept 30.4 Animals Have Evolved Circulatory Systems for Rapid Internal O₂ Transport 745

A closed circulatory system moves blood through blood vessels 746
 In an open circulatory system, blood leaves blood vessels 749
 Blood often contains respiratory pigments that enhance its O₂ transport capability 749
 Respiratory pigments combine with O₂ reversibly 750

Concept 30.5 A Beating Heart Propels the Blood 752

Vertebrate hearts are myogenic and multi-chambered 752
 An electrocardiogram records the electrical activity of the heart 755
 The myocardium must receive O₂ 756
 Crustacean hearts are neurogenic and single-chambered 756

Concept 30.6 The Vascular System Plays Many Roles 757

- A series circulatory plan is most common 757
- The nature of blood vessels varies with their position 758
- Pressure and linear velocity vary greatly as blood flows through the vascular system 759
- In a typical systemic capillary bed, blood flow leaves behind fluid that the lymphatic system picks up 760
- The vasculature plays major roles in adaptations of animals to their environments 761

31

Neurons, Sense Organs, and Nervous Systems 766**Concept 31.1 Nervous Systems Are Composed of Neurons and Glial Cells 767**

- Neurons are cells specialized to produce electric signals 768
- Glial cells work with neurons and help guide nervous system development 769

Concept 31.2 Neurons Generate Electric Signals by Controlling Ion Distributions 771

- Only small shifts of ions are required for rapid changes in membrane potential 772
- The sodium–potassium pump sets up concentration gradients of Na^+ and K^+ 773
- The resting potential is mainly a consequence of K^+ leak channels 773
- The Nernst equation predicts an ion's equilibrium potential 773
- Gated ion channels alter the membrane potential 774
- Changes in membrane potential can be graded or all-or-none, depending on whether a threshold is crossed 775
- An action potential is a large depolarization that propagates with no loss of size 776
- Action potentials travel particularly fast in large axons and in myelinated axons 778

Concept 31.3 Neurons Communicate with Other Cells at Synapses 778

- Chemical synapses are most common, but electrical synapses also exist 779

- The vertebrate neuromuscular junction is a model chemical synapse 779
- Many different neurotransmitters have been identified 780
- Within the nervous system, a postsynaptic cell may have synapses with hundreds of presynaptic cells 780
- Synaptic plasticity is a mechanism of learning and memory 782

Concept 31.4 Sensory Processes Provide Information on an Animal's External Environment and Internal Status 784

- Sensory receptor cells transform stimuli into electric signals 784
- Sensory receptor cells depend on specific receptor proteins 785
- Sensation depends on which neurons in the brain receive action potentials from sensory cells 785
- Sensations of stretch and smell exemplify ionotropic and metabotropic reception 786
- Auditory systems use mechanoreceptors to sense sound pressure waves 787
- The photoreceptors involved in vision detect light using opsin molecules such as rhodopsin 790
- The vertebrate retina is a developmental outgrowth of the brain and consists of specialized neurons 791
- Some retinal ganglion cells are photoreceptive and interact with the circadian clock 792
- Arthropods have compound eyes 792
- Animals have evolved a remarkable diversity of sensory abilities 792

Concept 31.5 Neurons Are Organized into Nervous Systems 794

- The autonomic nervous system controls involuntary functions 796
- Spinal reflexes represent a simple type of skeletal muscle control 797
- The most dramatic changes in vertebrate brain evolution have been in the forebrain 798
- Location specificity is an important property of the mammalian cerebral hemispheres 799

32

Control by the Endocrine and Nervous Systems 805**Concept 32.1 The Endocrine and Nervous Systems Play Distinct, Interacting Roles 806**

- The nervous and endocrine systems work in different ways 807
- Nervous systems and endocrine systems tend to control different processes 807
- The nervous and endocrine systems work together 807
- Chemical signaling operates over a broad range of distances 807

Concept 32.2 Hormones Are Chemical Messengers Distributed by the Blood 809

- Endocrine cells are neurosecretory or non-neural 809
- Most hormones belong to one of three chemical groups 810
- Receptor proteins can be on the cell surface or inside a cell 810
- Hormone action depends on the nature of the target cells 811
- A hormonal signal is initiated, has its effect, and is terminated 812

Concept 32.3 The Vertebrate Hypothalamus and Pituitary Gland Link the Nervous and Endocrine Systems 813

- Hypothalamic neurosecretory cells produce the posterior pituitary hormones 813
- Secretion of anterior pituitary hormones is controlled by hormones from hypothalamic neurosecretory cells 814
- Endocrine cells are organized into control axes 815
- Hypothalamic and anterior pituitary hormones are often released in pulses 816

Concept 32.4 Hormones Regulate Mammalian Physiological Systems 817

- The thyroid gland is essential for normal development and provides examples of hormone deficiency disease 818
- Sex steroids control reproductive development 819

Concept 32.5 The Insect Endocrine System Is Crucial for Development 821

33 Muscle and Movement 827

Concept 33.1 Muscle Cells Develop Forces by Means of Cycles of Protein–Protein Interaction 828

