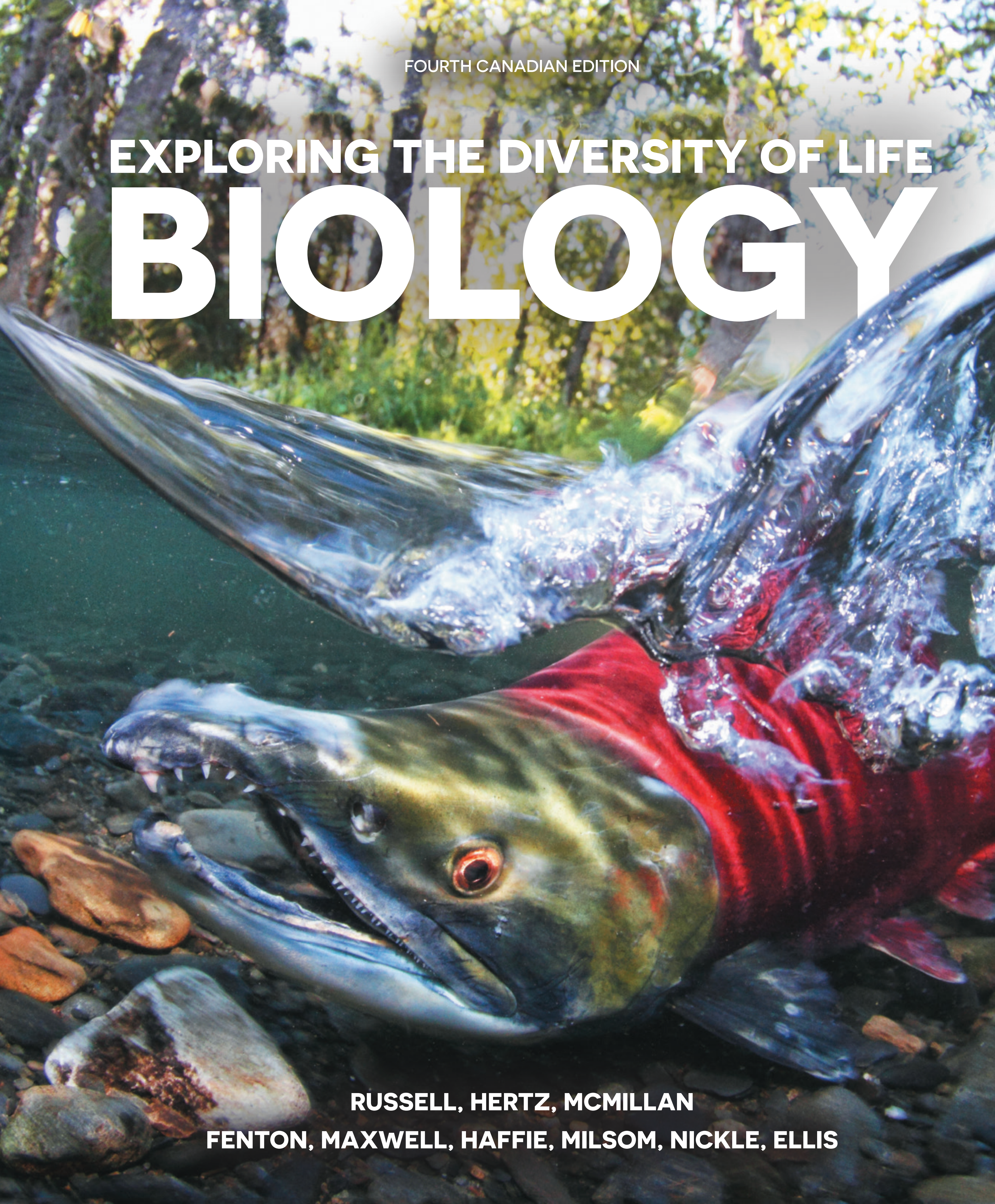
FOURTH CANADIAN EDITION

EXPLORING THE DIVERSITY OF LIFE
BIOLOGY



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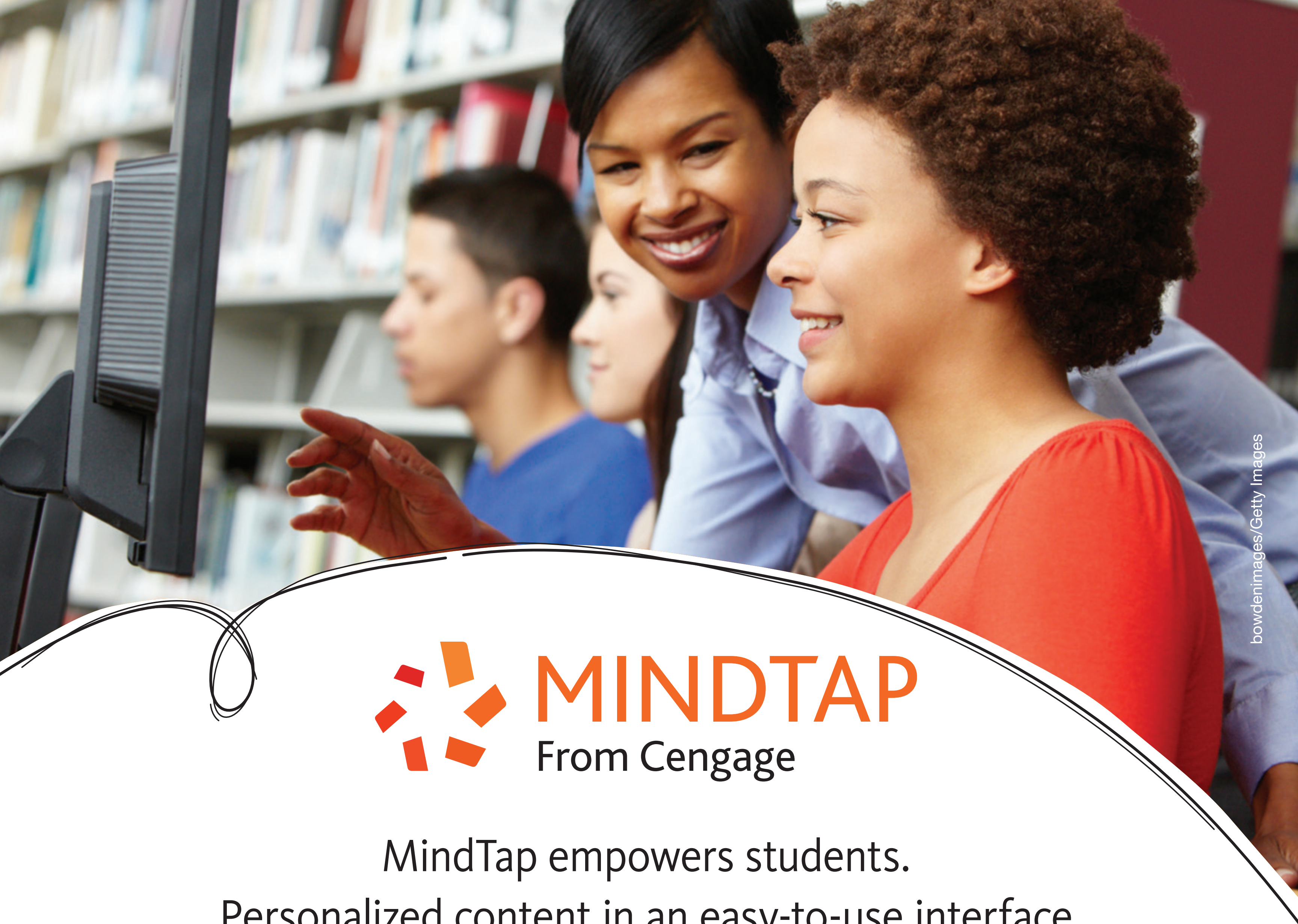

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FOURTH CANADIAN EDITION

EXPLORING THE DIVERSITY OF LIFE BIOLOGY

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Biology, Fourth Canadian Edition

by Peter J. Russell, Paul E. Hertz, Beverly McMillan, M. Brock Fenton, Denis Maxwell, Tom Haffie, Bill Milsom, Todd Nickle, Shona Ellis

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For, and because of,
our generations of students.

M.B. Fenton

About the Canadian Authors

M. B. Fenton

M. B. (Brock) Fenton received his Ph.D. from the University of Toronto in 1969. Since then, he has been a faculty member in biology at Carleton University, then at York University, and then at Western University. In addition to teaching parts of first-year biology, he has also taught vertebrate biology, animal biology, and conservation biology, as well as field courses in the biology and behaviour of bats. He has received awards for his teaching (Carleton University Faculty of Science Teaching Award; Ontario Confederation of University Faculty Associations Teaching Award; and a 3M Teaching Fellowship, Society for Teaching and Learning in Higher Education) in addition to recognition of his work on public awareness of science (Gordin Kaplan Award from the Canadian Federation of Biological Societies; Honorary Life Membership, Science North, Sudbury, Ontario; Canadian Council of University Biology Chairs Distinguished Canadian Biologist Award; The McNeil Medal for the Public Awareness of Science of the Royal Society of Canada; and the Sir Sandford Fleming Medal for public awareness of Science, the Royal Canadian Institute). He also received the C. Hart Merriam Award from the American Society of Mammalogists for excellence in scientific research. Bats and their biology, behaviour, evolution, and echolocation are the topics of his research, which has been funded by the Natural Sciences and Engineering Research Council of Canada (NSERC). In November 2014, Brock was inducted as a Fellow of the Royal Society of Canada.

Alan Noon

Denis Maxwell received his Ph.D. from the University of Western Ontario in 1995. His thesis, under the supervision of Norm Hüner, focused on photosynthetic acclimation in green algae. Following his doctorate, he undertook postdoctoral training at the Department of Energy Plant Research Laboratory at Michigan State University, where he studied the function of the mitochondrial alternative oxidase. After taking up a faculty position at the University of New Brunswick in 2000, he moved in 2003 to the Department of Biology at Western University. Denis served as Associate Chair for Undergraduate Education for the Department of Biology from 2009 to 2016. Currently, he is Assistant Dean for the Faculty of Science, with a portfolio that includes Recruitment and First-Year Studies and outreach. He has taught first-year Biology to over 15 000 students, most of the time with Tom Haffie.

Tom Haffie

Tom Haffie is a graduate of the University of Guelph and the University of Saskatchewan in the area of microbial genetics. Tom has devoted his 33-year career at Western University to teaching large biology classes in lecture, laboratory, and tutorial settings. He led the development of the innovative core laboratory course in the Biology program; he was an early adopter of computer animation in lectures; and, most recently, has overseen a deep blended redesign of introductory biology informed by a students-as-partners approach to development. He is the founding coordinator of the biennial Western Conference on Science Education. He holds a University Students' Council Award for Excellence in Teaching, a UWO Edward G. Pleva Award for Excellence in Teaching, a UWO Fellowship in Teaching Innovation, a Province of Ontario Award for Leadership in Faculty Teaching (LIFT), and a Canadian 3M National Teaching Fellowship for excellence in teaching. Tom is currently a Teaching Fellow for Science at Western University.


Bruce Moffat

Bill Milsom (Ph.D., University of British Columbia) is a professor in the Department of Zoology at the University of British Columbia, where he has taught a variety of courses, including first-year biology, for almost 40 years. His research interests include the evolutionary origins of respiratory processes and the adaptive changes in these processes that allow animals to exploit diverse environments. He examines respiratory and cardiovascular adaptations in vertebrate animals in rest, sleep, exercise, altitude, dormancy, hibernation, diving, and so on. This research contributes to our understanding of the mechanistic basis of biodiversity and the physiological costs of habitat selection. His research has been funded by NSERC, and he has received several academic awards and distinctions, including the Fry Medal of the Canadian Society of Zoologists, the August Krogh Distinguished Lectorship Award of the American Physiological Society, the Bidder Lecture of the Society for Experimental Biology, and the Izaak Walton Killam Award for Excellence in Mentoring. He has served as the President of the Canadian Society of Zoologists and as President of the International Congress of Comparative Physiology and Biochemistry.


Penny Nickle

Todd Nickle received his Ph.D. from Oklahoma State University in 1998, and has been teaching biology at Mount Royal University ever since. He advocates Active Learning: students come to class prepared to *work* with material rather than just hear about it. Student preparation involves reading the text and applying the concepts to online exercises, the results of which inform what the next lecture will be about. Class time focusses on exploring connections between concepts and ideas in biology and how they relate to other disciplines, which inspired him to coauthor a handbook for first-year science students (*Science*^{3}). His interest in promoting best teaching practices among educators had him confirm the Alberta Introductory Biology Association as an official Society of Alberta; Todd is currently President. His work put him in the first cohort of Full Professors at Mount Royal University in 2012, garnered the 2015 ACIFA Innovation in Teaching Award, and the Distinguished Faculty Award from MRU in 2016.


Andy Cotton

Shona Ellis (M.Sc., University of British Columbia) is a professor of teaching in the Botany Department and Associate Head of Biology at the University of British Columbia. She developed a keen interest in forests and the ocean growing up on the central coast of British Columbia. As an undergraduate, Professor Ellis pursued her interests in botany and entomology. Her M.Sc. research incorporated tissue culture, phytochemistry, and plant anatomy. As a teaching assistant, she realized a passion for teaching and joined the teaching faculty at the University of British Columbia in 1998. She teaches botany courses that have included nonvascular and vascular plants, economic botany, bryology, and plant systematics, as well as introductory biology. Professor Ellis has taught in a number of settings: large and small lectures, laboratories, and fieldtrips. While she feels the best classroom is outdoors, she integrates online technologies into all her courses; she is an early adopter of online teaching and learning resources. Professor Ellis has received two Killam Teaching Awards and the Charles Edwin Bessey Teaching Award from the Botanical Society of America.

About the U.S. Authors

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

Aaron Kinard

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

Courtesy of Beverly McMillan

Beverly McMillan has been a science writer for more than 25 years. She holds undergraduate and graduate degrees from the University of California, Berkeley, and is coauthor of a college text in human biology, now in its 11th edition. She has also written or coauthored numerous trade books on scientific subjects and has worked extensively in educational and commercial publishing, including eight years in editorial management positions in the college divisions of Random House and McGraw-Hill.

Brief Contents

Contents

Preface

Welcome to an exploration of the diversity of life. The main goal of this textbook is to guide you on a journey of discovery about life's diversity across levels ranging from molecules to genes, cells to organs, and species to ecosystems. Along the way, we will explore many questions about the mechanisms underlying diversity as well as the consequences of diversity, for our own species and for others.

An emphasis on the diversity of life …

At first glance, the riot of life that animates the biosphere overwhelms our minds. One way to begin to make sense of this diversity is to divide it into manageable sections on the basis of differences. We also consider features found in all life forms to stress similarities as well as differences. We examine how different organisms solve the common problems of finding nutrients, energy, and mates on the third rock from our Sun. What basic evolutionary principles inform the relationships among life forms regardless of their different body plans, habitats, or life histories? Unlike many other first-year biology texts, this book has chapters integrating basic concepts such as the effects of genetic recombination, light, and domestication across the breadth of life from microbes to mistletoe to moose. As you read this book, you will be referred frequently to other chapters for linked information that expands the ideas further.

Evolution provides a powerful conceptual lens for viewing and understanding the roots and history of the diversity of living things. We will demonstrate how knowledge of evolution helps us appreciate the changes we observe in organisms. Whether the focus is the conversion of free-living prokaryotic organisms into mitochondria and chloroplasts or the steps involved in the domestication of rice, selection for particular traits over time can explain the current condition.

Examining how biological systems work is another theme pervading this text and underlying the idea of diversity. We have intentionally tried to include examples that will tax your imagination, from sea slugs that steal chloroplasts for use as solar panels, to the molecular basis of high altitude adaptations in deer mice, to adaptive radiation of viruses. In each situation, we examine how biologists have explored and assessed the inner workings of organisms, from gene regulation to the challenges of digesting cellulose.

