THIRD CANADIAN EDITION

CAMPBELL BIOLOGY

THIRD CANADIAN EDITION

CAMPBELL BIOLOGY

Jane B. Reece
BERKELEY, CALIFORNIA

Lisa A. Urry
MILLS COLLEGE, OAKLAND, CALIFORNIA

Michael L. Cain
BOWDOIN COLLEGE, BRUNSWICK, MAINE

Steven A. Wasserman
UNIVERSITY OF CALIFORNIA, SAN DIEGO

Peter V. Minorsky
MERCY COLLEGE, DOBBS FERRY, NEW YORK

Fiona E. Rawle
UNIVERSITY OF TORONTO MISSISSAUGA, MISSISSAUGA, ONTARIO

Dion G. Durnford
UNIVERSITY OF NEW BRUNSWICK, FREDERICTON, NEW BRUNSWICK

Chris D. Moyes
QUEEN'S UNIVERSITY, KINGSTON, ONTARIO

Kevin Scott
UNIVERSITY OF MANITOBA, WINNIPEG, MANITOBA

Pearson

Pearson Canada Inc., 26 Prince Andrew Place, Don Mills, Ontario M3C 2T8.

Bound Book ISBN-13: 978-0-13-485171-6

Looseleaf ISBN: 978-0-13-516683-3

Library and Archives Canada Cataloguing in Publication
Title: Campbell biology / Jane B. Reece [and nine others]
Names: Reece, Jane B., author.
Description: Third Canadian edition. | Includes bibliographical references and index.
Identifiers: Canadiana 20190163356 | ISBN 9780134851716 (hardcover)
Subjects: LCSH: Biology—Textbooks. | LCGFT: Textbooks.
Classification: LCC QH308.2 R44 2019 | DDC 570—dc23

ScoutAutomatedPrintCode

Pearson

About the Authors

Lisa A. Urry Lisa Urry is Professor of Biology and Chair of the Biology Department at Mills College in Oakland, California, and a Visiting Scholar at the University of California, Berkeley. After graduating from Tufts University with a double major in biology and French, Lisa completed her Ph.D. in molecular and developmental biology at the Massachusetts Institute of Technology (MIT) in the MIT/Woods Hole Oceanographic Institution Joint Program. She has published a number of research papers, most of them focused on gene expression during embryonic and larval development in sea urchins. Lisa has taught a variety of courses, from introductory biology to developmental biology and senior seminar. As a part of her mission to increase understanding of evolution, Lisa also teaches a nonmajors course called Evolution for Future Presidents and is on the Teacher Advisory Board for the Understanding Evolution website developed by the University of California Museum of Paleontology. Lisa is also deeply committed to promoting opportunities in science for women and underrepresented minorities. Lisa is also a co-author of *Campbell Biology in Focus*.

Michael L. Cain Michael Cain is an ecologist and evolutionary biologist who is now writing full-time. Michael earned a joint degree in biology and math at Bowdoin College, an M.Sc. from Brown University, and a Ph.D. in ecology and evolutionary biology from Cornell University. As a faculty member at New Mexico State University and Rose-Hulman Institute of Technology, he taught a wide range of courses, including introductory biology, ecology, evolution, botany, and conservation biology. Michael is the author of dozens of scientific papers on topics that include foraging behaviour in insects and plants, long-distance seed dispersal, and speciation in crickets. In addition to his work on *CAMPBELL BIOLOGY* and *Campbell Biology in Focus*, Michael is the lead author of an ecology textbook.

Steven A. Wasserman Steve Wasserman is Professor of Biology at the University of California, San Diego (UCSD). He earned his A.B. in biology from Harvard University and his Ph.D. in biological sciences from MIT. Through his research on regulatory pathway mechanisms in the fruit fly *Drosophila*, Steve has contributed to the fields of developmental biology, reproduction, and immunity. As a faculty member at the University of Texas Southwestern Medical Center and UCSD, he has taught genetics, development, and physiology to undergraduate, graduate, and medical students. He currently focuses on teaching introductory biology. He has also served as the research mentor for more than a dozen doctoral students and more than 50 aspiring scientists at the undergraduate and high school levels. Steve has been the recipient of distinguished scholar awards from both the Markey Charitable Trust and the David and Lucile Packard Foundation. In 2007, he received UCSD's Distinguished Teaching Award for undergraduate teaching. Steve is also a co-author of *Campbell Biology in Focus*.

Peter V. Minorsky Peter Minorsky is Professor of Biology at Mercy College in New York, where he teaches introductory biology, evolution, ecology, and botany. He received his A.B. in biology from Vassar College and his Ph.D. in plant physiology from Cornell University. He is also the science writer for the journal *Plant Physiology*. After a postdoctoral fellowship at the University of Wisconsin at Madison, Peter taught at Kenyon College, Union College, Western Connecticut State University, and Vassar College. His research interests concern how plants sense environmental change. Peter received the 2008 Award for Teaching Excellence at Mercy College. Peter is also a co-author of *Campbell Biology in Focus*.

Jane B. Reece Jane Reece was Neil Campbell's longtime collaborator, and she has participated in every edition of *CAMPBELL BIOLOGY*. Earlier, Jane taught biology at Middlesex County College and Queensborough Community College. She holds an A.B. in biology from Harvard University, an M.S. in microbiology from Rutgers University, and a Ph.D. in bacteriology from the University of California, Berkeley. Jane's research as a doctoral student at UC Berkeley and postdoctoral fellow at Stanford University focused on genetic recombination in bacteria. Besides her work on *CAMPBELL BIOLOGY*, she has been a co-author on *Campbell Biology in Focus*, *Campbell Biology: Concepts & Connections*, *Campbell Essential Biology*, and *The World of the Cell*.

Neil A. Campbell Neil Campbell (1946–2004) combined the investigative nature of a research scientist with the soul of an experienced and caring teacher. He earned his M.A. in zoology from the University of California, Los Angeles, and his Ph.D. in plant biology from the University of California, Riverside, where he received the Distinguished Alumnus Award in 2001. Neil published numerous research articles on desert and coastal plants and how the sensitive plant (*Mimosa*) and other legumes move their leaves. His 30 years of teaching in diverse environments included introductory biology courses at Cornell University, Pomona College, and San Bernardino Valley College, where he received the college's first Outstanding Professor Award in 1986. Neil was a visiting scholar in the Department of Botany and Plant Sciences at the University of California, Riverside.

Fiona Rawle Fiona Rawle: (Units 1-3; editor Units 1-8) received her Ph.D. from Queen's University in Kingston, Ontario. She is an Associate Professor, Teaching Stream, at the University of Toronto Mississauga, where she teaches Introduction to Evolution and Evolutionary Genetics, Introductory Genetics, and Molecular Basis of Disease. Fiona's teaching and pedagogical research interests focus on several areas: (1) the development of case studies to immerse students in real-world biological challenges and allow students to connect with material from different perspectives; (2) the development of active learning techniques that can be used in large class settings; and (3) the development of scientific literacy interventions that can be used across the undergraduate biology curriculum. Fiona was the recipient of the 2018 University of Toronto President's Teaching Award, the 2016 University of Toronto Mississauga Teaching Excellence Award, and a 2010 Faculty Award for Teaching Excellence while at Wilfrid Laurier University.

Dion Durnford Dion Durnford (Units 4 and 5) is a professor at the University of New Brunswick, in Fredericton. He earned a B.Sc. in Biology from Dalhousie University and a Ph.D. in Botany from the University of British Columbia. His research has focused on the evolution of light-harvesting antenna systems and the role of these proteins in light harvesting and photo-protection in microalgae. His recent work is examining how microalgae age and their strategies for increasing longevity. Dion was the recipient of the 2002 Faculty of Science Excellence in Teaching award and the 2010 Allan P. Stewart Award for Excellence in Teaching.

Chris Moyes Chris Moyes (Unit 7) is a comparative physiologist, focusing on the muscle biochemistry and energetics. He received his Ph.D. in Zoology from the University of British Columbia (1991) and is currently a Professor in the Department of Biology, Queen's University. He has published more than 100 research papers and contributed to four books. He is co-author of *Principles of Animal Physiology,* first published in 2006.

Mike Latschislaw, University of Manitoba

Kevin Scott Kevin Scott (Units 6 and 8) is a senior instructor at the University of Manitoba where he teaches introductory biology for both biology majors and nonbiology majors; human physiology; and environmental physiology of animal laboratories. In the past, he has also taught courses in ecology for nonbiology majors, immunology, parasitology, and microbiology. He received a B.Sc. in Zoology and a Ph.D. joint between Zoology and Cellular, Molecular, and Microbial Biology at the University of Calgary. As an educator, Dr. Scott's career is centred on teaching and the classroom, where he shares his excitement for biology. His interest in plant biology has grown during his professional career and is a favourite topic in his classroom. Kevin was a co-author of *Campbell Biology: Concepts and Connections*, Canadian Edition.

Brief Contents

Detailed Contents

UNIT 2 THE CELL 99

6 A Tour of the Cell 103

7 Membrane Structure and Function 137

8 An Introduction to Metabolism 155

A01_REEC1716_03_SE_FM.indd 15 11/20/19 1:10 AM

A01_REEC1716_03_SE_FM.indd 20 11/20/19 1:10 AM

Preface

We are honoured to present the Third Canadian Edition of *Campbell BIOLOGY*. For the last three decades, *Campbell BIOLOGY* has been the leading university text in the biological sciences. It has been translated into 19 languages and has provided millions of students with a solid foundation in university-level biology. This success is a testament not only to Neil Campbell's original vision but also to the dedication of thousands of reviewers, who, together with editors, artists, and contributors, have shaped and inspired this work.

Our goals for the Third Canadian Edition include:

- **increasing visual literacy** through new figures, questions, and exercises that build students' skills in understanding and creating visual representations of biological structures and processes
- asking students to **practise scientific skills** by applying scientific skills to real-world problems
- **supporting instructors** by providing teaching modules with tools and materials for introducing, teaching, and assessing important and often challenging topics
- **integrating text and media** to engage, guide, and inform students in an active process of inquiry and learning

Our starting point, as always, is our commitment to crafting text and visuals that are accurate, current, and reflect our passion for teaching biology.

New to This Edition

Here we provide an overview of the new features that we have developed for the Third Canadian Edition; we invite you to explore pages xxvi–xxix for more information and examples.

