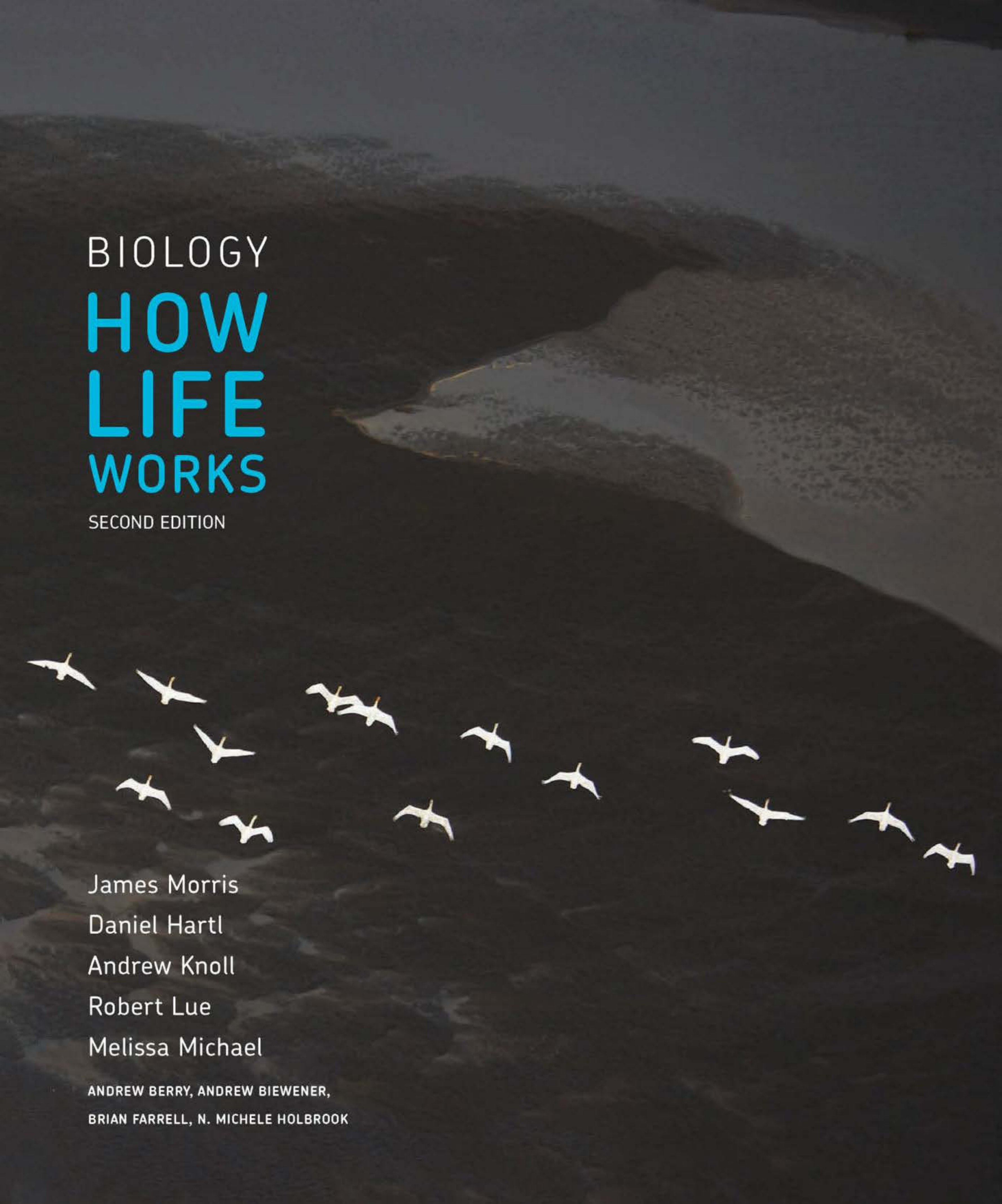

BIOLOGY
HOW LIFE WORKS

SECOND EDITION

James Morris
Daniel Hartl
Andrew Knoll
Robert Lue
Melissa Michael

ANDREW BERRY, ANDREW BIEWENER,
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DEDICATION

To all who are curious about life and how it works

ABOUT THE AUTHORS

JAMES R. MORRIS is Professor of Biology at Brandeis University. He teaches a wide variety of courses for majors and non-majors, including introductory biology, evolution, genetics and genomics, epigenetics, comparative vertebrate anatomy, and a first-year seminar on Darwin's *On the Origin of Species*. He is the recipient of numerous teaching awards from Brandeis and Harvard. His research focuses on the rapidly growing field of epigenetics, making use of the fruit fly *Drosophila melanogaster* as a model organism. He currently pursues this research with undergraduates in order to give them the opportunity to do genuine, laboratory-based research early in their scientific careers. Dr. Morris received a PhD in genetics from Harvard University and an MD from Harvard Medical School. He was a Junior Fellow in the Society of Fellows at Harvard University, and a National Academies Education Fellow and Mentor in the Life Sciences. He also writes short essays on science, medicine, and teaching at his Science Whys blog (http://blogs.brandeis.edu/sciencewhys).

DANIEL L. HARTL is Higgins Professor of Biology in the Department of Organismic and Evolutionary Biology at Harvard University and Professor of Immunology and Infectious Diseases at the Harvard Chan School of Public Health. He has taught highly popular courses in genetics and evolution at both the introductory and advanced levels. His lab studies molecular evolutionary genetics and population genetics and genomics. Dr. Hartl is the recipient of the Samuel Weiner Outstanding Scholar Award as well as the Gold Medal of the Stazione Zoologica Anton Dohrn, Naples. He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences. He has served as President of the Genetics Society of America and President of the Society for Molecular Biology and Evolution. Dr. Hartl's PhD is from the University of Wisconsin, and he did postdoctoral studies at the University of California, Berkeley. Before joining the Harvard faculty, he served on the faculties of the University of Minnesota, Purdue University, and Washington University Medical School. In addition to publishing more than 400 scientific articles, Dr. Hartl has authored or coauthored 30 books.

ANDREW H. KNOLL is Fisher Professor of Natural History in the Department of Organismic and Evolutionary Biology at Harvard University. He is also Professor of Earth and Planetary Sciences. Dr. Knoll teaches introductory courses in both departments. His research focuses on the early evolution of life, Precambrian environmental history, and the interconnections between the two. He has also worked extensively on the early evolution of animals, mass extinction, and plant evolution. He currently serves on the science team for NASA's mission to Mars. Dr. Knoll received the Phi Beta Kappa Book Award in Science for *Life on a Young Planet*. Other honors include the Paleontological Society Medal and Wollaston Medal of the Geological Society, London. He is a member of the National Academy of Sciences and a foreign member of the Royal Society of London. He received his PhD from Harvard University and then taught at Oberlin College before returning to Harvard.

ROBERT A. LUE is Professor of Molecular and Cellular Biology at Harvard University and the Richard L. Menschel Faculty Director of the Derek Bok Center for Teaching and Learning. Dr. Lue has a longstanding commitment to interdisciplinary teaching and research, and chaired the faculty committee that developed the first integrated science foundation in the country to serve science majors as well as pre-medical students. The founding director of Life Sciences Education at Harvard, Dr. Lue led a complete redesign of the introductory curriculum, redefining how the university can more effectively foster new generations of scientists as well as science-literate citizens. Dr. Lue has also developed award-winning multimedia, including the animation "The Inner Life of the Cell." He has coauthored undergraduate biology textbooks and chaired education conferences on college biology for the National Academies and the National Science Foundation and on diversity in science for the Howard Hughes Medical Institute and the National Institutes of Health. In 2012, Dr. Lue's extensive work on using technology to enhance learning took a new direction when he became faculty director of university-wide online education initiative HarvardX; he now helps to shape Harvard's engagement in online learning to reinforce its commitment to teaching excellence. Dr. Lue earned his PhD from Harvard University.

MELISSA MICHAEL is Director for Core Curriculum and Assistant Director for Undergraduate Instruction for the School of Molecular and Cellular Biology at the University of Illinois at Urbana-Champaign. A cell biologist, she primarily focuses on the continuing development of the School's undergraduate curricula. She is currently engaged in several projects aimed at improving instruction and assessment at the course and program levels. Her research focuses primarily on how creative assessment strategies affect student learning outcomes, and how outcomes in large-enrollment courses can be improved through the use of formative assessment in active classrooms.

ANDREW BERRY is Lecturer in the Department of Organismic and Evolutionary Biology and an undergraduate advisor in the Life Sciences at Harvard University. With research interests in evolutionary biology and history of science, he teaches courses that either focus on one of the areas or combine the two. He has written two books: *Infinite Tropics*, a collection of the writings of Alfred Russel Wallace, and, with James D. Watson, *DNA: The Secret of Life*, which is part history, part exploration of the controversies surrounding DNA-based technologies.

ANDREW A. BIEWENER is Charles P. Lyman Professor of Biology in the Department of Organismic and Evolutionary Biology at Harvard University and Director of the Concord Field Station. He teaches both introductory and advanced courses in anatomy, physiology, and biomechanics. His research focuses on the comparative biomechanics and neuromuscular control of mammalian and avian locomotion, with relevance to biorobotics. He is currently Deputy Editor-in-Chief for the Journal of Experimental Biology. He also served as President of the American Society of Biomechanics.

BRIAN D. FARRELL is Director of the David Rockefeller Center for Latin American Studies and Professor of Organismic and Evolutionary Biology and Curator in Entomology at the Museum of Comparative Zoology at Harvard University. He is an authority on coevolution between insects and plants and a specialist on the biology of beetles. He is the author of many scientific papers and book chapters on the evolution of ecological interactions between plants, beetles, and other insects in the tropics and temperate zone. Professor Farrell also spearheads initiatives to repatriate digital information from scientific specimens of insects in museums to their tropical countries of origin. In 2011–2012, he was a Fulbright Scholar to the Universidad Autónoma de Santo Domingo in the Dominican Republic. Professor Farrell received a BA degree in Zoology and Botany from the University of Vermont and MS and PhD degrees from the University of Maryland.

N. MICHELE HOLBROOK is Charles Bullard Professor of Forestry in the Department of Organismic and Evolutionary Biology at Harvard University. She teaches an introductory course on biodiversity as well as advanced courses in plant biology. She studies the physics and physiology of vascular transport in plants with the goal of understanding how constraints on the movement of water and solutes between soil and leaves influences ecological and evolutionary processes.

ASSESSMENT AUTHORS

JEAN HEITZ is a Distinguished Faculty Associate at the University of Wisconsin in Madison, WI. She has worked with the two-semester introductory sequence for biological sciences majors for over 30 years. Her primary roles include developing both interactive discussion/recitation activities designed to uncover and modify misconceptions in biology and open-ended process-oriented labs designed to give students a more authentic experience with science. The lab experience includes engaging all second-semester students in independent research, either mentored research or a library-based meta-analysis of an open question in the literature. She is also the advisor to the Peer Learning Association and is actively involved in TA training. She has taught a graduate course in "Teaching College Biology," has presented active-learning workshops at a number of national and international meetings, and has published a variety of lab modules, workbooks, and articles related to biology education.

MARK HENS is Associate Professor of Biology at the University of North Carolina Greensboro, where he has taught introductory biology since 1996. He is a National Academies Education Mentor in the Life Sciences and is the director of his department's Introductory Biology Program. In this role, he guided the development of a comprehensive set of assessable student learning outcomes for the two-semester introductory biology course required of all science majors at UNCG. In various leadership roles in general education, both on his campus and statewide, he was instrumental in crafting a common set of assessable student learning outcomes for all natural science courses for which students receive general education credit on the sixteen campuses of the University of North Carolina system.

JOHN MERRILL is Director of the Biological Sciences Program in the College of Natural Science at Michigan State University. This program administers the core biology course sequence required for all science majors. He is a National Academies Education Mentor in the Life Sciences. In recent years he has focused his research on teaching and learning with emphasis on classroom interventions and enhanced assessment. A particularly active area is the NSF-funded development of computer tools for automatic scoring of students' open-ended responses to conceptual assessment questions, with the goal of making it feasible to use open-response questions in large-enrollment classes.

RANDALL PHILLIS is Associate Professor of Biology at the University of Massachusetts Amherst. He has taught in the majors introductory biology course at this institution for 19 years and is a National Academies Education Mentor in the Life Sciences. With help from the Pew Center for Academic Transformation (1999), he has been instrumental in transforming the introductory biology course to an active learning format that makes use of classroom communication systems. He also participates in an NSF-funded project to design model-based reasoning assessment tools for use in class and on exams. These tools are being designed to develop and evaluate student scientific reasoning skills, with a focus on topics in introductory biology.

DEBRA PIRES is an Academic Administrator at the University of California, Los Angeles. She teaches the introductory courses in the Life Sciences Core Curriculum. She is also the Instructional Consultant for the Center for Education Innovation & Learning in the Sciences (CEILS). Many of her efforts are focused on curricular redesign of introductory biology courses. Through her work with CEILS, she coordinates faculty development workshops across several departments to facilitate pedagogical changes associated with curricular developments. Her current research focuses on what impact the experience of active learning pedagogies in lower division courses may have on student performance and concept retention in upper division courses.