Contraction occurs by a sliding-filament mechanism 828
 Actin and myosin filaments slide in relation to each other during muscle contraction 829
 ATP-requiring actin–myosin interactions are responsible for contraction 831
 Excitation leads to contraction, mediated by calcium ions 832

Concept 33.2 The Function of Skeletal Muscle Depends on Interaction with the Skeleton and on ATP Supply, Cell Type, and Training 836

In vertebrates, muscles pull on the bones of the endoskeleton 836
 In arthropods, muscles pull on interior extensions of the exoskeleton 837
 Hydrostatic skeletons have important relationships with muscle 838
 A muscle's power output depends on the current rate at which it is making ATP 838
 Muscle cell types affect power output and endurance 840
 Training modifies muscle performance 841

Concept 33.3 Many Distinctive Types of Muscle Have Evolved 843

Vertebrate cardiac muscle is both similar to and different from skeletal muscle 843
 Vertebrate smooth muscle powers slow contractions of many internal organs 844
 Some insect flight muscle has evolved unique excitation–contraction coupling 844
 Catch muscle in clams and scallops stays contracted with little ATP use 845
 Fish electric organs are composed of modified muscle 845

34 Animal Reproduction 849

Concept 34.1 Sexual Reproduction Depends on Gamete Formation and Fertilization 850

Most animals reproduce sexually 851
 Gametogenesis in the gonads produces the haploid gametes 852
 Fertilization may be external or internal 854
 The sex of an offspring is sometimes determined at fertilization 856
 Some animals undergo sex change during their adult lives 857

Concept 34.2 The Mammalian Reproductive System Is Hormonally Controlled 859

Ova mature in the ovaries and move to the uterus 859
 Ovulation is either spontaneous or induced 859
 Pregnancy is a specialized hormonal state 862
 Birth depends on a hormonally mediated positive-feedback loop 862
 Male sex organs produce and deliver semen 863
 Many contraceptive methods are available 865

Concept 34.3 Reproduction Is Integrated with the Life Cycle 866

Animals often gain flexibility by having mechanisms to decouple the steps in reproduction 866
 Some animals can reproduce only once, but most can reproduce more than once 867
 Seasonal reproductive cycles are common 868

35 Animal Development 871

Concept 35.1 Fertilization Activates Development 872

Egg and sperm make different contributions to the zygote 872
 Polarity is established early in development 873

Concept 35.2 Cleavage Creates Building Blocks to Make an Embryo 874

Specific blastomeres generate specific tissues and organs 876
 The amount of yolk affects cleavage 877
 Cleavage in placental mammals is unique 877

Concept 35.3 Gastrulation Sets the Stage for Morphogenesis 880

Yolk affects gastrulation 880



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A new body cavity, the coelom, forms 882
 Organs develop from the three germ layers 882
 The notochord induces formation of the neural tube 883
 Mesoderm forms tissues of the middle layer 886
 Positional information guides vertebrate limb formation 887

Concept 35.4 Extraembryonic Membranes Protect and Nourish the Embryo 888

Extraembryonic membranes form with contributions from all germ layers 888
 Extraembryonic membranes in mammals form the placenta 889
 Fishes also make yolk sacs 890

Concept 35.5 Development Continues throughout Life 891

Offspring of some animals undergo direct development 891
 Offspring of other animals undergo indirect development 891
 Determination precedes differentiation 892
 Stem cells provide new cells for growth and maintenance 894
 Stem cells can be isolated from embryos or induced from differentiated cells 895

36 Immunology: Animal Defense Systems 900

Concept 36.1 Animals Use Innate and Adaptive Mechanisms to Defend Themselves against Pathogens 901

Innate defenses evolved before adaptive defenses 901
Mammals have both innate and adaptive defenses 902
Blood and lymph tissues play important roles in defense 903

Concept 36.2 Innate Defenses Are Nonspecific 904

Barriers and local agents defend the body against invaders 904
Cell signaling pathways stimulate additional innate defenses 905
Inflammation is a coordinated response to infection or injury 906
Inflammation can cause medical problems 907

Concept 36.3 The Adaptive Immune Response Is Specific 907

Adaptive immunity has four key features 908
Macrophages and dendritic cells play a key role in activating the adaptive immune system 910
Two types of adaptive immune responses interact 910

Concept 36.4 The Adaptive Humoral Immune Response Involves Specific Antibodies 912

Plasma cells produce antibodies that share a common overall structure 912
Antibody diversity results from DNA rearrangements and other mutations 913
Antibodies bind to antigens and activate defense mechanisms 915

Concept 36.5 The Adaptive Cellular Immune Response Involves T Cells and Their Receptors 916

T cell receptors specifically bind to antigens on cell surfaces 916
MHC proteins present antigens to T cells and result in recognition 916
 T_H cells contribute to the humoral and cellular immune responses 917
Activation of the cellular response results in death of the targeted cell 918
Regulatory T cells suppress the humoral and cellular immune responses 918
AIDS is an immune deficiency disorder 918