- **Visualizing Figures** and **Visual Skills Questions** give students practice in interpreting and creating visual representations in biology. The Visualizing Figures have embedded questions that guide students in exploring how diagrams, photographs, and models represent and reflect biological systems and processes. Assignable questions are also available in Mastering Biology to give students practice with the visual skills addressed in the figures.
- **Numeracy Questions** and **Problem-Solving Exercises** challenge students to apply scientific skills and interpret data in solving real-world problems. These exercises are designed to engage students through compelling case studies and provide practice with data analysis skills. Problem-Solving Exercises have assignable versions in Mastering Biology. Some also have more extensive "Solve It" investigations to further explore a given topic.
- **Ready-to-Go Teaching Modules** on key topics provide instructors with assignments to use before and after class, as well as in-class activities that use clickers or Learning Catalytics™ for assessment.
- **Integrated text and media:** Media references in the printed book direct students to the wealth of online self-study resources available to them in the Study Area section of Mastering Biology. In the eText, these resources are integrated directly into the eText. The new online learning tools include:
  - **Figure Walkthroughs** that guide students through key figures with narrated explanations, figure markups, and questions that reinforce important points. Additional questions can be assigned in Mastering Biology.
  - More than **450 animations and videos** that bring biology to life. These include resources from **HHMI BioInteractive** that engage students in topics from the discovery of the double helix to evolution.
  - **Interviews** from the First Edition through the Third Canadian Edition of Campbell BIOLOGY are referenced in the chapter where they are most relevant. The interviews show students the human side of science by featuring diverse scientists talking about how they became interested in what they study, how they began, and what inspires them.
- The impact of climate change at all levels of the biological hierarchy is explored throughout the text, starting with a new figure (Figure 1.12) and discussion in Chapter 1 and concluding with a new Unit 8 Make Connections Figure and expanded coverage on causes and effects of climate change in Chapter 56.
  - As in each new edition of Campbell BIOLOGY, the Third Canadian Edition incorporates new content and pedagogical improvements. These are summarized on pp. vi–viii, following this Preface. Content updates reflect rapid, ongoing changes in technology and knowledge in the fields of genomics, gene editing technology (CRISPR), evolutionary biology, microbiology, and more. In addition, significant

revisions to Unit 8, Ecology, improve the conceptual framework for core ecological topics (such as population growth, species interactions, and community dynamics) and more deeply integrate evolutionary principles.

Our Hallmark Features

Teachers of general biology face a daunting challenge: to help students acquire a conceptual framework for organizing an ever-expanding amount of information. The hallmark features of *CAMPBELL BIOLOGY* provide such a framework while promoting a deeper understanding of biology and the process of science. Chief among the themes of *CAMPBELL BIOLOGY* is **evolution.** Chapters throughout the text include at least one Evolution section that explicitly focuses on evolutionary aspects of the chapter material, and chapters end with an Evolution Connection Question and a Write about a Theme Question.

To help students distinguish the "forest from the trees," each chapter is organized around a framework of three to seven carefully chosen **Key Concepts**. The text, Concept Check Questions, Summary of Key Concepts, and Mastering Biology all reinforce these main ideas and essential facts.

In an effort to act on the Calls to Action from the Truth and Reconciliation Commissioners' Report (2012) , the Canadian authors were committed to including more Indigenous content in this text. Pearson's fist step in this third Canadian edition is to acknowledge and highlight terminologies that come from Indigenous origins and include references to how Traditional Ecological Knowledge (TEK) is being used in Chapter 21 and 54. The authors recognize this is just the beginning in a long process of responding to Truth and Reconciliation with Indigenous Peoples of this land.

Because text and illustrations are equally important for learning biology, **integration of text and figures** has been a hallmark of this text since the first edition. In addition to the new Visualizing Figures, our popular Exploring Figures and Make Connections Figures epitomize this approach. Each Exploring Figure is a learning unit of core content that brings together related illustrations and text. Make Connections Figures reinforce fundamental conceptual connections throughout biology, helping students overcome tendencies to compartmentalize information. The Third Canadian Edition features two new Make Connections Figures. There are also Guided Tour Figures that walk students through complex figures as an instructor would.

To encourage **active reading** of the text, *CAMPBELL BIOLOGY* includes numerous opportunities for students to stop and think about what they are reading, often by putting pencil to paper to draw a sketch, annotate a figure, or graph data. Active reading questions include Make Connections Questions, What If? Questions, Figure Legend Questions, Draw It Questions, Summary Questions, and the new Synthesize Your Knowledge and Interpret the Data Questions. The answers to most of these questions require students to write as well as think and thus help develop the core competency of communicating science.

Finally, *CAMPBELL BIOLOGY* has always featured **scientific inquiry**, an essential component of any biology course. Complementing stories of scientific discovery in the text narrative, the unit-opening interviews, and our standard-setting Inquiry Figures all deepen the ability of students to understand how we know what we know. Scientific Inquiry Questions give students opportunities to practise scientific thinking, along with the Problem-Solving Exercises, Scientific Skills Exercises, and Interpret the Data Questions. Together, these activities provide students practice both in applying the process of science and in using quantitative reasoning.

Mastering Biology®

Mastering Biology, the most widely used online assessment and tutorial program for biology, provides an extensive library of homework assignments that are graded automatically. In addition to the **new Figure Walkthroughs, Problem-Solving Exercises, and Visualizing Figures**, Mastering Biology offers Dynamic Study Modules, Adaptive Follow-Up Assignments, Scientific Skills Exercises, Interpret the Data Questions, Solve It Tutorials, HHMI Bio-Interactive Short Films, BioFlix. Tutorials with 3-D Animations, Experimental Inquiry Tutorials, Interpreting Data Tutorials, BLAST Tutorials, Make Connections Tutorials, Video Field Trips, Video Tutor Sessions, Get Ready for Biology, Activities, Reading Quiz Questions, Student Misconception Questions, 4500 Test Bank Questions, and Mastering Biology Virtual Labs. Mastering Biology also includes the *CAMPBELL BIOLOGY* eText, Study Area, and Instructor Resources. Go to www.masteringbiology.com for more details.

Our Partnership with Instructors and Students

A core value underlying our work is our belief in the importance of a partnership with instructors and students. One primary way of serving instructors and students, of course, is providing a text that teaches biology well. In addition, Pearson Education offers a rich variety of instructor and student resources, in both print and electronic form. In our continuing efforts to improve the book and its supplements, we benefit tremendously from instructor and student feedback, not only in formal reviews from hundreds of scientists, but also via e-mail and other forms of informal communication.

The real test of any textbook is how well it helps instructors teach and students learn. We welcome comments from both students and instructors. Please address your suggestions to Fiona Rawle, Lead Author, at fiona.rawle@utoronto.ca, and Cathleen Sullivan, Executive Acquisitions Editor, cathleen.sullivan@pearsoned.com

New and Featured Content

This section highlights selected new and featured content and organizational changes in *CAMPBELL BIOLOGY,* Third Canadian Edition.

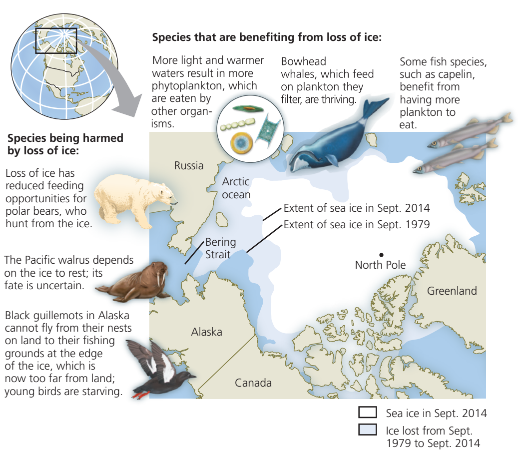
CHAPTER 1 Evolution, the Themes of Biology, and Scientific Inquiry

To help students focus on the big ideas of biology, we continue to emphasize five themes: Organization, Information, Energy and Matter, Interactions, and the core theme of Evolution. Chapter 1 opens with a new introduction to a case study about the Canadian Yew tree.

UNIT 1 THE CHEMISTRY OF LIFE

In Unit 1, new content engages students in learning this foundational material. The new **Figure 3.7** shows organisms affected by **loss of Arctic sea ice**. Chapter 5 has updates on lactose intolerance, trans fats, the effects of diet on blood cholesterol, protein sequences and structures, and intrinsically disordered proteins. New Visualizing Figure 5.16 helps students understand various ways proteins are depicted. A new Problem-Solving Exercise engages students by having them compare DNA sequences in a case of possible fish fraud. Unit 1 also highlights research by the Department of Fisheries and Oceans, discussion of Frances Oldham Kelsey and thalidomide, as well as work by Edward Fon and Kalle Gehring from McGill University on the structure of the parkin protein. A new interview featuring Roberta Hamme, from the University of Victoria, is also included.

Figure 3.7 Effects of climate change on the Arctic.



UNIT 2 THE CELL

Our main goal for this unit was to make the material more accessible and inviting to students. New Visualizing Figure 6.32 shows the profusion of molecules and structures in a cell, all drawn to scale. In Chapter 7, a new figure illustrates levels of LDL receptors in people with and without familial hypercholesterolemia. Chapter 8 includes a beautiful new photo of a geyser with thermophilic bacteria in Figure 8.17, bringing to life the graphs of optimal temperatures for enzyme function. Chapter 10 discusses current research trying to genetically modify rice (a C3 crop) so that it is capable of carrying out C4 photosynthesis to increase yields. Chapter 11 includes a new Problem-Solving Exercise that guides students through assessing possible new treatments for bacterial infections by blocking quorum sensing. In Chapter 12, the mechanism of chromosome movement in bacteria has been updated and more cell cycle control checkpoints have been added, including one recently proposed by researchers. Unit 2 also features the identification of LHON mutations by Eric Shoubridge at McGill University; the International Cancer Genome Consortium, co-founded by Thomas Hudson, Scientific Director of the Ontario Institute of Cancer Research; and work on membrane proteins by Frances Sharom at the University of Guelph. A new interview featuring Jason Treberg, from the University of Manitoba, is also included.

