BIOLOG
CONCEPTS & CONNECTIONS

Campbell • Mitchell • Reece

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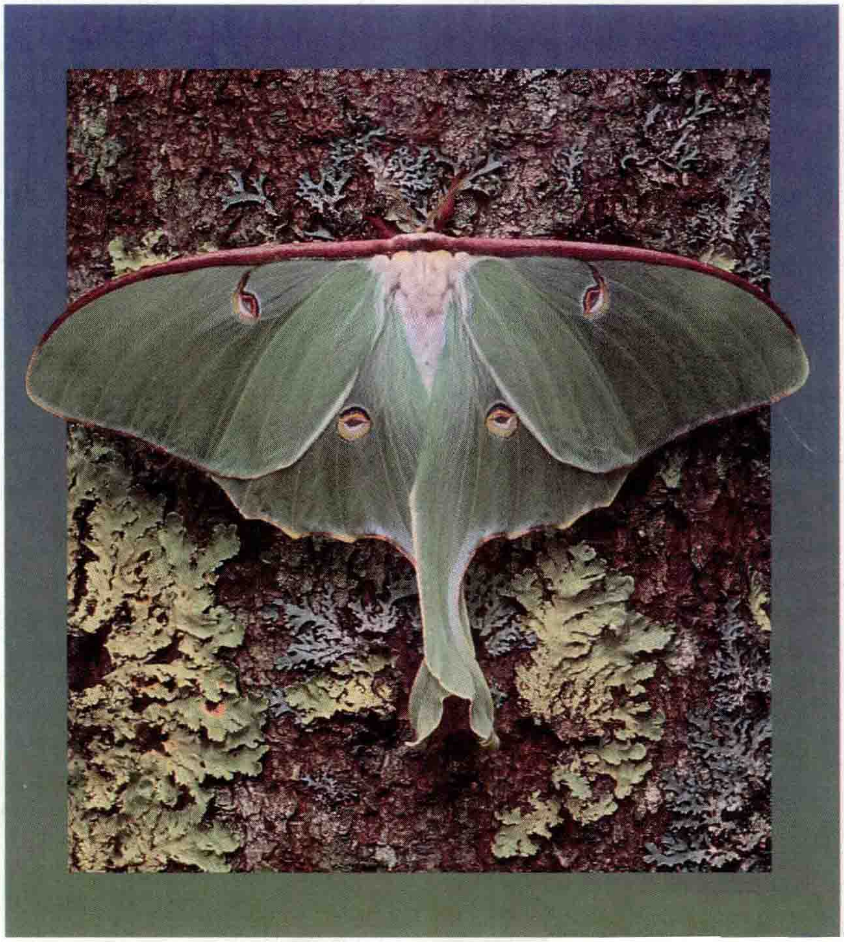
Neil A. Campbell
Lawrence G. Mitchell
Jane B. Reece



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A luna moth on a lichen-covered tree. The luna moth (*Actias luna*) belongs to the family of giant silkworm moths. Found exclusively in North America, the luna moth occurs most frequently in the eastern half of the continent, from southern Canada into Mexico.

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To Rochelle and Allison, with love

N.A.C.

To Mary, Roberta, Wesley, and Ben

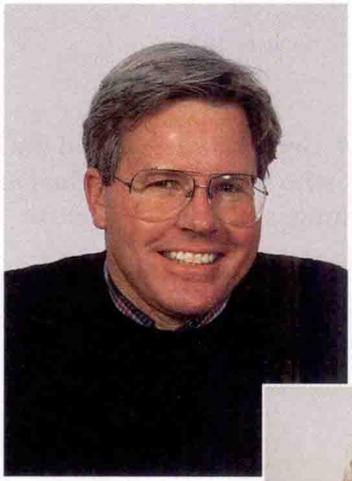
L.G.M.

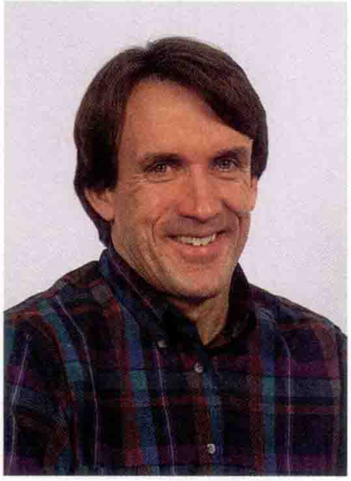
To my parents, George M. Reece and the late
Rose Long Reece, who showed me by their example
that learning is a lifelong endeavor

J.B.R.

