Biology for AP® Courses

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openstax™

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PREFACE

Welcome to *Biology for AP® Courses*, an OpenStax resource. This textbook was written to increase student access to high-quality learning materials, maintaining highest standards of academic rigor at little to no cost.

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OpenStax is a nonprofit based at Rice University, and it's our mission to improve student access to education. Our first openly licensed college textbook was published in 2012, and our library has since scaled to over 25 books for college and AP® courses used by hundreds of thousands of students. Our adaptive learning technology, designed to improve learning outcomes through personalized educational paths, is being piloted in college courses throughout the country. Through our partnerships with philanthropic foundations and our alliance with other educational resource organizations, OpenStax is breaking down the most common barriers to learning and empowering students and instructors to succeed.

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Format

You can access this textbook for free in web view or PDF through openstax.org, and for a low cost in print.

About *Biology for AP® Courses*

Biology for AP® Courses covers the scope and sequence requirements of a typical two-semester Advanced Placement® biology course. The text provides comprehensive coverage of core biology concepts and foundational research through an evolutionary lens. *Biology for AP® Courses* was designed to meet and exceed the requirements of the College Board's AP® Biology framework while allowing significant flexibility for instructors. Each section of the book includes an introduction based on the AP® curriculum as well as rich features that engage students in scientific practice and AP® test preparation. It also highlights careers and research opportunities in the biological sciences.

Coverage and Scope

In developing *Biology for AP®*, we relied on experts in the goals and approach of the AP® curriculum, carefully considered the AP® framework design, and listened to the advice of hundreds of high school and college biology instructors.

The result is a book that provides excellent coverage of the AP® framework while addressing the sheer breadth of biology topics in the modern age. We provide a thorough treatment of biology's foundational concepts while condensing selected topics. We also strive to make biology, as a discipline, interesting and accessible to students. In addition to a comprehensive coverage of core concepts and foundational research, we have incorporated features that draw learners into the discipline in meaningful ways.

Unit 1: The Chemistry of Life. Our opening unit introduces students to the sciences, including scientific methods and the fundamental concepts of chemistry and physics that provide a framework within which learners comprehend biological processes.

Unit 2: The Cell. Students will gain solid understanding of the structures, functions, and processes of the most basic unit of life: the cell.

Unit 3: Genetics. Our comprehensive genetics unit takes learners from the earliest experiments that revealed the basis of inheritance through the intricacies of DNA's structure, replication, and expression, to current applications in the studies of biotechnology and genomics.

Unit 4: Evolutionary Processes. The core concepts of evolution are discussed in this unit with examples illustrating evolutionary processes. Additionally, the evolutionary basis of biology reappears throughout the textbook in general discussion and is also reinforced through special call-out features highlighting specific topics in evolution.

Unit 5: Biological Diversity. The diversity of life is explored through detailed study of all phyla of organisms as well as discussion of their phylogenetic relationships. The unit begins with viruses and then moves through prokaryotes and eukaryotes, ending with a discussion of vertebrates and, finally, humans.

Unit 6: Plant Structure and Function. Our plant anatomy and physiology unit thoroughly covers the fundamental structure and function of plant cells, tissues, and organs. It also covers important plant physiological functions such as tissue differentiation, material transport, and the roles of plant hormones.

Unit 7: Animal Structure and Function. An introduction to the form and function of the animal body is followed by detailed chapters on specific body systems and their physiological function. This unit touches on the biology of all organisms while maintaining an engaging focus on human anatomy and physiology that helps students connect to the topics.

Unit 8: Ecology. Ecological concepts are broadly covered in this unit, beginning with the small-scale relationships of population ecology and gradually building to the large-scale processes of ecosystem ecology. Localized, real-world issues of conservation and biodiversity are presented at numerous points along the way.

AP® Connections

Every section of the textbook — over 200 total — begins with a "Connection for AP® Courses." Section. Written by Julianne Zedalis, the College Board's AP® Biology Curriculum Committee Co-Chair, these valuable overviews provide meaningful support for students and instructors.

Each Connection highlights the key concepts of the section in the context of the AP® Biology Curriculum Framework and explains their importance in brief, engaging language.