UNIT 3 GENETICS

In Chapters 13–17, we have incorporated changes that help students grasp the more abstract concepts of genetics and their chromosomal and molecular underpinnings. For example, a new Visual Skills Question with Figure 13.6 asks students to identify where in the three life cycles haploid cells undergo mitosis, and what type of cells are formed. Chapter 14 includes new information from a recent genomic study on the number of genes and genetic variants contributing to height. Chapters 14 and 15 are more inclusive, clarifying the meaning of the term "normal" in genetics and explaining that sex is no longer thought to be simply binary. Other updates in Chapter 15 include new research in sex determination and a technique being developed to avoid passing on mitochondrial diseases. New Visualizing Figure 16.7 shows students various ways that DNA is illustrated. To help students understand the Beadle and Tatum experiment, new Figure 17.2 explains how they obtained nutritional mutants. A new Problem-Solving Exercise asks students to identify mutations in the insulin gene and predict their effect on the protein. Chapters 18–21 are extensively updated, driven by exciting new discoveries based on DNA sequencing and gene-editing technology. Chapter 18 has updates on histone modifications, nuclear location and the persistence of transcription factories, chromatin remodelling by ncRNAs, long noncoding RNAs (lncRNAs), the role of master regulatory genes in modifying chromatin structure, and the possible role of p53 in the low incidence of cancer in elephants. Make Connections Figure 18.27, "Genomics, Cell Signalling, and Cancer," has been expanded to include more information on cell signaling. Chapter 19 expands the section that covers bacterial defences against bacteriophages and describes the CRISPRCas9 system (Figure 19.8); updates include the Ebola, Chikungunya, and Zika viruses (Figure 19.12) and discovery of the largest virus known to date. A discussion has been added of mosquito transmission of diseases and concerns about the effects of global climate change on disease transmission. In Chapter 21, in addition to the usual updates of sequence-related data (speed of sequencing, number of species' genomes sequenced, etc.), there are several research updates, including some early results from the new Roadmap Epigenomics Project and results from a 2015 study focusing on 414 important yeast genes.

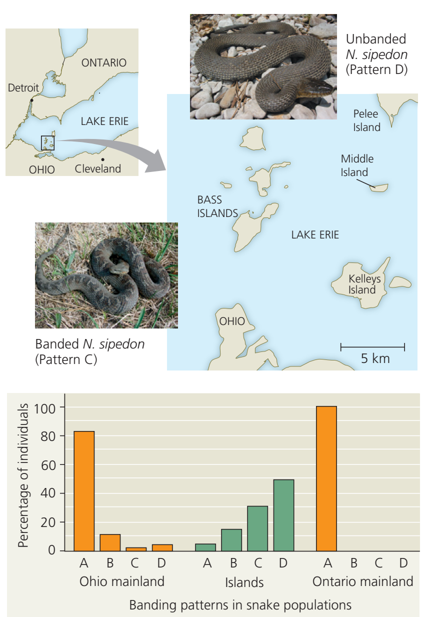
Unit 3 also features the work of Stephen Scherer, who produced a detailed annotated map and DNA sequence of human chromosome 7; Calvin Harley and the discovery of telomeres; Michael Houghton, whose research team recently developed a vaccine for the hepatitis C virus at the University of Alberta; the

Michael Smith Genome Sciences Centre in Vancouver, which generated the first genome sequence of SARS; Frank Plummer at the National Microbiology Laboratory in Winnipeg, whose team sequenced the full genome of H1N1 flu samples; James Till and Ernest McCulloch, the Canadian scientists who discovered stem cells; and Michael Rudnicki, who led the team that discovered adult muscle stem cells at the Sprott Centre for Stem Cell Research in Ottawa. In addition, a range of genomics research in Canada is featured in the updated Exploring Figure 21.6. A new interview featuring Julie Claycomb, from the University of Toronto, is also included.

UNIT 4 MECHANISMS OF EVOLUTION

A major goal for this revision was to strengthen how we help students understand and interpret visual representations of evolutionary data and concepts. Toward this end, we have added a new figure (Figure 25.8), "Visualizing the Scale of Geologic Time," and a new figure (Figure 23.11) on gene flow. Several figures have been revised to improve the presentation of data, including Figure 24.6 (on reproductive isolation in mosquitofish), Figure 24.10 (on allopolyploid speciation), and Figure 25.26 (on the origin of the insect body plan). A new Problem-Solving Exercise is included in Chapter 24 on how hybridization may have led to the spread of insecticide resistance genes in mosquitoes that transmit malaria. The unit also includes new chapter opening stories in Chapter 22 (expanding on the evolution of the bombardier beetle defence mechanism) and Chapter 23 (on the Vancouver Island marmot and population change over time). Additional changes include new text in Concept 22.3 emphasizing how populations can evolve over short periods of time, a new table (Table 23.1) highlighting the five conditions required for a population to be in Hardy-Weinberg equilibrium, and new material in Concept 25.1 describing how researchers recently succeeded for the first time in constructing a "protocell" in which replication of a template strand of RNA could occur. Unit 4 includes updated data on MRSA incidence at Canadian hospitals, and profiles the research of Darla Zelenitsky at the University of Calgary on the discovery of a winged dinosaur with feathers in the Badlands of Alberta, the research of Hans Larsson from McGill University on phenotype plasticity in tetrapods, and the research of Charles Henderson and others who pinpointed the end-Permian mass extinction. A new interview featuring Maydianne Andrade, from the University of Toronto Scarborough, is also included.

Figure 23.11 Gene flow and local adaptation in the Lake Erie water snake (*Nerodia sipedon*).



UNIT 5 THE EVOLUTIONARY HISTORY OF BIOLOGICAL DIVERSITY

In keeping with our goal of improving how students interpret and create visual representations in biology, we have added a new figure (Figure 26.6, "Visualizing Phylogenetic Relationships") that introduces the visual conventions used in phylogenetic trees and helps students understand what such trees do and don't convey. Students are also provided many opportunities to practise their visual skills, with more than ten new Visual Skills Questions on topics ranging from interpreting phylogenetic trees to predicting which regions of a bacterial flagellum are hydrophobic. The unit also contains new content on tree thinking, emphasizing such key points as how sister groups provide a clear way to describe evolutionary relationships and how trees do not show a "direction" in evolution. Other major content changes include new text in Concepts 26.6, 27.4, and 28.1 on the 2015 discovery of the Lokiarchaeota, a group of archaea that may represent the sister group of the eukaryotes, new text and a new figure (Figure 26.22) on horizontal gene transfer from prokaryotes to eukaryotes, new text in Concept 27.6 describing the CRISPR-Cas9 system and a new figure (Figure 27.22) that illustrates one example of how CRISPR-Cas 9 technology has opened new avenues of research on HIV, and new material in Concept 29.3 describing how early forests contributed to global climate change (in this case, global cooling). A new Problem-Solving Exercise in Chapter 34 engages students in interpreting data from a study investigating whether frogs can acquire resistance to a fungal pathogen through controlled exposure to it. Other updates include the revision of many phylogenies to reflect recent phylogenomic data, new chapter-opening stories in Chapter 28 (on the role of heterotrophy in establishing endosymbioses), Chapter 31 (on how mycorrhizae link trees of different species on the importance of yeast in creating ethanol, an important biofuel.) and Chapter 33 (on the visual perception by the eyes of the blue-eyed scallop). There is also new text and a new figure (Figure 34.38) on the adaptations of the kangaroo rat to its arid environment, and new material in Concept 34.7, including a new figure (Figure 34.52) describing fossil and DNA evidence indicating that humans and Neanderthals interbred, producing viable offspring. The discussion of human evolution also includes new text and a new figure (**Figure 34.54**) on Homo naledi, the most recently discovered member of the human evolutionary lineage. This unit also highlights research on mycorrhizal networks by Suzanne Simard at the University of British Columbia; research on early eukaryotic evolution by Patrick Keeling at the University of British Columbia; data from COSEWIC (Committee on the Status of Endangered Wildlife in Canada), a profile of the Banff spring snail, and endangered species; the Hydrocarbon Metagenome projects run out of the University of Calgary and the University of Alberta, and the Wildlife DNA Forensic

Figure 34.54 Fossils of hand bones and foot bones (top and side views) of *Homo naledi*.

Laboratory at Trent University. A new interview featuring Laura Hug, from the University of Waterloo, is also included.

UNIT 6 PLANT FORM AND FUNCTION

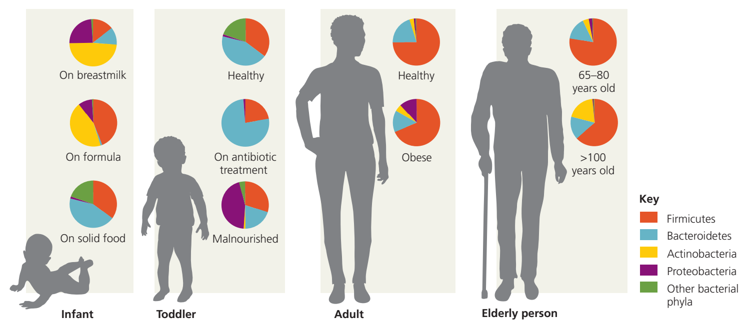
A major aim in revising Chapter 35 was to help students better understand how primary and secondary growth are related. New Visualizing Figure 35.11 enables students to picture growth at the cellular level. Also, the terms protoderm, procambium, and ground meristem have been introduced to underscore the transition of meristematic to mature tissues. A new flowchart (Figure 35.24) summarizes growth in a woody shoot. New text and a figure (Figure 35.26) focus on genome analysis of Arabidopsis ecotypes, relating plant morphology to ecology and evolution. In Chapter 36, new Figure 36.8 illustrates the fine branching of leaf veins, and information on phloem-xylem water transfer has been updated. New Make Connections Figure 37.10 highlights mutualism across kingdoms and domains. Figure 37.13 and the related text include new findings on how some soil nitrogen derives from weathering of rocks. New Figure 38.3 clarifies how the terms *carpel* and *pistil* are related. The text on flower structure and the angiosperm life cycle figure identify carpels as megasporophylls and stamens as microsporophylls, correlating with the plant evolution discussion in Unit 5. In Concept 38.3, the current problem of glyphosate-resistant crops is discussed in detail. A revised Figure 39.7 helps students visualize how cells elongate. Figure 39.8 now addresses apical dominance in a Guided Tour format. Information about the role of sugars in controlling apical dominance has been added. In Concept 39.4, a new Problem-Solving Exercise highlights how global climate change affects crop productivity. Figure 39.26 on defence responses against pathogens has been simplified and improved.

Amongst others, we highlight the work of Rob Guy at the University of British Columbia on balsam poplar trees; Doug Larson at the University of Guelph on cedars growing out of the rock face of the Niagara Escarpment; R. Keith Downey at the Ministry of Agriculture in Saskatoon and Baldur Stefansson at the University of Manitoba in Winnipeg on canola oil, and Mark Belmonte at the University of Manitoba on disease resistance in plants. An Inquiry Figure features the work of Bruce Greenberg and Bernie Glick at the University of Waterloo on the possible effects of soil bacteria. A new interview featuring Jacqueline Monaghan, from Queen's University, is also included.