Solving problems is another theme that runs throughout the book. Whether the topic is gene therapy to treat a disease in people, increasing crop production, or reducing the incidence of human obesity, both the problem and the solution lie in biology. We will explore large problems facing planet Earth and the social implications that arise from them.

Emphasizing the big picture …

Many biology textbooks use the first few chapters to review fundamentals of chemistry and biochemistry as well as information on the scientific method. Instead of focusing on this background information, we have used the first chapter, in particular, to immediately engage students by conveying the excitement that is modern biology. We have put important background information in the centre of the book as a distinct reference section entitled *The Chemical and Physical Foundations of Biology.* With their purple borders, these pages are distinct and easy to find, and have become affectionately known as *The Purple Pages.* These pages enable information to be readily identifiable and accessible to students as they move through the textbook rather than being tied to a particular chapter. In this edition, the concepts of atoms, molecules, and macromolecules are connected through the theme of "emergent properties." By considering how the "stuff of life" interrelates as a function of increasing complexity rather than just memorizing the attributes of individual items, students can better grasp *why* biology works the way it does, rather than be awed by how much information we know about it.

We hope that Canadian students will find the subject of biology as it is presented here accessible and engaging because it is presented in familiar contexts. We have highlighted the work of Canadian scientists, used examples of Canadian species, and referred to Canadian regulations and institutions.

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

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

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

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

We have endeavoured to make the science of biology come alive by describing how biologists formulate hypotheses and evaluate them using hard-won data; how data sometimes tell only part of a story; and how the results of studies often end up posing more questions than they answer. Our exploration of the Tully Monster in Chapter 27 is a case in point. Since its fossil discovery and description, this mainly soft-bodied animal has been tentatively classified with species in five different groups of animals. Through this example, and throughout Chapter 27, we explore the current recognition that the historical and traditional grouping of animals into protostomes and deuterostomes is more artificial than real.

Although students might prefer simply to learn the "right" answer to a question, they must be encouraged to embrace "the unknown," those gaps in knowledge that create opportunities for further research. An appreciation of what biologists do *not* yet know will draw more students into the field. And by defining *why* scientists do not understand interesting phenomena, we encourage students to think critically about possible solutions and to follow paths dictated by their own curiosity. We hope that this approach will encourage students to make biology a part of their daily lives by having informal discussions and debates about new scientific discoveries.

Presenting the story line of the research process …

Science is by its nature a progressive enterprise in which answers to questions open new questions for consideration. In preparing this book, we developed several special features to help students broaden their understanding of the material presented and of the research process itself:

- The chapter openers, titled ***Why It Matters,*** are engaging, short vignettes designed to capture students' imaginations and whet their appetites for the topic that the chapter addresses. In many cases, this feature uses current Canadian examples and tells the story of how a researcher or researchers arrived at a key insight, or how biological research solved a major societal problem, explained a fundamental process, or elucidated a phenomenon. The Why It Matters feature links the insight from the vignette to the contents of the chapter to spark student interest in the topic at hand.
- Three types of specially designed *research figures* provide more detailed information about how biologists formulate specific hypotheses and test them by gathering and interpreting data. ***Experimental Research*** figures describe specific studies in which researchers used both experimental and control treatments, either in the laboratory or in the field, to test hypotheses or answer research questions by manipulating the system they studied. ***Observational Research*** figures describe specific studies in which biologists have tested hypotheses by comparing systems under varying natural circumstances. ***Research Method*** figures provide examples of important techniques, such as light and electron microscopy, the polymerase chain reaction, making a knockout mouse, DNA microarray analysis, plant cell culture, producing monoclonal antibodies, radiometric dating, and cladistic analysis. Each *Research Method* figure leads a student through the purpose of the technique and protocol, and describes how scientists interpret the data it generates.

Integrating effective, high-quality visuals into the narrative …

Today's students are accustomed to receiving ideas and information visually, making the illustrations and photographs in a textbook and the fully integrated online resources critically important. From the first Canadian edition, our illustration program has provided an exceptionally clear supplement to the narrative in a style that is consistent throughout the book. Graphs and anatomical drawings are annotated with interpretive explanations that lead students, step by step, through the major points they convey.

Over subsequent editions, we have continued to enhance the illustration program, focusing on features that reviewers and users of the book identified as the most useful pedagogical tools. In revising the text, we reevaluated each illustration and photograph, and made appropriate changes to improve their utility as teaching tools.

For this most recent edition, we have made some exciting new additions to our illustration program through the creation of ***Chapter Roadmaps*** and ***Summary Illustrations*** for every chapter the book. Chapter Roadmaps appear at the beginning of each chapter and provide a visual overview of the chapter contents. Connections between topics across chapters are emphasized to give students a sense of how the content of each chapter fits within the larger context of the book, and biology as a whole. At the end of each chapter, we have created vivid and engaging

Summary Illustrations that depict the core concepts—and teaching heart—of the chapter. These illustrations provide students with a visual overview of the connections between key concepts, and provide a unique touchstone to review and gauge understanding of the chapter contents.

Organizing chapters around important concepts …

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

- The organization within chapters presents material in digestible sections, building on students' knowledge and understanding as they acquire it. Each major section covers one broad topic.
- ***Study Break*** questions follow every major section. These reading comprehension questions encourage students to pause at the end of a section and review what they have learned before going on to the next topic within the chapter. If a student isn't able to answer a study break question, they can immediately revisit the previous section to solidify their understanding. We feel that this is a better learning tool than directly providing the answers to these questions. If the answer does not come easily, then rereading the material associated with the answer is as important as seeing the answer itself.
- ***Self-Test Questions*** are found at the end of each chapter. These chapter review questions are organized according to Bloom's taxonomy into three sections: Recall/Understand, Apply/Analyze, and Create/Evaluate. This structure allows students to review the material in a sequence that moves from the basic knowledge of factual material, to more challenging and sophisticated applications of that knowledge, to novel situations. Answers to the Self-Test Questions are found in an appendix at the back of the book.
- *The Chemical and Physical Foundations of Biology,* also known as ***The Purple Pages,*** keep background information out of the main text, allowing students to focus on the bigger picture.
- *Unit 5: The Diversity of Life,* also known as ***The Green Pages,*** contains readily identifiable chapters that introduce the tremendous variability among living organisms.

Effectively introducing digital solutions into your classroom—online or in class—is now easier than ever …

The fourth Canadian edition of *Biology: Exploring the Diversity of Life* represents a fully integrated package of print and media, providing comprehensive learning tools and flexible delivery options. In preparing this edition, we conducted extensive research to determine how instructors prefer to present online learning opportunities. The result of this research is a new MindTap course organized around the instructors' preferred workflow. Instructors can now select just the content they want to assign, chosen from a comprehensive set of learning materials provided with the course for each chapter. Many types of learning activities are assignable and offer students immediate feedback and automated instructor assessment.

Research also indicates that online content is most effective when it enhances conceptual understanding through the use of relevant applications. In this edition, we have developed new assessable online learning activities that provide students the opportunity to explore and practice biology the way scientists practice biology:

- ***Interpret the Data*** exercises have been enhanced by an additional online exercise to further develop student quantitative analysis and mathematical reasoning skills.
- The ***Design an Experiment*** feature is delivered online as a guided learning activity that takes the student through the process of designing an experiment.
- ***Conceptual Learning Activities*** are repeatable in alternate versions to help students learn the material.

The ***Instructor Resource Center*** provides everything you need for your course in one place. This collection of lecture and class tools is available online for instructors only via **www.nelson.com/instructor.** There you can access and download PowerPoint presentations, images, the Instructor's Manual, the Test Bank, videos, animations, and more.

To maximize the chances of producing a useful text that draws in students (and instructors), we sought the advice of colleagues who teach biology (members of the MindTap Advisory Board). We also asked students (members of the Student Advisory Boards) for their advice and comments. These groups evaluated the effectiveness of important visuals in the textbook, evaluated draft chapters, and provided valuable feedback on the MindTap, but any mistakes are ours.

In summary, we have applied our collective experience as teachers, researchers, and writers to create a readable and understandable foundation for students who may choose to enrol in more advanced biology courses in the future. Where appropriate, we provide straightforward explanations of fundamental concepts from the evolutionary perspective that binds together all the biological sciences. Recognizing that students in an introductory biology course face a potentially daunting quantity of ideas and information, we strive to provide an appropriate balance between factual and conceptual material, taking great care to provide clear explanations of how scientists draw conclusions from empirical data. Our approach helps students understand how we achieved our present knowledge. Clarity of presentation, thoughtful organization, a logical and seamless flow of topics within chapters, and carefully designed illustrations are key to our approach.

We hope that you are as captivated by the biological world as we are, and are drawn from one chapter to another. But don't stop there; use the digital and other resources to broaden your search for understanding, and, most important, observe and enjoy the diversity of life around you.

M. Brock Fenton
Denis Maxwell
Tom Haffie
Bill Milsom
Todd Nickle
Shona Ellis
London, Calgary, and Vancouver
January 2018

New to This Edition

The enhancements we have made in the fourth Canadian edition of *Biology: Exploring the Diversity of Life* reflect our commitment to providing a textbook that introduces students to new developments in biology while fostering active learning and critical thinking.

Our revisions to the new edition were guided by five important principles:

- Reduce the size of the book
- Ensure content is relevant and engaging for students and instructors
- Emphasize connections
- Support concepts with visuals wherever possible
- Extensively revise and rewrite Unit Four: Evolution and Classification

A streamlined textbook …

In response to feedback from students and instructors across the country, we have made some important changes that have resulted in a briefer edition.

Organizational Changes

By combining and reorganizing information, we have reduced the number of chapters in the book from 52 to 46. The material on protostomes and deuterostomes has been combined into a single super chapter on animals. Using the latest research as our guide, Chapter 27: Animals captures the excitement of how new developments in molecular phylogenetic techniques have resulted in many taxonomic reclassifications as well as changes to phylogenies. This chapter features a unique research box on the Tully Monster as a case in point.

We have also streamlined our coverage of systems and processes in animals by combining reproduction and development to create Chapter 44: Animal Reproduction. The chapters on neural control and neural integration have been combined to create Chapter 45: Control of Animal Processes: Neural Control.

We have also rewritten former Chapter 33: Putting Selection to Work and Chapter 52: Conservation and Evolutionary Physiology into a collection of case studies and placed them on the MindTap for the book.

Streamlined Pedagogy and Prose

Our revisions to the fourth Canadian edition were also informed by a desire to reduce redundancy across the book, including only essential, testable information. As a result, students and instructors will find an efficient use of prose across the new edition, as well as extensive use of cross-references to other chapters, where necessary. The feature boxes "Molecule behind Biology," "People behind Biology," and "Life on the Edge" have also been moved from the book to the Instructor's Manual, allowing instructors to continue to draw upon these engaging stories and vignettes, without increasing the length of the textbook.

Engaging and relevant content …

From personal genome reports to cues to recognizing human female ovulation, the new edition is full of engaging examples that reflect everyday biology and its impact on society. In addition to references to Canadian research and researchers throughout the book, our MindTap features profiles of 13 former biology students, and what they have done with their biology degrees in "Where Are They Now?"

Emphasizing connections …

We recognize that part of the challenge of an introduction to biology course lays in covering a large breadth of knowledge while making meaningful connections across topics, concepts, and the discipline as a whole. In *Biology: Exploring the Diversity of Life*, every chapter begins with a ***Chapter Roadmap*** that provides students with a visual overview of the chapter contents, while making connections between parts of the chapter and other chapters in the book. Within chapters, students will find cross-references and connections to other chapters where a concept is explored further or from a different perspective. Furthermore, every chapter concludes with a ***Summary Illustration,*** a two-page spread that synthesizes, integrates, and illustrates connections between important concepts covered in the chapter.

Clear and thoughtful visuals …

Each of the figures in the new edition delivers a clear and thoughtful message that is tied directly to the discussion it accompanies. The new edition contains over 200 new and 55 revised figures. We have further enhanced this connection through the refinement and integration of research figures. ***Experimental Research, Observational Research,*** and ***Research Methods*** are further highlighted in a vivid new design, drawing attention to how biologists formulate and test specific hypotheses by gathering and interpreting data.

Extensively Revised Unit Four: Evolution and Classification

The fundamental concepts of evolution are essential for students to grasp as they explain the diversity of living organisms as well as the commonalities that organisms possess. That said, many first-year students come to university with a poor understanding of evolutionary principles; whether it's the importance of chance mutation as a driver of evolutionary change or that evolution can occur in the absence of natural selection.

With this in mind, we have extensively revised this unit to focus more clearly on conveying the fundamental concepts of evolution, to provide greater clarity on the processes that cause evolutionary change, as well as to make critical connections between evolution and genetics. Chapter 16: Evolution by Natural Selection now includes a section and Research Figure focused on experimental evolution in *E. coli,* as well as a concluding figure that explains the major misconceptions students have concerning evolution and natural selection. Chapter 17: Microevolution: Changes Within Populations has been rewritten to make stronger connections to genetics, which are often not made in the context of evolution, by fully explaining terms such as *allele, gene, gene pool,* and *locus*. This chapter also emphasizes the role of random mutation in evolution and its importance in introducing genetic novelty. Chapter 18: Speciation and Macroevolution has improved flow and clarity, including simpler and more informative figures. Chapter 19: Systematics and Phylogenetics: Revealing the Tree of Life is now its own dedicated chapter. This allows for more clear discussion of the tools and approaches used today to infer evolutionary histories. Great care has been taken to clearly define and present concepts of homology and convergent evolution.

Major revisions to selected chapters are listed below:

Chapter 1: Light and Life

- Streamlined to be more concise

Chapter 2: The Cell: An Overview

- NEW Research Figure about cell fractionalization

Chapter 3: Energy and Enzymes

- More precise description of fundamentals of thermodynamics
- Improved and clarified figures related to exergonic and endergonic reactions

Chapter 4: Cell Membranes and Signalling

- NEW Research Figure: Frye–Edidin Experiment Demonstrating that the Phospholipid Bilayer Is Fluid
- NEW Research Figure: Freeze Fracture

Chapter 5: Cellular Respiration

- Clarified section on chemical basis of cellular respiration to include stronger connections with Chapter 3

Chapter 6: Photosynthesis

- Clarified and improved selected figures

Chapter 7: Cell Cycles

- NEW Why It Matters about algal blooms in Lake Erie
- NEW material on DNA packaging
- NEW figure clarifying replicated versus unreplicated chromosomes

Chapter 8: Genetic Recombination

- Added explicit reference to cytokinesis
- Specified creation of haploid cells

Chapter 9: The Chromosomal Basis of Mendelian Inheritance

- NEW Canadian Why It Matters about the spirit bears of British Columbia
- Enhanced discussion connecting genes/alleles to proteins and protein products, and to the expression of alleles in the phenotype as dominant/recessive

Chapter 10: Genetic Linkage, Sex Linkage, and Other Non-Mendelian Inheritance Mechanisms

- NEW Canadian Why It Matters about disease incidence in Quebec
- NEW figures and examples dealing with translocations, imprinting, and pedigree analysis

Chapter 11: DNA Structure, Replication, and Repair

- NEW Canadian Why It Matters about woolly mammoths in Canada
- Highlighted mechanisms of repair of DNA damage

Chapter 12: Gene Structure, Expression, and Mutation

- NEW Canadian Why It Matters about poisonous mushrooms in British Columbia
- Expanded material on mutations and how they can affect protein function
- NEW discussion about ENCODE versus the junk DNA debate
- Expanded and clarified discussion of mutagenesis

Chapter 13: Regulation of Gene Expression

- NEW Why It Matters featuring epigenetic regulation of honeybee castes

- Updated material on lncRNA
- Updated material on cancer genetics

Chapter 14: DNA Technologies

- NEW section on CRISPR and qPCR
- Clarified and expanded Health Canada position on genetically modified foods
- Added material on knockout mouse protocol

Chapter 15: Genomics

- Fully updated
- NEW section on comparative genomics
- Linked advances in sequencing technologies from Sanger to early next-gen methods to DNA replication outlined in Chapter 11
- Enhanced explanation of principles behind BLAST

Chapter 16: Evolution: The Development of the Theory

- Completely rewritten with a greater focus on fundamental concepts of evolution and less emphasis on historical development
- NEW Why It Matters about antibiotic resistance
- Section and Experimental Research Figure focused on experimental evolution in *E. coli*
- Concluding figure explains the major misconceptions students have with evolution and natural selection

Chapter 17: Microevolution: Changes within Populations

- Completely rewritten with greater clarity on the processes that cause evolutionary change
- Stronger connections with genetics by fully explaining terms such as allele, gene, gene pool, locus
- Emphasis on the role of random mutation, the different types and when they occur, that may drive the introduction of genetic novelty

Chapter 18: Speciation and Macroevolution

- Improved flow and clarity of the writing
- Simpler and more informative figures

Chapter 19: Systematics and Phylogenetics: Revealing the Tree of Life

- In the previous edition, systematics and phylogenetics were grouped with the history of life (geological record) as a single chapter. This made it somewhat disjointed. In this edition, systematics and phylogenetics is its own dedicated chapter. This allows for clearer discussion of the tools and approaches used today to infer evolutionary histories.
- The concepts of homology and convergent evolution are more clearly presented.