ASSESSMENT CONTRIBUTORS

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VISION AND STORY OF *BIOLOGY: HOW LIFE WORKS*

Dear students and instructors,

One of the most frequent questions we get about the second edition of *Biology: How Life Works* is, "Has science really changed that much in three years?"

Ongoing discoveries in biology mean that a new edition of an introductory biology textbook will certainly have some new science content. But, more importantly, our second edition is new in the sense that we had the opportunity, for the first time, to listen to students and instructors who used *HLW* in the classroom. The second edition is responsive to this group and their input has proven invaluable.

What we heard from this community is that the philosophy of *HLW* resonates with students and instructors. They appreciate a streamlined text that rigorously focuses on introductory biology, an emphasis on integration, a modern treatment of biology, and equal attention to text, assessment, and media. These elements haven't changed—they are the threads that connect the first and second editions. In fact, all of the changes of the second edition are integrated within the framework of the first edition; they are not simply add-ons.

We are particularly excited about the work we've done in assessment. In the first edition, we worked with a creative and dedicated team of assessment authors to create something wholly new: not a standard test bank, but a thoughtful, curated, well-aligned set of questions that can be used for teaching as well as testing. These questions are written at a variety of cognitive levels. In addition, they can be used in a variety of contexts, including pre-class, in-class, homework, and exam, providing a learning path for students.

Our approach was so well received that we took it a step further in the second edition. The *HLW* team is excited to have Melissa Michael, our lead assessment author in the first edition, join us as a lead author in the second edition. Her new role allows her to work more closely with the text and media, which makes for an even tighter alignment among these various components.

Instructors have told us that they especially like the activities that can be used in class to foster active learning among students. In response, the second edition includes a rich set of activities across the introductory biology curriculum. Some are short, taking just a couple of minutes to explore a specific topic or concept. Others are longer, spanning several class periods and exploring topics and concepts across many chapters.

Although students and instructors appreciated a streamlined text, we also heard that more attention was needed in ecology. In response, we added a chapter that focuses on physical processes and global ecology. This new chapter also had a ripple effect throughout the later chapters of Part 2, giving us more space to explore other ecological concepts more deeply as well.

The media in *HLW* is many layered, so that a static visual synthesis on the page becomes animated online — and even interactive — through visual synthesis maps and simulations, using a consistent visual language and supported by assessment. Media resources for this new edition have been expanded to reflect its increased emphasis on global ecology — for example, there is a new Visual Synthesis figure and online map on the flow of matter and energy in ecosystems. We also developed additional media resources that focus on viruses, cells, and tissues.

We feel that this edition is a wonderful opportunity for us to continue to develop an integrated set of resources to support instructor teaching and student learning in introductory biology. Thank you for taking the time to use it in the classroom.

Sincerely,
The *Biology: How Life Works* Author Team

RETHINKING **BIOLOGY**

The *Biology: How Life Works* team set out to create a resource for today's biology students that would reimagine how content is created and delivered. With this second edition, we've refined that vision using feedback from the many dedicated instructors and students who have become a part of the *How Life Works* community.

We remain committed to the philosophy of *How Life Works*: a streamlined, integrated, and modern approach to introductory biology.

Thematic

We wrote *How Life Works* with six themes in mind. We used these themes as a guide to make decisions about which concepts to include and how to organize them. The themes provide a framework that helps students see biology as a set of connected concepts rather than disparate facts.

- The scientific method is a deliberate way of asking and answering questions about the natural world.
- Life works according to fundamental principles of chemistry and physics.
- The fundamental unit of life is the cell.
- Evolution explains the features that organisms share and those that set them apart.
- Organisms interact with one another and with their physical environment, shaping ecological systems that sustain life.
- In the 21st century, humans have become major agents in ecology and evolution.

Selective

It is unrealistic to expect the majors course to cover everything. We envision *How Life Works* not as a reference for all of biology, but as a resource focused on foundational concepts, terms, and experiments. We explain fundamental topics carefully, with an appropriate amount of supporting detail, so that students leave an introductory biology class with a framework on which to build.

Integrated

How Life Works moves away from minimally related chapters to provide guidance on how concepts connect to one another and the bigger picture. Across the book, key concepts such as chemistry are presented in context and Cases and Visual Synthesis figures throughout the text provide a framework for connecting and assimilating information.

WHAT'S NEW IN **THE SECOND EDITION?**

Expanded ecology coverage on physical processes and global ecology provides additional emphasis on ecological concepts, while ensuring that content is integrated into the larger theme of evolution. *Learn more about the expanded ecology coverage on page xviii.*

Visual Synthesis Figures and Online Maps on the Flow of Matter and Energy through Ecosystems, Cellular Communities, and Viruses allow students to explore connections between concepts through dynamic visualizations. *Learn more about the new media on page xix.*

Lead Author Melissa Michael guides our assessment team in refining and expanding our collection of thoughtful, well-curated assessments. Dr. Michael's role ensures a tight alignment between the assessments and the media and text. *Learn more on page xvi.*

A rich collection of in-class activities provides active learning materials for instructors to use in a variety of settings. *Learn more about the new in-class activities on page xvii.*

Improved LaunchPad functionality makes it easier to search and filter within our expansive collection of assessment questions. *Learn more about new LaunchPad functionality on page xii.*

TABLE OF CONTENTS

The table of contents is arranged in a familiar way to allow its easy use in a range of introductory biology courses. On closer look, there are significant differences that aim to help biology teachers incorporate the outlooks and research of biology today. **Key differences** are identified by ● and **unique chapters** by ✪.

EVOLUTION COVERAGE: Chapter 1 introduces evolution as a major theme of the book before discussing gene expression in Chapters 3 and 4 as a foundation for later discussions of the conservation of metabolic pathways and enzyme structure (Chapters 6–8) and genetic and phenotypic variation (Chapters 14 and 15). After the chapters on the mechanisms and patterns of evolution (Chapters 21–24), we discuss the diversity of all organisms in terms of adaptations and comparative features, culminating in ecology as the ultimate illustration of evolution in action.

CHEMISTRY: Chemistry is taught in the context of biological processes, emphasizing the key principle that structure determines function.

THE CELL: The first set of chapters emphasizes three key aspects of a cell—information flow (Chapters 3 and 4), actively maintaining a constant internal environment (Chapter 5), and harnessing energy (Chapters 6–8). Placing these basic points at the start of the textbook gives them emphasis and helps students build their knowledge of biology naturally.

CASE STUDIES: Biology is best understood when presented using real and engaging examples as a framework for synthesizing information. Eight carefully positioned Cases help provide this framework. For example, the Case about your personal genome is introduced before the set of chapters on genetics and is revisited in each of these chapters where it serves to reinforce important concepts.

GENETICS: The genetics chapters start with genomes and move to inheritance to provide a modern, molecular look at genetic variation and how traits are transmitted.

UNIQUE CHAPTERS: *Biology: How Life Works*, Second Edition includes chapters that don't traditionally appear in introductory biology texts, one in almost every major subject area. These novel chapters represent shifts toward a more modern conception of certain topics in biology and are identified by ✪.

“The approach to teaching is something my colleagues and I had been waiting for in a textbook. However, the text is flexible enough to accommodate a traditional teaching style.”

–Steve Uyeda, *Pima Community College*

To hear the authors talk about the table of contents in more depth, visit **biologyhowlifeworks.com**

BIOGEOCHEMICAL CYCLES: We present the carbon cycle as a bridge between the molecular and organismal parts of the book, showing how different kinds of organisms use the biochemical processes discussed in the first half of the book to create a cycle that drives life on Earth and creates ecosystems. The carbon cycle along with other biogeochemical cycles—sulfur and nitrogen—provides the conceptual backbone around which prokaryotic diversity is organized.

PLANT DEFENSE: The chapter on plant defense provides a strong ecological and case-based perspective on the strategies plants use to survive their exploitation by pathogens and herbivores.

DIVERSITY AND PHYSIOLOGY: Diversity follows physiology in order to provide a basis for understanding the groupings of organisms and to avoid presenting diversity as a list of names to memorize. When students understand how organisms function, they can understand the different groups in depth and organize them intuitively. To give instructors maximum flexibility, brief descriptions of unfamiliar organisms and the major groups of organisms have been layered in the physiology chapters, and the diversity chapters include a brief review of organismal form and function.

NEW CHAPTER 48: BIOMES AND GLOBAL ECOLOGY is part of the greatly expanded ecology coverage on physical processes and global ecology. The new coverage broadens connections between ecological concepts, and is carefully integrated into the larger theme of evolution.

RETHINKING THE TEXTBOOK **THROUGH LAUNCHPAD**

Ordinarily, textbooks are developed by first writing chapters, then making decisions about art and images, and finally assembling a test bank and ancillary media. *Biology: How Life Works* develops the text, visual program, and assessment at the same time. These three threads are tied to the same set of core concepts, share a common language, and use the same visual palette, which ensures a seamless learning experience for students throughout the course.

The text, visuals, and assessments come together most effectively through LaunchPad, Macmillan's integrated learning management system. In LaunchPad, students and instructors can access all components of *Biology: How Life Works*.

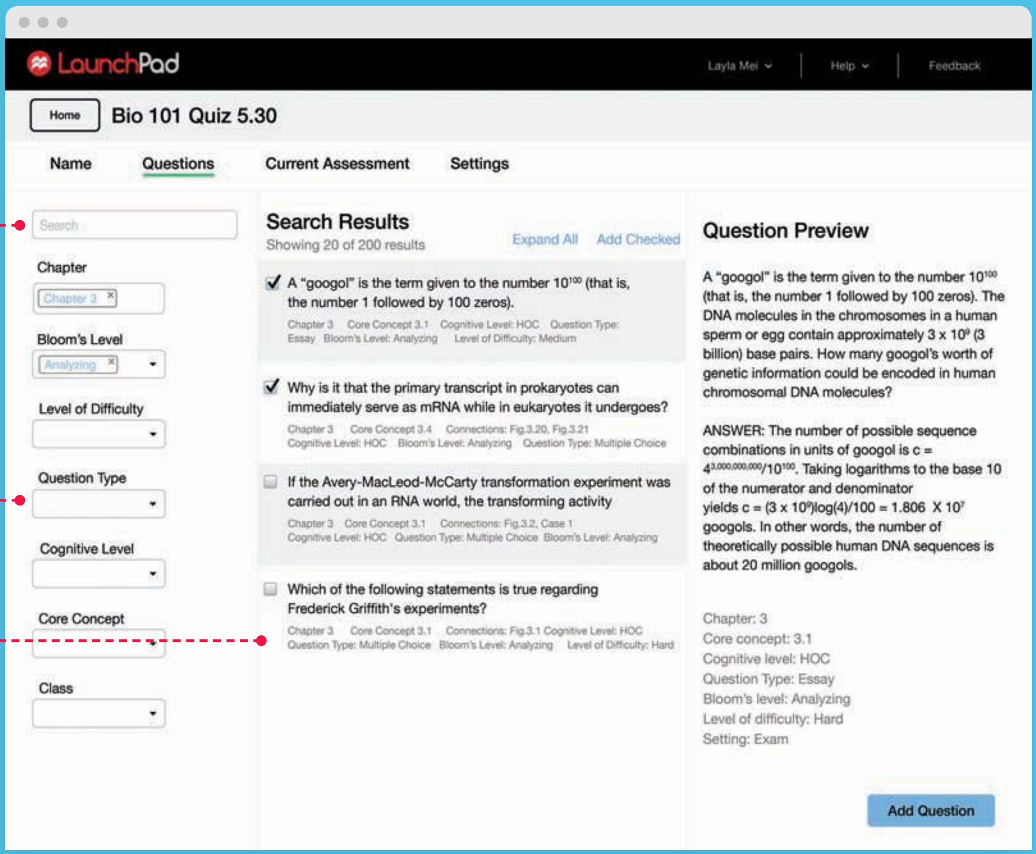
LaunchPad resources for *How Life Works* are flexible and aligned. Instructors have the ability to select the visuals, assessments, and activities that best suit their classroom and students. All resources are aligned to one another as well as to the text to ensure effectiveness in helping students build skills and develop knowledge necessary for a foundation in biology.

NEW IN LAUNCHPAD FOR *BIOLOGY: HOW LIFE WORKS*, SECOND EDITION

Functionality to search the question database and filter questions for a number of variables including Core Concept, difficulty level, Bloom's level, and class setting allows instructors to make best use of the robust assessment assets of *How Life Works.*

New question types include sequenced questions and multiple true-false. *Learn more on page xviii.*

Metadata tags for each question show at a glance information, including instructional guidance for select questions.



LAUNCHPAD

Where content counts.
Where service matters.
Where students learn.

LAUNCHPADWORKS.COM

Powerful, Simple, and Inviting

LaunchPad for *How Life Works* includes:

The complete *Biology: How Life Works* interactive e-Book

Carefully curated multimedia visuals and assessments, assignable by the instructor and easily accessible by students.

LearningCurve adaptive quizzing that puts "testing to learn" into action, with individualized question sets and feedback for each student based on his or her correct and incorrect responses. All the questions are tied back to the e-Book to encourage students to use the resources at hand.

Pre-built units that are easy to adapt and augment to fit your course.

A Gradebook that provides clear feedback to students and instructors on performance in the course as a whole and individual assignment.