UNIT 7 ANIMAL FORM AND FUNCTION

A major goal of the Unit 7 revision was to transform how students interact with and learn from representations of anatomy and physiology. For example, gastrulation is now introduced with a Visualizing Figure (Figure 47.8) that provides a clear and carefully paced introduction to three-dimensional processes that may be difficult for students to grasp. In addition, a number of the new and revised figures help students explore spatial relationships in anatomical contexts, such as the interplay of lymphatic and cardiovascular circulation (Figure 42.15) and the relationship of the limbic system to overall brain structure (Figure 49.14). A new Problem-Solving Exercise in Chapter 45 taps into student interest in medical mysteries through a case study that explores the science behind laboratory testing and diagnosis. Content updates help students appreciate the continued evolution of our understanding of even familiar phenomena, such as the evolution of hemoglobin in high altitude animals (Concept 42.7), the sensation of thirst (Concept 44.4) and the locomotion of kangaroos and jellies (Concept 50.6). Furthermore, new text and figures introduce students to cutting-edge technology relating to such topics as RNA-based antiviral defence in invertebrates (Figure 43.4) and rapid, comprehensive characterization of viral exposure (Figure 43.24), as well as recent discoveries regarding brown fat in adult humans (Figure 40.14), the microbiome (Figure 41.18), parthenogenesis (Concept 46.1), and magnetoreception (Concept 50.1). As always, there is fine-tuning of pedagogy, as in discussions of the complementary roles of inactivation and voltage gating of ion channels during action potential formation (Concept 48.3) and of the experimental characterization of genetic determinants in bird migration (Figure 51.24). Additional research highlighted in this unit includes Janet Rossant at the University of Toronto on cell fate determination; Naweed Syed at the University of Calgary on synaptic repair; University of British Columbia researchers exploring the impact of global warming trends on salmon; University of Manitoba explores the evolution of the thermogenin gene in mammals; Karen Kidd at the University of New Brunswick on environmental estrogens; Barrie Frost of Queen's University, who explored the navigational mechanisms used by monarch butterflies; and Suzie Currie of Mount Allison University on phenotypic plasticity and environmental stress. A new interview featuring Matt Vijayan, from the University of Calgary, is also included.

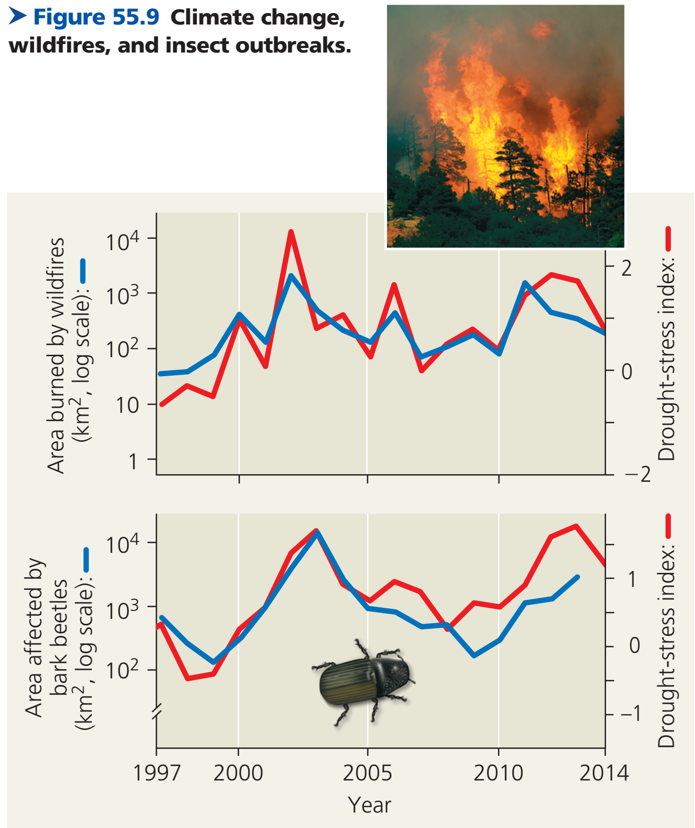
Figure 41.18 Variation in human gut microbiome at different life stages.



UNIT 8 ECOLOGY

The Ecology Unit has been extensively revised for the Third Canadian Edition. We have reorganized and improved the conceptual framework with which students are introduced to the following core ecological topics: life tables, per capita population growth, intrinsic rate of increase ("r"), exponential population growth, logistic population growth, density dependence, species interactions (in particular, parasitism, commensalism, and mutualism), and MacArthur and Wilson's island biogeography model. The revision also includes a deeper integration of evolutionary principles, including a new Key Concept (52.5) and two new figures (Figures 52.20 and 52.21) on the reciprocal effects of ecology and evolution, new material in Concept 52.4 on how the geographic distributions of species are shaped by a combination of evolutionary history and ecological factors, and five new Make Connections Questions that ask students to examine how ecological and evolutionary mechanisms interact. In keeping with our goal of expanding and strengthening our coverage of climate change, we have added a new discussion and a new figure (Figure 52.20) on how climate change has affected the distribution of a keystone species, a new section of text in Concept 55.2 on how climate change affects NPP, a new figure (**Figure 55.9**) on how climate change has caused an increase in wildfires and insect outbreaks, a new Problem-Solving Exercise in Chapter 55 that explores how insect outbreaks induced by climate change can cause an ecosystem to switch from a carbon sink to a carbon source, a new figure (Figure 56.29) on the greenhouse effect, new text in Concept 56.4 on biological effects of climate change, and a new Unit 8 Make Connections Figure on how climate change affects all levels of biological organization. Additional updates include a new figure (Figure 53.26) on per capita ecological footprints, a new chapter-opening story in Chapter 54 on a seemingly unlikely mutualism between a shrimp and a much larger predatory fish, new text in Concept 54.1 emphasizing that each partner in a mutualism experiences both benefits and costs, new text in Concept 54.1 describing how the outcome of an ecological interaction can change over time, two new figures (Figures 54.29 and 54.30) on the island equilibrium model, a new figure (Figure 54.31) documenting two shrew species as unexpected hosts of the Lyme disease, new text in Concept 56.1 comparing extinction rates today with those typically seen in the fossil record, and a new discussion and figure (Figure 56.20) on the restoration of a degraded urban stream. Unit 8 also profiles the research of David Schindler from the University of Alberta, and Verena Tunnicliffe from the University of Victoria. A new interview featuring Erin Bertrand, from Dalhousie University, is also included. The book ends on a hopeful note, charging students to use biological knowledge to help solve problems and improve life on Earth.

➤ Figure 55.9 Climate change, wildfires, and insect outbreaks.



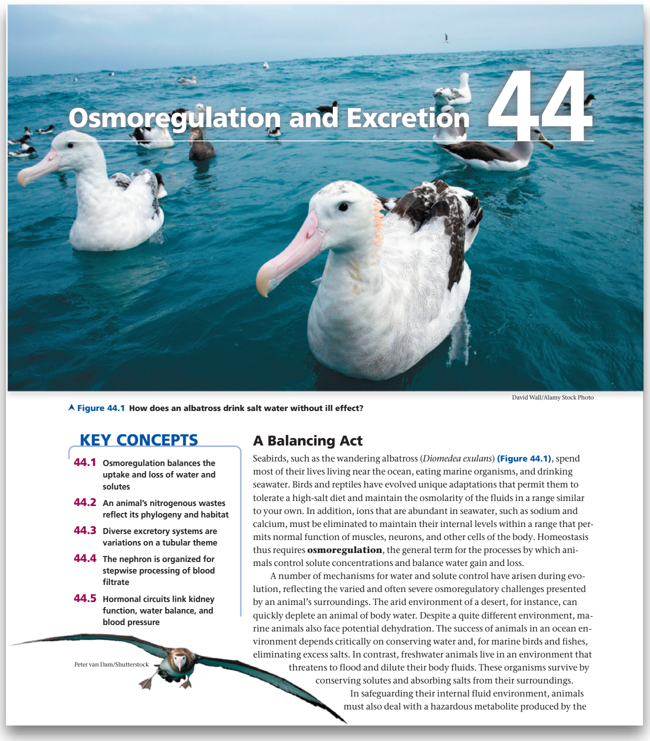
See the Big Picture

KEY CONCEPTS

Each chapter is organized around a framework of 3 to 7 **Key Concepts** that focus on the big picture and provide a context for the supporting details.

Every chapter opens with a visually dynamic **photo** accompanied by an **intriguing question** that invites students into the chapter.

The **List of Key Concepts** introduces the big ideas covered in the chapter.



Osmoregulation and Excretion 44

David Wall/Alamy Stock Photo

Figure 44.1 How does an albatross drink salt water without ill effect?

KEY CONCEPTS

44.1 Osmoregulation balances the uptake and loss of water and solutes

44.2 An animal's nitrogenous wastes reflect its phylogeny and habitat

44.3 Diverse excretory systems are variations on a tubular theme

44.4 The nephron is organized for stepwise processing of blood filtrate

44.5 Hormonal circuits link kidney function, water balance, and blood pressure

Peter van Dam/Shutterstock

A Balancing Act

Seabirds, such as the wandering albatross (*Diomedea exulans*) **(Figure 44.1)**, spend most of their lives living near the ocean, eating marine organisms, and drinking seawater. Birds and reptiles have evolved unique adaptations that permit them to tolerate a high-salt diet and maintain the osmolarity of the fluids in a range similar to your own. In addition, ions that are abundant in seawater, such as sodium and calcium, must be eliminated to maintain their internal levels within a range that permits normal function of muscles, neurons, and other cells of the body. Homeostasis thus requires **osmoregulation**, the general term for the processes by which animals control solute concentrations and balance water gain and loss.

A number of mechanisms for water and solute control have arisen during evolution, reflecting the varied and often severe osmoregulatory challenges presented by an animal's surroundings. The arid environment of a desert, for instance, can quickly deplete an animal of body water. Despite a quite different environment, marine animals also face potential dehydration. The success of animals in an ocean environment depends critically on conserving water and, for marine birds and fishes, eliminating excess salts. In contrast, freshwater animals live in an environment that threatens to flood and dilute their body fluids. These organisms survive by conserving solutes and absorbing salts from their surroundings.

In safeguarding their internal fluid environment, animals must also deal with a hazardous metabolite produced by the

After reading a Key Concept section, students can check their understanding using the **Concept Check Questions**.

Questions throughout the chapter encourage students to **read the text actively**.

What if? Questions ask students to apply what they've learned.

Make Connections Questions ask students to relate content in the chapter to material presented earlier in the course.