The explanations build upon the knowledge gained in previous sections, reinforcing the most significant concepts and alerting students of the foundational basis of upcoming material. This helps students build a more comprehensive understanding and helps instructors reference prior explanations.

Direct references to the relevant sections of the AP® Curriculum Framework are first explained and then outlined in table format emphasizing their importance and relating them to the overall design of the course. Students and teachers using these reference tables can easily see their progression through and coverage of the required curriculum.

Scientific Practices

The AP® Biology Science Practices are presented to students through several active learning features.

Science Practice Connections for AP® Courses provide a context and suggested activity linking the concepts with the relevant science practices. Students are often asked to build representations, undertake brief research, or answer critical thinking questions.

Science Practice Questions, designed and authored by John Eggebrecht and Julianne Zedalis, present a complex scenario or data set and ask students a series of multiple-choice and open-ended questions based on a complex scenario or data set. These robust activities hone students' scientific thinking skills and prepare them for similar questions on the AP® Examination.

Pedagogical Foundation and Features

Biology for AP® Courses® is grounded in a solid scientific base, with features that engage the students in scientific inquiry:

Evolution Connection features highlight the importance and relevance of evolutionary theory to all biological study. Through discussions like "The Evolution of Metabolic Pathways" and "Algae and Evolutionary Paths to Photosynthesis," the student is able to see how evolution pervades all aspects of biology.

Scientific Methods Connection call-outs walk students through actual or thought experiments that elucidate scientific processes and procedures for a variety of topics. Features include "Determining the Time Spent in Cell Cycle Stages" and "Testing the Hypothesis of Independent Assortment."

Career Connection features present information on a variety of careers in the biological sciences. They are meant to introduce students to professions and day-to-day work related to the current section content. Examples include microbiologist, ecologist, neurologist, and forensic scientist.

Everyday Connection features tie biological concepts to students' everyday lives as well as emerging world issues related to biology. Topics include "Chesapeake Bay" and "Can Snail Venom Be Used as a Pharmacological Pain Killer?"

Illustrations and Animations That Engage

Illustrations within the book are designed to help students visualize the concepts of biology using figures with simple, clear, designs and color schemes that go side-by-side with vivid photos and micrographs. *Biology for AP® Courses* also incorporates links to relevant animations and interactive exercises that help bring biology to life.

Art Connection features identify core figures in each chapter for student study. Questions about key figures, including clicker questions that can be used in the classroom, engage students' critical thinking to ensure genuine understanding.

Link to Learning features direct students to online interactive exercises and animations that add greater context to core content.

Additional Resources

Student and Instructor Resources

We've compiled additional resources for both students and instructors, including Getting Started Guides and teacher's notes. Instructor resources require a verified instructor account, which you can apply for when you log in or create your account on openstax.org. Take advantage of these resources to supplement your OpenStax book.

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About the Authors

Senior Contributing Authors

Julianne Zedalis

Julianne M. Zedalis teaches AP Biology and forensic science at The Bishop's School in La Jolla, CA. She earned her undergraduate and graduate degrees in biology at Occidental College, holds the Balgrowsky-Hinshaw Endowed Chair of Biology, and is a recipient of the Siemens Award for Advanced Placement and the Presidential Award for Excellence in Science and Mathematics Teaching. In 2006, the College Board selected Ms. Zedalis to sit on the AP Biology Redesign Commission. She co-chaired the Development Committee for AP Biology tasked with writing the AP exam, and was the lead writer for the AP Biology investigative lab manual. Ms. Zedalis serves in an advisory capacity for Bio-Rad and continues to develop instructional material for teachers.

John Eggebrecht

John Eggebrecht served as Director of the AP Science Redesign. Before his doctorate in Engineering from Cornell University, he earned degrees in Biology and Chemistry. He taught at Iowa State University, Illinois Mathematics and

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Curriculum Framework for AP® Biology

Big Idea 1: The process of evolution drives the diversity and unity of life.