LMS integration allows LaunchPad to be easily integrated into your school's learning management system so your Gradebook and roster are always in sync.

LEARNINGCURVE

LEARNINGCURVEWORKS.COM

Students agree that LearningCurve is extremely helpful in their studies.

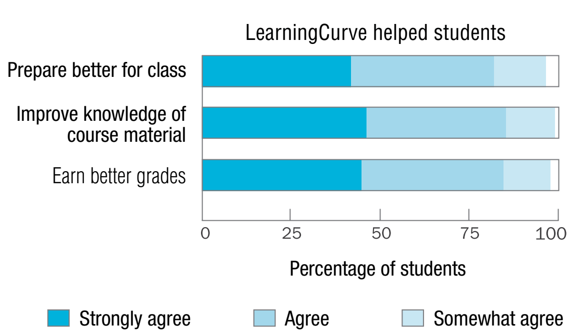
Macmillan's LearningCurve adaptive quizzing is part of almost every LaunchPad and has been enthusiastically embraced by students and instructors alike. LearningCurve provides specific feedback for every question and includes links to relevant sections of the e-Book. Questions are written exclusively for the LaunchPad in which they are offered and the question banks are robust and varied.

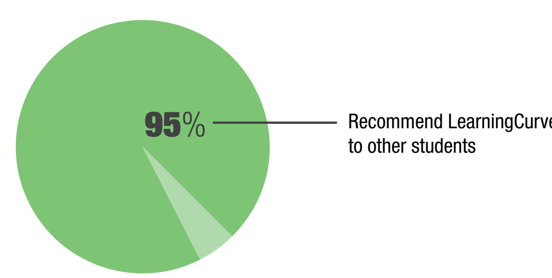
LearningCurve is **BENEFICIAL**

OVER 90% of students said LearningCurve helped them get better grades

95% of students would recommend LearningCurve to another student

LearningCurve is **APPROVED** by students

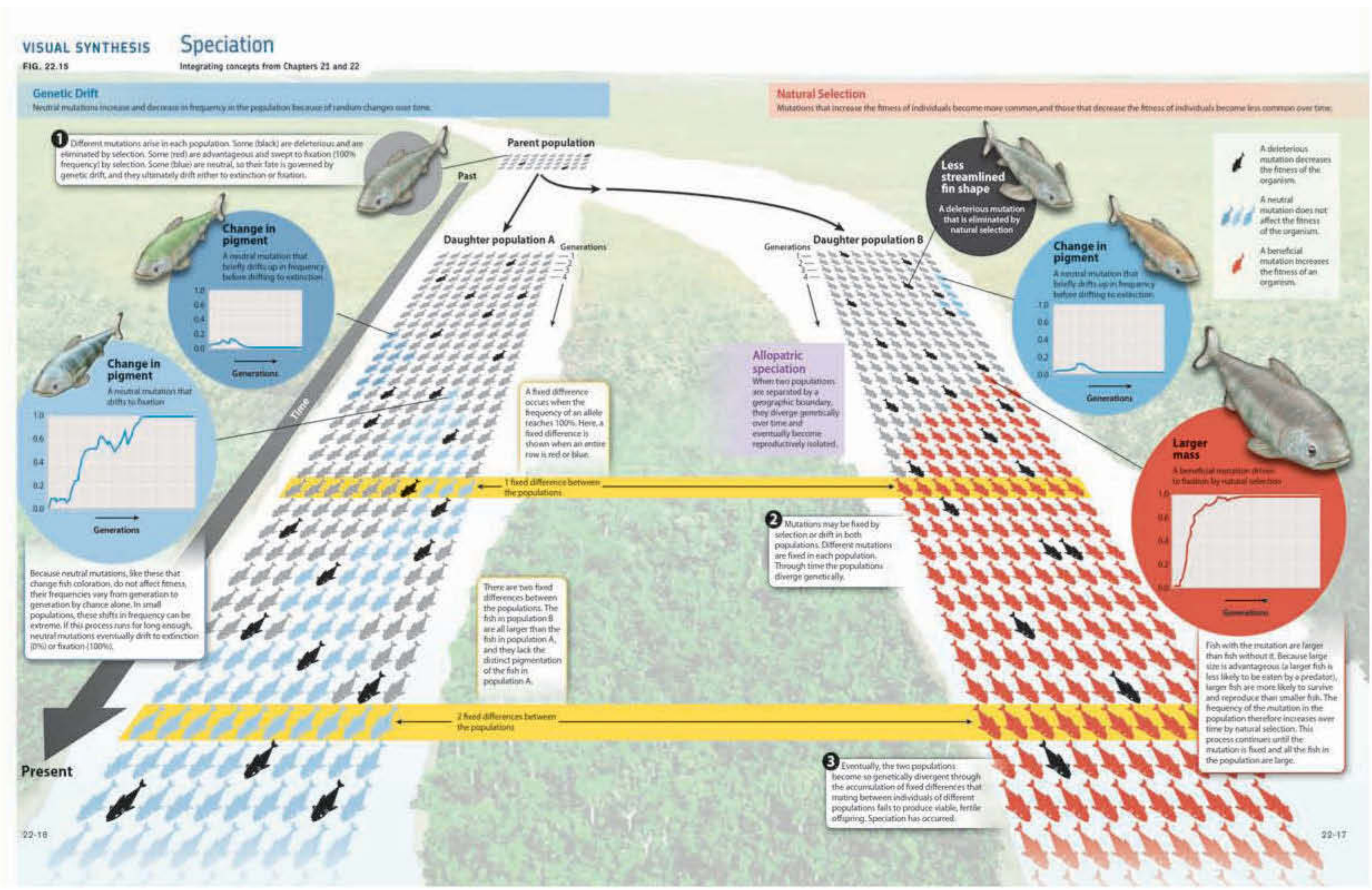




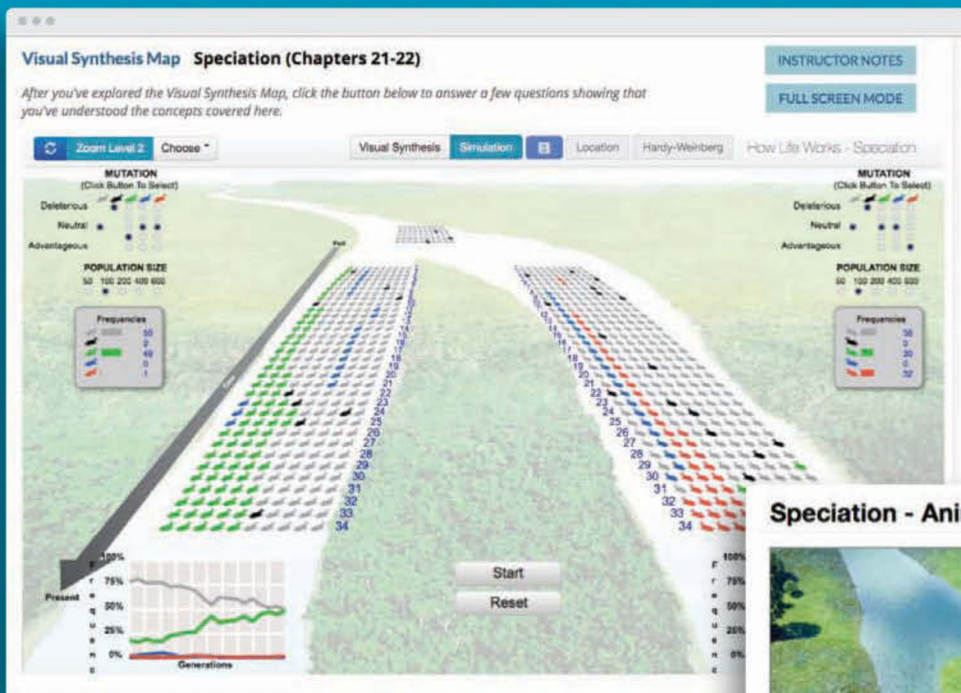
RETHINKING **THE VISUAL PROGRAM**

The art in the text of *How Life Works* and the associated media in LaunchPad were developed in coordination with the text and assessments to present an integrated and engaging visual experience for students.

Two of the biggest challenges introductory biology students face are connecting concepts across chapters and building a contextual picture, or visual framework, of a complex process. To help students think like biologists, we provide **Visual Synthesis** figures at twelve key points in the book. These figures bring together multiple images students have already seen into a visual summary, helping students see how individual concepts connect to tell a single story.

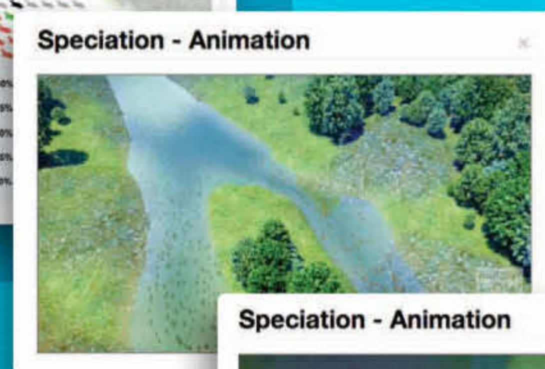


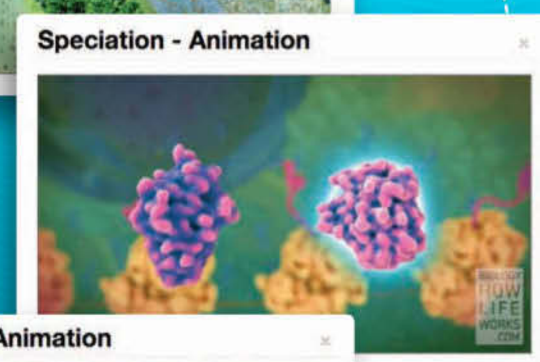
This Visual Synthesis figure on Speciation brings together multiple concepts from the chapters on evolution.

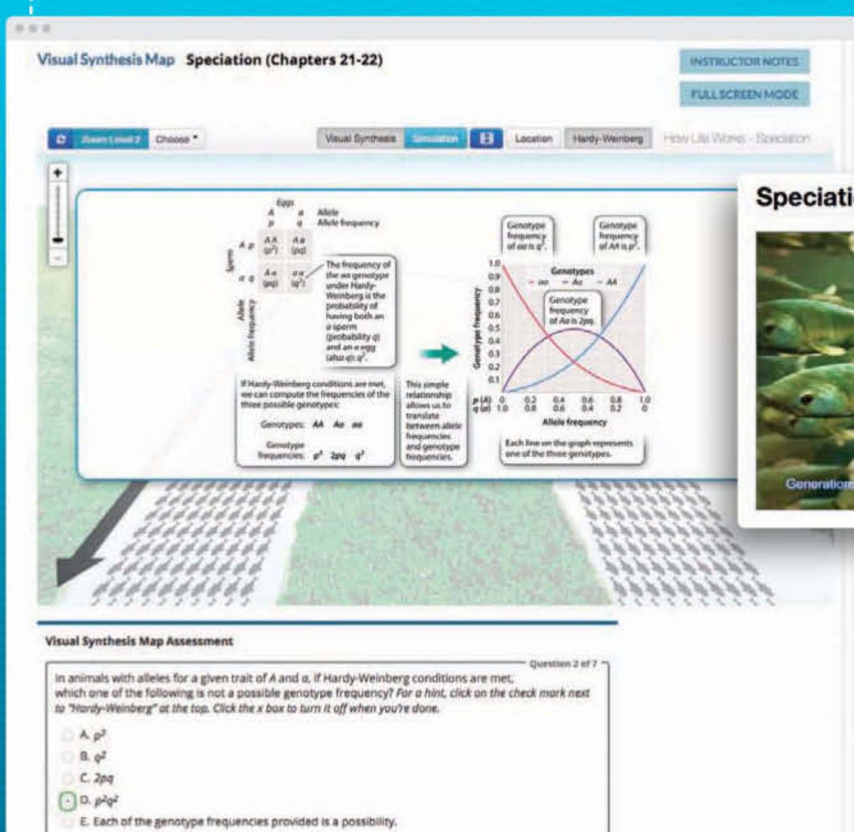


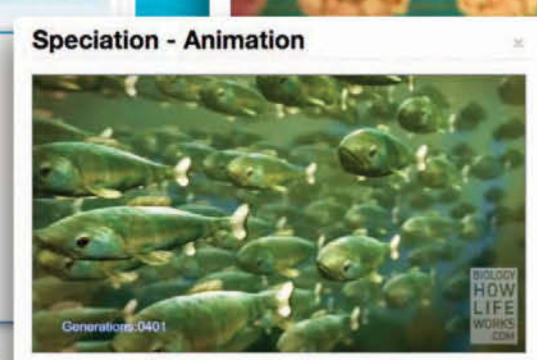
Online, the Visual Synthesis figures turn into zoomable, dynamic **Visual Synthesis Maps** where students can explore both the big picture and the details.

Many of the Visual Synthesis Maps also include **3D animations** (for concepts that are best learned by ***seeing*** them in action) and **simulations** (for concepts best learned by ***doing***).









Assessment questions accompany all Visual Synthesis Maps, 3D animation activities, and simulations to help students work through a core concept in a variety of ways.