About the Authors

Neil Campbell has taught general biology for 25 years and is the author of *Biology*, the most widely used text for biology majors. His enthusiasm for sharing the fun of science with students stems from his own undergraduate experience. He began at Long Beach State College as a history major, but switched to zoology after general education requirements "forced" him to take a science course. Following a B.S. from Long Beach, he earned an M.A. in Zoology from UCLA and a Ph.D. in Plant Biology from the University of California, Riverside. He has published numerous research articles on how certain desert plants survive in salty soil and how the sensitive plant (*Mimosa*) and other legumes move their leaves. His diverse teaching experiences include courses for nonbiology majors at Cornell University, Pomona College, and San Bernardino Valley College, where he received the college's first Outstanding Professor Award in 1986. Dr. Campbell is currently a visiting scholar in the Department of Botany and Plant Sciences at UC Riverside.





Larry Mitchell is an affiliate professor of biological sciences at the University of Montana. He holds a B.S. in Zoology from the Pennsylvania State University and a Ph.D. in Zoology and Microbiology from the University of Montana. Dr. Mitchell has 21 years of experience teaching biology and zoology at both undergraduate and graduate levels, mostly at Iowa State University. While a professor at Iowa State, he helped develop self-paced instruction and videotaped lectures in environmental biology, as part of a science education project sponsored by the National Science Foundation. Dr. Mitchell received the Outstanding Teacher Award at Iowa State in 1982. His research has focused on the ecology and systematics of parasitic protists. In addition to numerous research publications, he has coauthored the textbook *Zoology*, a laboratory manual, and a study guide for introductory biology. He has also developed television courses in general biology and has written, produced, and narrated programs on wildlife biology for public television. Since 1989, Dr. Mitchell has devoted most of his time to writing.

Jane Reece, like her coauthors, has had a career in biology divided among research, teaching, and textbook publishing—but in different proportions. After receiving an A.B. from Harvard University, she did graduate work at Rutgers University and at the University of California, Berkeley, where she earned a Ph.D. in Bacteriology. At Berkeley and later as a postdoctoral fellow at Stanford University, her research focused on genetic recombination in bacteria. She has taught introductory biology to a wide spectrum of students at Middlesex County College (New Jersey) and Queensborough Community College (New York). Since 1978, Dr. Reece has worked in the editorial department at Benjamin/Cummings. She has contributed to all three editions of Neil Campbell's *Biology* and is the sponsoring editor for *Molecular Biology of the Gene*, by James D. Watson et al.

Preface

So much biology, so little time! It's the problem all biology teachers face. How do we share the exciting progress in biology without crushing our students' enthusiasm and curiosity under an overload of information and vocabulary? How do we interest students in biology's connections to their own lives without neglecting basic biological concepts every educated person should understand? The subtitle of this textbook, *Concepts and Connections*, reflects the authors' convictions as teachers and scientists. We believe that students benefit more from developing and applying a framework of general biological concepts than from memorizing specific biological facts. We also believe that a conceptual framework will mean more to students if they understand its connections—how the ideas fit together and how they relate to students' lives. Many colleagues who share these teaching values encouraged us to produce a new kind of textbook; *Biology: Concepts and Connections* is our response.

Concept Modules Focus the Student on Each Chapter's Main Ideas

We created *Biology: Concepts and Connections* primarily to serve college students who are not biology majors, although it is also appropriate for courses that enroll both majors and nonmajors. We have made difficult decisions in balancing breadth and depth—hard choices about which topics to explain in greatest detail, and even harder choices about what to leave out of the book. One trait of the best classroom teachers is their skill at maintaining a focus on the big ideas of biology even as they enrich their students' understanding of these key concepts by judiciously applying a layer of details and useful terminology. It is that teaching model we adopted for *Biology: Concepts and Connections.*

Each chapter of this textbook consists of a series of **concept modules**. The heading of a module—for example, "Chemical cycles in our environment depend on bacteria"—announces a concept we think students should understand. The module's text and illustrations support the concept with explanation and evidence. The illustrations were developed along with the text to teach the concept in an integrated way. For example, if understanding the concept involves learning about some sequential process, such as how a cell builds a protein, then numbered steps in the text correspond to numbers in the illustration. In class-testing, students who described themselves as visual learners said that after they read a module heading, they next studied the figure and then read the text to learn more about the concept. Students who said they were verbal learners read the text right after reading the module heading, and then used the figure to reinforce what they had read. No matter what the student's learning style, the close integration of text and art within a module will keep the focus on the main concept.

We realize from our classroom experience that "getting lost in the forest because of the trees" is the major reason so many biology students fail to develop a conceptual understanding of life. To the beginning student, each bit of information seems equally important, and rote memorization is the unfortunate result. This book's concept modules will help students structure what they learn into a hierarchical scheme, where details and terms are clearly subordinate to the main ideas they support. Moreover, each chapter is structured to help students fit these ideas into an even broader conceptual framework. The concept modules are not isolated chunks of information, but are organized to help students structure their study of biology. Transitional statements and many transitional modules link the modules into a unified lesson that builds on the chapter introduction. In fact, a good way for a student to preview a chapter is to read the introduction and then page through the rest of the chapter to read the module headings. And after reading the chapter, reviewing the module headings is a good way to reinforce the main points.