Chapter 20: Humans and Evolution

- Unchanged from previous edition

Chapter 21: Defining Life and Its Origins

- In this edition, this chapter includes a section on the fossil record.
- Expanded section discussing possible energy sources for early life
- More in-depth discussion on LUCA

Chapter 22: Viruses, Viroids, and Prions: Infectious Biological Particles

- NEW Canadian example about tracking viral disease
- NEW Research Figure: A New Discovery for Hepatitis C Therapy

Chapter 23: Bacteria and Archaea

- Phylogenetic tree updated to reflect latest research
- NEW Research Figure: Genetic Recombination in Bacteria
- NEW discussion of a recent finding of a group within Archaea (Lokiarchaeota) that has a number of genes in common with eukaryotes

Chapter 24: Protists

- Phylogenetic tree updated to reflect latest research
- Incorporated recent research on Diplonemids that had been previously known from only a single environmental gene from marine planktonic samples
- NEW Research Figure: Isolation and Identification of Marine Diplonemids

Chapter 25: Fungi

- Incorporated information on a recent discovery in lichens related to the third symbiont, a basidiomycete yeast that is part of the symbiosis that influences the morphology of lichen
- Added material on the *Puccinia*–grain interaction
- NEW Research Figure: Hidden Third Partner in Lichen Symbiosis

Chapter 26: Plants

- NEW Research Figure: Exploring a Possible Early Angiosperm Adaptation for Efficient Photosynthesis in Dim Environments
- Extensive revision of key figures for clarity

Chapter 27: Animals

- NEW chapter that combines both protostomes and deuterostomes
- Includes latest research on phylogenetic tree
- NEW Research in Biology box on the Tully Monster

Chapter 28: Conservation of Biodiversity

- NEW Why It Matters featuring the extinction of passenger pigeons
- NEW section on the Anthropocene
- Enhanced discussion of human impact on landscapes
- NEW material on ecosystem services
- NEW discussion of the impact of wolf predation on populations of caribou

Chapter 29: Population Ecology

- NEW Why It Matters about the other malaria
- NEW Research Figure: Evaluating Density-Dependent Interactions between Species
- NEW section on Human Administered Population Control

Chapter 30: Species Interactions and Community Ecology

- NEW Why It Matters about oxpeckers and their hosts
- NEW coverage of blood feeders
- NEW material on venoms, how animals use them and how they work

Chapter 31: Ecosystems

- NEW Why It Matters about cave ecosystems
- Updated discussion of mass mortality
- Enhanced discussion of urban ecosystems

Chapter 32: Animal Behaviour

- NEW Why It Matters about bird migration
- NEW discussion about changing behaviour, featuring moose, salt, and cars
- NEW coverage of echolocation
- NEW material on the evolution of human language

Chapter 33: Organization of the Plant Body

- Incorporation of current research that demonstrates, with the discovery of new transcription factors, that there is an unexpectedly complex regulatory network governing secondary wall development
- NEW Research Figure: Networking the Secondary Cell Wall

Chapter 34: Transport in Plants

- NEW Research Figure: Translocation Pressure

Chapter 35: Reproduction and Development in Flowering Plants

- NEW section explaining the genetics behind the ABC model of floral development
- NEW section showing how plant tissue culture can generate virus-free plants from infected donors

Chapter 36: Plant Nutrition

- Assimilation of nutrients connected with material in *The Purple Pages*

Chapter 37: Plant Signals and Responses to the Environment

- Updated section on Darwin's experiments using light and oat coleoptiles

Chapter 38: Introduction to Animal Organization and Physiology

- NEW Research Figure: Demonstration of the Use of the Bill for Thermoregulation in Birds

Chapter 39: Animal Nutrition

- NEW Research Figure: Association of Bacterial Populations in the Gut Microbiome with Obesity in Humans
- NEW definition of essential nutrients, malnutrition, and undernutrition
- NEW figure illustrating intracellular digestion

Chapter 40: Gas Exchange: The Respiratory System

- NEW Why It Matters, featuring a discussion of adaptations that allow animals to live in oxygen-limited environments (burrows, during diving, at altitude)
- NEW Research Figure: Demonstration of a Molecular Basis for High-Altitude Adaptation in Deer Mice

Chapter 41: Internal Transport: The Circulatory System

- NEW Why It Matters, featuring the effects of animal body size on resting heart rate (but not longevity)
- NEW Research Figure: Demonstration of a Vasodilatory Signalling Molecule

Chapter 42: Regulation of the Internal Environment: Water, Solutes, and Temperature

- NEW Research Figure: ADH-Stimulated Water Reabsorption in the Kidney Collecting Duct

- Added new section on the regulation of mammalian kidney function
- Refined discussion to clarify the difference between osmolality and osmolarity

Chapter 43: Control of Animal Processes: Endocrine Control

- NEW Why It Matters, featuring endocrine control of mating behaviour in elk
- NEW Research Figure: Demonstration That Epinephrine Acts by Binding to a Plasma Membrane Receptor

Chapter 44: Animal Reproduction

- NEW chapter created by combining reproduction and development
- Added sexual reproduction as a route for infection
- Clarified discussion of where organelles were in the sperm
- NEW Research Figure: Vocal Cues of Ovulation in Human Females

Chapter 45: Control of Animal Processes: Neural Control

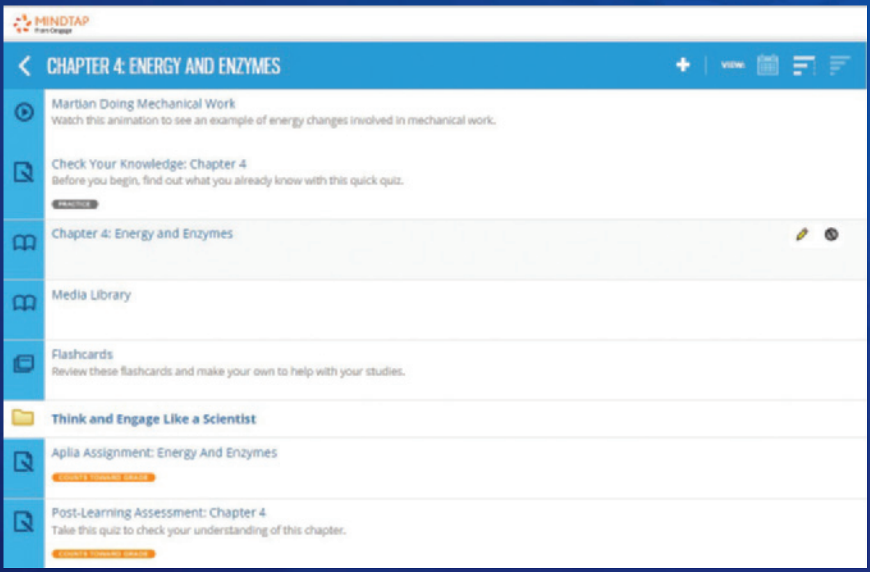
- NEW chapter created by combining neural control and integration
- Clarified the difference between the spike initiation zone and the axon hillock
- Clarified resting and membrane potential
- NEW Concept Fix addressing passive versus gated channels
- Enhanced discussion of the refractory period and why it is important for nerve conduction
- NEW Research Figure: Demonstration of Chemical Transmission of Nerve Impulses at Synapses

Chapter 46: Muscles, Skeletons, and Body Movements

- NEW Concept Fix addressing the misconceptions about muscles getting smaller as they contract
- More human examples integrated throughout
- NEW Research Figure: The Sliding Filament Model of Muscle Contraction

Welcome to *Biology: Exploring the Diversity of Life,* 4Ce

Biology: Exploring the Diversity of Life and MindTap **engage students so they learn not only WHAT scientists know, but HOW they know it and what they still need to learn.**



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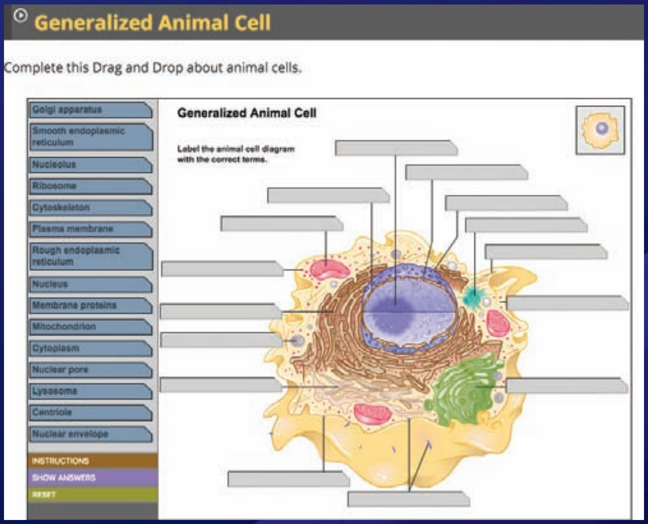
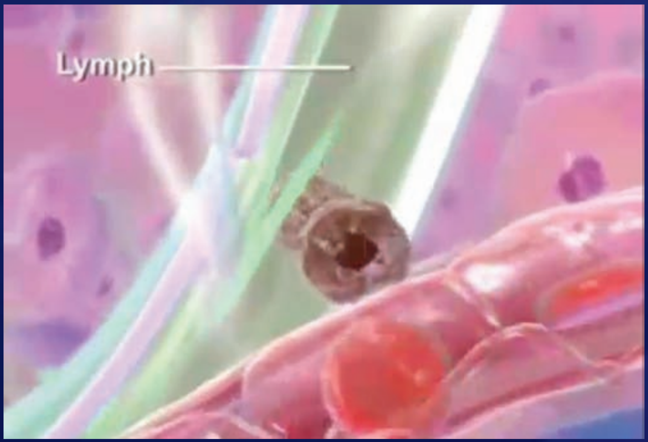
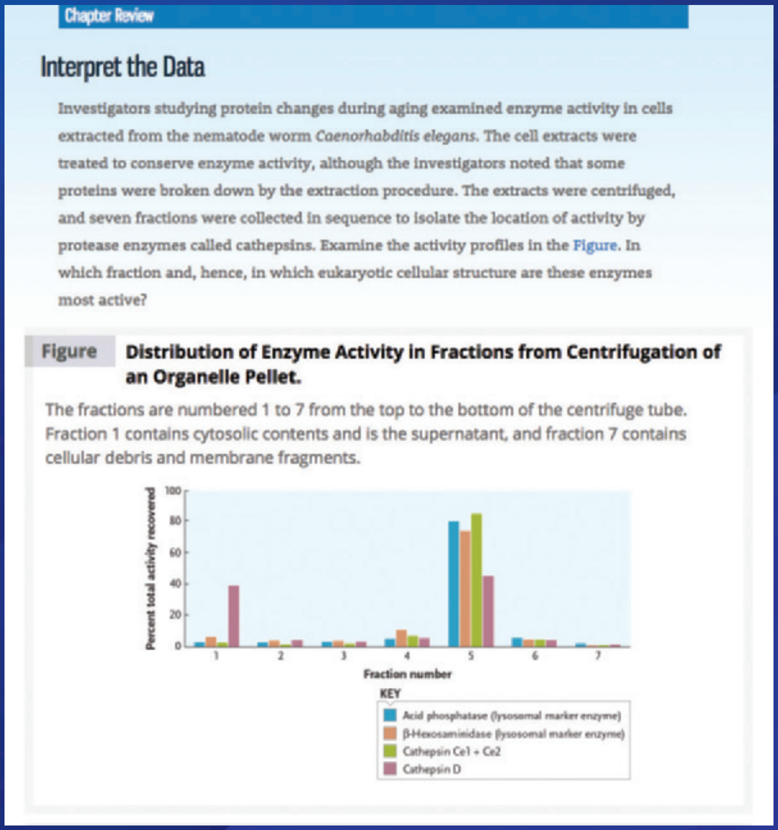




▲ **Engage!** The learning path for each chapter begins with an engaging video designed to pique your interest in the chapter contents. Take the tutorial quiz to assess gaps in your knowledge, and strengthen your knowledge of concepts by reviewing the ebook.


Chapter Review

Interpret the Data

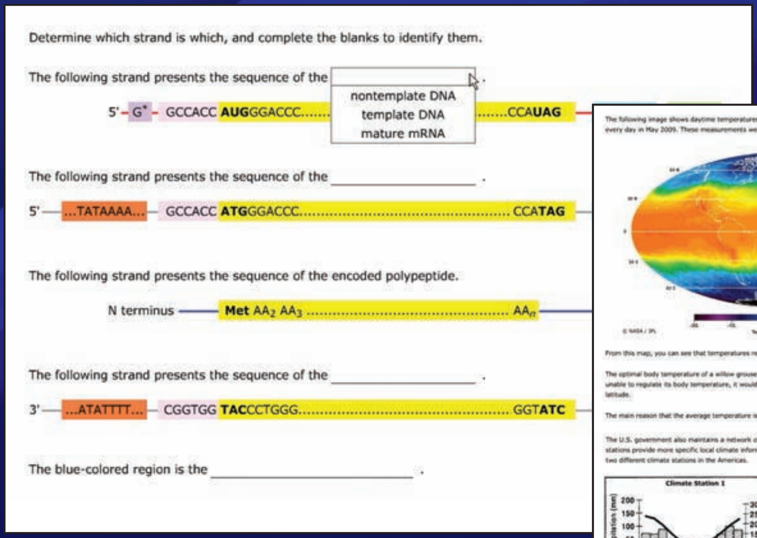
Investigators studying protein changes during aging examined enzyme activity in cells extracted from the nematode worm *Caenorhabditis elegans*. The cell extracts were treated to conserve enzyme activity, although the investigators noted that some proteins were broken down by the extraction procedure. The extracts were centrifuged, and seven fractions were collected in sequence to isolate the location of activity by protease enzymes called cathepsins. Examine the activity profiles in the Figure. In which fraction and, hence, in which eukaryotic cellular structure are these enzymes most active?