RETHINKING **ASSESSMENT**

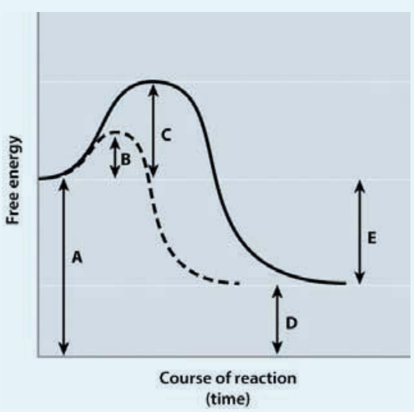
Well-designed assessment is a tremendous tool for instructors in gauging student understanding, actively teaching students, and preparing students for exams. The *Biology: How Life Works* assessment author team applied decades of experience researching and implementing assessment practices to create a variety of questions and activities for pre-class, in-class, homework, and exam settings. All assessment items are carefully aligned with the text and media and have the flexibility to meet the needs of instructors with any experience level, classroom size, or teaching style.

Alignment

If the questions, exercises, and activities in the course aren't aligned with course objectives and materials, practice with these resources may not help students succeed in their exam or in future biology courses. Each *How Life Works* assessment item is carefully aligned to the goals and content of the text, and to the assessment items used in other parts of the course. Students are guided through a learning path that provides them with repeated and increasingly challenging practice with the important concepts illustrated in the text and media.

Flexibility

The *How Life Works* assessment authors teach in a variety of classroom sizes and styles, and recognize that there is a wide diversity of course goals and circumstances. Each set of materials, from in-class activities to exam questions, includes a spectrum of options for instructors. All the assessment items are housed in the LaunchPad platform, which is designed to allow instructors to assign and organize assessment items to suit the unique needs of their course and their students.



Sample assessment questions, including a sequenced question based on a graph.

Answer the following questions about the reactions shown in the graph.

Which arrow indicates the activation energy of the catalyzed reaction?

❑ A | ■ **B** | ❑ C | ❑ D | ❑ E

Which arrow indicates the activation energy of the uncatalyzed reaction?

❑ A | ❑ B | ■ **C** | ❑ D | ❑ E

Which arrow represents the free energy of the substrate?

■ **A** | ❑ B | ❑ C | ❑ D | ❑ E

Which arrow indicates the free energy of the products?

❑ A | ❑ B | ❑ C | ■ **D** | ❑ E

Which arrow indicates the change in free energy (ΔG) of the reaction?

❑ A | ❑ B | ❑ C | ❑ D | ■ **E**

Is the reaction illustrated by the solid line endergonic or exergonic?

a.) endergonic **b.) exergonic**

Is the reaction illustrated by the dashed line endergonic or exergonic?

a.) endergonic **b.) exergonic**

Which of the following reactions would you predict could be coupled to ATP synthesis from ADP + Pi? Select all that apply.

a.) creatine phosphate + H_2O → creatine + Pi, ΔG -10.3 kcal/mol
b.) phosphoenolpyruvate + H_2O → pyruvate + Pi, ΔG -14.8 kcal/mol
c.) glucose 6-phosphate + H_2O → glucose + Pi, Δ*G* -3.3 kcal/mol
d.) glucose 1-phosphate + H_2O → glucose + Pi, Δ*G* -5.0 kcal/mol
e.) glutamic acid + NH_3 → glutamine, Δ*G* +3.4 kcal/mol

The emperor penguins of Antarctica live on a diet of fish and crustaceans obtained from the cold Antarctic seawaters. During their annual breeding cycle, however, they migrate across the frozen continent to their breeding grounds 50 miles away from the sea (and 50 miles away from their source of food). For over two months the male emperor penguins care for and incubate the eggs while the females return to the sea to feed. During this time a male penguin can lose up to 50% of its biomass (by dry weight). Where did this biomass go?

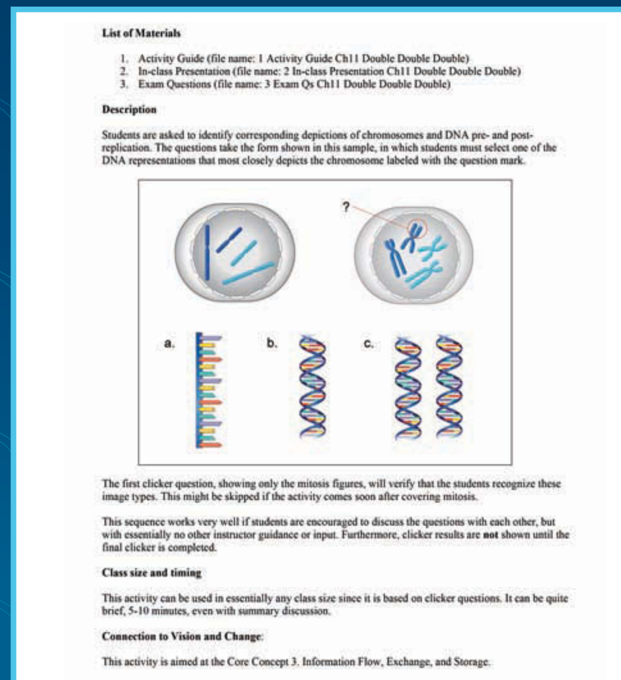
a.) It was converted to CO_2 and H_2O and then released.
b.) It was converted to heat and then released.
c.) It was converted to ATP molecules.

RETHINKING **ACTIVITIES**

Active learning exercises are an important component of the learning pathway and provide students with hands-on exploration of challenging topics and misconceptions. The second edition of *Biology: How Life Works* includes a new collection of over 40 in-class activities crafted to address the concepts that students find most challenging.

The activities collection was designed to cover a range of classroom sizes and complexity levels, and many can be easily adapted to suit the available time and preferred teaching style. Each activity includes a detailed activity guide for instructors. The activity guide introduces the activity, outlines learning objectives, and provides guidance on how to implement and customize the activity.

Many of the assessment questions and activities throughout *How Life Works* incorporate experimental thinking and data analysis. In addition, two activity types round out the assessment collection by providing applied practice with the data sets and examples from the text. Through ***Working with Data*** activities, students explore and analyze the experiment from a *How Do We Know?* figure from the text. ***Mirror Experiment*** activities introduce students to a new scientific study that relates to, or "mirrors," one of the *How Do We Know?* experiments and ask them to apply what they have learned about data analysis to this new scenario.



List of Materials

1. Activity Guide (file name: 1 Activity Guide Ch11 Double Double Double)
2. In-class Presentation (file name: 2 In-class Presentation Ch11 Double Double Double)
3. Exam Questions (file name: 3 Exam Qs Ch11 Double Double Double)

Description

Students are asked to identify corresponding depictions of chromosomes and DNA pre- and post-replication. The questions take the form shown in this sample, in which students must select one of the DNA representations that most closely depicts the chromosome labeled with the question mark.

The first clicker question, showing only the mitosis figures, will verify that the students recognize these image types. This might be skipped if the activity comes soon after covering mitosis.

This sequence works very well if students are encouraged to discuss the questions with each other, but with essentially no other instructor guidance or input. Furthermore, clicker results are **not** shown until the final clicker is completed.

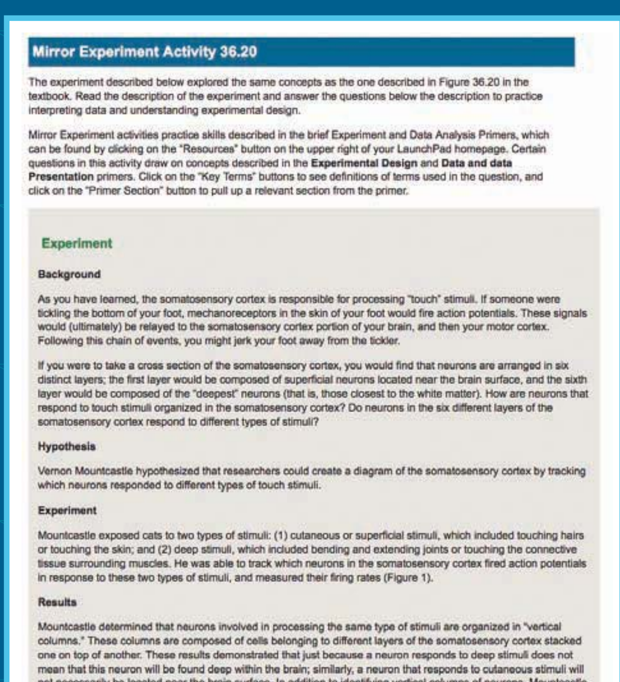
Class size and timing

This activity can be used in essentially any class size since it is based on clicker questions. It can be quite brief, 5-10 minutes, even with summary discussion.

Connection to Vision and Change:

This activity is aimed at the Core Concept 3. Information Flow, Exchange, and Storage.

Excerpts of activities from Chapters 11 and 36



Mirror Experiment Activity 36.20

The experiment described below explored the same concepts as the one described in Figure 36.20 in the textbook. Read the description of the experiment and answer the questions below the description to practice interpreting data and understanding experimental design.

Mirror Experiment activities practice skills described in the brief Experiment and Data Analysis Primers, which can be found by clicking on the "Resources" button on the upper right of your LaunchPad homepage. Certain questions in this activity draw on concepts described in the **Experimental Design** and **Data and data Presentation** primers. Click on the "Key Terms" buttons to see definitions of terms used in the question, and click on the "Primer Section" button to pull up a relevant section from the primer.

Experiment

Background

As you have learned, the somatosensory cortex is responsible for processing "touch" stimuli. If someone were tickling the bottom of your foot, mechanoreceptors in the skin of your foot would fire action potentials. These signals would (ultimately) be relayed to the somatosensory cortex portion of your brain, and then your motor cortex. Following this chain of events, you might jerk your foot away from the tickler.

If you were to take a cross section of the somatosensory cortex, you would find that neurons are arranged in six distinct layers; the first layer would be composed of superficial neurons located near the brain surface, and the sixth layer would be composed of the "deepest" neurons (that is, those closest to the white matter). How are neurons that respond to touch stimuli organized in the somatosensory cortex? Do neurons in the six different layers of the somatosensory cortex respond to different types of stimuli?

Hypothesis

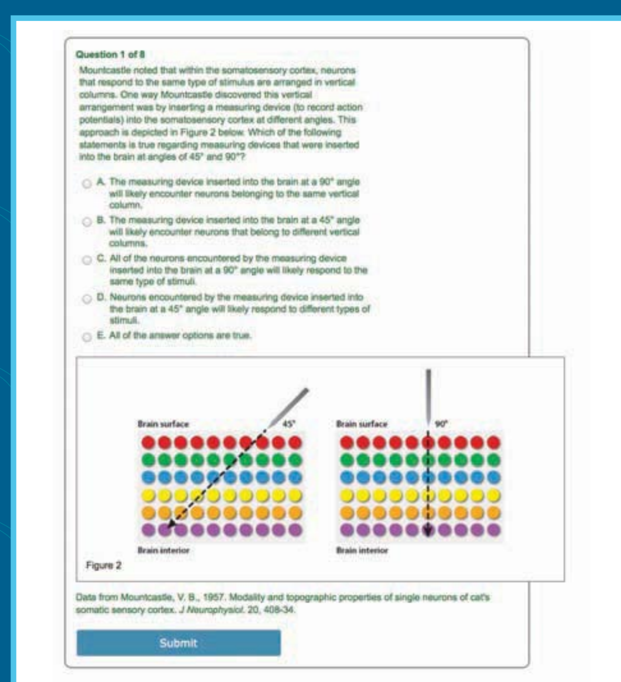
Vernon Mountcastle hypothesized that researchers could create a diagram of the somatosensory cortex by tracking which neurons responded to different types of touch stimuli.

Experiment

Mountcastle exposed cats to two types of stimuli: (1) cutaneous or superficial stimuli, which included touching hairs or touching the skin; and (2) deep stimuli, which included bending and extending joints or touching the connective tissue surrounding muscles. He was able to track which neurons in the somatosensory cortex fired action potentials in response to these two types of stimuli, and measured their firing rates (Figure 1).

Results

Mountcastle determined that neurons involved in processing the same type of stimuli are organized in "vertical columns." These columns are composed of cells belonging to different layers of the somatosensory cortex stacked one on top of another. These results demonstrated that just because a neuron responds to deep stimuli does not mean that this neuron will be found deep within the brain; similarly, a neuron that responds to cutaneous stimuli will not necessarily be located near the brain surface. In addition to identifying vertical columns of neurons, Mountcastle



Question 1 of 8

Mountcastle noted that within the somatosensory cortex, neurons that respond to the same type of stimulus are arranged in vertical columns. One way Mountcastle discovered this vertical arrangement was by inserting a measuring device (to record action potentials) into the somatosensory cortex at different angles. This approach is depicted in Figure 2 below. Which of the following statements is true regarding measuring devices that were inserted into the brain at angles of 45° and 90°?

- A. The measuring device inserted into the brain at a 90° angle will likely encounter neurons belonging to the same vertical column.
- B. The measuring device inserted into the brain at a 45° angle will likely encounter neurons that belong to different vertical columns.
- C. All of the neurons encountered by the measuring device inserted into the brain at a 90° angle will likely respond to the same type of stimuli.
- D. Neurons encountered by the measuring device inserted into the brain at a 45° angle will likely respond to different types of stimuli.
- E. All of the answer options are true.