At the end of each chapter, students will find a summary keyed to the modules, rephrasing the major ideas and directing students to the appropriate places in the chapter where they can work more on any concepts that are still giving them trouble. In crafting chapters that keep students focused on the main ideas instead of "getting lost in the forest," we hope to help students develop study skills that will serve them throughout their education.

Connections Provide Context

A conceptual framework is only as strong as its connections; without a context, even concepts are reduced to facts to be memorized for the next exam. *Biology: Concepts and Connections* helps students integrate what they learn into a context synthesized from content connections (relationships between different biological topics), evolutionary connections, ecological connections, human connections, interdisciplinary connections, and connections to science as a process.

Content Connections A biology course can start with either molecules or ecosystems (or anything in between) and cover the same major concepts by the end of the course.

Biology is cyclical. A textbook, however, is linear, its chapters physically bound into a particular sequence. But in this text, professors will find it remarkably easy to rearrange chapter assignments to fit a variety of syllabi, including an "ecology first" course. The book's versatility is based on content connections that place each field of biology into broader context.

Because the biological level that is often most appealing to students is the organism, we link all other levels, from molecules to ecosystems, to whole organisms. To keep students connected to organisms, each chapter begins with a natural scene painted with words and pictures, an illustrated essay generally concentrating on a particular organism and something interesting about the way it lives. This opening essay sets a context for the chapter by using the organism to introduce the topic at hand, as when the endothermic great white shark introduces "Control of the Internal Environment" (Chapter 25) or the garden spider with its web of silk protein introduces "The Molecules of Cells" (Chapter 3). These chapter introductions are among the places where the book makes content connections that help students integrate the biology they learn, regardless of the order in which they study the chapters.

Evolutionary Connections The book's strong organismal context is complemented by evolutionary connections that help students frame a historical view of biological diversity. For example, we trace the structure and physiology of plants in the evolutionary context of adaptation to the problems of living on land. The evolutionary theme is a unifying thread that runs through the entire book.

Ecological Connections Considering organisms as members of populations, communities, and ecosystems makes their evolutionary adaptations more meaningful for students. For example, the diverse shapes, sizes, and colors of flowers begin to make sense in the context of symbiotic relationships with insects and other pollinators. *Biology: Concepts and Connections* places organisms in their environmental context and builds the interdependence of life into the student's conceptual framework.

Human Connections Students are most readily motivated to learn biological concepts with which they can personally identify—concepts related to issues of health, economic survival, environmental quality, ethical values, and social responsibility. This book connects biology to students' lives with over eighty application modules that apply the basic concepts of chapters to health, social, and environmental concerns. In addition, the text highlights biology's relevance in many of the chapter introductions (hereditary deafness on Martha's Vineyard in Chapter 13, for example) and concept modules. And the learning aids at the end of each chapter include "Science, Technology, and Society" questions that encourage students to integrate biology and its implications into their world view. *Biology: Concepts and Connections* is not a "human biology" text, but we believe that linking concepts to human concerns makes biology more interesting and significant to our students.

Interdisciplinary Connections *Biology: Concepts and Connections* views science as integral to a liberal education and fits biology into the context of a student's other courses. Throughout human history, science and its applications have evolved along with the rest of culture, its priorities shaped in part by the changing interests and needs of society. For example, the exploits of European explorers during the sixteenth and seventeenth centuries helped make the description and classification of biological diversity fashionable. Conversely, science and technology have had a profound impact on every other aspect of culture. The development of agriculture, for instance, was a breakthrough stage in the evolution of civilizations. Many of this book's chapter introductions, modules, and chapter-end questions relate biology to the social sciences and humanities.

Connections to Science as a Process One of the most valuable contributions a biology course can make to students' general education is to give them experience with the power and limitations of the scientific process. *Biology: Concepts and Connections* introduces science as a process in Chapter 1 and illustrates how science works, with examples of key experiments and the historical development of theories in many other chapters. The book also personalizes science with "Talking About Science" modules, short profiles that feature influential scientists and reveal science as a social activity of creative men and women rather than an impersonal collection of facts. And many of the questions at the ends of chapters enable students to practice critical thinking by applying some elements of the scientific process: the development of testable hypotheses and the critical evaluation of evidence for and against those hypotheses. Other chapter-end questions give students a chance to explain biological concepts in their own words. Writing about biology is a great way to learn the subject. In fact, *Biology: Concepts and Connections* will work best for students who participate actively in learning how biology is connected to their lives.