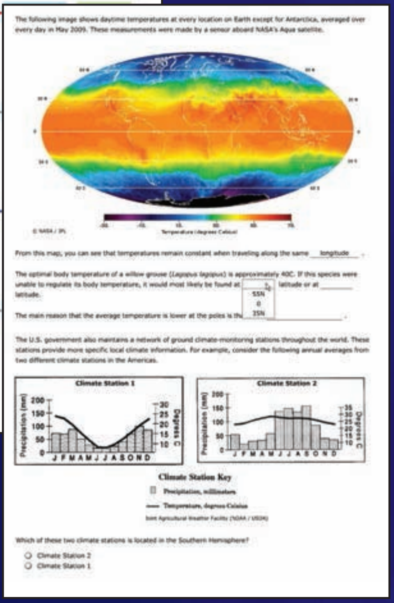
Figure Distribution of Enzyme Activity in Fractions from Centrifugation of an Organelle Pellet.

The fractions are numbered 1 to 7 from the top to the bottom of the centrifuge tube. Fraction 1 contains cytosolic contents and is the supernatant, and fraction 7 contains cellular debris and membrane fragments.

◄ **Master!** Think and engage like a scientist by taking gradable short-answer quizzes:

- **Apply Evolutionary Thinking** questions ask you to interpret a relevant topic in relation to the principles of evolutionary biology.
- **Design an Experiment** challenges your understanding of the chapter and helps you deepen your understanding of the scientific method as you consider how to develop and test hypotheses about a situation that relates to a main chapter topic.
- **Interpret the Data** questions help you develop analytical and quantitative skills by asking you to interpret graphical or tabular results of experimental or observational research experiments for which the hypotheses and methods of analysis are presented.





Test your mastery of concepts with **Aplia for Biology,** a series of **Conceptual Problem Sets** that complement the text and help you learn and understand key concepts through focused assignments, an engaging variety of problem types, exceptional text/art integration, and immediate feedback.

Assess your knowledge of chapter concepts by taking the **Post-Learning Assessment,** a set of higher-level quiz questions designed to test the depth of your understanding.

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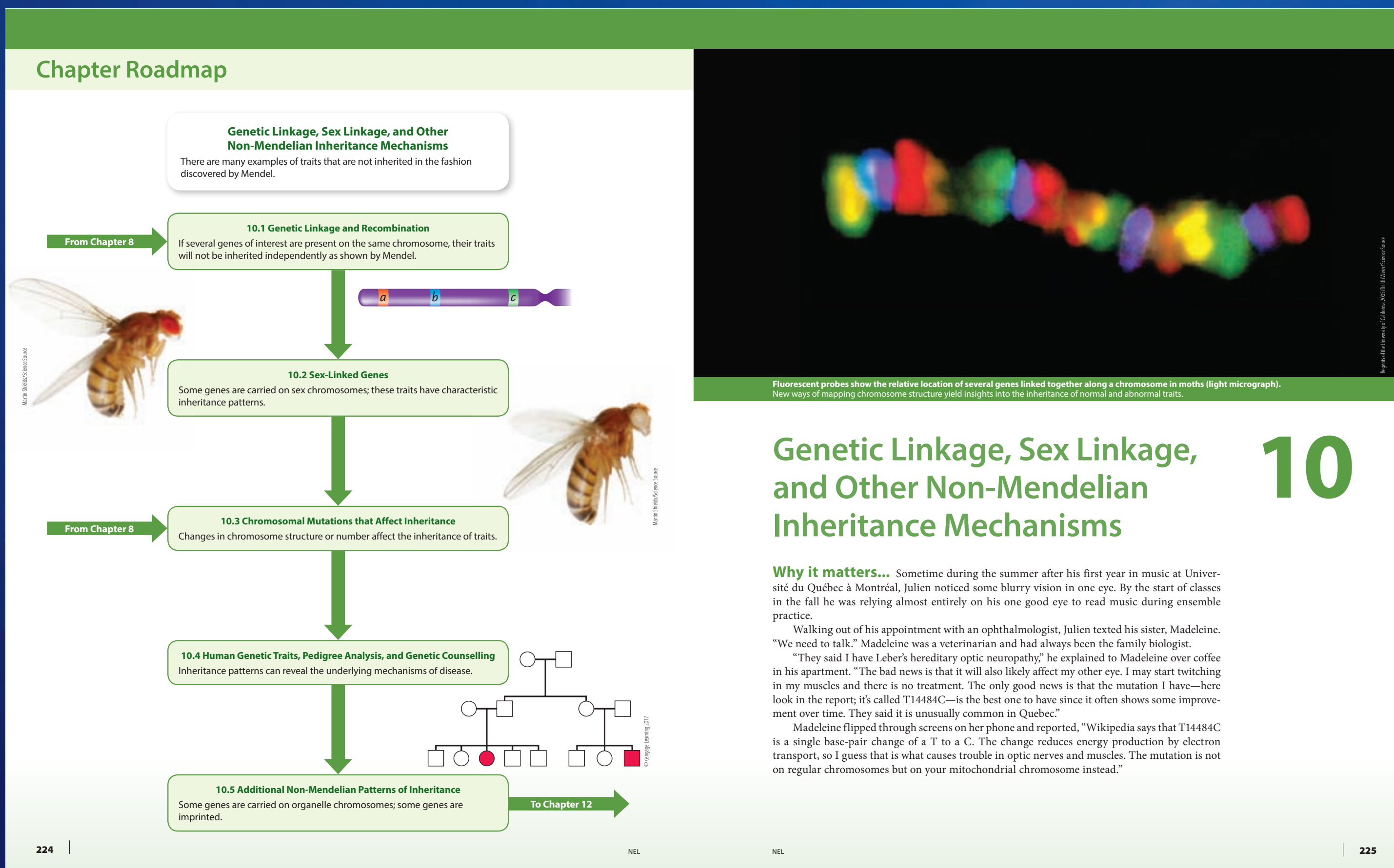
Visually stunning features that engage your students in the process of learning because an engaged student is a successful student.



Chapter Roadmap

Genetic Linkage, Sex Linkage, and Other Non-Mendelian Inheritance Mechanisms
There are many examples of traits that are not inherited in the fashion discovered by Mendel.

From Chapter 8

10.1 Genetic Linkage and Recombination
If several genes of interest are present on the same chromosome, their traits will not be inherited independently as shown by Mendel.

a b c

10.2 Sex-Linked Genes
Some genes are carried on sex chromosomes; these traits have characteristic inheritance patterns.

From Chapter 8

10.3 Chromosomal Mutations that Affect Inheritance
Changes in chromosome structure or number affect the inheritance of traits.

10.4 Human Genetic Traits, Pedigree Analysis, and Genetic Counselling
Inheritance patterns can reveal the underlying mechanisms of disease.

10.5 Additional Non-Mendelian Patterns of Inheritance
Some genes are carried on organelle chromosomes; some genes are imprinted.

To Chapter 12

Martin Shields/Science Source

Martin Shields/Science Source

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224 NEL

Regents of the University of California 2005/Dr. Uli Weier/Science Source

Fluorescent probes show the relative location of several genes linked together along a chromosome in moths (light micrograph).
New ways of mapping chromosome structure yield insights into the inheritance of normal and abnormal traits.

Genetic Linkage, Sex Linkage, and Other Non-Mendelian Inheritance Mechanisms 10

Why it matters... Sometime during the summer after his first year in music at Université du Québec à Montréal, Julien noticed some blurry vision in one eye. By the start of classes in the fall he was relying almost entirely on his one good eye to read music during ensemble practice.

Walking out of his appointment with an ophthalmologist, Julien texted his sister, Madeleine. "We need to talk." Madeleine was a veterinarian and had always been the family biologist.

"They said I have Leber's hereditary optic neuropathy," he explained to Madeleine over coffee in his apartment. "The bad news is that it will also likely affect my other eye. I may start twitching in my muscles and there is no treatment. The only good news is that the mutation I have—here look in the report; it's called T14484C—is the best one to have since it often shows some improvement over time. They said it is unusually common in Quebec."

Madeleine flipped through screens on her phone and reported, "Wikipedia says that T14484C is a single base-pair change of a T to a C. The change reduces energy production by electron transport, so I guess that is what causes trouble in optic nerves and muscles. The mutation is not on regular chromosomes but on your mitochondrial chromosome instead."

NEL 225

▲ **Chapter Roadmaps** The Chapter Roadmaps provide a visual overview of the major sections in the chapter and show the connections between the topics in the chapter and other chapters in the book.

Why It Matters … Why It Matters draws students in with an engaging vignette that is linked to the concepts discussed in the chapter.

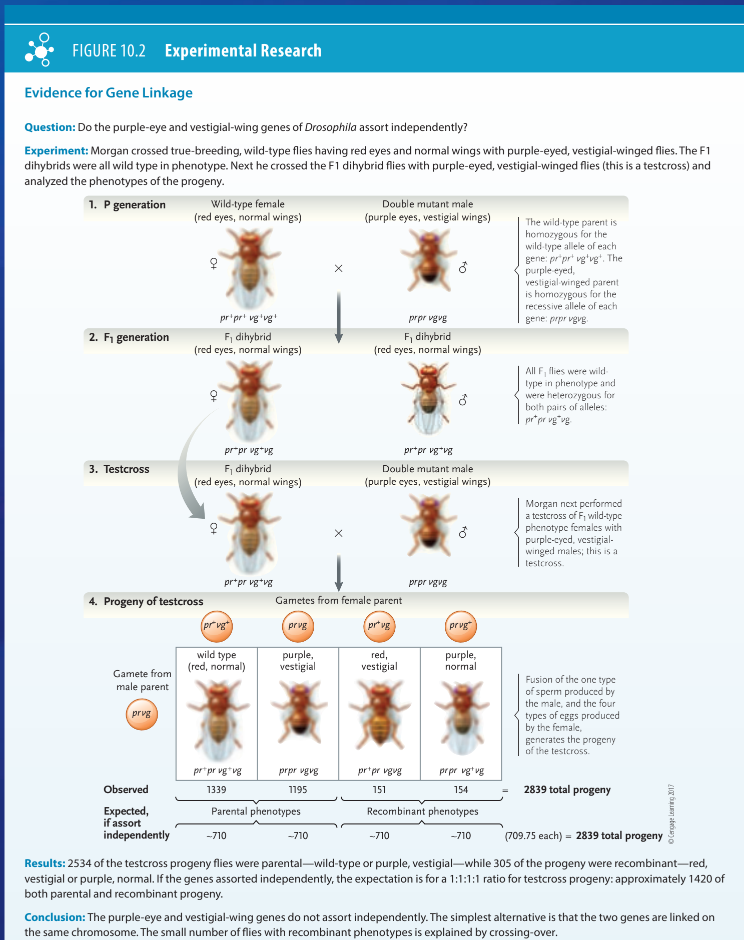
STUDY BREAK QUESTIONS

1. What are the three interrelated systems that contribute to the eukaryotic cell cycle?
2. What is a chromosome composed of?
3. When is a chromosome composed of two chromatids?

▲ **Study Breaks** The Study Breaks fall at the end of each major section and encourage students to pause and review what they have learned before going on to the next topic within the chapter.

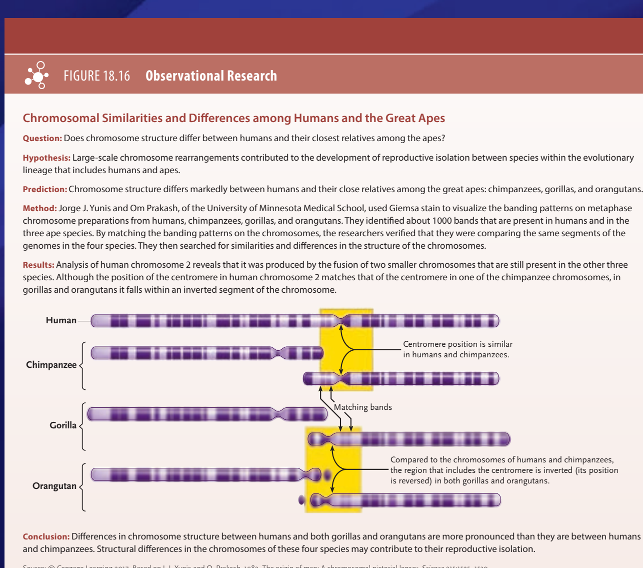
Concept Fix Icons Concept Fixes draw on the extensive research literature dealing with misconceptions commonly held by biology students. Strategically placed throughout the text, these short segments help students identify—and correct—a wide range of misunderstandings. ▼

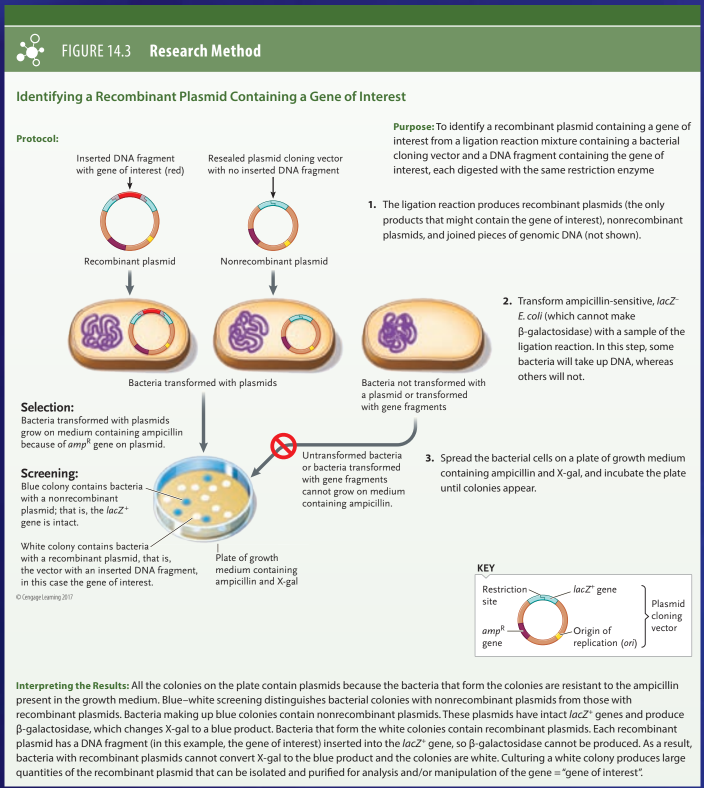
CONCEPT FIX Coming out of high school, many students think that ATP is a product of the respiratory ETC. This is a misconception that we need to fix. The generation of ATP by the ATP synthase complex is linked, or coupled, to electron transport by the proton gradient established across the inner mitochondrial membrane. But electron transport and the chemiosmotic generation of ATP are separate and distinct processes and are not always completely coupled (**Figure 5.17**). For example, it is possible to have high rates of electron transport (and thus high rates of oxygen consumption) and yet no ATP generated by chemiosmosis. This uncoupling of the two processes occurs when mechanisms prevent the formation of a proton-motive force.



◀ **Experimental Research Figures** Experimental Research figures describe specific studies in which research used both experimental and control treatments—either in the laboratory or in the field—to test hypotheses or answer research questions by manipulating the system they studied.