Figure 2

Data from Mountcastle, V. B., 1957. Modality and topographic properties of single neurons of cat's somatic sensory cortex. *J Neurophysiol.* 20, 408-34.

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WHAT'S NEW IN THE SECOND EDITION?

From the start, *Biology: How Life Works* was envisioned not as a reference book for all of biology, but as a resource focused on foundational concepts, terms, and experiments, all placed in a framework that motivates student interest through a coherent and authentic presentation of current science. In preparing this edition, we carefully considered the latest breakthroughs and incremental, but nevertheless significant, changes across the fields of biology. We also reached out to adopters, instructors not using our book, and primary literature to determine what concepts and details are relevant, important, and necessary additions. Our integrated approach to text, media, and assessment means that all changes are carefully reflected in each of these areas.

MAJOR CHANGES AND UPDATES

We've greatly expanded the coverage of ecology in the second edition of *Biology: How Life Works.*

A new ecology chapter, Chapter 48: Biomes and Global Ecology, takes a broad look at ecology on the largest scale. It begins with how and why climates are distributed as they are around the world and introduces Earth's major biomes. Biomes crystallize the relationships among ecology, evolution, and physical environment—landscapes look different in different parts of the world because of the morphological and physiological adaptations that plants and animals have made to different climates. The chapter is distinguished by extensive discussion of biomes in the aquatic realm, especially in the oceans.

Chapter 47: Species Interactions, Communities, and Ecosystems **includes expanded coverage of the ways species interact with one another in communities**. This chapter now has more detail on facilitation, herbivory, and biodiversity.

Chapter 49: The Anthropocene: Humans as a Planetary Force **includes new discussions exploring how human activities affect ecology**. The chapter now examines fracking and its effects on the carbon cycle, habitat loss and its effects on biodiversity, and the overexploitation of resources and its effects on community ecology. The chapter ends with a new section on conservation biology that explores how conservationists are working to preserve natural habitats.

A new Visual Synthesis figure on the flow of matter and energy through ecosystems illustrates, explores, and physically situates the relationships among concepts from Chapters 25, 26, 47, 48, and 49. In LaunchPad, students and instructors can interact with an accompanying dynamic, zoomable, and interactive Visual Synthesis Map based on this figure.

Our new collection of over 40 in-class activities provides tools for instructors to engage their students in active learning. In-class activities are designed to address difficult concepts, and can be used with a variety of classroom sizes and teaching styles. Each activity includes a detailed activity guide for instructors.

We've expanded our collection of high-quality assessment questions by adding over 1000 new questions. New questions are particularly focused on higher-order thinking, including questions based on figures or data, and questions that ask students to consider how perturbing a system would affect outcomes. As in the first edition, questions are carefully aligned with core concepts from the text. New and revised assessment questions also accompany Visual Synthesis Maps, simulations, animations, and other visual media, to more effectively probe student understanding of the media tools they've explored.

The second edition also includes several new question types. **Sequenced questions** ask students several, individually scored questions about a single scenario or system. These questions often build on one another to guide students from lower-order thinking to higher-order thinking about the same concept. **Multiple true–false questions** ask students several, individually scored true–false questions about a single scenario or system.

Improved functionality in LaunchPad allows instructors to search the question database and filter questions by a number of variables, including core concept, difficulty level, Bloom's level, and class setting. Metadata tags for each question show additional information at a glance, including instructional guidance for select questions.

NEW MEDIA

Cell Communities Visual Synthesis Map to accompany the printed Visual Synthesis figure

Virus Visual Synthesis Map to accompany the printed Visual Synthesis figure

New Visual Synthesis figure and map on the Flow of Matter and Energy in Ecosystems

Virus Video featuring author Rob Lue

Cell Membrane simulation

New Animations

- Chapter 9: Basic Principles of Cell Signaling
- Chapter 9: G protein-coupled Receptor Signaling
- Chapter 9: Signal Amplification
- Chapter 10: Dynamic Nature of Microtubules
- Chapter 10: Motor Proteins
- Chapter 10: Dynamic Nature of Actin Filaments
- Chapter 19: Lac Operon
- Chapter 20: ABC Model of Floral Development
- Chapter 40: Glucose Absorption in the Small Intestine
- Chapter 42: Gastrulation

NEW TOPICS AND OTHER REVISIONS

The following is a detailed list of content changes in this edition. These range from the very small (nucleotides shown at physiological pH) to quite substantial (an entire new chapter in the ecology section). Especially important changes are indicated with an asterisk (✪).

- ✪ New coverage of functional groups (Chapter 2)
- Nucleotides now shown at physiological pH (Chapter 3)
- Amino acids now shown at physiological pH (Chapter 4)
- The story of the evolution of photosynthesis now brought together in a single major section at the end of Chapter 8 (section 8.5)
- ✪ Chapters 9 and 10 streamlined to better match our mission statement
- A new discussion of cellular response and what determines it (Chapter 9)
- ✪ New inclusion of the trombone model of DNA replication (Chapter 12)
- ✪ Addition of CRISPR technology (Chapter 12)
- Expanded coverage of retrotransposons and reverse transcriptase (Chapter 13)
- A new *How Do We Know?* figure explaining Mendel's experimental results (Chapter 16)
- New coverage of the mechanism of *X*-inactivation (Chapter 19)
- An expanded discussion of non-random mating and inbreeding depression (Chapter 21)
- ✪ Addition of the effect of mass extinctions on species diversity (Chapter 23)
- Updated discussion of the relationship between Neanderthals and *Homo sapiens*, as well as Denisovans (Chapter 24)
- Significantly revised link between the carbon cycle, biodiversity, and ecology (Chapter 25)
- New branching order of the eukaryote tree to reflect new research in the past three years (Chapter 27 and onward)
- A new paragraph on ciliates (Chapter 27)
- A new explanation of protist diversity (Chapter 27)
- ✪ A new discussion of plant nutrients with a table (Chapter 29)
- ✪ An enhanced discussion of seeds, including the development of the embryo and dispersal structures (Chapter 30)
- New coverage of the genetic advantages of alternation of generations, and how it allows inbreeding (Chapter 30)
- Addition of apomixis (Chapter 30)
- The section on the role of plant sensory systems in the timing of plant reproduction moved from Chapter 30 to Chapter 31
- Completely revised explanation of the basis for angiosperm diversity (Chapter 33)
- Brief descriptions of unfamiliar organisms and the major groups of organisms layered in the animal physiology chapters to make it easier to teach physiology before diversity (Chapters 35-42)
- ✪ Brief review of organismal form and function in the plant and animal diversity chapters (Chapters 33 and 44), allowing these chapters to be used on their own or before the physiology chapters and giving instructors maximum flexibility
- ✪ A new section on the composition of blood (Chapter 39)
- New diagrams of hormone feedback loops in the menstrual cycle (Chapter 42)
- A new introduction to the immune system (Chapter 43)
- ✪ A new discussion of nematodes (Chapter 44)
- Introduction of a newly discovered species, *Dendrogramma enigmatica* (Chapter 44)
- A simplified population growth equation (Chapter 46)
- A new discussion of facilitation (Chapter 47)
- An expanded discussion of herbivory (Chapter 47)
- A new example of microbial symbionts (Chapter 47)
- A new discussion of biodiversity and its importance (Chapter 47)
- ✪ An entirely new chapter on physical processes that underlie different biomes (Chapter 48)
    - Differential solar energy around the globe and seasonality
    - Wind and ocean currents
    - Effects of circulation and topography on rainfall
    - Expanded discussion of terrestrial biomes
    - Freshwater and marine biomes
    - Integration of concepts of biogeochemical cycles from Chapters 25 and 26 with ecological concepts
    - Global patterns of primary production
    - Global biodiversity
- ✪ A new exploration of the effect of fracking on the carbon cycle (Chapter 49)
- ✪ New coverage of habitat loss and biodiversity (Chapter 49)
- ✪ New coverage of overexploitation of resources and its effects on community ecology (Chapter 49)
- ✪ A new Core Concept and discussion of conservation biology (Chapter 49)

PRAISE FOR *HOW LIFE WORKS*

I have taught botany and then Biology II for over 20 years and have been very frustrated when I have realized how little knowledge students retained. Since we have gone to this textbook, I find that the questions students are asking in class are much more probing than those in the past, and the students seem much more engaged in the topics. I am hopeful that this approach will help our students be deeper thinkers and better scientists.

– **GLORIA CADDELL, University of Central Oklahoma**

One of the things that really sold me on this text was the LaunchPad system: easy to use; intuitive navigation; really good questions that match the sophistication of the text; love the LearningCurve activities; use most of the animations in my lectures!

– **SARA CARLSON, University of Akron**

This is the best set of questions I've ever seen in a textbook. They are thorough and the right mix of challenging the student with requiring memorization of important details.

– **KURT ELLIOT, Northwest Vista College**

We have all seen an improvement in our students' understanding of the material this year, the first year that we used the Morris text.

– **ANUPAMA SESHAN, Emmanuel College**

I like the figures, especially the 3D ones — we focus on "perceptual ability" training in our classes and figures that encourage students to think about cells in 3D are excellent!

– **KIRKWOOD LAND, University of the Pacific**

These chapters all seem to draw students through the course by referencing what they have learned previously and then adding new information. This makes the course seem like a complete story instead of a series of encyclopedia entries to be learned in isolation.

– **TIM KROFT, Auburn University at Montgomery**

We used this book last year and overall felt that it represented a major improvement from our previous text.

– **PETER ARMBRUSTER, Georgetown University**

Good questions are just as important as a good textbook. The available variety of assessment tools was very important for our adoption of this text.

– **MATTHEW BREWER, Georgia State University**

If the whole book reads like this I would love to use it! This is the way I like to teach! I want students to understand rather than memorize and this chapter seems aimed at this.

– **JENNIFER SCHRAMM, Chemeketa Community College**

The artwork seems very clear-cut and geared to giving the students a very specific piece of information with a very simple example. This should greatly help students with forming a visual image of the various subjects.

– **CHRIS PETRIE, Eastern Florida State College**

The writing style is excellent, it makes a great narrative and incorporates key scientific experiments into the explanation of photosynthesis.

– **DIANNE JENNING, Virginia Commonwealth University**

I think *HLW* does a better job of presenting introductory material than our current text, which tends to overwhelm students.

– **LAURA HILL, University of Vermont**

With the quick checks and the experiments the first chapter already has the learners thinking about experiments and critical analysis.

– **JOHN KOONTZ, University of Tennessee Knoxville**

This book moves teaching away from merely understanding all of the bold terms in a textbook in order to spit them back on a multiple-choice test. I can use this text in order to prepare my students to understand and learn the general principles and concepts in biology and how those concepts translate across different levels of biology. I would not trade this textbook for any other book on the market.

– **PAUL MOORE, Bowling Green State University**

ACKNOWLEDGMENTS

Biology: How Life Works is not only a book. Instead, it is an integrated set of resources to support student learning and instructor teaching in introductory biology. As a result, we work closely with an entire community of authors, publishers, instructors, reviewers, and students. We would like to thank this dedicated group.

First and foremost, we thank the thousands of students we have collectively taught. Their curiosity, intelligence, and enthusiasm have been sources of motivation for all of us.

Our teachers and mentors have provided us with models of patience, creativity, and inquisitiveness that we strive to bring into our own teaching and research. They encourage us to be life-long learners, teachers, and scholars.

We feel very lucky to be a partner with W. H. Freeman and Macmillan Learning. From the start, they have embraced our project, giving us the space and room to achieve something unique, while at the same time providing guidance, support, and input from the broader community of instructors and students.

Beth Cole, our acquisitions editor, deserves thanks for taking on the second edition and becoming our leader. She keeps a watchful eye on important trends in science, education, and technology, carefully listens to what we want to do, and helps us put our aspirations in a larger context.

Lead developmental editor Lisa Samols continues to have just the right touch — the ability to listen as well as offer intelligent suggestions, serious with a touch of humor, quiet but persistent. Senior developmental editor Susan Moran has an eye for detail and the uncanny ability to read the manuscript like a student. Developmental editor Erica Champion brings intelligence and thoughtfulness to her edits.

Karen Misler kept us all on schedule in a clear and firm but always understanding and compassionate way.

Lindsey Jaroszewicz, our market development manager, is remarkable for her energy and enthusiasm, her attention to detail, and her creativity in ways to reach out to instructors and students. Will Moore, our marketing manager, refined the story of *How Life Works* 2e and works tirelessly with our sales teams to bring the second edition to instructors and students everywhere.

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We are extremely grateful for all of the hard work and expertise of the sales representatives, regional managers, and regional sales specialists. We have enjoyed meeting and working with this dedicated sales staff, who are the ones that ultimately put the book in the hands of instructors.

Countless reviewers made invaluable contributions to this book and deserve special thanks. From catching mistakes to suggesting new and innovative ways to organize the content, they provided substantial input to the book. They brought their collective years of teaching to the project, and their suggestions are tangible in every chapter.

Finally, we would like to thank our families. None of this would have been possible without their support, inspiration, and encouragement.