CONCEPT CHECK 44.5

1. How does alcohol affect regulation of water balance in the body?
2. Why could it be dangerous to drink a very large amount of water in a short period of time?
3. **WHAT IF?** > Conn's syndrome is a condition caused by tumours of the adrenal cortex that secrete high amounts of aldosterone in an unregulated manner. What would you expect to be the major symptom of this disorder?

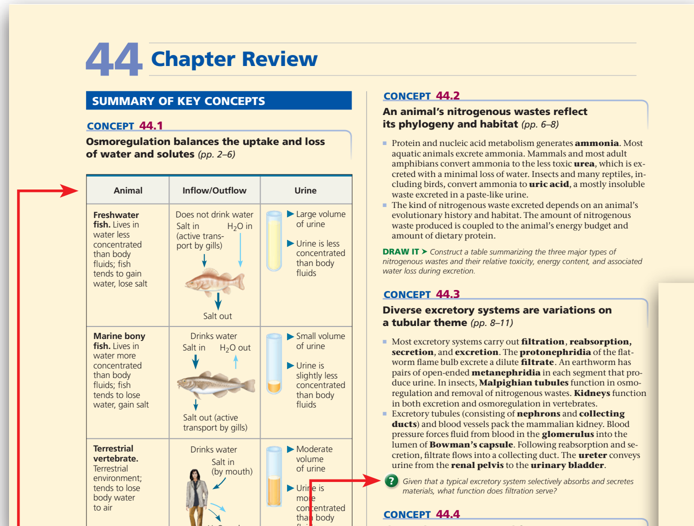
For suggested answers, see Appendix A.

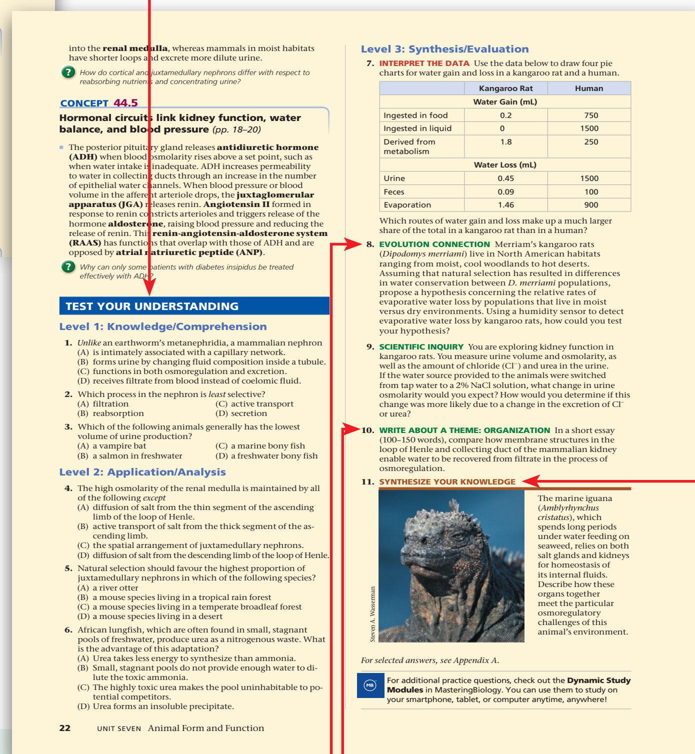
The **Summary of Key Concepts** refocuses students on the main points of the chapter.

Test Your Understanding Questions at the end of each chapter are organized into three levels based on **Bloom's Taxonomy**:

- Level 1: Knowledge/Comprehension
- Level 2: Application/Analysis
- Level 3: Synthesis/Evaluation

Test Bank questions and multiple-choice questions in Mastering Biology® are also categorized by Bloom's Taxonomy.





Summary Figures recap key information in a visual way.

Summary of Key Concepts Questions check students' understanding of a key idea from each concept.

THEMES

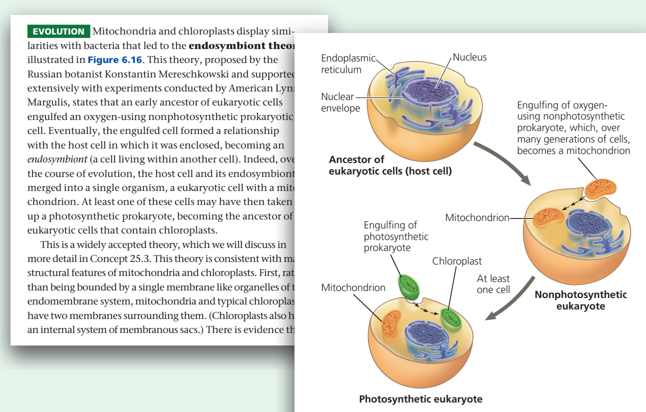
To help students focus on the big ideas of biology, five **themes** are introduced in Chapter 1 and woven throughout the text:

- Evolution
- Organization
- Information
- Energy and Matter
- Interactions

To reinforce the themes, every chapter ends with an **Evolution Connection Question** and a **Write About a Theme Question**.

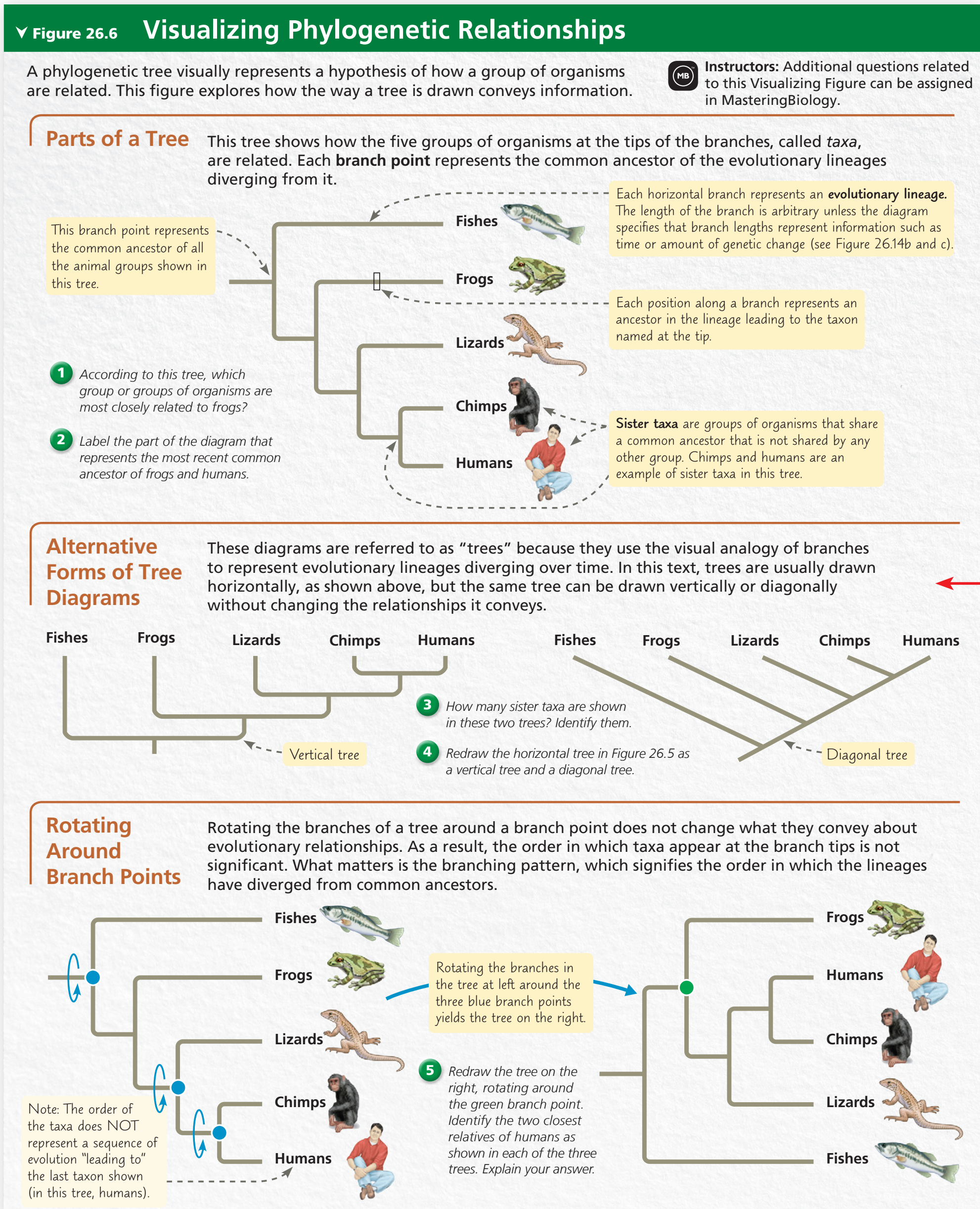
Synthesize Your Knowledge Questions ask students to apply their understanding of the chapter content to explain an intriguing photo.

Every chapter has a section explicitly relating the chapter content to **evolution**, the fundamental theme of biology.



Build Visual Skills

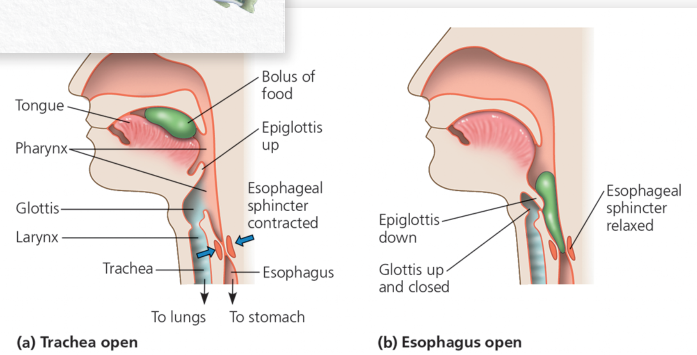
NEW! Visualizing Figures teach students how to interpret diagrams and models in biology. Embedded questions give students practice applying visual skills as they read the figure.



For more practice, each Visualizing Figure is accompanied by an automatically graded assignment in Mastering Biology with feedback for students.

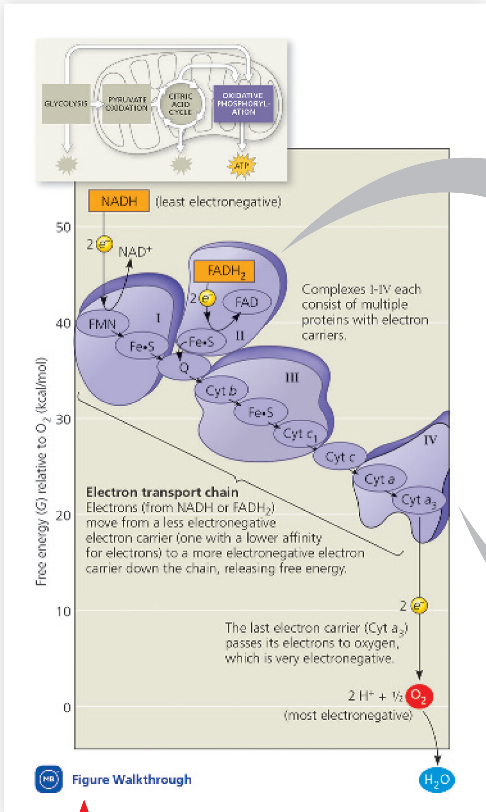
Visualizing Figures include:

Visual Skills Questions give students practice interpreting illustrations and photos in the text.