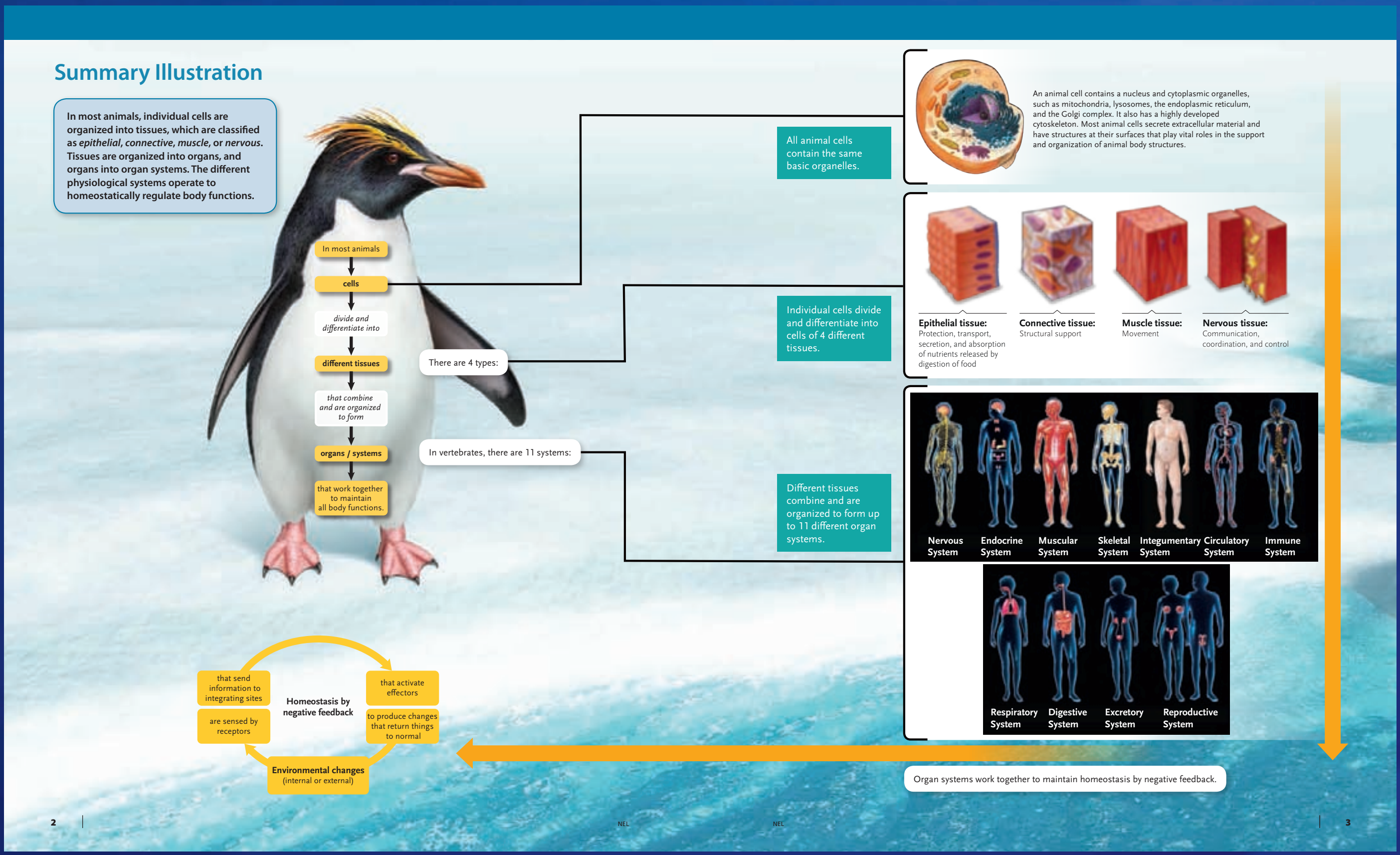
Research Method Figures Research Method Figures provide examples of important techniques, lead students through the purpose of the technique and protocol, and describe how scientists interpret the data generated. ▼





▲ **Observational Research Figures** Observational Research Figures describe specific studies in which biologists have tested hypotheses by comparing systems under varying natural circumstances.

Summary Illustrations Vivid, engaging, and carefully developed Summary Illustrations appear at the end of each chapter and help students visualize the main concepts covered in the chapter. ▼



Self-Test Questions These chapter review questions are organized according to Bloom's taxonomy into three sections: Recall/Understand, Apply/Analyze, and Create/Evaluate. This structure allows students to review the material in a sequence that moves from the basic knowledge of factual material, to more challenging and sophisticated applications of that knowledge to novel situations. Answers to the Self-Test Questions are found in an appendix at the back of the book. ▼

SELF-TEST QUESTIONS

Recall/Understand

1. Which of these factors is found in organic molecules that are considered good fuels?
   a. many C—H bonds
   b. many C=C double bonds
   c. an abundance of oxygen
   d. a high molecular weight
2. What is one of the places in a cell where cellular respiration occurs?
   a. in plant mitochondria, but not in animal mitochondria
   b. in plant chloroplasts
   c. in the mitochondria of both animals and plants
   d. in animal mitochondria, but not in plant mitochondria
3. Which of these processes occurs during glycolysis?
   a. oxidation of pyruvate
   b. reduction of glucose
   c. oxidative phosphorylation
   d. substrate-level phosphorylation
4. Which of these processes links glycolysis and the citric acid cycle?
   a. chemiosmosis
   b. formation of G3P
   c. reduction of NAD^+
   d. pyruvate oxidation

Apply/Analyze

5. The breakdown of fats releases fatty acids. In what form do the carbon molecules enter the respiratory pathway?
   a. as NADH
   b. as acetyl-CoA
   c. a glucose
   d. as pyruvate
6. You are reading this text while breathing in oxygen and breathing out carbon dioxide. Which two processes are the sources of the carbon dioxide?
   a. glycolysis and pyruvate oxidation
   b. glycolysis and oxidative phosphorylation
   c. pyruvate oxidation and the citric acid cycle
   d. the citric acid cycle and oxidative phosphorylation
7. Under conditions of low oxygen, what key role is played by fermentation in overall metabolism?
   a. It regenerates the NAD^+ required for glycolysis.
   b. It synthesizes additional NADH for the citric acid cycle.
   c. It allows for pyruvate to be oxidized in mitochondria.
   d. By activating oxidative phosphorylation, it allows for the synthesis of extra ATP.
8. Suppose you are a doctor and your patient complains of feeling hot all the time, even on the coldest winter days. The young man perspires constantly and his skin is always flushed. He also eats a lot but is rather thin. You perform some laboratory tests, and find that the patient consumes lots of oxygen in his metabolic pathways. What would you suspect this patient suffers from and why?

Create/Evaluate

9. In cellular respiration, which of the following does the term *uncoupled* refer to specifically?
   a. The two parts of glycolysis are running independently of each other.
   b. Respiratory electron transport is operating, but chemiosmosis is inhibited.
   c. Respiratory electron transport is operating, but proton pumping is inhibited.
   d. Oxidative phosphorylation is occurring, but the proton-motive force remains high.
10. Phosphofructokinase (PFK) is regulated by a number of metabolites. In addition to those mentioned in the text, which one of the following would also make sense?
    a. Pyruvate could function as an activator of PFK.
    b. Glucose could function as an inhibitor of PFK.
    c. ADP could function as an activator of PFK.
    d. Acetyl-CoA could act as an activator of PFK.
11. Which of these statements *best* describes the "paradox of aerobic life"?
    a. Humans are completely protected from the toxic effects of oxygen.
    b. Hydrogen peroxide is formed when a single electron is donated to O_2.
    c. Cytochrome oxidase is a major source of reactive oxygen species.
    d. Strict anaerobes often lack the enzyme(s) superoxide dismutase and/or catalase.
12. Compare direct burning of glucose and cellular respiration with reference to their progression.
13. Distinguish between reduction and oxidation during redox reactions.
14. Explain what happens with hydrogen and its bonding electrons during cellular respiration.
15. Cyanide is a strong toxin that reacts with the final protein in the electron transport chain (ETC). Explain why it can kill a human within a few minutes.

Appendix A: Answers to Self-Test Questions

Chapter 1

1. a 2. a 3. d 4. a 5. c 6. d 7. c 8. a 9. b 10. a 11. c 12. b 13. d
14. Eyes are usually not exposed to full sunlight for a very long period of time, such as the photosynthetic apparatus is. Damage due to exposure of photosystems can be repaired by removing damaged proteins and replacing them with newly synthesized ones, which is not possible in a damaged eye.
15. Melanin protects skin cells because it absorbs ultraviolet light, and it is increasingly synthesized upon exposure to the Sun, which results in the darker shade of her skin.

Chapter 2

1. d 2. c 3. c 4. a 5. a 6. b 7. b 8. a 9. d 10. a 11. d 12. d 13. c
14. ribosomes, rough ER, transport vesicle, Golgi complex, secretory vesicle, plasma membrane
15. Anchoring junctions function to reinforce cell-to-cell connections made by adhesion molecules. Tight junctions seal the spaces between cells. Gap junctions create direct channels for communicating between adjacent cells.

Chapter 3

1. c 2. d 3. b 4. a 5. b 6. c 7. c 8. d 9. c 10. d
11. As they dissolve, the sugar molecules raise their entropy. However, the crystals re-form because the water decreases in its order, changing from compact liquid to disordered vapour.
12. Any substance in ordered state (minimum entropy) will contain molecules with maximum free energy. On the contrary, any substance in disordered state (maximum entropy) will contain molecules with minimum free energy. The relationship is reversed.
13. In an exergonic reaction, reactants contain more free energy than the products; energy is released and the reaction is spontaneous. In an endergonic reaction, reactants contain less free energy than the products; energy is required and the reaction is not spontaneous.
14. At any time in a cell, there must be exergonic reactions happening to provide enough energy for endergonic reactions. In addition, the energy released by exergonic reactions must be higher than the energy needed for endergonic reactions because some energy is always transferred to heat (second law of thermodynamics).

Chapter 4

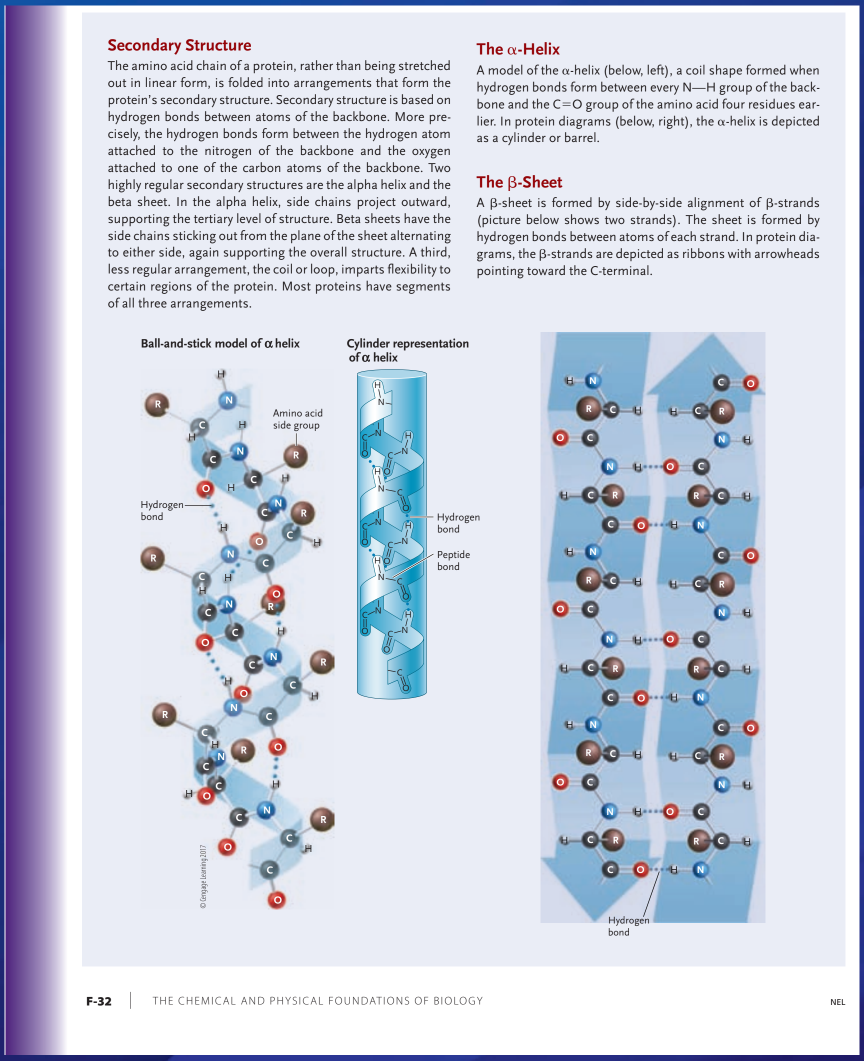
1. a 2. c 3. b 4. c
5. Some proteins perform transport; others have enzymatic activities; some are a part of signal transduction process; and others are involved in attachment and/or recognition.
6. b 7. c 8. b 9. c 10. c 11. b 12. a 13. d
14. Passive transport occurs down the concentration gradient of the solute, and active transport occurs against the gradient of the transported solute. Active transport therefore requires a protein and energy to perform.
15. They are both a form of passive transport, but facilitated diffusion utilizes proteins to speed up the transport of solute across the membrane.

Chapter 5

1. a 2. c 3. d 4. d 5. b 6. c 7. a
8. This patient might have defective mitochondria in his cells. This condition is common in a number of diseases. The reason why it was suspected is that, based on his symptoms, probably little ATP is synthesized, in spite of high oxygen consumption, since his cells dissipated a lot of heat (the patient was hot all the time).
9. b 10. c 11. d
12. Direct burning of glucose is an uncontrolled process; cellular respiration occurs in a series of steps and is therefore a form of controlled combustion.
13. Reduction is the acceptance of electrons during a redox reaction. Oxidation is the loss of electrons during a redox reaction.
14. Hydrogen and its electrons move from sugar to oxygen, forming water.
15. The process of oxidative phosphorylation produces the large number of ATP molecules needed for the endergonic reactions in the cell that we are so dependent on. One of the major sequences of proteins embedded in the mitochondrial membrane—called the electron transport chain—can accept electrons rich in energy. As the energized electrons fall from protein to protein in the ETC, they deposit energy that they carry. At the end of the ETC, there must be oxygen ions present to accept these energetically depleted electrons. If these energy-depleted electrons are not carried away by the oxygen ions, ATP production would stop. Cyanide exerts its deadly effects by reacting with the final protein in ETC, blocking oxygen from accepting electrons from this protein.

Chapter 6

1. d 2. c 3. c 4. a 5. c
6. A group of pigment proteins form an antenna complex that surrounds a reaction centre. Light energy absorbed anywhere in the antenna complex is transferred to a special chlorophyll *a* molecule in the reaction centre. The absorbed light is converted to chemical energy when an excited electron from the chlorophyll *a* is transferred to a primary



Secondary Structure

The amino acid chain of a protein, rather than being stretched out in linear form, is folded into arrangements that form the protein's secondary structure. Secondary structure is based on hydrogen bonds between atoms of the backbone. More precisely, the hydrogen bonds form between the hydrogen atom attached to the nitrogen of the backbone and the oxygen attached to one of the carbon atoms of the backbone. Two highly regular secondary structures are the alpha helix and the beta sheet. In the alpha helix, side chains project outward, supporting the tertiary level of structure. Beta sheets have the side chains sticking out from the plane of the sheet alternating to either side, again supporting the overall structure. A third, less regular arrangement, the coil or loop, imparts flexibility to certain regions of the protein. Most proteins have segments of all three arrangements.

The α-Helix

A model of the α-helix (below, left), a coil shape formed when hydrogen bonds form between every N—H group of the backbone and the C=O group of the amino acid four residues earlier. In protein diagrams (below, right), the α-helix is depicted as a cylinder or barrel.

The β-Sheet

A β-sheet is formed by side-by-side alignment of β-strands (picture below shows two strands). The sheet is formed by hydrogen bonds between atoms of each strand. In protein diagrams, the β-strands are depicted as ribbons with arrowheads pointing toward the C-terminal.

F-32 | THE CHEMICAL AND PHYSICAL FOUNDATIONS OF BIOLOGY NEL

◄ *The Purple Pages:* **The Chemical and Physical Foundations of Biology** While many textbooks use the first few chapters to introduce and/or review, we believe that the first chapters should convey the excitement and interest of biology itself. We therefore placed important background information about biology and chemistry in the reference section entitled *The Chemical and Physical Foundations of Biology,* in the centre of the book. With their purple borders, these pages are distinct and easy to find and have become affectionately known as ***The Purple Pages.*** References to material covered in *The Purple Pages* are set in purple throughout the text.