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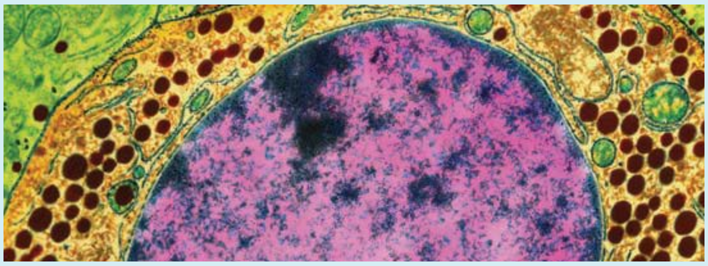

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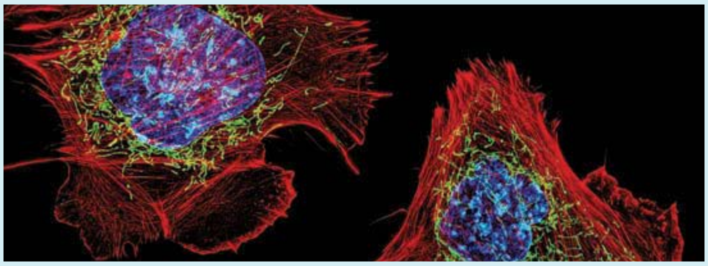

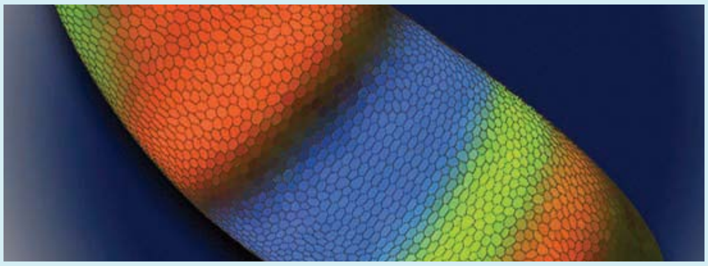

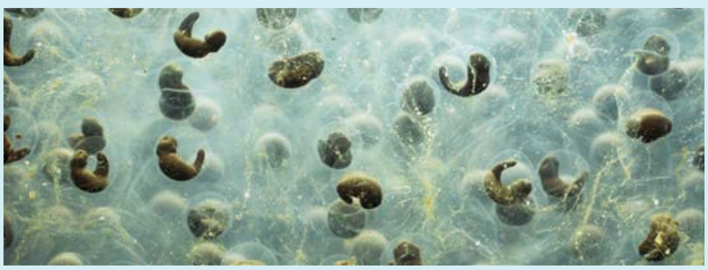

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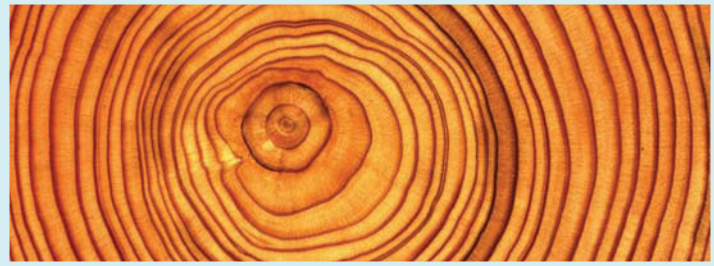

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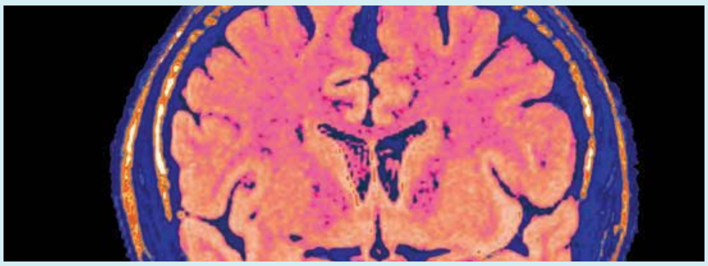

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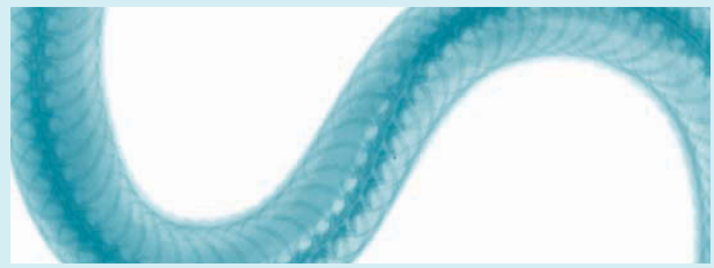

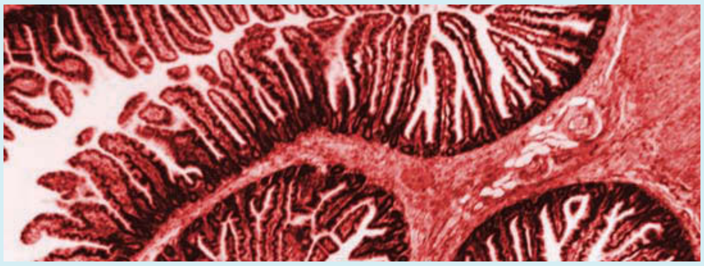

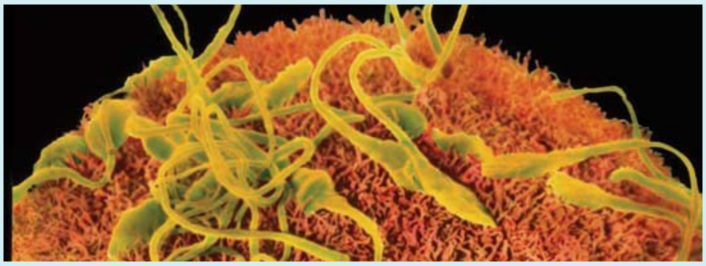

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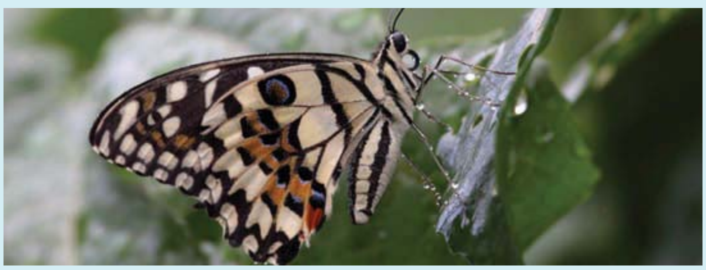

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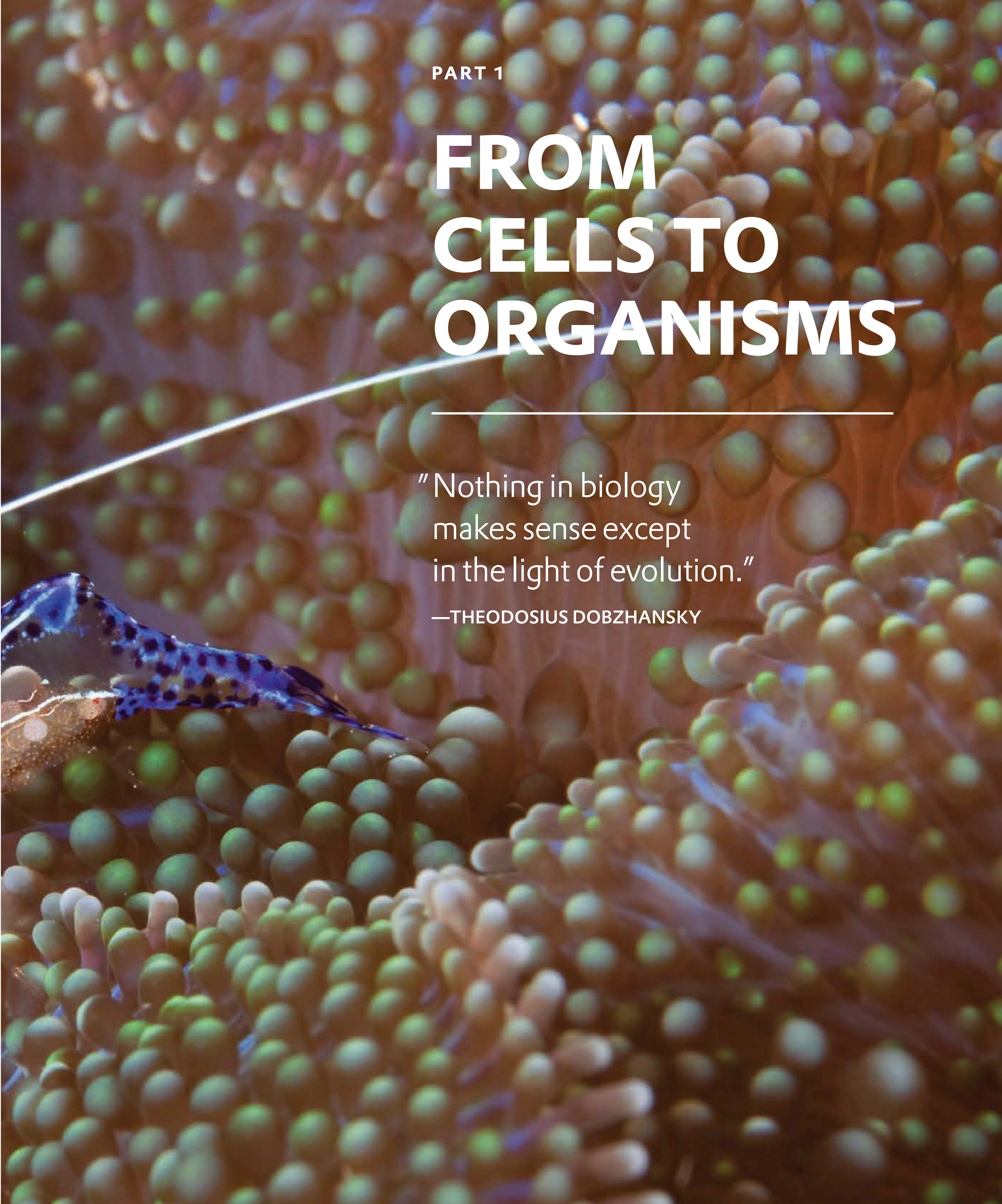
BIOLOGY

HOW LIFE WORKS



PART 1

FROM CELLS TO ORGANISMS

"Nothing in biology makes sense except in the light of evolution."

—THEODOSIUS DOBZHANSKY

Giovanna Griffo/Gallery Stock.

CHAPTER 1

Life

Chemical, Cellular, and Evolutionary Foundations

Core Concepts

1.1 The scientific method is a deliberate way of asking and answering questions about the natural world.

1.2 Life works according to fundamental principles of chemistry and physics.

1.3 The fundamental unit of life is the cell.

1.4 Evolution explains the features that organisms share and those that set them apart.

1.5 Organisms interact with one another and with their physical environment, shaping ecological systems that sustain life.

1.6 In the 21st century, humans have become major agents in ecology and evolution.

Every day, remarkable things happen within and around you. Strolling through a local market, you come across a bin full of crisp apples, pick one up, and take a bite. Underlying this unremarkable occurrence is an extraordinary series of events. Your eyes sense the apple from a distance, and nerves carry that information to your brain, permitting identification. Biologists call this cognition, an area of biological study. Stimulated by the apple and recognizing it as ripe and tasty, your brain transmits impulses through nerves to your muscles. How we respond to external cues motivates behavior, another biological discipline. Grabbing the apple requires the coordinated activities of dozens of muscles that move your arm and hand to a precise spot. These movements are described by biomechanics, yet another area of biological research. And, as you bite down on the apple, glands in your mouth secrete saliva, starting to convert energy stored in the apple as sugar into energy that you will use to fuel your own activities. Physiology, like biomechanics, lies at the heart of biological function.

The study of cognition, behavior, biomechanics, and physiology are all ways of approaching **biology,** the science of how life works. **Biologists,** scientists who study life, have come to understand a great deal about these and other processes at levels that run from molecular mechanisms within the cell, through the integrated actions of many cells within an organ or body, to the interactions among different organisms in nature. We don't know everything about how life works—in fact, it seems as if every discovery raises new questions. But biology provides us with an organized way of understanding ourselves and the world around us.

Why study biology? The example of eating an apple was deliberately chosen because it is an everyday occurrence that we ordinarily wouldn't think about twice. The scope of modern biology, however, is vast, raising questions that can fire our imaginations, affect our health, and influence our future. How, for example, will our understanding of the human genome change the way that we fight cancer? How do bacteria in our digestive system help determine health and well-being? Will expected increases in the temperature and acidity of seawater doom coral reefs? Is there, or has there ever been, life on Mars? And, to echo the great storyteller Rudyard Kipling, why do leopards have spots, and tigers stripes?

We can describe six grand themes that connect and unite the many dimensions of life science, from molecules to the biosphere. These six themes are stated as Core Concepts for this chapter and are introduced in the following sections. Throughout the book, these themes will be visited again and again. We view them as the keys to understanding the many details in subsequent chapters and relating them to one another. Our hope is that by the time you finish this book, you will have an understanding of how life works, from the molecular machines inside cells and the metabolic pathways that cycle carbon through the biosphere to the process of evolution, which has shaped the living world that surrounds (and includes) us. You will, we hope, see the connections among these different ways of understanding life, and come away with a greater understanding of how scientists think about and ask questions about the natural world. How, in fact, do we know what we think we know about life? And we hope you will develop a basis for making informed decisions about your life, career, and the actions you take as a citizen.