* * * *

Long after students forget most of the specific facts and terms of biology, they will be left with general impressions and attitudes that formed during their semester or two in a general biology course. We hope that *Biology: Concepts and Connections* supports the instructor's goals for sharing the fun of biology. To help us do this even better in the next edition, we invite correspondence from students and instructors to:

Neil Campbell, Larry Mitchell, or Jane Reece
c/o Neil Campbell
Department of Botany and Plant Sciences
University of California
Riverside, CA 92521

Supplements

Study Guide
Richard Liebaert, Linn-Benton Community College

Written by the author of *Biology: Concepts and Connections* end-of-chapter study questions, this study guide offers a variety of interactive exercises.

Instructor's Guide
Fred Rhoades, Western Washington University

This Instructor's Guide contains lecture outlines and instructional activities. It also includes course outlines for instructors who use alternative syllabi. Also available on disk.

Test Bank
Contributions from Deborah Langsam, University of North Carolina-Charlotte, Linda Simpson, University of North Carolina-Charlotte, Lisa Shimeld, Crafton Hills College, David Tauck, Santa Clara University, and Marshall Sundberg, Louisiana State University.

The test bank includes questions at three levels: factual, conceptual, and applications-based. Also available on both IBM and Macintosh test-generating programs. (Available to qualified college adopters.)

Transparency Acetates, Masters, and Slides

All art from *Biology: Concepts and Connections* is available on either full-color acetates or black-line masters, with enlarged labels for effective classroom use. In addition, 35 mm slides are available for the same illustrations that appear as acetates. (Available to qualified college adopters.)

BioShow: The Videodisc

This is a videodisc of text art, original animations, and motion sequences to accompany *Biology: Concepts and Connections.* Art conversion from Neil Campbell's *Biology* to still figures, stepped figures, and animations was developed and executed by Tom Dallman, Ph.D. Art conversion from *Biology: Concepts and Connections* to still figures, stepped figures, and animations was developed by Iain Miller, Ph.D. BioShow is available to qualified college adopters and is accompanied by a barcode manual.

B/C Tutor Animated Tutorial Software
Donald Keefer, Loyola College

This animated tutorial program, keyed to the text, can be used by students for review or for quizzes. Available for both IBM and Macintosh.

Related titles coming in 1995

- **Laboratory Manual with Annotated Instructor's Edition and Preparatory Guide** by Jean L. Dickey, Clemson University
- **The Diversity of Life**, a complement to the diversity coverage in the text, by Lawrence G. Mitchell

Acknowledgments

One of life's great pleasures is working as part of a team. This book has been a team effort at every stage. The nucleus of our team was formed when biology editor Robin Heyden, now executive editor for science at Benjamin/Cummings, brought the three of us together as coauthors. Under Robin's leadership, the project was launched in a novel way, with the immediate formation of a book team representing the full range of publishing functions.

To our delight, our author trio has worked out even better than hoped. Not only have we had fun, but we believe the resulting book is better than any one of us could have produced individually. Senior developmental editor Susan Weisberg was our partner from the book's inception, and she has the unique distinction of being the only person other than ourselves to have read every word of our manuscript at least three times. Susan brought her uncompromisingly high standards, remarkable organizational skills, and extraordinary patience to bear on every module. Susan is a top-notch editor: She helped us keep in mind the overarching goals of the book as she helped us fine-tune the manuscript right down to the level of choosing the best color for the potatoes in a carbohydrate diagram. At the same time, Susan was a continual source of emotional support and realistic perspective.

The book has greatly benefited from the contributions of Richard Liebaert of Linn-Benton Community College, who created the Chapter Review sections. We are grateful to Richard for his patience with our constantly evolving ideas for this material and his incisive suggestions for improving the main text. Richard is also the author of the excellent study guide for the book. We thank Steve Lebsack of Linn-Benton for checking the Answers section in Appendix Three.

Another biologist who contributed substantially to the manuscript is John A. Mutchmor of Iowa State University. We thank John for creating a scientifically sound and well-designed first-draft figure manuscript for Unit Three.

In 1990, Robin Heyden was succeeded as sponsoring editor by Edith Beard Brady, another accomplished and creative editor. Edith brought new enthusiasm and a host of fresh ideas. She became our main "ear" to the needs and trends in introductory biology courses and obtained a wealth of valuable feedback on our manuscript from many dedicated instructors and students. Both Robin and Edith played major roles in shaping the book's vision and in supporting us during its creation. Don O'Neal became sponsoring editor in the spring of 1993 and has been instrumental in pulling together the large supplements package.

We are deeply indebted to all the instructors, students, and others who provided valuable criticisms and suggestions at various stages of the project. We benefited from discussions with numerous colleagues about specific topics. Charles D. Drewes, Eugenia S. Farrar, Richard J. Hoffman, and Edwin C. Powell of Iowa State University and Ira Herskowitz of UC San Francisco were especially helpful. Other colleagues and friends kindly provided photographs for use in the book (see the Photograph Credits in Appendix Four).