The Green Pages: Unit 5: The Diversity of Life We emphasize the richness and tremendous variability among living organisms in *The Green Pages*. With their green borders, these pages identify chapters that introduce and explore the tree of life. ▼

FIGURE 25.1 **Example of a wood decay fungus: sulfur shelf fungus *(Polyporus)***

essential components in all ecosystems and Earth's premier decomposers **(Figure 25.1)**.

Despite their profound impact on ecosystems and other life forms, most of us have only a passing acquaintance with fungi, perhaps limited to the mushrooms on our pizza or the invisible but annoying types that cause skin infections, such as athlete's foot. This chapter provides you with an overview of fungal biology. We begin with the features that set fungi apart from all other organisms, and discuss the diversity of fungi existing today before revisiting associations between fungi and other organisms.

25.1 General Characteristics of Fungi

We begin our survey of fungi by examining the features that distinguish fungi from other forms of life, how fungi obtain nutrients, and adaptations for reproduction and growth that enable fungi to spread far and wide through the environment.

Fungi are heterotrophic eukaryotes that obtain carbon by breaking down organic molecules synthesized by other organisms. Although all fungi are heterotrophs, fungi can be divided into two broad groups based on how they obtain carbon. If a fungus obtains carbon from non-living material, it is a **saprotroph**. Fungi that decompose dead plant and animal tissues, for example, are saprotrophs. If a fungus obtains carbon from living organisms, it is a **symbiont**. Symbiosis is the living together of two (or sometimes more) organisms for extended periods; symbiotic relationships range along a continuum from **parasitism**, in which one organism benefits at the expense of the other, to **mutualism**, in which both organisms benefit. Although we often think of fungi as decomposers, fully half of all identified fungi live as symbionts with another organism.

FIGURE 25.2 **Fungal structure: mycelia, hyphae. (a)** Illustration of themycelium of a mushroom-forming fungus, which consists of branching septate hyphae. *Inset:* Micrograph of fungal hyphae **(b)** Rhizomorph – a cordlike aggregation of hyphae formed by some basidiomycete fungi.

Regardless of their nutrient source, fungi feed by **absorptive nutrition**: they secrete enzymes into their environment, breaking down large molecules into smaller soluble molecules that can then be absorbed into their cells. This mode of nutrition means that fungi cannot be stationary, as they would then deplete all the food in their immediate environment. Instead, fungi have evolved the ability to proliferate quickly through their environment, digesting nutrients as they grow. How can fungi proliferate so quickly? Although some fungi grow as unicellular yeasts, which reproduce asexually by **budding** or binary fission (see Figure 25.13), most are composed of **hyphae** ("web"; singular, *hypha*; **Figure 25.2**), fine filaments that spread through whatever substrate the fungus is growing in—soil, decomposing wood, your skin—forming a network, or **mycelium** (Figure 25.2). Hyphae are essentially tubes of cytoplasm surrounded by cell walls made of chitin, a polysaccharide also found in the exoskeletons of insects and other arthropods.

Hyphae grow only at their tips, but because a single mycelium contains many, many tips, the entire mycelium grows outward very quickly. Together, this **apical growth** and absorptive nutrition account for much of the success of fungi. As the hyphal tips extend, they exert a mechanical force, allowing them to push through their substrate, releasing enzymes and absorbing nutrients as they go. Fungal species differ in the particular digestive enzymes they synthesize, so a substrate that is a suitable food source for one species may be unavailable to another. Although there are exceptions, fungi typically thrive only in moist environments, where they can directly absorb water, dissolved ions, simple sugars, amino acids, and other small molecules. When some of a mycelium's hyphal filaments contact a source of food, growth is channelled in the direction of the food source.

Nutrients are absorbed at the porous tips of hyphae; small atoms and molecules pass readily through these tips, and then transport mechanisms move them through the underlying plasma membrane. Some hyphae have regular cross-walls, or **septa** ("fences" or "walls"; singular, *septum*), that separate a hypha into compartments **(Figure 25.3)**, whereas others lack septa and are effectively one large cell. But even septate hyphae should be thought of as interconnected compartments rather than separate cells, as all septa have pores that allow cytoplasm and, in some fungi, even nuclei and other large organelles to flow through the mycelium. By a mechanism called **cytoplasmic streaming** (flow of cytoplasm and organelles around a cell or, in this case, a mycelium), nutrients obtained by one part of a mycelium can be translocated to other non-absorptive regions, such as reproductive structures.

When a fungus releases enzymes into its substrate, it faces competition from bacteria and other organisms for the nutrients that are now available. How can a fungus prevent these competitors from stealing the nutrients that it has just expended energy and resources to obtain? Many fungi produce antibacterial compounds and toxins that inhibit the growth of competing organisms. Many of these compounds are **secondary metabolites**, which are not required for day-to-day survival but are beneficial to the fungus. As we will see, many of these compounds not only are important in the life of a fungus but also benefit organisms associated with the fungus. Many are also of commercial or medical importance to humans; for example, the antibiotic penicillin is a secondary metabolite produced by a species of *Penicillium*.

FIGURE 25.3 **Septa.** In some fungi, septa divide each hypha into separate compartments.

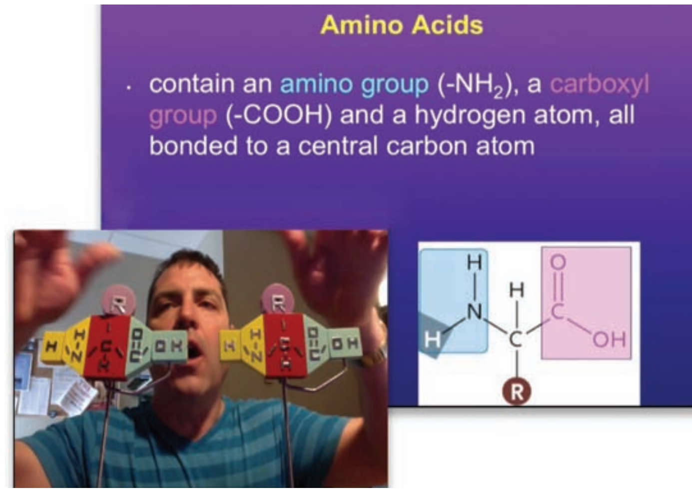
Fungi reproduce by spores, and this spore production can be amazingly prolific, with some species of fungi producing billions of spores per day **(Figure 25.4).** These spores are microscopic, featherlight, and able to survive in the environment for extended periods after they are released. Reproducing via such spores allows fungi to be opportunists, germinating only when favourable conditions exist and quickly exploiting food sources that occur unpredictably in the environment. Releasing vast numbers of spores, as some fungi do, improves the odds that the spores will germinate and produce a new individual.

Spores can be produced asexually or sexually; some fungi produce both asexual and sexual spores at different stages of their lives. Sexual reproduction in fungi is complex. In all organisms, sexual reproduction involves three stages: the fusion of two haploid cells (**plasmogamy**), bringing together their two nuclei in one common cytoplasm. Cytoplasmic fusion in most organisms is quickly followed by nuclear fusion (**karyogamy**), but in fungi the cells can remain bi-nucleate as the organism grows. Nuclear fusion is often followed by meiosis to produce genetically distinct haploid spores. As we will see, fungi are unique in that plasmogamy and karyogamy can be separated in time for durations ranging from seconds to many years.

FIGURE 25.4 **Spore production by fungal fruiting bodies.** Some fruiting bodies can release billions of spores per day.

Student and Instructor Resources

Succeed in the course with these dynamic resources!



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Editorial and Student Advisory Boards

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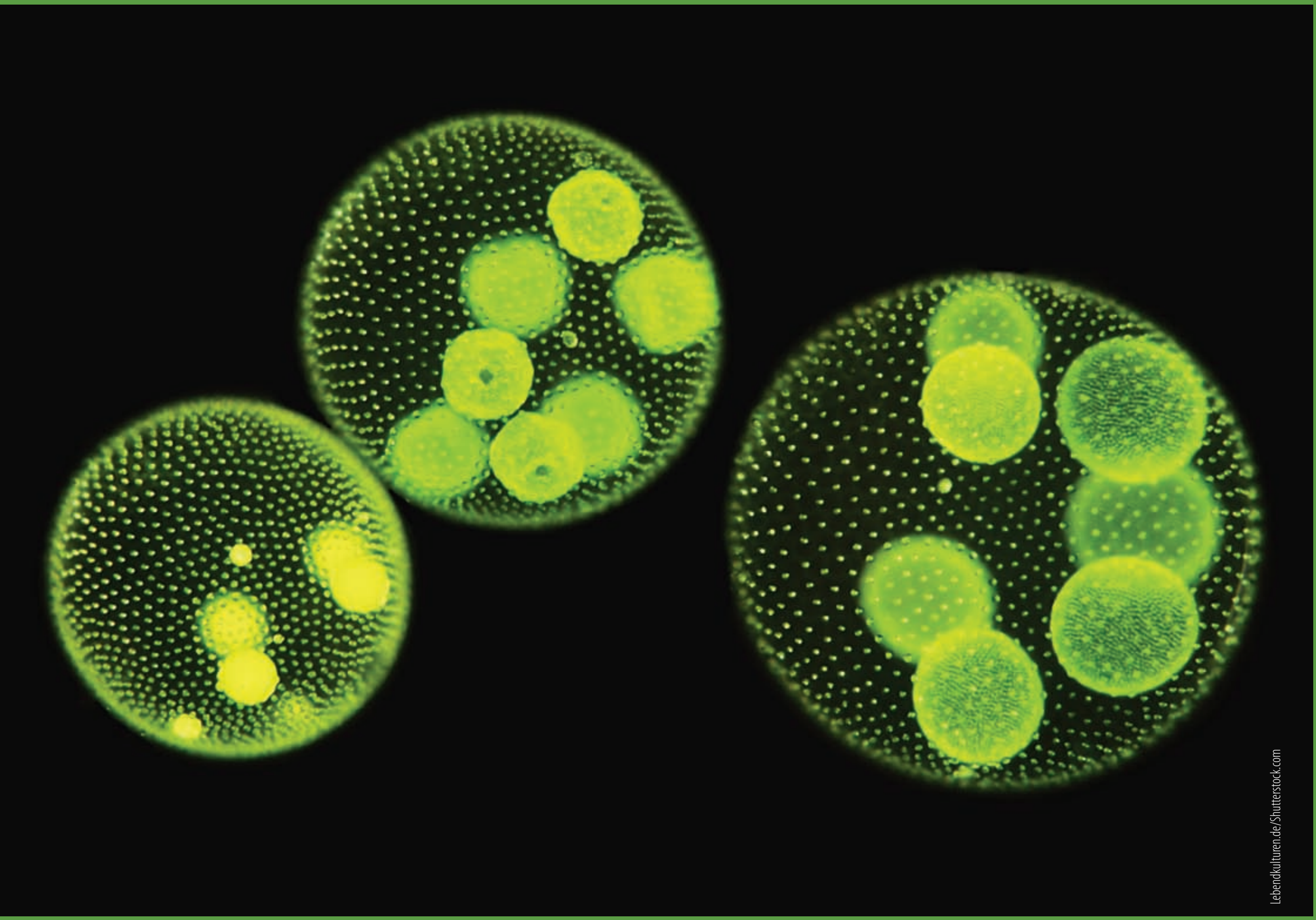
BIOLOGY OF THE CELL

VOLUME 1



***Volvox* is a genus of green algae.** As photosynthetic eukaryotes, *Volvox* cells exist in colonies of thousands of cells. Some of the cells are vegetative (non-reproductive); a smaller number of much larger reproductive cells are found in the interior of the colony.

There is a huge diversity of life on Earth; some estimates peg the total number of species at over 1 billion (with most yet to be described!). Yet, what this opening volume of the textbook should covey to you is that underlying that diversity is a remarkable level of similarity. From monkeys to mycoplasma to monocots, everything that is alive on Earth employs a variation on that remarkable innovation: the cell. No matter if that cell is communicating with other cells in the brain of a fruit fly, or capturing sunlight in a spruce needle, or driving the muscles of a sprinting cheetah, or thriving in the mineral-rich water of deep-sea vents, no matter what their role or activity, all cells share a remarkably long list of common features. Volume 1 explores these common features in detail.

The invention of the microscope allowed scientists to finally understand how living organisms were built from cells, which to early scientists were astonishingly small. Further work clearly delineated two major divisions in cell types: those without a nucleus (prokaryotic) and those with a nucleus (eukaryotic). And within both these groups there are clear subdivisions: for example, plants, fungi, and animal cells, in eukaryotes.

The chapters of Unit 1 talk a lot about energy because without it living cells would die. Like the non-living world, all forms of life abide by the foundational laws of thermodynamics and need to bring in energy and matter from the environment to maintain their highly ordered state. In part, energy is required to build complex things (e.g., proteins) out of simpler things (amino acids). In addition to energy, the evolution of life is tied to the development of a remarkable group of proteins called *enzymes*, which when they get tied to a biochemical reaction can increase its rate by 10^{10} times!

Another remarkable feature of cells that we dedicate a chapter to in Unit 1 is membranes. These self-forming lipid bilayers act as the gatekeepers of the cell: they allow certain things in but keep other things out. How they do this is by acting in concert with membrane-specific proteins that shuttle molecules from one side to another. Membrane proteins also play a remarkable role in transducing signals from outside the cells and compartments to the inside. As we will see, the transduction of signals associated with hormones, for example, can profoundly affect cell function.

What you may not realize is that virtually all the energy used by living systems comes ultimately from sunlight being harvested and converted into a useable chemical form through photosynthesis. This process evolved perhaps as early as 3.5 billion years ago and used photons of light energy to extract electrons from water, releasing oxygen as a by-product. The rise in oxygen in an atmosphere that previously had none led to an explosion of life as the mechanism of cellular respiration evolved that could use that oxygen, and enabled cells to produce huge amounts of energy.

The chapters of Units 2 and 3 are dedicated to molecular biology and genetics, the central player being the gene. All cells possess genes that are coded by the molecule DNA that, through the process of transcription, get copied into RNA. All cells contain ribosomes where some kinds of RNAs get translated into **proteins**, the fundamental structural, functional, and regulatory molecule of the cell.

Genes are stretches of DNA sequence in an organism that collectively comprise a kind of library of information about how a cell functions. Recent advances in technology have made it relatively easy to determine the entire DNA sequence of an organism, including individual humans. As a result, modern biology is awash in the As, Ts, Gs, and Cs of DNA sequence revealed by thousands of sequencing projects. New insights into evolutionary history as well as gene structure and function are arising from bioinformatic analysis of such extensive data sets.

The elegant double-strandedness of DNA, whereby two long strands of nucleotides are held together by hydrogen bonds formed between complementary base pairs, affords a straightforward mechanism for replication that was recognized early on by Watson and Crick. Although conceptually simple, the mechanism for unwinding the DNA **double helix** and polymerizing new complementary bases is rather complicated and managed by a suite of interacting enzymes. Again, we see that all DNA on the planet is replicated using variations on one underlying strategy.

DNA genes provide the cell with needed RNA by transcription. One remarkable feature of all protein-coding genes is that, with minor exceptions, the information they carry is specified by a universal code. That is, a gene from one organism can be "understood" by any other organism, even if only distantly related: a gene from a spider can be expressed by a goat; a gene from a jellyfish can be expressed in a flower. The field of genetic engineering is devoted to developing the tools and applications of this technology for moving genes from one organism to another.