1.1 THE SCIENTIFIC METHOD

How do we go about trying to understand the vastness and complexity of nature? For most scientists, studies of the natural world involve the complementary processes of observation and experimentation. **Observation** is the act of viewing the world around us. **Experimentation** is a disciplined and controlled way of asking and answering questions about the world in an unbiased manner.

Observation allows us to draw tentative explanations called hypotheses.

Observations allow us to ask focused questions about nature. Let's say you observe a hummingbird like the one pictured in **Fig. 1.1** hovering near a red flower, occasionally dipping its long beak into the bloom. What motivates this behavior? Is the bird feeding on some substance within the flower? Is it drawn to the flower by its vivid color? What benefit, if any, does the flower derive from this busy bird?

Observations such as these, and the questions they raise, allow us to propose tentative explanations, or **hypotheses.** We might, for example, hypothesize that the hummingbird is carrying pollen from one flower to the next, facilitating reproduction in the plant. Or we might hypothesize that nectar produced deep within the flower provides nutrition for the hummingbird—that the hummingbird's actions reflect the need to take in food. Both hypotheses provide a reasonable explanation of the behavior we observed, but they may or may not be correct. To find out, we have to test them.

Charles Darwin's classic book, *On the Origin of Species,* published in 1859, beautifully illustrates how we can piece together individual observations to construct a working hypothesis. In this book, Darwin discussed a wide range of observations, from pigeon breeding to fossils and from embryology to the unusual animals and plants found on islands. Darwin noted the success of animal breeders in selecting specific individuals for reproduction and thereby generating new breeds for agriculture or show. He appreciated that selective breeding is successful only if specific features of the animals can be passed from one generation to the next by inheritance. Reading economic treatises by the English clergyman Thomas Malthus, he understood that limiting environmental resources could select among the variety of different individuals in populations in much the way that breeders select among cows or pigeons.

Gathering together all these seemingly disparate pieces of information, Darwin argued that life has evolved over time by means of natural selection. Since its formulation, Darwin's initial hypothesis has been tested by experiments, many thousands of

FIG. 1.1 **A hummingbird visiting a flower.** This simple observation leads to questions: Why do hummingbirds pay so much attention to flowers? Why do they hover near red flowers? *Source: Charles J. Smith.*

them. Our knowledge of many biological phenomena, ranging from biodiversity to the way the human brain is wired, depends on direct observation followed by careful inferences that lead to models of how things work.

A hypothesis makes predictions that can be tested by observation and experiments.

Not just any idea qualifies as a hypothesis. Two features set hypotheses apart from other ways of attacking problems. First, a good hypothesis makes predictions about observations not yet made or experiments not yet run. Second, because hypotheses make predictions, we can test them. That is, we can devise an experiment to see whether the predictions made by the hypothesis actually occur, or we can go into the field to try to make further observations predicted by the hypothesis. A hypothesis, then, is a statement about nature that can be tested by experiments or by new observations. Hypotheses are testable because, even as they suggest an explanation for observations made previously, they make predictions about observations yet to be made.

→ **Quick Check 1** Mice that live in sand dunes commonly have light tan fur. Develop a hypothesis to explain this coloration.

Once we have a hypothesis, we can test it to see if its predictions are accurate. Returning to the hummingbird and flower, we can test the hypothesis that the bird is transporting pollen from one flower to the next, enabling the plant to reproduce. Observation provides one type of test: If we catch and examine the bird just after it visits a flower, do we find pollen stuck to its beak or feathers? If so, our hypothesis survives the test.

Note, however, that we haven't proved the case. Pollen might be stuck on the bird for a different reason—perhaps it provides food for the hummingbird. However, if the birds *didn't* carry pollen from flower to flower, we would reject the hypothesis that they facilitate pollination. In other words, a single observation or experiment can lead us to reject a hypothesis, or it can support the hypothesis, but it cannot prove that a hypothesis is correct. To move forward, then, we might make a second set of observations. Does pollen that adheres to the hummingbird rub off when the bird visits a second flower of the same species? If so, we have stronger support for our hypothesis.

We might also use observations to test a more general hypothesis about birds and flowers. Does red color generally attract birds and so facilitate pollination in a wide range of flowers? To answer this question, we might catalog the pollination of many red flowers and ask whether they are pollinated mainly by birds. Or we might go the opposite direction and catalog the flowers visited by many different birds—are they more likely to be red than chance alone might predict?

Finally, we can test the hypothesis that the birds visit the flowers primarily to obtain food, spreading pollen as a side effect of their feeding behavior. We can measure the amount of nectar in the flower before and after the bird visits and calculate how much energy has been consumed by the bird during its visit. Continued observations over the course of the day will tell us whether the birds gain the nutrition they need by drinking nectar, and whether the birds have other sources of food.

In addition to observations, in many cases we can design experiments to test hypotheses. One of the most powerful types of experiment is called a controlled experiment. In a controlled experiment, the researcher sets up several groups to be tested, keeping the conditions and setup as similar as possible from one group to the next. Then, the researcher deliberately introduces something different, known as a **variable,** into one group that he or she hypothesizes might have some sort of an effect. This is called the **test group.** In another group, the researcher does not introduce this variable. This is a **control group,** and the expectation is that no effect will occur in this group.

Controlled experiments are extremely powerful. By changing just one variable at a time, the researcher is able to determine if that variable is important. If many variables were changed at once, it would be difficult, if not impossible, to draw conclusions from the experiment because the researcher would not be able to figure out which variable caused the outcome. The control group plays a key role as well. Having a group in which no change is expected ensures that the experiment works as it is supposed to and provides a baseline against which to compare the results of the test groups.

For example, we might test the hypothesis that hummingbirds facilitate pollination by doing a controlled experiment. In this case, we could set up groups of red flowers that are all similar to one another. For one group, we could surround the flowers with a fine mesh that allows small insects access to the plant but keeps hummingbirds away. For another group, we would not use a mesh. The variable, then, is the presence of a mesh; the test group is the flowers with the mesh; and the control group is the flowers without the mesh since the variable was not introduced in this group.

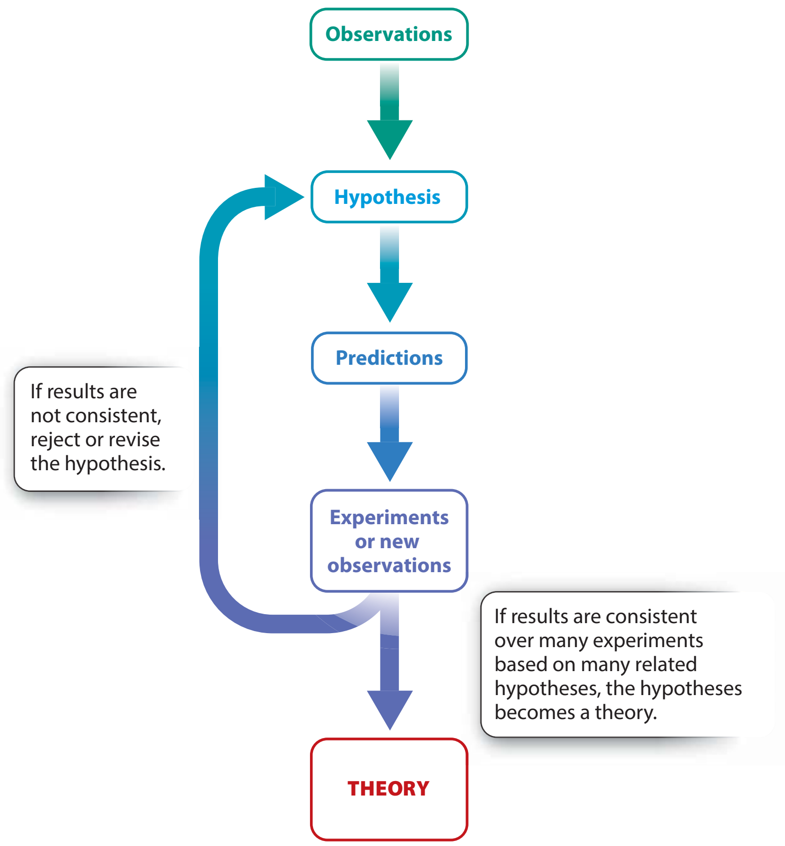
Will the flowers be pollinated? If only the group without the mesh is pollinated, this result lends support to our initial hypothesis. In this case, the hypothesis becomes less tentative and more certain. If both groups are pollinated, our hypothesis is not supported, in which case we may discard it for another explanation or change it to account for the new information.

→ **Quick Check 2** Design a controlled experiment that tests the hypothesis that cigarette smoke causes lung cancer.

Using observations to generate a hypothesis and then making predictions based on that hypothesis that can be tested experimentally are the first two steps in the **scientific method,** outlined in **Fig. 1.2.** The scientific method is a deliberate and careful way of asking questions about the unknown. We make observations, collect field or laboratory samples, and design and carry out experiments or analyses to make sense of things we initially do not understand. The scientific method has proved to be spectacularly successful in helping us to understand the world around us. We explore several aspects of the scientific method, including experimental design, data and data presentation, probability and statistics, and scale and approximation on LaunchPad.

To emphasize the power of the scientific method, we turn to a famous riddle drawn from the fossil record (**Fig. 1.3**). Since the nineteenth century, paleontologists have known that before mammals expanded to their current ecological importance, other large animals dominated Earth. Dinosaurs evolved about 210 million years ago and disappeared abruptly 66 million years ago, along with many other species of plants, animals, and microscopic organisms. In many cases, the skeletons and shells of these creatures were buried in sediment and became fossilized. Layers of sedimentary rock therefore record the history of Earth.

FIG. 1.2 The scientific method.



Working in Italy, the American geologist Walter Alvarez collected samples from the precise point in the rock layers that corresponds to the time of the extinction. Careful chemical analysis showed that rocks at this level are unusually enriched in the element iridium. Iridium is rare in most rocks on continents and the seafloor, but is relatively common in rocks that fall from space—that is, in meteorites. From these observations, Alvarez and his colleagues developed a remarkable hypothesis: 66 million years ago, a large (11-km diameter) meteor slammed into Earth, and in the resulting environmental havoc, dinosaurs and many other species became extinct. This hypothesis makes specific predictions, described in Fig. 1.3, which turned out to be supported by further observations. Thus, observational tests support the hypothesis that nearly 150 million years of dinosaur evolution were undone in a moment.

General explanations of natural phenomena supported by many experiments and observations are called theories.

As already noted, a hypothesis may initially be tentative. Commonly, in fact, it will provide only one of several possible ways of explaining existing data. With repeated observation and experimentation, however, a good hypothesis gathers strength,

FIG. 1.3

HOW DO WE KNOW?

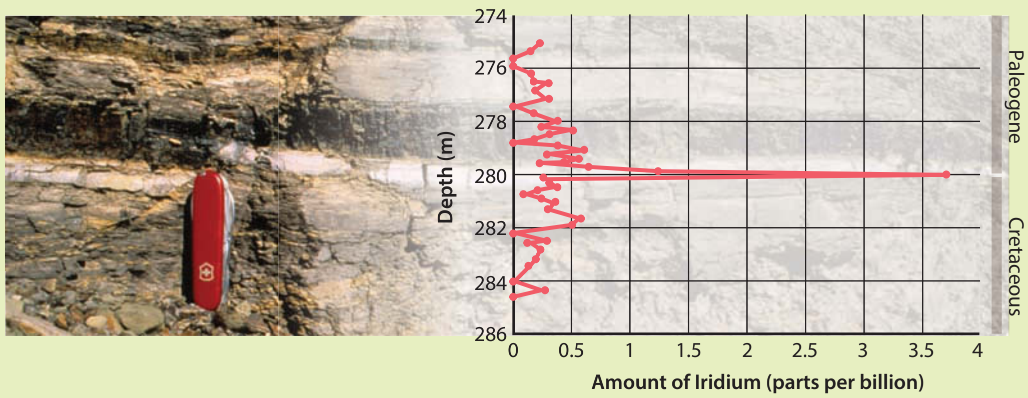
What caused the extinction of the dinosaurs?

BACKGROUND Dinosaurs were diverse and ecologically important for nearly 150 million years but became extinct about 66 million years ago.

OBSERVATION

Iridium, common in meteorites, was discovered in rock layers corresponding to the time of extinction.

Photo Source: Kirk Johnson, Denver Museum of Nature & Science.

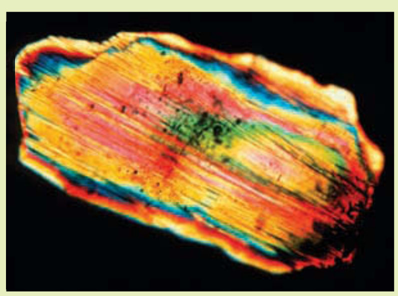


HYPOTHESIS The impact of a large meteorite disrupted communities on land and in the sea, causing the extinction of the dinosaurs and many other species.