Over 100 instructors contributed their scientific and teaching expertise in the form of written reviews of the manuscript. In addition, 52 instructors and 15 students participated in group discussions focusing on various aspects of the book. We are particularly grateful to Mary Harris, Marshall Sundberg, and Kathy Thompson and their students at Louisiana State University for class-testing the second draft of Chapters 2–4 and 14–16. All of these people were crucial members of our team, and we gave serious attention to every one of their comments and suggestions. Nonetheless, we are fully responsible for any errors that remain. We hope readers who find problems will help us improve future editions by telling us about them.

Natasha Banta, Sissy Lemon, Christine Ruotolo, Kimberly Viano, and Thomas Viano provided editorial assistance—mocking up chapters so that reviewers could see, even in draft stages, how the text and art would actually work together; trafficking the many reviews; helping prepare the art manuscript; researching information for last-minute updating; and preparing the manuscript for production. Hilair Chism applied her biological knowledge and eagle eye to checking of the final art. We are especially grateful to Mary Mitchell, who researched new literature and suggested several of the topics for our introductory essays. Thanks also to Daniel Terdiman, Dan Gillen, Trudy Reece, and Marty Granahan for their help.

As the manuscript entered production, we were lucky to have senior developmental editor Pat Burner join the team. Benjamin/Cummings' reigning expert on art manuscript development, Pat played a major role in setting art styles that would give us figures both attractive and pedagogically effective. She also scrutinized the initial page layouts for every chapter, fine-tuning them for optimal clarity and teaching effectiveness. Another top publishing professional, Betsy Dilernia, copyedited our manuscript. Betsy's commitment to excellence and consistency is a model to us all.

Benjamin/Cummings broke new ground in using computer technology in developing and producing this book.

We are grateful to Gary Head of Publishing Principals for guiding Jane through the early months of working in QuarkXPress, for the use of his office and computer during that period, and for instructing her on the basic principles of good page layout. But most of all, we thank him for the clean, functional, inviting chapter design he created; it plays an important part in making our modular approach work. Also contributing significantly to the design and overall look of the book were Benjamin/Cummings art and design manager Michele Carter and designer John Martucci of Martucci Studio, who did most of the final page design. In this area, we also thank Bonnie Grover, who got the project off to a strong start before leaving to teach desktop publishing in Cairo, and Betty Gee, our first art supervisor.

During the production of the book, art supervisor M. Elizabeth Williamson and senior art supervisor Kelly Hall organized and trafficked hundreds of pieces of art. We appreciate their high standards and cooperative attitude when we wanted to make "one more change." We are particularly grateful to Kelly for her herculean efforts during the last two months of production. The book benefited greatly from her extensive production experience, knowledge of biology, professionalism, and creativity. Also working on the illustration program and/or layout were Shirley Bortoli, Val Felts, Denise Schmidt, Karl Miyajima, and Carol Ann Smallwood. It was a pleasure working with all of them, and they contributed to the book in no small way.

We can't talk about the look of the book—or even about how well it presents concepts and connections—without mention of our excellent artists. First, we want to thank all the artists who created art for Neil Campbell's *Biology*, because we made use of many of those pieces for this book. For new and modified figures, we were privileged to have biological artists Carla Simmons, Georg Klatt, Laurie O'Keefe, Barbara Cousins, Mary Bryson, and Kevin Somerville on the team. Carla Simmons, the principal artist on Campbell's *Biology,* also served as our art consultant. We benefited from the experience, knowledge, and talents of all these outstanding artists, both in their own drawings and paintings and in much of the artwork rendered in final form on the computer. Our hardworking computer artists were Terry Toyama, Nea Bisek, Pamela Drury-Wattenmaker, Bill Glass, Tom Dallman, Illustrious, Inc., and JAK Graphics.

Senior photo editor Cecilia Mills and photo researchers Darcy Lanham Wilding and Amy Howorth did a fine job on the challenging photo program. We appreciate their willingness to search far and wide for just the right photograph. (We could illustrate an entire chapter with the out-takes for the sloth photo in Chapter 1!)

The production of the book could not have come together as well as it did without the leadership of senior production editor Anne Friedman. Unflappably professional, Anne kept everything running smoothly, while simultaneously managing to make a number of creative contributions to the book, and we are grateful to her. We also thank executive managing editor Glenda Miles for administrative direction and advice. In addition, we thank final reader Margot Otway and indexer Kathy Pitcoff, who are both unusual in bringing a knowledge of biology to their jobs, and Benjamin/Cummings computer gurus Guy Mills and Ari Davidow. We gratefully acknowledge the important, behind-the-scenes work of composition and film buyer Lillian Hom, manufacturing supervisor Casi Kostecki, and senior manufacturing coordinator Merry Free Osborn in making the book itself an object of beauty and utility.