Vaccination induces long-lasting immunity 919

37 Animal Behavior 923

Concept 37.1 Behavior Is Controlled by the Nervous System and Integrated with the Rest of Function 924

The distinction between proximate and ultimate causes is a fundamental concept for all studies of behavior 924
Behavior has a neural basis 926
Behaviors evolve 926
Despite its neural basis, behavior is not necessarily simplistically deterministic 928
Behavior is integrated with the rest of function 928
Behaviors are often integrated with body size and growth 929

Concept 37.2 Behavior Is Influenced by Learning and Early Experience 930

Specific information of critical survival value is often learned during early postnatal development 930
Early experience also has other, more global effects on an individual's behavior 932

Concept 37.3 Moving through Space Presents Distinctive Challenges 933

Trail following and path integration are two mechanisms of navigation 933
Animals have evolved multiple mechanisms for determining direction 934
Honey bee workers communicate distance and direction by a waggle dance 935
Many animals undertake migrations 936

Concept 37.4 Behavior Structures Social Groups and Plays Key Ecological Roles 937

Some societies consist of individuals of equal status 937
Some societies are composed of individuals of differing status 939
Eusociality represents an extreme type of differing status in a society 939
Animals often behaviorally partition space into territories or home ranges 940
Behavior helps structure ecological communities 940

Behavior often maintains species distinctions 940
Behavior helps structure ecological relationships among species 941

ON Water and Salt Balance (Online only)

Concept ON.1 Kidneys Regulate the Composition of the Body Fluids

Kidneys make urine from the blood plasma
Kidneys regulate the composition and volume of the blood plasma
Urine/plasma (U/P) ratios are essential tools for understanding kidney function
Our day-to-day urine concentrations illustrate these principles
The renege of action of the kidneys varies from one animal group to another
Extrarenal salt excretion sometimes provides abilities the kidneys cannot provide

Concept ON.2 Nitrogenous Wastes Need to Be Excreted

Most water-breathing aquatic animals excrete ammonia
Most terrestrial animals excrete urea, uric acid, or compounds related to uric acid

Concept ON.3 Aquatic Animals Display a Wide Diversity of Relationships to Their Environment

Most invertebrates in the ocean are isosmotic with seawater
Ocean bony fish are strongly hyposmotic to seawater
All freshwater animals are hyperosmotic to fresh water
Some aquatic animals face varying environmental salinities

Concept ON.4 Dehydration Is the Principal Challenge for Terrestrial Animals

Humidic terrestrial animals have rapid rates of water loss that limit their behavioral options
Xeric terrestrial animals have low rates of water loss, giving them enhanced freedom of action
Some xeric animals are adapted to live in deserts

Concept ON.5 Kidneys Adjust Water Excretion to Help Animals Maintain Homeostasis

Fluid enters a nephron by ultrafiltration driven by blood pressure

The processing of the primary urine in amphibians reveals fundamental principles of nephron function

Mammalian kidneys produce exceptionally high urine concentrations

The Malpighian tubules of insects employ a secretory mechanism of producing primary urine

Part 7 Ecology

38 Ecological Systems in Time and Space 946

Concept 38.1 Ecological Systems Vary over Space and Time 947

Organisms plus their environments are dynamic ecological systems 947
Ecological systems occur on a hierarchy of levels 947
Ecological systems can be small 947
Ecological systems vary, but in ways that can be understood with scientific methods 948

Concept 38.2 Solar Energy Input and Topography Shape Earth's Physical Environments 950

Variation in solar energy input drives patterns of weather and climate 951
The circulation of Earth's atmosphere redistributes heat energy 951
Ocean circulation also influences climate 953
Topography contributes to environmental heterogeneity 954
Climate diagrams summarize climates in an ecologically relevant way 955

Concept 38.3 Biogeography Reflects Physical Geography 956

Similarities in terrestrial vegetation led to the biome concept 956
Climate is not the only factor that molds terrestrial biomes 956
The biome concept can be extended to aquatic environments 959

Concept 38.4 Biogeography Reflects Geological History 960

Barriers to dispersal affect biogeography 960
Continental drift creates barriers to dispersal 960
Phylogenetic methods contribute to our understanding of biogeography 962

Concept 38.5 Human Activities Influence Ecological Systems on a Global Scale 964

We are altering natural ecosystems as we use their resources 964
We are converting natural ecosystems to human-modified ecosystems 964
We are blurring biogeographic boundaries and changing communities 965
Science provides tools for conserving and restoring ecological systems 965

39 Populations 969

Concept 39.1 Populations Are Patchy in Space and Dynamic over Time 970

Population size is usually estimated from population density and spatial extent 970
Population size varies in space and time 970

Concept 39.2 Births Increase and Deaths Decrease Population Size 972

Concept 39.3 Life Histories Determine Population Growth Rates 973

Life histories are diverse 974
Resources and physical conditions shape life histories 975
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