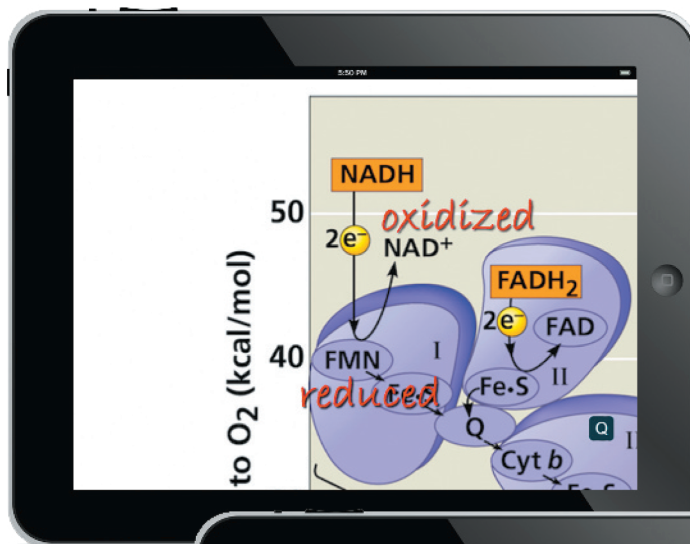


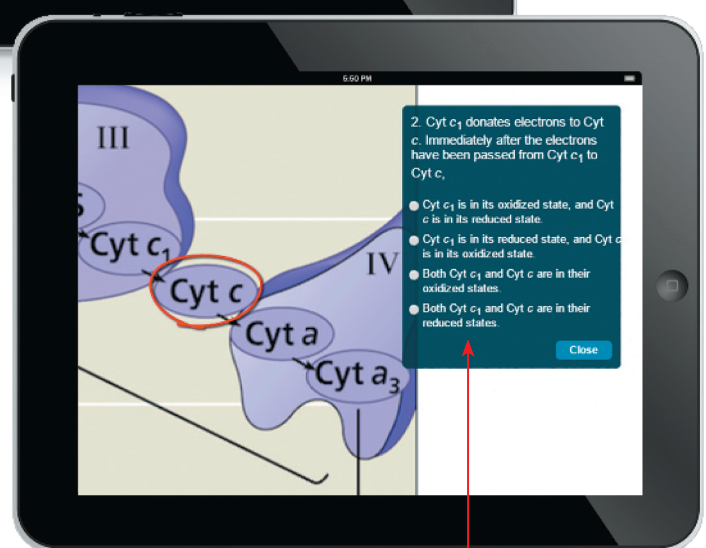
VISUAL SKILLS ➤ *If you laugh while drinking water, the liquid may be ejected from your nostrils. Use this diagram to explain why this happens, taking into account that laughing involves exhaling.*

Figure Walkthroughs guide students through key figures with narrated explanations, figure markups, and questions that reinforce important points.



A note in the print book lets students and instructors know when a Figure Walkthrough is available in the Study Area.





Questions embedded in each Figure Walkthrough encourage students to be active participants in their learning. The Figure Walkthroughs can also be assigned in Mastering Biology with higher-level questions.

Figure 2.17
Photosynthesis: a solar-powered rearrangement of matter. *Elodea*, a freshwater plant, produces sugar by rearranging the atoms of carbon dioxide and water in the chemical process known as photosynthesis, which is powered by sunlight. Much of the sugar is then converted to other food molecules. Oxygen gas (O_2) is a by-product of photosynthesis; notice the bubbles of O_2 gas escaping from the leaves submerged in water.

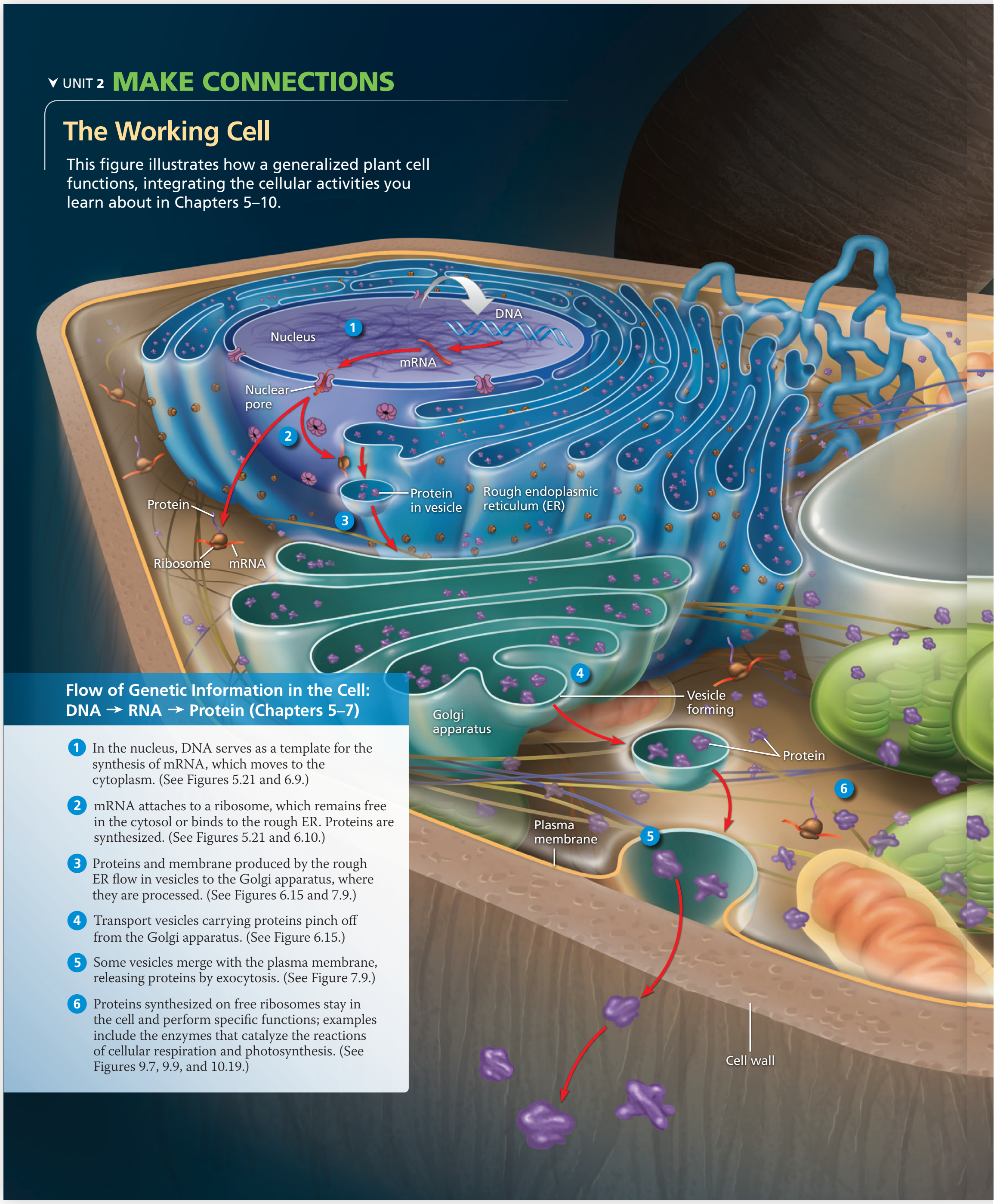
DRAW IT *Add labels and arrows on the photo showing the reactants and products of photosynthesis as it takes place in a leaf.*

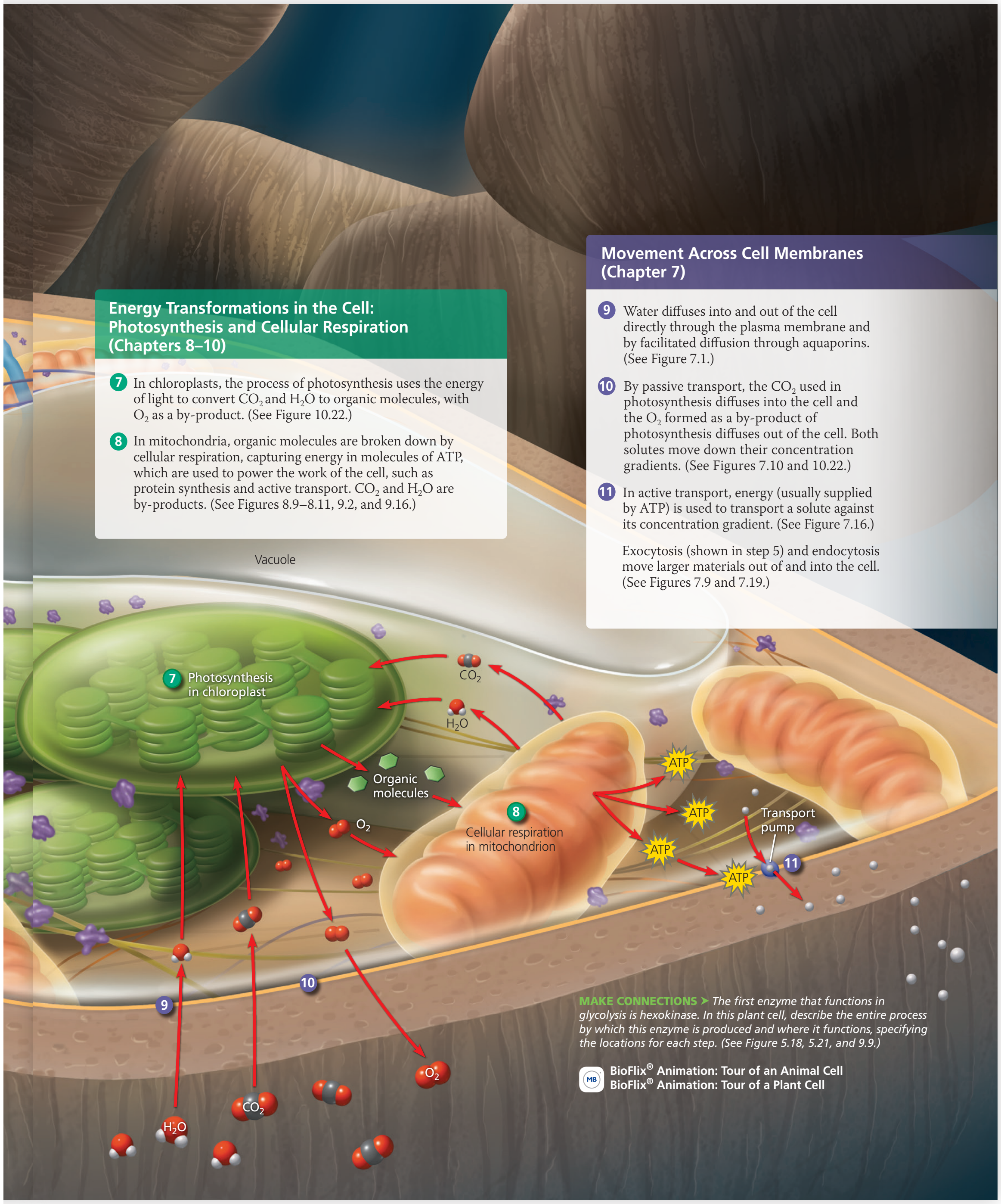
EXPANDED! Draw It exercises give students practice creating visuals. Students are asked to put pencil to paper and draw a structure, annotate a figure, or graph experimental data.