We also owe thanks to the Benjamin/Cummings marketing department, in particular executive marketing manager Anne Emerson. Anne has been a member of our team from the start. Through mail surveys, campus interviews, focus groups, and additional class-testing, Anne has helped us stay in touch with what professors and students want and need in an introductory biology textbook. Both the look and the content of the book reflect her input. We have enjoyed working with Anne and her staff, especially Nathalie Mainland, David Harris, Bob Ting, Rosemarie Forrest, and freelancer Karryl Nason. And throughout our years of work we have been bolstered by the enthusiastic encouragement of the sales groups.

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Neil Campbell
Larry Mitchell
Jane Reece

Reviewers

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Schoolcraft College
Dick Botwell
Missouri Western State College
Charles Brown
Santa Rosa Junior College
Virginia Buckner
Johnson County Community College
Christine Case
Skyline College
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University of Cincinnati
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Santa Monica College
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City College of San Francisco
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Eastern Michigan University
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Colorado College
Gerald Summers
University of Missouri, Columbia
Corrine Thomas
Saint Louis Community College, Meramec
Mark Wallert
Moorhead State University
Barry Welch
San Antonio College
Edwin Wodehouse
Skyline College

San Francisco City College Student Focus Group Participants

Cindy Erwin and Vic Chow, Faculty Sponsors
Sam Ang
Eric Johnson
Mildred Thomas
Quinton Tieu
Mary Yan

University of North Carolina at Chapel Hill Student Focus Group Participants

Jean DeSaix, Faculty Sponsor
Caroline Ames
Steven Austin
William Graham IV
Eugena Maria Harrington
Meredith Key

North Carolina State University Student Focus Group Participants

James Mickle, Faculty Sponsor
Susan Everett
Patrick Nolan
Dennis Rogers
Gabriel Smith
Mary Zadigian

Manuscript Reviewers

Daryl Adams
Mankato State University
Dawn Adrian Adams
Baylor University
Olushola Adeyeye
Duquesne University
Dan Alex
Chabot College
Sylvester Allred
Northern Arizona University
Jane Aloi
Saddleback College
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James Dekloe
Solano Community College
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Southwest Missouri State University
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University of North Carolina at Chapel Hill
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Clemson University
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St. Louis University
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University of South Carolina
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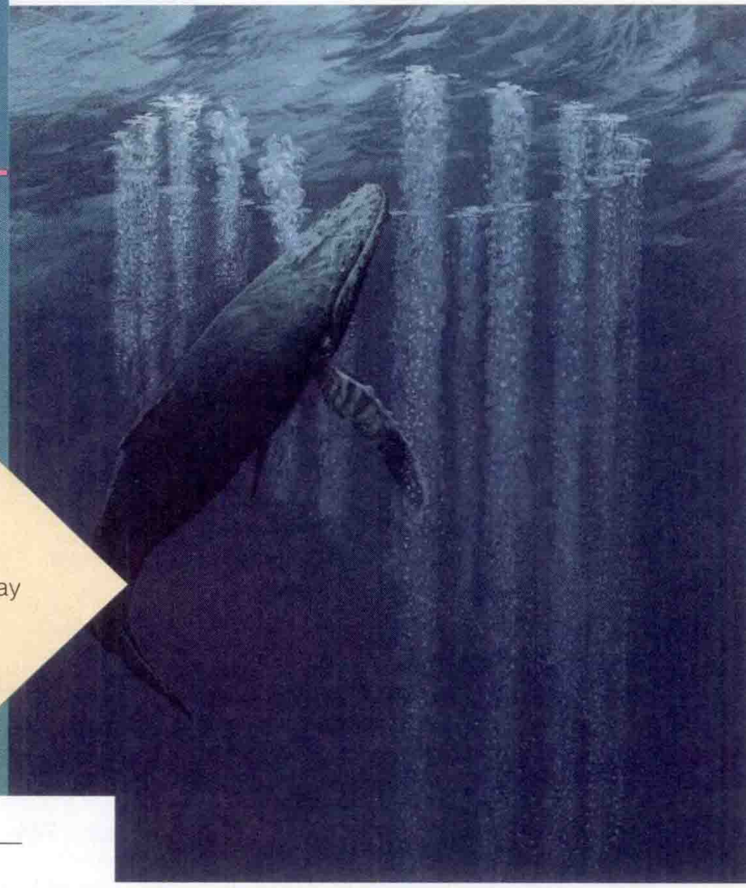


To the Student:

The following four pages show you how to use *Biology: Concepts and Connections* in the most effective way—so you can make studying easier and understand how biology connects with your own life.

Chapter openers are your entry into the chapter

- Most chapters begin with an organism that is representative of the chapter's main subject.
- The illustrated introductory essay tells you about the way the organism lives, its unique characteristics, and how it interacts with its environment.
- You will find references to the organism helping to illustrate concepts later in the chapter.