In a story that is about to come full circle, synthetic biologists have extensively customized naturally occurring cells and have made important advances toward their ultimate goal of creating novel life forms artificially in the lab. As students of biology in the early twenty-first century, you can well expect to witness a momentous event in Earth's history, the creation of one life form by another.

Chapter Roadmap

Light and Life

Light serves two important functions for life on Earth: First, it is the ultimate source of energy for almost all organisms. Second, light provides many organisms with information about the physical world that surrounds them.

1.1 The Physical Nature of Light

To be used as a source of energy or information, photons of light must be absorbed by a molecule.

To Purple Pages

1.2 Light as a Source of Energy

The energy of light can be used in photosynthesis to convert carbon dioxide into carbohydrates.

To Chapter 6

1.3 Light as a Source of Information

The photoreceptor, a pigment molecule bound to a protein, is the common molecule used in sensing light in the environment.

To Chapter 37

To Chapter 45

1.4 The Uniqueness of Light

Light possesses an ideal amount of energy: enough energy to excite electrons, but not enough to directly destroy biological molecules.

1.5 Light Can Damage Biological Molecules

Organisms possess mechanisms to both protect themselves from the damaging effects of light and repair the inevitable damage that light causes.

1.6 Using Light to Tell Time

Organisms have evolved circadian clocks, which allow them to keep track of time on a daily and seasonal scale.

Anita Patterson Peppers / Shutterstock.com

1.7 The Role of Light in Behaviour and Ecology

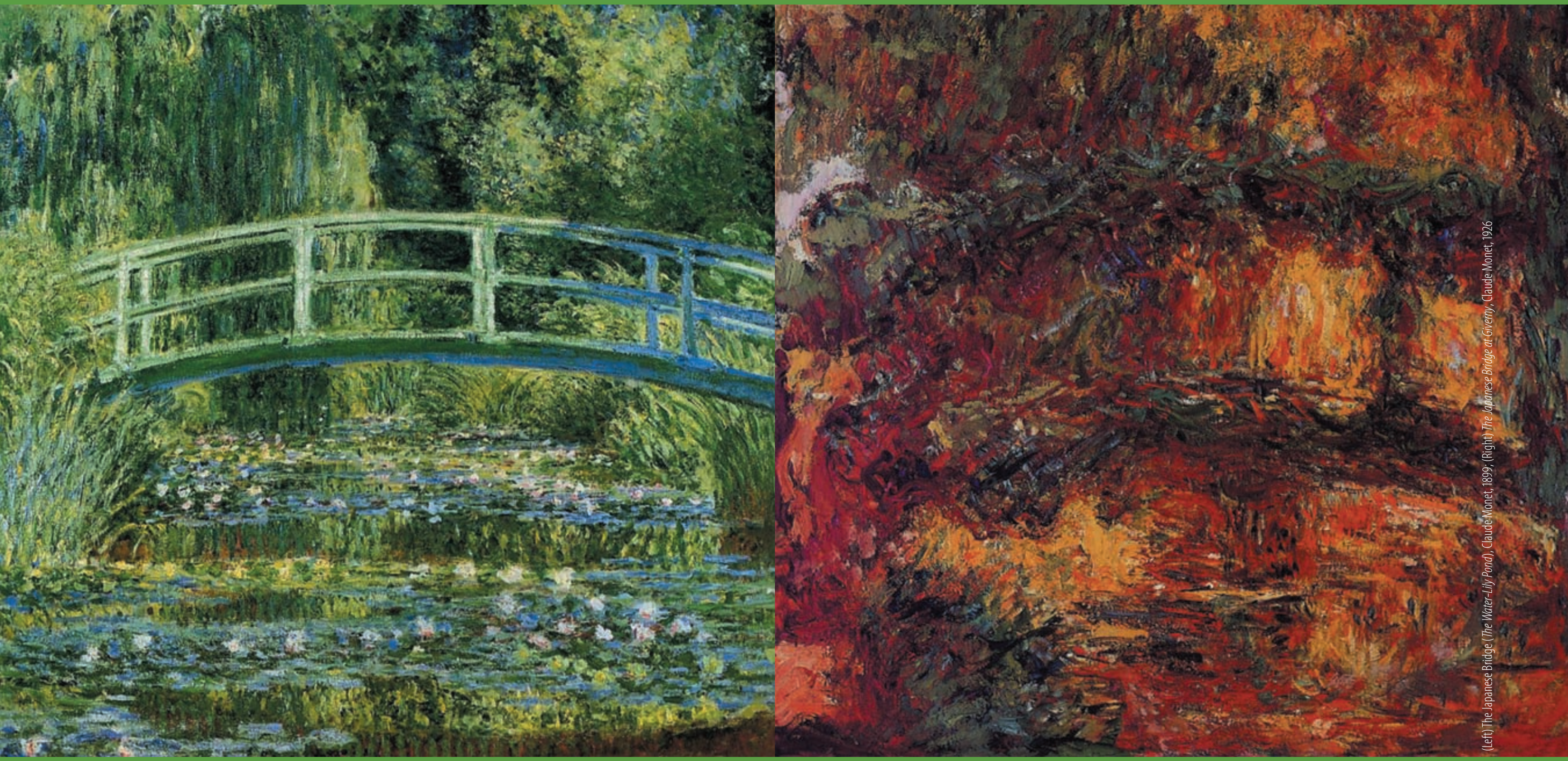
The light environment of a particular habitat plays a central role in adaptation. It leads to unique colouration that may serve to attract a mate or hide from predators.

To Chapter 30

To Chapter 32

1.8 Organisms Making Their Own Light

Some organisms generate their own light to attract a mate or prey, or for communication.



(Left) The Japanese Bridge (*The Water-Lily Pond*), Claude Monet, 1899; (Right) *The Japanese Bridge at Giverny*, Claude Monet, 1926

Paintings by Claude Monet (1840–1926). Compared to his early works, including *The Water Lily Pond* **(a)**, his later paintings, including *The Japanese Footbridge* **(b)**, bordered on the abstract, with almost complete loss of light blue. Monet suffered from cataracts, a degenerative vision disease, diagnosed in 1912.

Light and Life

1

Why it matters . . . Claude Monet (1840–1926), a French painter, is considered by many to be the master of the impressionist form that rose to prominence in the late nineteenth century. Impressionism as an art movement was characterized by the use of small visible brush strokes that emphasized light and colour, rather than lines, to define an object. The artists used pure, unmixed colour, not smoothly blended, as was the custom at the time. For example, instead of physically mixing yellow and blue paint, they placed unmixed yellow paint on the canvas next to unmixed blue paint so that the colours would mingle in the eye of the viewer to create the impression of green. The impressionists found that they could capture the momentary and transient effects of sunlight and the changing colour of a scene by painting *en plein air* (in the open air), outside the studio, where they could more accurately paint the reflected light of an immediate scene.

Interestingly, compared with his early works, which included *The Water Lily Pond* (1899), Monet's later paintings verge on the abstract, with colours bleeding into each other and with a lack of rational shape and perspective. For example, *The Japanese Footbridge* is an explosion of orange, yellow, and red hues, with heavy, broad brush strokes, leaving the viewer barely able to discern the vague shape of the arched bridge. In many of Monet's later works, the colours in his paintings became more muted, far less vibrant and bright, with a pronounced colour shift from blue–green to red–yellow and an almost total absence of light blues. The sense of atmosphere and light that he was famous for in his earlier works disappeared.

Although the change in Monet's paintings could easily be explained by an intentional change in style or perhaps an age-related change in manual dexterity, Monet himself realized that it was not his style or dexterity that had changed but, rather, his ability to see. Monet suffered from cataracts, a vision-deteriorating disease diagnosed in both eyes when he was 72. A cataract is a change in the lens of the eye, making it more opaque, which changes the ability to see different colours of light.

In this chapter, the first of the 46 of this textbook, we introduce you to the science of biology by using light as a central connecting theme. Light is arguably the most fundamental of natural phenomena, and foundational experiments into the nature of light were a key part of the scientific revolution that took place in the sixteenth and seventeenth centuries. Beyond formally defining light and discussing its properties, in this chapter we explore the huge diversity of areas of biology that light influences, from the molecular to the ecological. This introductory tour is not intended to be complete or exhaustive but to simply set the stage for the topics that come in subsequent chapters.

1.1 The Physical Nature of Light

Light serves two important functions for life on Earth: First, it is the ultimate source of energy that sustains virtually all organisms. Second, light provides many organisms with information about the physical environment in which they live. These two roles for light are nicely illustrated by the green alga *Chlamydomonas* **(Figure 1.1)**. *Chlamydomonas* is a single-celled, photosynthetic eukaryote that is commonly found in ponds and lakes. *Chlamydomonas* contains a single large chloroplast that harvests light energy and uses it to make energy-rich molecules through the process of photosynthesis. In addition, each cell contains a light sensor called an *eyespot* that allows *Chlamydomonas* to gather information about the direction and intensity of the light in its environment. With this information, cells can move toward or away from the light source using a pair of flagella. Regardless of whether the light is used as a source of energy or as a source of information about the environment, both rely on the same fundamental properties of light.

1.1a What Is Light?

Through the process of nuclear fusion, the Sun transforms a staggering 3.4×10^{38} hydrogen nuclei into helium each second **(Figure 1.2)**. In the process, about 4 million tonnes of matter are converted into energy. This energy is given off by the Sun as *electromagnetic radiation,* which travels in the form of a wave at a speed of 1.1×10^9 km/h (the speed of light) and reaches Earth in just over 8 minutes. Electromagnetic radiation is generated at a range of wavelengths **(Figure 1.3)**: cosmic rays have a wavelength of less than one picometre (10^{-12} m); radio waves have a wavelength longer than one kilometre (10^6 m). The complete range of wavelengths of electromagnetic radiation is referred to as the **electromagnetic spectrum**.

So what is light? **Light** is most commonly defined as the portion of the electromagnetic spectrum that we can detect with our eyes. As shown in Figure 1.3, this is a very narrow portion of the total electromagnetic spectrum, spanning only the wavelengths from about 400 to 700 nm.

The physical nature of light has been the focus of scientific inquiry for hundreds of years, and in many ways it remains a mystery. Unlike the atoms that make up matter, light has no mass. And although the results of some experiments suggest

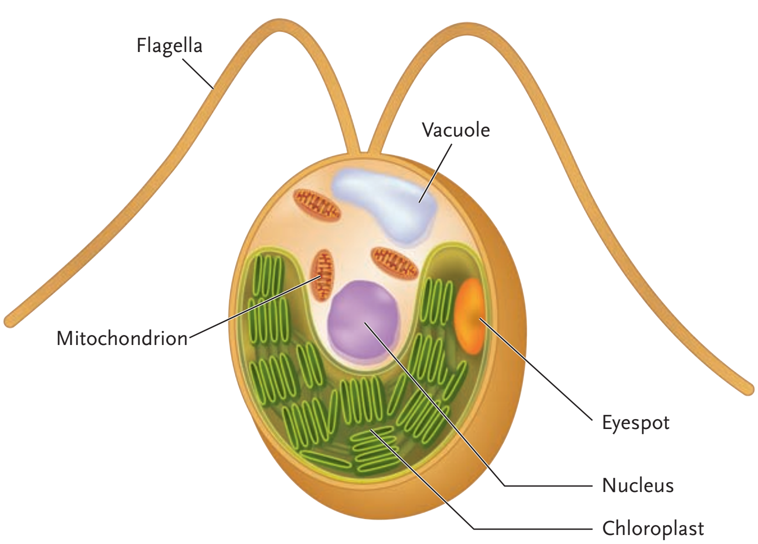


FIGURE 1.1 ***Chlamydomonas.*** Each cell contains a single chloroplast used for photosynthesis, as well as an eyespot for sensing light in the environment.

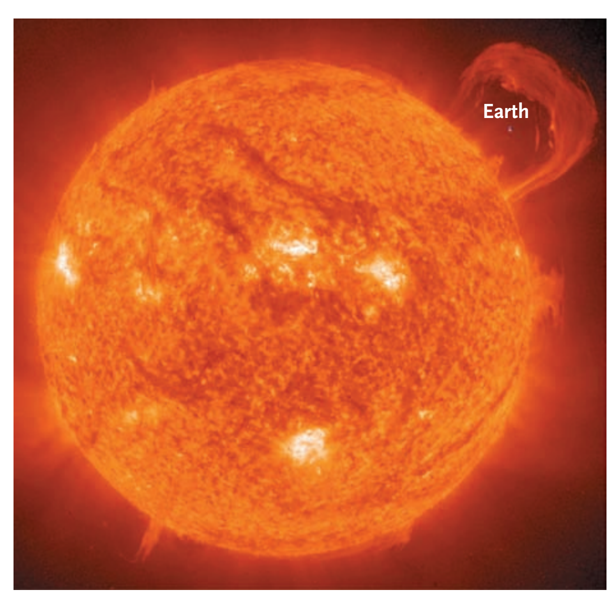


FIGURE 1.2 **The Sun.** Like most stars, the Sun generates electromagnetic radiation as a result of the nuclear fusion of hydrogen nuclei into helium. Note the superimposed image of Earth used to illustrate the relative sizes.

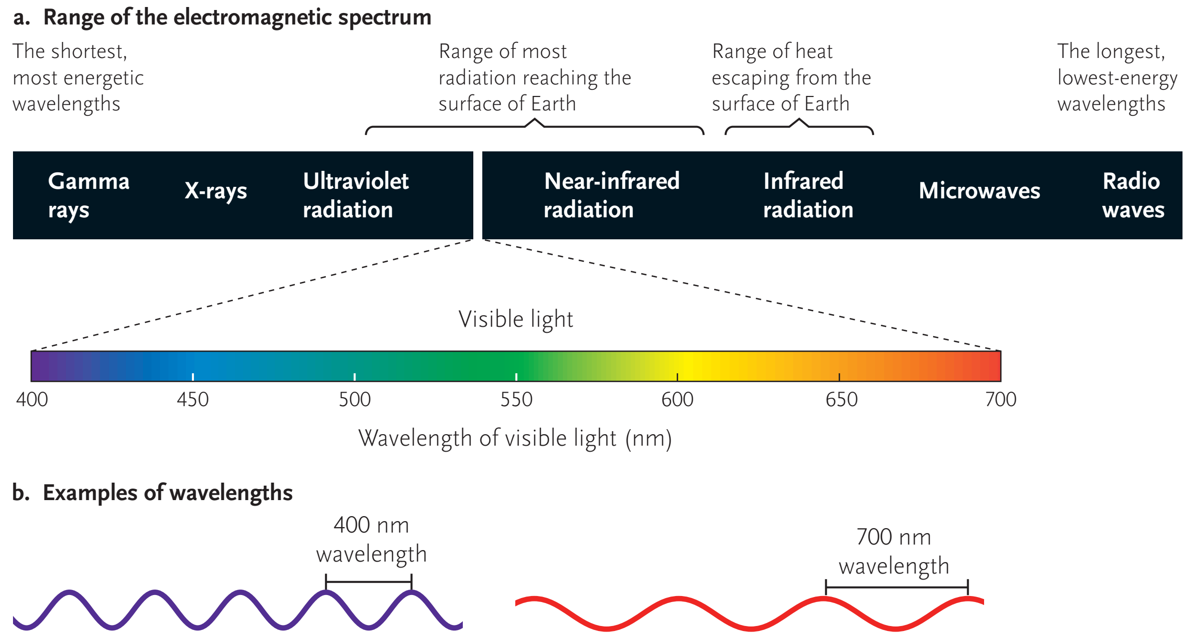


FIGURE 1.3 The electromagnetic spectrum. (a) The electromagnetic spectrum ranges from gamma rays to radio waves; visible light and the wavelengths used for photosynthesis occupy only a narrow band of the spectrum. **(b)** Examples of wavelengths show the difference between the longest and shortest wavelengths of visible light.

that light behaves as a wave as it travels through space, other experiments indicate that light behaves more like discrete particles of energy called **photons**. In the end, we are left with a compromise description: light is best understood as a wave of photons. An important aspect of light to remember is that there is an inverse relationship between the energy of a photon and the wavelength of light. Looking at Figure 1.3, this means that shorter-wavelength blue light consists of photons of higher energy than red light, which has a longer wavelength and thus photons of lower energy.