Make Connections Visually

Make Connections Figures pull together content from different chapters, providing a visual representation of "big picture" relationships.

Make Connections Figures include:





Make Connections Questions ask students to relate content in the chapter to material presented earlier in the course. Every chapter has at least three Make Connections Questions.

Practise Scientific Skills

Scientific Skills Exercises use real data to build key skills needed for biology, including data analysis, graphing, experimental design, and math skills.

Photos provide visual interest and context.

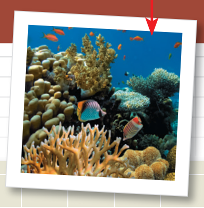
Each Scientific Skills Exercise is based on **an experiment related to the chapter content**.

Most Scientific Skills Exercises use **data from published research**.

Questions build in difficulty, walking students through new skills step by step and providing opportunities for higher-level critical thinking.

SCIENTIFIC SKILLS EXERCISE

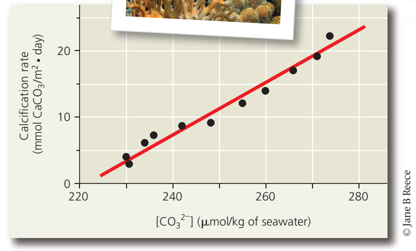
Interpreting a Scatter Plot with a Regression Line



How Does the Carbonate Ion Concentration of Seawater Affect the Calcification Rate of a Coral Reef? Scientists predict that acidification of the ocean due to higher levels of atmospheric CO_2 will lower the concentration of dissolved carbonate ions, which living corals use to build calcium carbonate reef structures. In this exercise, you will analyze data from a controlled experiment that examined the effect of carbonate ion concentration ($[CO_3^{2-}]$) on calcium carbonate deposition, a process called calcification.

How the Experiment Was Done The Biosphere 2 aquarium in Arizona contains a large coral reef system that behaves like a natural reef. For several years, a group of researchers measured the rate of calcification by the reef organisms and examined how the calcification rate changed with differing amounts of dissolved carbonate ions in the seawater.

Data from the Experiment The black data points in the graph form a scatter plot. The red line, known as a linear regression line, is the best-fitting straight line for these points.



Data from "Effect of Calcium Carbonate Saturation State on the Calcification Rate of an Experimental Coral Reef" by Chris Langdon, et al., from *Global Biogeochemical Cycles*, June 2000, Volume 14(2).

INTERPRET THE DATA

1. When presented with a graph of experimental data, the first step in analysis is to determine what each axis represents. (a) In words, explain what is being shown on the *x*-axis. Be sure to include the units. (b) What is being shown on the *y*-axis (including units)? (c) Which variable is the independent variable—the variable that was *manipulated* by the researchers? (d) Which variable is the dependent variable—the variable that responded to or depended on the treatment, which was *measured* by the researchers? (For additional information about graphs, see the Scientific Skills Review in Appendix E and in the Study Area in MasteringBiology.)
2. Based on the data shown in the graph, describe in words the relationship between carbonate ion concentration and calcification rate.
3. (a) If the seawater carbonate ion concentration is 270 µmol/kg, what is the approximate rate of calcification, and approximately how many days would it take 1 square metre of reef to accumulate 30 mmol of calcium carbonate ($CaCO_3$)? (b) If the seawater carbonate ion concentration is 250 µmol/kg, what is the approximate rate of calcification, and approximately how many days would it take 1 square metre of reef to accumulate 30 mmol of calcium carbonate? (c) If carbonate ion concentration decreases, how does the calcification rate change, and how does that affect the time it takes coral to grow?
4. (a) Referring to the equations in Figure 3.12, determine which step of the process is measured in this experiment. (b) Are the results of this experiment consistent with the hypothesis that increased atmospheric $[CO_2]$ will slow the growth of coral reefs? Why or why not?

MB **Instructors:** A version of this Scientific Skills Exercise can be assigned in MasteringBiology.

Each Scientific Skills Exercise **cites the published research**.

EVERY CHAPTER HAS A SCIENTIFIC SKILLS EXERCISE

Apply Scientific Skills to Solving Problems

NEW! Problem-Solving Exercises guide students in applying scientific skills and interpreting real data in the context of solving a real-world problem.

PROBLEM-SOLVING EXERCISE

Are you a victim of fish fraud?

When buying salmon, perhaps you prefer the more expensive wild-caught Pacific salmon (*Oncorhynchus* species) over farmed Atlantic salmon (*Salmo salar*). But studies reveal that about 40% of the time, you aren't getting the fish you paid for!

Instructors: A version of this Problem-Solving Exercise can be assigned in Chapter 5 of MasteringBiology. A more extensive investigation is in Chapter 26 of MasteringBiology.

In this exercise, you will investigate whether a piece of salmon has been fraudulently labelled.

Your Approach The principle guiding your investigation is that DNA sequences from within a species or from closely related species are more similar to each other than are sequences from more distantly related species.

Your Data You've been sold a piece of salmon labelled as coho salmon (*Oncorhynchus kisutch*). To see whether your fish was labelled correctly, you will compare a short DNA sequence from your sample to standard sequences from the same gene for three salmon species. The sequences are:

	Sample labelled as *O. kisutch* (coho salmon)	5′-CGGCACCGCCCTAAGTCTCT-3′
Standard sequences	Sequence for *O. kisutch* (coho salmon)	5′-AGGCACCGCCCTAAGTCTAC-3′
	Sequence for *O. keta* (chum salmon)	5′-AGGCACCGCCCTGAGCCTAC-3′
	Sequence for *Salmo salar* (Atlantic salmon)	5′-CGGCACCGCCCTAAGTCTCT-3′

Your Analysis

1. Scan along the standard sequences (*O. kisutch, O. keta*, and *S. salar*), base by base, circling any bases that do not match the sequence from your fish sample.
2. How many bases differ between (a) *O. kisutch* and your fish sample? (b) *O. keta* and the sample? (c) *S. salar* and the sample?
3. For each standard, what percentage of its bases are identical to your sample?
4. Based on these data alone, state a hypothesis for the species identity of your sample. What is your reasoning?

A version of each Problem-Solving Exercise can also be assigned in Mastering Biology.

Problem-Solving Exercises include:

Ch. 5: Are you a victim of fish fraud? *Shown at left and on p. 95*

Ch. 11: Can a skin wound turn deadly? *p. 224*

Ch. 17: Are insulin mutations the cause of three infants' neonatal diabetes? *p. 380*

Ch. 24: Is hybridization promoting insecticide resistance in mosquitoes that transmit malaria? *p. 548*

Ch. 34: Can declining amphibian populations be saved by a vaccine? *p. 781*

Ch. 39: How will climate change affect crop productivity? *p. 916*

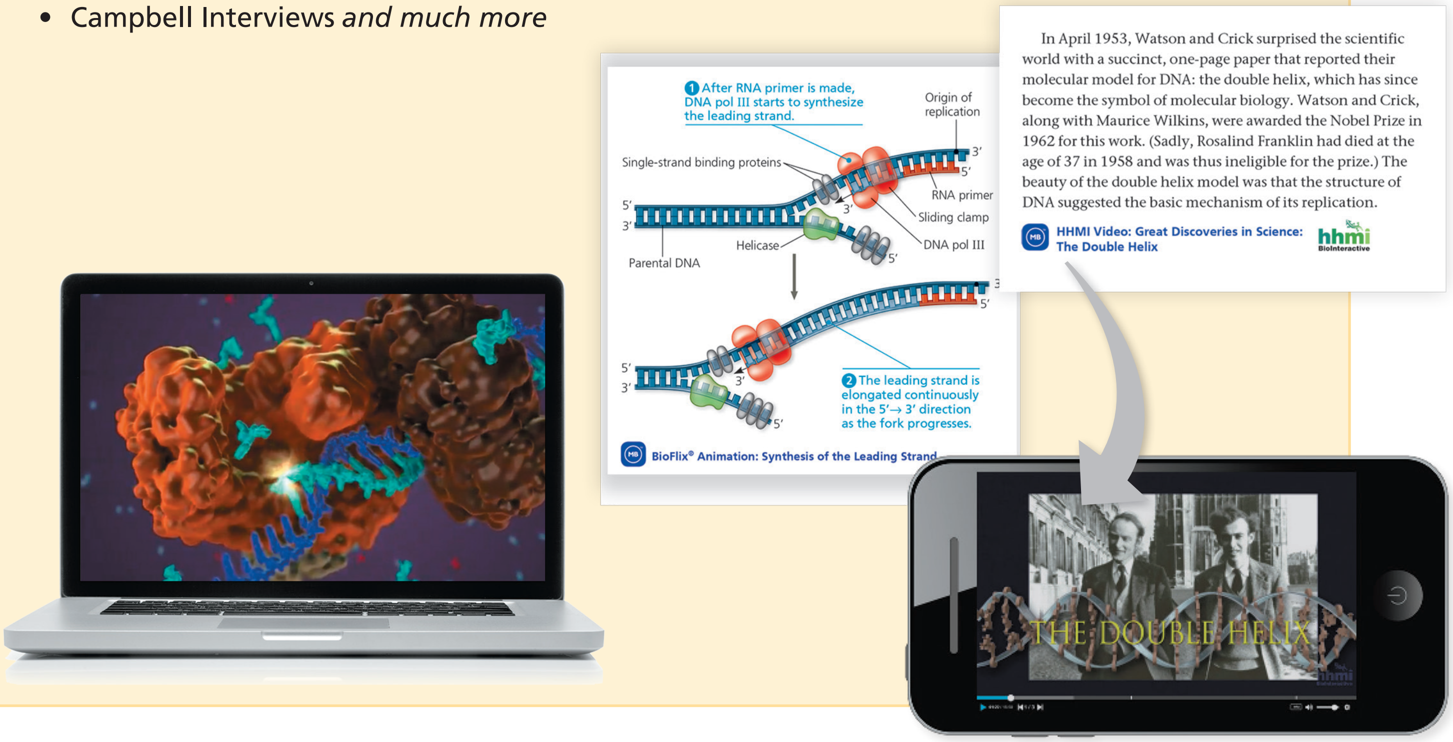
Ch. 45: Is thyroid regulation normal in this patient? *p. 1069*

Bring Biology to Life

Over 400 carefully chosen and edited **videos and animations** have been integrated into the print book, Mastering Biology Study Area, and the eText at point of use to help students learn biology visually.