19.10 Most animals have segmented bodies

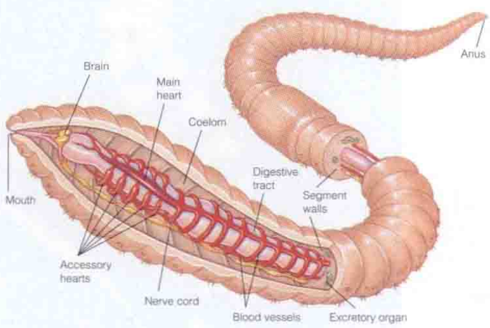
The phyla we will now discuss illustrate another body feature that had profound influence on animal history—body **segmentation**, the subdivision of the body along its length into a series of repeated parts (segments). This feature played a central role in the evolution of many complex animals.

Segmentation is an obvious feature of an animal like an earthworm (Figure A), in which the segments are marked off externally by grooved rings. Internally, the coelom is partitioned by walls (only two are fully shown here). The nervous system (yellow) includes a ventral nerve cord with a dense cluster of nerve cells in each segment. Excretory organs (green), which dispose of fluid wastes, are also repeated in each segment. The digestive tract, however, is not segmented; it penetrates the segment walls and runs the length of the animal. The main channels of the circulatory system—a dorsal blood vessel and a ventral blood vessel—are also unsegmented. But they are connected by segmental vessels, including five pairs of accessory hearts near the anterior end. The main heart is simply the anterior region of the dorsal blood vessel.

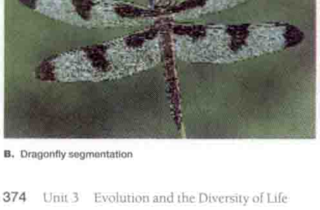
The dragonfly (Figure B) is also segmented, though less uniformly than the earthworm. Its segments are most pronounced in its abdomen; its head and mid-region (thorax) are each formed from several fused segments. Each pair of its six walking legs and each pair of its four wings emerge from a body segment in the thorax.

Segmentation also occurs in the human body (Figure C). We have a backbone formed of a repeated series of bones called vertebrae, and muscles associated with our vertebrae are segmented. We also have segmented abdominal muscles, clearly visible in body builders as "stomach ripples."

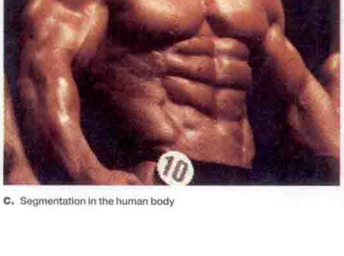
A segmented body is advantageous in many ways. It allows greater body flexibility and mobility, and it probably evolved as an adaptation that aids in movement. The earthworm uses its flexible, segmented body to crawl over wet surfaces and burrow rapidly into the soil. In the dragonfly, segmentation occurs in both its tough external skeleton and the muscles that move its head, thorax, and abdomen. Also, the segments provide flexibility for flying, perching, mating, and laying eggs.



A. Segmentation in an earthworm



B. Dragonfly segmentation



C. Segmentation in the human body

Modules feature concepts

- Each module focuses on a single concept which is stated in the heading.
- Use the concept headings as your "road map" through the chapter.
- To preview the chapter, read through the headings before you start studying individual modules.
- Modules are numbered for easy reference and are never longer than two facing pages

Nutrition and Digestion 21

Whales are the largest animals in the world. Few other species, living or extinct, even approach their great size. The humpback whale, shown in the pictures here, is a medium-sized member of the whale clan. It can be 16 meters (53 ft) long and weigh up to 65,000 kg (72 tons), about as much as 70 midsize cars.

It takes an enormous amount of food to support a 72-ton animal. Humpback whales eat small fishes and crustaceans called krill. The painting at the left shows a remarkable technique they often use to corral food organisms before gulping them in. Beginning about 20 meters below the ocean surface, a humpback swims slowly in an upward spiral, blowing air bubbles as it goes. The rising bubbles form a cylindrical screen, or "bubble net." Krill and fish inside the bubble net swim away from the bubbles and become concentrated in the center of the cylinder. The whale then surges up through the center of the net with its mouth open, harvesting the catch in one giant gulp.

Humpback whales are filter feeders, meaning they strain their food from seawater. Instead of teeth, these giants have an array of brushlike plates called baleen on each side of their upper jaw. You can see the white, comblike baleen in the open mouth of the whale in the photograph at the right. The baleen is used to sift food from the ocean. To start feeding, a humpback whale opens its mouth, expands its throat, and takes a huge gulp of seawater. When its mouth closes, the water squeezes out through spaces in the baleen, and a mass of food is trapped in the mouth. The food is then swallowed whole, passing into the stomach, where digestion begins. The humpback's stomach can hold about half a ton of food at a time, and in a typical day, the animal's digestive system will process as much as 2 tons of krill and fish.