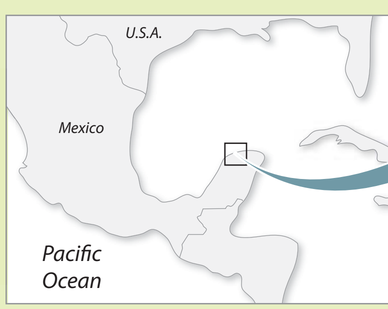
PREDICTIONS Independent evidence of a meteor impact should be found in rock layers corresponding to the time of the extinction and be rare or absent in older and younger beds.

FURTHER OBSERVATIONS

Quartz crystals that form only at high temperature and pressure—conditions met by giant meteors as they crash into Earth—occur abundantly in rock layers dated to the time of the extinction.



By 1990, geologists had located the "smoking gun"—a crater of just the right age and size in the Yucatán Peninsula of Mexico.



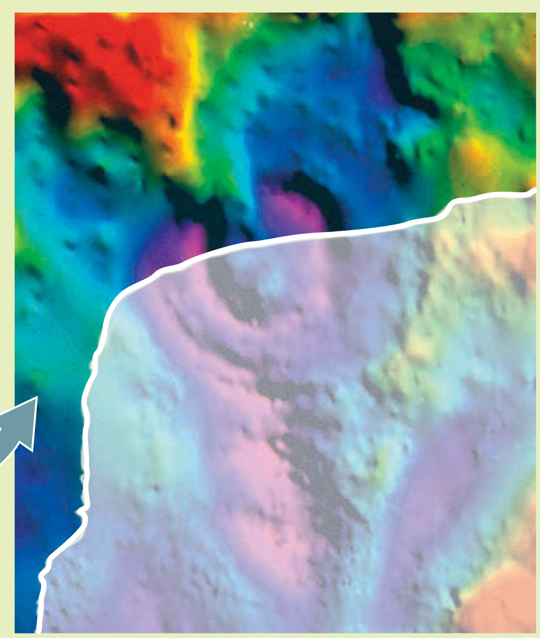


Photo Sources: (top left) Dr. David Kring/Science Source; (right) Image courtesy of V. L. Sharpton/Lunar and Planetary Institute.

CONCLUSION A giant meteor struck Earth 66 million years ago, causing the extinction of the dinosaurs and many other species.

FOLLOW-UP WORK Researchers have documented other mass extinctions, but the event that eliminated the dinosaurs appears to be the only one associated with a meteorite impact.

SOURCE Alvarez, W. 1998. *T. rex and the Crater of Doom.* New York: Vintage Press.

and we have more and more confidence in it. When a number of related hypotheses survive repeated testing and come to be accepted as good bases for explaining what we see in nature, scientists articulate a broader explanation that accounts for all the hypotheses and the results of their tests. We call this statement a **theory**, a general explanation of the world supported by a large body of experiments and observations (see Fig. 1.2).

Note that scientists use the word "theory" in a very particular way. In general conversation, "theory" is often synonymous with "hypothesis," "idea," or "hunch"—"I've got a theory about that." But in a scientific context, the word "theory" has a specific meaning. Scientists speak in terms of theories only if hypotheses have withstood testing to the point where they provide a general explanation for many observations and experimental results. Just as a good hypothesis makes testable predictions, a good theory both generates good hypotheses and predicts their outcomes. Thus, scientists talk about the theory of gravity—a set of hypotheses you test every day by walking down the street or dropping a fork. Similarly, the theory of evolution is not one explanation among many for the unity and diversity of life. It is a set of hypotheses that has been tested for more than a century and shown to provide an extraordinarily powerful explanation of biological observations that range from the amino acid sequences of proteins to the diversity of ants in a rain forest. In fact, as we discuss throughout this book, evolution is the single most important theory in all of biology. It provides the most general and powerful explanation of how life works.

1.2 CHEMICAL AND PHYSICAL PRINCIPLES

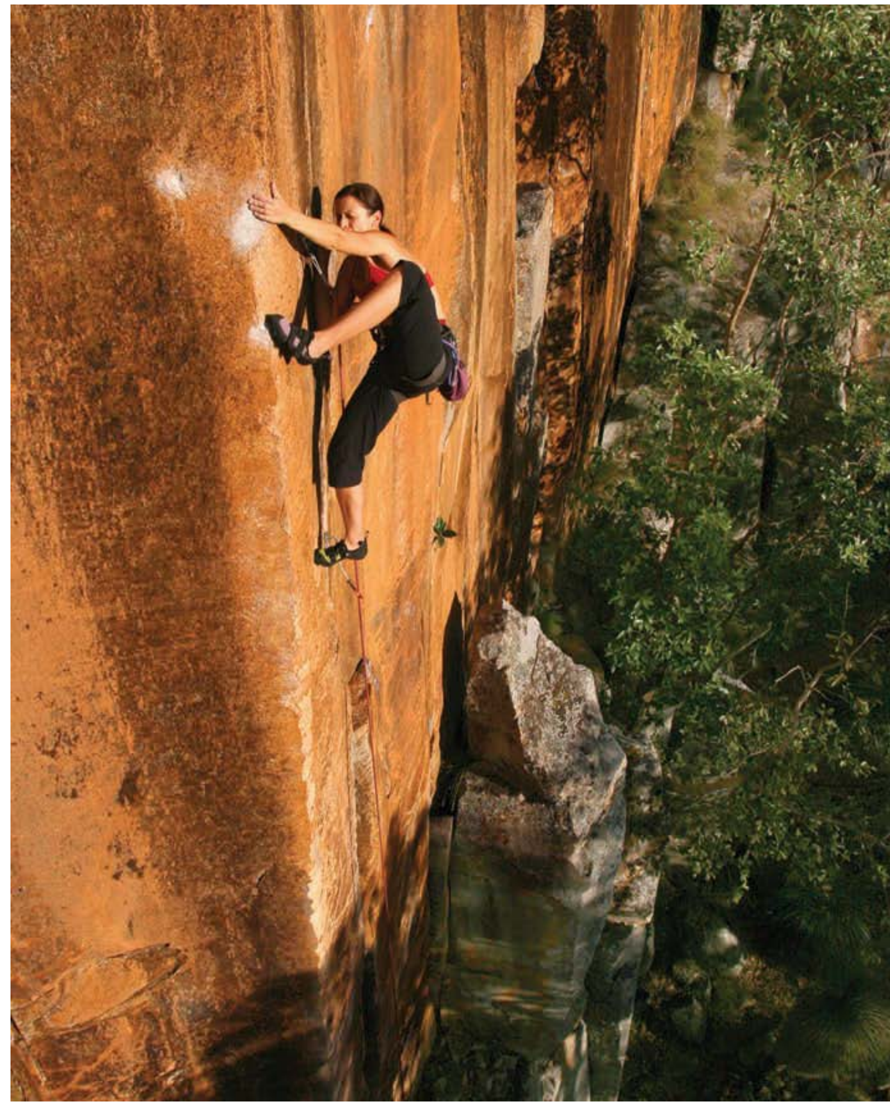
We stated earlier that biology is the study of life. But what exactly *is* life? As simple as this question seems, it is frustratingly difficult to answer. We all recognize life when we see it, but coming up with a definition is harder than it first appears.

Living organisms are clearly different from nonliving things. But just how different is an organism from the rock shown in **Fig. 1.4?** On one level, the comparison is easy: The rock is much simpler than any living organism we can think of. It has far fewer components, and it is largely static, with no apparent response to environmental change on timescales that are readily tracked.

In contrast, even an organism as relatively simple as a bacterium contains many hundreds of different chemical compounds organized in a complex manner. The bacterium is also dynamic in that it changes continuously, especially in response to the environment. Organisms reproduce, which minerals do not. And organisms do something else that rocks and minerals don't: They evolve. Indeed, the molecular biologist Gerald Joyce has defined life as a chemical system capable of undergoing Darwinian evolution.

From these simple comparisons, we can highlight four key characteristics of living organisms: (1) complexity, with precise spatial organization on several scales; (2) the ability to change in response to the environment; (3) the ability to reproduce; and (4) the capacity to evolve. Nevertheless, the living and nonliving worlds share an important attribute: Both are subject to the basic laws of chemistry and physics.

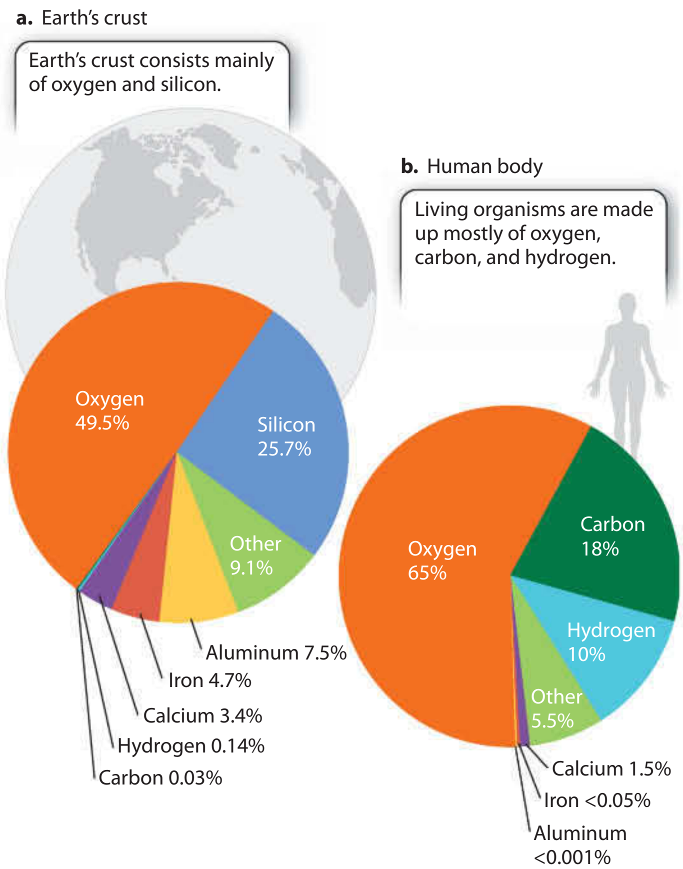
FIG. 1.4 A climber scaling a rock. Living organisms like this climber contain chemicals that are found in rocks, but only living organisms reproduce in a manner that allows for evolution over time. *Source: Scott Hailstone/Getty Images.*



The living and nonliving worlds follow the same chemical rules and obey the same physical laws.

The chemical elements found in rocks and other nonliving things are no different from those found in living organisms. In other words, all the elements that make up living things can be found

FIG. 1.5 Composition of (a) Earth's crust and (b) cells in the human body. The Earth beneath our feet is made up of the same elements found in our feet, but in strikingly different proportions.



in the nonliving environment—there is nothing special about our chemical components when taken individually. That said, the *relative* abundances of elements in organisms differ greatly from those in the nonliving world. In the universe as a whole, hydrogen and helium make up more than 99% of known matter, while Earth's crust contains mostly oxygen and silicon, with significant amounts of aluminum, iron, and calcium (**Fig. 1.5a**). In organisms, by contrast, oxygen, carbon, and hydrogen are by far the most abundant elements (**Fig. 1.5b**). As discussed more fully in Chapter 2, carbon provides the chemical backbone of life. The particular properties of carbon make possible a wide diversity of molecules that, in turn, support a wide range of functions within cells.

All living organisms are subject to the physical laws of the universe. Physics helps us to understand how animals move and why trees don't fall over; it explains how redwoods conduct water upward through their trunks and how oxygen gets into the cells that line your lungs. Indeed, two laws of thermodynamics, both of which describe how energy is transformed in any system, determine how living organisms are able to do work and maintain their spatial organization.

The **first law of thermodynamics** states that energy can neither be created nor destroyed; it can only be transformed from one form into another. In other words, the total energy in the universe is constant, but the form that energy takes can change. Living organisms are energy transformers. They acquire energy from the environment and transform it into a chemical form that cells can use. All organisms obtain energy from the sun or from chemical compounds. Some of this energy is used to do work—such as moving, reproducing, and building cellular components—and the rest is dissipated as heat. The energy that is used to do work plus the heat that is generated is the total amount of energy, which is the same as the input energy (**Fig. 1.6**). In other words, the total amount of energy remains constant before and after energy transformation.

The **second law of thermodynamics** states that the degree of disorder (or the number of possible positions and motions of molecules) in the universe tends to increase. Think about a box full of marbles distributed more or less randomly; if you want to line up all the red ones or blue ones in a row, you have to do work—that is, you have to add energy. In this case, the addition of energy increases the order of the system, or, put another way, decreases its disorder. Physicists quantify the amount of disorder (or the number of possible positions and motions of molecules) in a system as the **entropy** of the system.

Living organisms are highly organized. As with lining up marbles in a row, energy is needed to maintain this organization. Given the tendency toward greater disorder, the high level of organization of even a single cell would appear to violate the second law. But it does not. The key is that a cell is not an isolated system and therefore cannot be considered on its own; it exists in an environment. So we need to take into account the whole system, the cell plus the environment that surrounds it. As energy

FIG. 1.6 Energy transformation and the first law of thermodynamics. The first law states that the total amount of energy in any system remains the same. Organisms transform energy from one form to another, but the total energy in any system is constant.