Media references in the print book direct students to digital resources in the Study Area and the eText:

- Figure Walkthroughs
- HHMI BioInteractive Videos and Animations
- BioFlix Animations
- Campbell Interviews *and much more*



Access the complete textbook online!
The Campbell eText includes powerful interactive and customization functions, such as instructor and student note-taking, highlighting, bookmarking, search, and links to glossary terms.

Featured Figures

Make Connections Figures

Exploring Figures

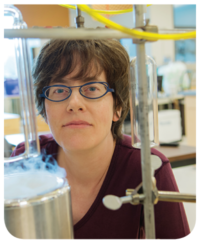
Inquiry Figures

Research Method Figures

Impact Figures

Interviews

UNIT 1 THE CHEMISTRY OF LIFE 27



Roberta Hamme

School of Earth and Ocean Sciences,
University of Victoria

UNIT 2 THE CELL 99

Jason Treberg

Department of Biological Sciences,
University of Manitoba

UNIT 3 GENETICS 267

Julie Claycomb

Department of Molecular Genetics,
University of Toronto

UNIT 4 MECHANISMS OF EVOLUTION 495

Maydianne Andrade

Department of Biological Sciences,
University of Toronto Scarborough

UNIT 5 THE EVOLUTIONARY HISTORY OF BIOLOGICAL DIVERSITY 583

Laura Hug

Environmental Microbiology,
University of Waterloo

UNIT 6 PLANT FORM AND FUNCTION 805

Jacqueline Monaghan

Department of Biology,
Queen's University

UNIT 7 ANIMAL FORM AND FUNCTION 925

Matt Vijayan

Department of Biology Sciences,
University of Calgary

UNIT 8 ECOLOGY 1227

Erin Bertrand

Department of Biology,
Dalhousie University

Acknowledgments

The authors wish to express their gratitude to the global community of instructors, researchers, students, and publishing professionals who have contributed to this edition.

As authors of this text, we are mindful of the daunting challenge of keeping up to date in all areas of our rapidly expanding subject. We are grateful to the many scientists who helped shape this text by discussing their research fields with us, answering specific questions in their areas of expertise, and sharing their ideas about biology education. We are especially grateful to the following, listed alphabetically: Monika Abedin, John Archibald, Chris Austin, Kristian Axelsen, Myriam Barbeau, Jamie Bascom, Ethan Bier, Jorg Bohlmann, Barbara Bowman, Daniel Boyce, Jean DeSaix, Amy Dobberteen, Graham Forbes, Ira Greenbaum, Ken Halanych, Robert Hebbel, Erin Irish, Duncan Irschick, Azarias Karamanlidis, Patrick Keeling, Nikos Kyrpides, Teri Liegler, Gene Likens, Tom Owens, Kevin Peterson, Michael Pollock, Amy Rappaport, Andrew Roger, Andrew Roth, Andrew Schaffner, Thomas Schneider, Alastair Simpson, Doug Soltis, Pamela Soltis, Anna Thanukos, Elisabeth Wade, Phillip Zamore, and Christine Zardecki. In addition, the biologists listed on page xlv provided detailed reviews, helping us ensure the text's scientific accuracy and improve its pedagogical effectiveness. We thank Marty Taylor, author of the Study Guide, for her many contributions to the accuracy, clarity, and consistency of the text; and we thank Carolyn Wetzel, Ruth Buskirk, Joan Sharp, Jennifer Yeh, and Charlene D'Avanzo for their contributions to the Scientific Skills Exercises.

Thanks also to the other professors and students, from all over the world, who contacted the authors directly with useful suggestions. We alone bear the responsibility for any errors that remain, but the dedication of our consultants, reviewers, and other correspondents makes us confident in the accuracy and effectiveness of this text.

Interviews with prominent scientists have been a hallmark of *Campbell Biology* since its inception, and conducting these interviews was again one of the great pleasures of revising the book. To open the eight units of this edition, we are proud to include interviews with Roberta Hamme, Jason Treberg, Julie Claycomb, Maydianne Andrade, Laura Hug, Jacqueline Monaghan, Matt Vijayan, and Erin Bertrand.

This Third Canadian Edition of *Campbell Biology* is the result of the combined efforts of many talented and hardworking people. We wish to extend our heartfelt appreciation to the authors of the U.S. Edition: Jane Reece, Lisa Urry, Michael Cain, Peter Minorsky, Steve Wasserman, and Robert Jackson.

Campbell Biology, Third Canadian Edition, results from an unusually strong synergy between a team of scientists and a team of publishing professionals. Our editorial team at Pearson Canada demonstrated unmatched talents, commitment, and pedagogical insights. Cathleen Sullivan, Executive Portfolio Manager, Kimberly Teska, Senior Marketing Manager, Kamilah Reid-Burrell, Content Manager, Jennifer Murray, Content Developer, Tamara Capar, Media Content Developer, Pippa Kennard, Project Manager, Susan Bindernagel, Copyeditor, Meaghan Lloyd, Project Manager, Permissions.

We likewise appreciate the commitment of the biologists who conducted a meticulous quality check of the textbook's pages. We thank Mike Weber, Michael Durrant, Reehan Mirza, Rachel Krause, Agata Becalska, Sanja-Hinic Frlog, and Sean Modesto. Their subject matter expertise and attention to detail helped the publisher maintain *Campbell Biology's* tradition of accuracy.

The Pearson sales team, which represents *Campbell Biology* on campus, is an essential link to the users of the text. They tell us what you like and don't like about the text, communicate the features of the text, and provide prompt service. We thank them for their hard work and professionalism. For representing our text to our international audience, we thank our sales and marketing partners throughout the world. They are all strong allies in biology education.

Finally, we wish to thank our families and friends for their encouragement and patience throughout this long project. Our special thanks to Adrian, Lucas, Anna, and Emmie (F.R.); Jackie, Dax, and Dana (D.D.); and Janice, Eleanor, and Amelia (K.S.).

Fiona Rawle, Dion Durnford, Chris Moyes, and Kevin Scott

Fiona Rawle dedicates this textbook to Alvin Singh (1988–2019),
a dedicated teaching assistant and passionate instructor.
Alvin embodied so much of what we want in our students:
unlimited curiosity, dedication, collaboration,
patience, integrity, and caring for others.

Reviewers

Canadian Edition Reviewers

Ron Aiken, *Mount Allison University*
Eric Alcorn, *Acadia University*
Edward William Awad, *Vanier College*
Randall Barley, *University of Lethbridge*
Greg Beaulieu, *University of Victoria*
Todd Bishop, *Dalhousie University*
Richard Calve, *Dawson College*
Bruce Campbell, *Okanagan College*
Priscila Castillo-Ruiz, *Champlain Regional College*
Dora Cavallo-Medved, *University of Windsor*
Brett Couch, *University of British Columbia*
David Creasey, *University of Victoria*
Suzie Currie, *Mount Allison University*
Leslie Dafoe, *Sault College of Applied Arts & Technology*
Mrinal Das, *Grant MacEwan University*
Kathy Davies, *Grant MacEwan University*
Vivian Dayeh, *University of Waterloo*
Rajinder Dhindsa, *McGill University*
Heidi Engelhardt, *University of Waterloo*
Kerri Finlay, *University of Regina*
Kevin Friesen, *Grant MacEwan University*
Sheryl Gares, *University of Alberta*
Chris Garside, *University of Toronto*
Sharon Gillies, *University of the Fraser Valley*
Catherine Glass, *Langara College*
Lawrence Hale, *University of Prince Edward Island*
Jonathan Horsman, *Medicine Hat College*
Anna Hicks, *Memorial University*
William Huddleston, *University of Calgary*
Mariola Maja Janowicz, *Concordia University, College of Alberta*
Amy H. Jeon, *Kwantlen Polytechnic University*
Joan Kearvell, *Champlain Regional College*
Carson Keever, *Kwantlen Polytechnic University*
Blaine Legaree, *Keyano College*
Vett Lloyd, *Mount Allison University*
Elaine Dodge Lynch, *Memorial University*
Sharon Mansiere, *Okanagan College*
Paul McMillan, *Capilano University*
Ann Meitz, *Capilano University*
Reehan Mirza, *Nipissing University*
Ivona Mladenovic, *Simon Fraser University*
Betty Mosher, *College of the Rockies*
Michael Mucz, *University of Alberta*
Kirsten Muller, *University of Waterloo*
Ken Naumann, *Langara College*
Tracy O'Connor, *Mount Royal University*
Mary Olaveson, *University of Toronto Scarborough*
Robin Owen, *Mount Royal University*
William Paton, *Brandon University*
Carol Pollock, *University of British Columbia*
Melanie Rathburn, *Mount Royal University*
Scott Reid, *University of British Columbia*
Heidi Richter, *University of the Fraser Valley*
Tatiana Rogasevskaia, *Mount Royal University*
Owen Rowland, *Carleton University*
Eleftherios (Terry) Saropoulos, *Vanier College*
Ross Shaw, *Grant MacEwan University*
Andrew Taylor, *Keyano College*
Sophia Ushinsky, *Concordia University*
Patrick von Aderkas, *University of Victoria*
Richard Walker, *University of Calgary*
Michael Weber, *Carleton University*
Frank Williams, *Langara College*
Tony Williams, *Simon Fraser University*
Sherry Wilson, *Kwantlen Polytechnic University*
Jonathan Wright, *Dalhousie University*