The humpback and most other large whales are endangered species, having been hunted almost to extinction for meat and whale oil by the 1960s. Today, most nations honor an international ban on whaling, and some species are showing signs of recovery. Humpbacks still roam the Atlantic and Pacific oceans. They feed in polar regions during summer months and migrate to warmer oceans to breed when temperatures begin to fall. The photograph below was taken during summer in Glacier Bay, Alaska. Food is so abundant there that humpbacks harvest much more energy than they burn each day. Much of the excess is stored as a thick layer of fat, or blubber, just under their skin. After a summer of feasting, humpback whales leave Glacier Bay and head south to breeding and calving grounds off the Hawaiian Islands, some 6000 km (3600 mi) away. Living off body fat, they eat little, if at all, until they return to Alaskan waters eight months later.

In about four months, a humpback whale eats, digests, and stores as fat enough food to keep its 72-ton body active for an entire year—a remarkable feat, and a fitting introduction to this chapter on animal nutrition and digestion. We will return to the whale as we examine the diverse ways that animals obtain and process nutrients.

36.11 An energy pyramid explains why meat is a luxury for humans

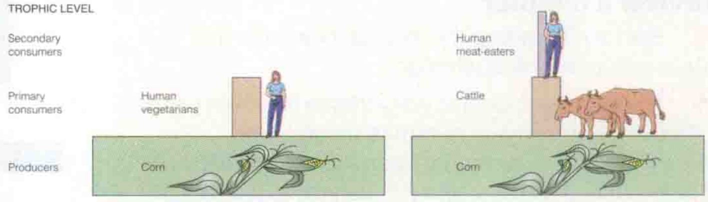
The dynamics of energy flow apply to the human population as much as to other organisms. Like other consumers, we depend entirely on productivity by plants for our food. As omnivores, we eat both plant material and meat. When we eat grain or fruits, we are primary consumers; when we eat beef or other meat from herbivores, we are secondary consumers. When we eat fish like trout and salmon (which eat insects and other small animals), we are tertiary or quaternary consumers.

The energy pyramid on the left below indicates energy flow from primary producers to humans as vegetarians. The energy in the producer trophic level comes from a corn crop. The pyramid on the right illustrates energy flow from the same corn crop, with humans as secondary consumers, eating cattle. These pyramids are generalized models, based on the rough estimate that about 10% of the energy available in a trophic level appears at the next higher trophic level. Thus, the pyramids indicate that the human population has about ten times more energy available to it when people eat grain than when they process the same amount of grain through another trophic level and eat grain-fed beef. Put another way, the pyramids indicate that it takes about ten times more energy to feed the human population when we eat meat than when we eat plants directly.

Actually, the 10% figure is high for energy flow involving cattle and humans. As endotherms, cattle expend a great deal of the energy they take in on heat production—much more than do ectotherms, such as grasshoppers (see Module 25.4). Accounting for the energy loss in heat production, it may actually take closer to 100 times more energy to feed us on cattle (and other mammals and birds) than on plants directly.

Eating meat of any kind is an expensive luxury, both economically and environmentally. In many countries, people cannot afford to buy much meat or their country cannot afford to produce it, and people are vegetarians by necessity. Whenever meat is eaten, producing it requires that more land be cultivated, more water be used for irrigation, and more chemical fertilizers and pesticides be applied to croplands used for growing grain. It is likely that, as the human population expands, meat consumption will become even more of a luxury than it is today.

The laws of thermodynamics and the fact that energy does not cycle within ecosystems explain why the human population has a limited supply of energy available to it. We turn next to the subject of chemical nutrients, all of which differ from energy in that they follow cyclic pathways within ecosystems.



Food energy available to the human population at different trophic levels

36.12 Chemicals are recycled between organic matter and abiotic reservoirs

The sun keeps most ecosystems supplied with energy, but there are no extraterrestrial sources of water or the other chemical nutrients essential to life. Life, therefore, depends on the recycling of chemicals. In the next four modules, we look at the cyclic movement of four substances within the biosphere: water, carbon, nitrogen, and phosphorus. In each case, we see that chemicals pass back and forth between organic matter and the abiotic components of ecosystems. We call the part of the ecosystem where a chemical accumulates or is stockpiled outside of living organisms an abiotic reservoir. The main abiotic reservoirs are highlighted in white boxes in the figures. Let's begin with the cycling of water.

There are two kinds of modules

- Blue-tabbed numbers identify modules that present basic scientific concepts.
- Red-tabbed numbers identify modules that apply concepts to human issues. These include "Talking About Science" modules—profiles of men and women working in the world of science. (You can see an example on p. 288.)