1.1b Light Interacts with Matter

Although light has no mass, it is still able to interact with matter and cause change. This change is what allows the energy of light to be used by living things. When a photon of light hits an object, the photon has three possible fates: it can be reflected off the object, transmitted through the object, or absorbed by the object. To be used as a source of energy or information by an organism, the light must be absorbed. Light is absorbed when the energy of the photon is transferred to an **electron** within a molecule. This transfer of energy excites the electron, moving it from its ground state to a higher energy level that is referred to as an *excited state* **(Figure 1.4)**.

Molecules differ considerably in their ability to absorb photons of light. There is a major class of molecules that is very efficient at absorbing photons of specific wavelengths; those molecules are called **pigments (Figure 1.5)**. As you would expect, there is a huge diversity of pigments, including chlorophyll *a*, which is involved in photosynthesis; retinal, which is involved in vision; and indigo, which is used to dye jeans their distinctive blue colour.

An important question we can ask is: What is it about pigments that enable them to capture light? At first glance, the molecules shown in Figure 1.5 seem to be very different from each other structurally. However, they all have a common feature critical to light absorption: a region where carbon atoms are covalently bonded to each other with alternating single and double bonds. This bonding arrangement is called a *conjugated system,* and it results in the delocalization of electrons. These electrons are not closely associated with a particular atom or involved in bonding to another atom, and instead are available to absorb the energy of a photon of light.

While the presence of a conjugated system is common to all pigments, differences in the arrangement of the conjugated

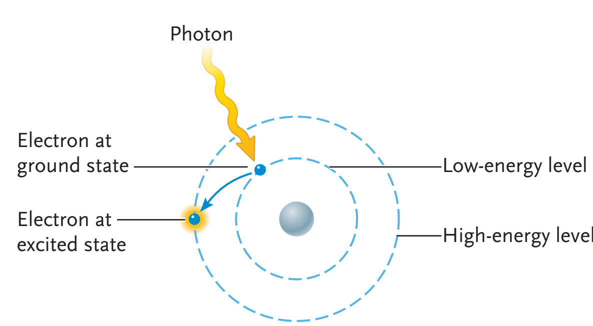


FIGURE 1.4 The absorption of a photon by a molecule results in the energy being transferred to an electron. This causes the energy to move to a higher-energy, excited state.

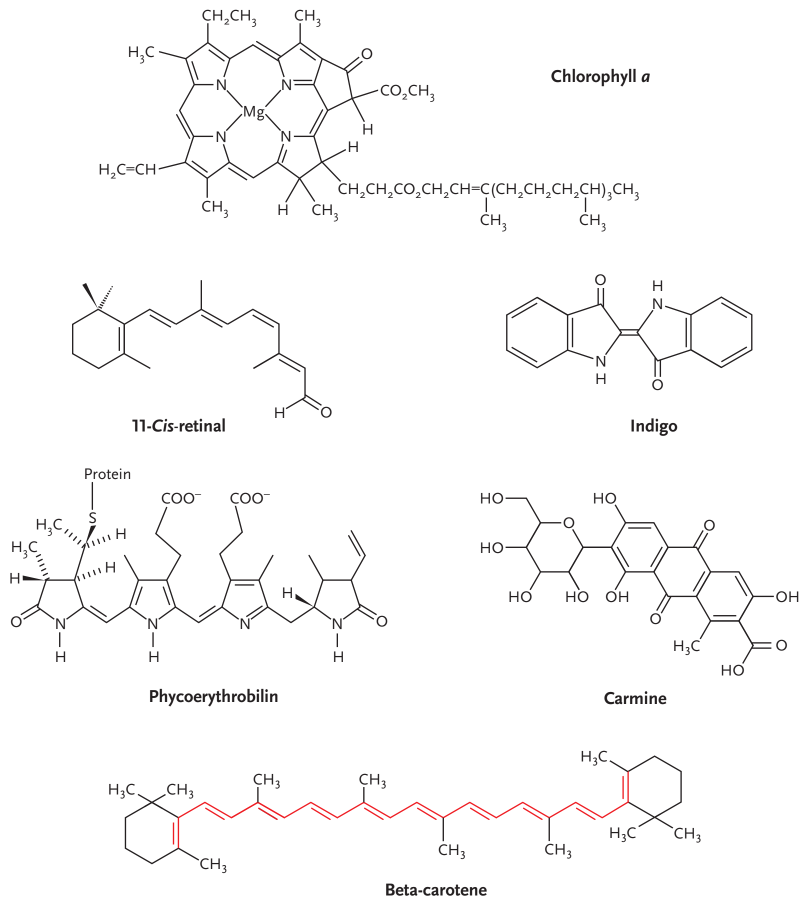


FIGURE 1.5 Structure of some common pigments. Chlorophyll *a*, photosynthesis; 11-*cis*-retinal, vision; indigo, dye; phycoerythrobilin, red photosynthetic pigment found in red algae; carmine, scale pigment found in some insects; beta-carotene, an orange accessory photosynthetic pigment. A common feature of all these pigments that is critical for light absorption is the presence of a conjugated system of double/single carbon bonds (shown in red for beta-carotene).

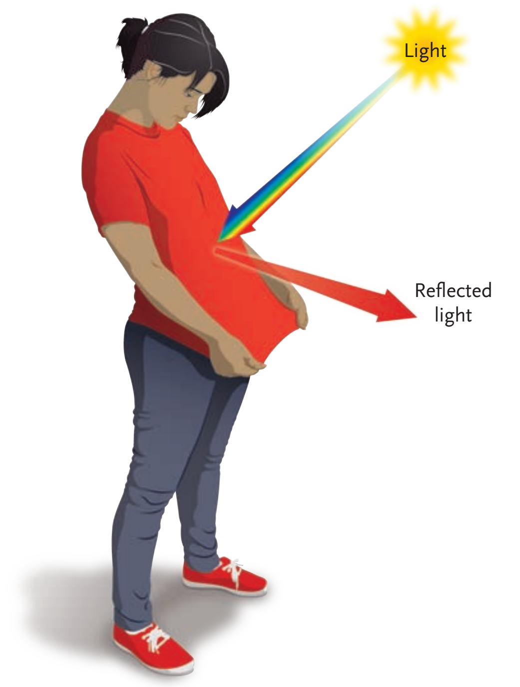


FIGURE 1.6 Why the T-shirt is red. Pigment molecules bound to the fabric of the shirt absorb blue, green, and yellow photons of light. Red photons are not absorbed and are instead transmitted through the shirt or are reflected.

system as well as differences in the overall chemical structure explain why each type of pigment absorbs light of only certain wavelengths. This is because, for a photon to be absorbed, the energy of the photon must match the amount of energy needed to move a delocalized electron from its ground state to a specific excited state. If the energies don't match, then the photon of light is not absorbed and instead is transmitted through the molecule or reflected off the molecule.

CONCEPT FIX The ability of pigments to absorb specific wavelengths of light is what determines their colour. A pigment's colour is the result of photons of light that it *does not* absorb. Instead of being absorbed, these photons are reflected off the pigment or transmitted through the pigment and reach your eyes **(Figure 1.6)**.

STUDY BREAK QUESTIONS

1. What has to occur for a photon to be absorbed?
2. What structural feature is common to all pigments?

1.2 Light as a Source of Energy

The ultimate source of the energy used by almost all organisms that make up the biosphere is light from the Sun. The energy of electromagnetic radiation is made accessible through the ability of plants and related organisms to convert the energy of photons into chemical energy. Through photosynthesis, plants absorb photons of light and use that energy to convert carbon dioxide and water into sugars and other molecules.

Following light absorption by the pigment chlorophyll, the high potential energy of excited-state electrons is used in photosynthetic electron transport to synthesize the energy-rich compounds NADPH (nicotinamide adenine dinucleotide phosphate) and ATP (adenosine triphosphate). These molecules are in turn consumed in the biochemical reactions of the Calvin cycle of photosynthesis to convert carbon dioxide into carbohydrates **(Figure 1.7)**. Although the energy of one photon is very small, the photosynthetic apparatus within the chloroplast of a single plant leaf absorbs millions of photons each second. And a single cell within a typical plant leaf contains hundreds of chloroplasts!

While photosynthesis converts carbon dioxide into carbohydrates, it is the process of cellular respiration, which is found in all organisms, that breaks down carbohydrates and other energy-rich molecules, trapping the released energy as ATP (Figure 1.7). The value of ATP is that it is the universal energy

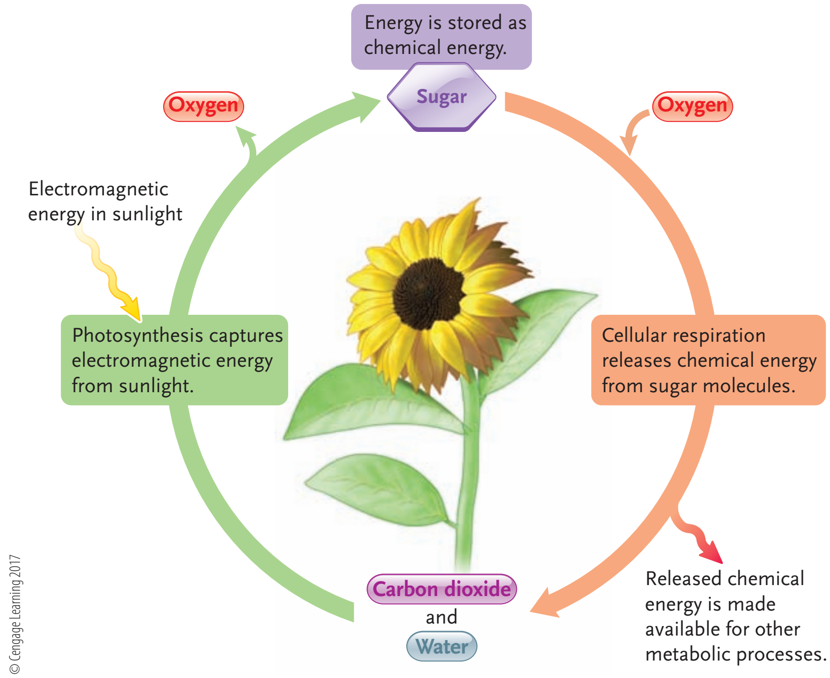


FIGURE 1.7 Photosynthesis converts light energy into chemical energy. Photosynthesis uses the energy in sunlight to build sugar molecules from carbon dioxide and water, releasing oxygen as a by-product. The process of cellular respiration breaks down the products of photosynthesis and releases usable energy.

currency, and can be readily used for the energy-requiring metabolic and biosynthetic processes that are required to maintain all life.

Photosynthesis is the dominant process of the biosphere that directly uses the light of the Sun as a source of energy, but you may be surprised to know that it isn't the only one. Another light-driven process used to acquire energy is found in a group of microbes called *Halobacterium*. These organisms are not eukaryotes or even bacteria, but rather they belong to the third domain of life, the Archaea. We will introduce you to the three domains of life in Chapter 21, and will discuss the Archaea in greater detail in Chapter 22. Most often found in extreme habitats, *Halobacterium* contains a pigment–protein complex called *bacteriorhodopsin*, which is found on the plasma membrane and functions as a light-driven proton pump. When the pigment component of bacteriorhodopsin captures a photon of light, it triggers changes in the protein component, resulting in the specific transport of protons out of the cell. The resulting difference in H^+ concentration across the plasma membrane represents a source of energy that is used by the enzyme ATP synthase to generate ATP from ADP and inorganic phosphate (Pi) **(Figure 1.8)**. Like all organisms, the

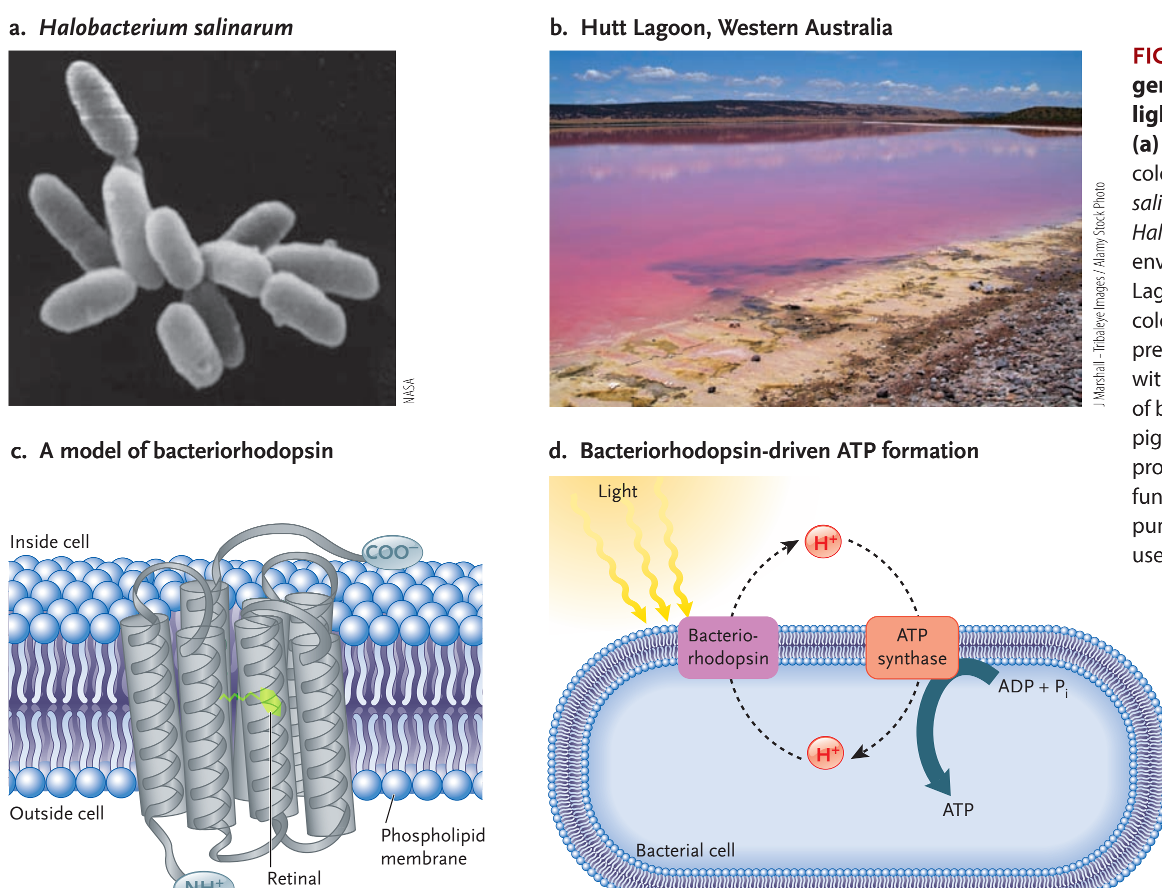


FIGURE 1.8 *Halobacterium* is a genus of Archaea that have a light-driven proton pump. **(a)** Electron micrograph of a colony of *Halobacterium salinarum*. **(b)** Species of *Halobacterium* thrive in high-salt environments, such as Hutt Lagoon in Australia. The pink colour of the water is due to the presence of bacteriorhodopsin within individual cells. **(c)** A model of bacteriorhodopsin shows the pigment retinal bound to a protein. **(d)** Bacteriorhodopsin functions as a light-driven proton pump, the proton gradient being used to synthesize ATP.