Enduring understanding 1.A. Change in the genetic makeup of a population over time is evolution.	**Chapter/Key Concepts**
1.A.1. Natural selection is a major mechanism of evolution.	5.3, 18.1, 18.2, 19.1, 19.2, 19.3, 21.2, 23.5
1.A.2. Natural selection acts on phenotypic variations in populations.	7.3, 7.6, 18.2, 19.2, 19.3, 36.5
1.A.3. Evolutionary change is also driven by random processes.	19.1, 19.2
1.A.4. Biological evolution is supported by scientific evidence from many disciplines, including mathematics.	2.1, 5.2, 8.2, 11.1, 14.1, 17.1 18.1, 19.3
Enduring understanding 1.B. Organisms are linked by lines of descent from common ancestry.	**Chapter/Key Concepts**
1.B.1. Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.	3.4, 4.3, 4.6, 8.2, 15.3, 13.2, 14.1, 15.5, 18.1, 20.1, 20.2
1.B.2. Phylogenetic trees and cladograms are graphical representations (models) of evolutionary history that can be tested.	14.4, 20.1, 20.2, 20.3
Enduring understanding 1.C. Life continues to evolve within a changing environment.	**Chapter/Key Concepts**
1.C.1. Speciation and extinction have occurred throughout the Earth's history.	14.4, 18.2, 20.1, 38.1
1.C.2. Speciation may occur when two populations become reproductively isolated from each other.	18.2, 19.2, 23.5
1.C.3. Populations of organisms continue to evolve.	7.3, 7.6, 18.1, 18.3, 19.1, 19.2, 20.1, 20.2, 23.5
Enduring understanding 1.D. The origin of living systems is explained by natural processes.	**Chapter/Key Concepts**
1.D.1. There are several hypotheses about the natural origin of life on Earth, each with supporting scientific evidence.	8.2, 18.1, 20.1, 21.1, 20.3
1.D.2. Scientific evidence from many different disciplines supports models of the origin of life.	8.2, 18.1, 20.2, 28.1

Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce and to maintain dynamic homeostasis.

Enduring understanding 2.A. Growth, reproduction and maintenance of the organization of living systems require free energy and matter.	**Chapter/Key Concepts**
2.A.1. All living systems require constant input of free energy	6.1, 6.2, 6.3, 6.4, 6.7, 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 8.2, 23.1, 23.5, 36.3, 37.2
2.A.2. Organisms capture and store free energy for use in biological processes.	3.2, 4.3, 6.1, 6.4, 6.5, 7.1, 7.2, 7.3, 7.4, 7.4, 7.5, 7.6, 8.1, 8.2, 8.3, 9.2, 22.1, 22.2, 23.1, 23.5, 37.2
2.A.3. Organisms must exchange matter with the environment to grow, reproduce and maintain organization.	2.1, 2.2, 3.3, 4.2, 4.6, 6.1, 6.8, 22.4, 22.5, 23.5, 25.8, 37.3
Enduring understanding 2.B. Growth, reproduction and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.	**Chapter/Key Concepts**
2.B.1. Cell membranes are selectively permeable due to their structure.	3.2, 3.3, 5.1, 5.2, 5.3, 5.4, 8.3,
2.B.2. Growth and dynamic homeostasis are maintained by the constant movement of molecules across membranes.	2.3, 3.3, 5.2, 5.3, 5.4,
2.B.3. Eukaryotic cells maintain internal membranes that partition the cell into specialized regions.	3.3, 4.2, 4.3, 4.4
Enduring understanding 2.C. Organisms use feedback mechanisms to regulate growth and reproduction, and to maintain dynamic homeostasis.	**Chapter/Key Concepts**
2.C.1. Organisms use feedback mechanisms to maintain their internal environments and respond to external environmental changes.	5.2, 5.3, 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 8.2, 10.1, 11.1, 21.1, 23.5, 24.3, 28.3,
2.C.2. Organisms respond to changes in their external environments.	2.1, 6.4, 7.5, 7.6, 22.5, 23.5, 26.3, 26.5,
Enduring understanding 2.D. Growth and dynamic homeostasis of a biological system are influenced by changes in the system's environment.	**Chapter/Key Concepts**
2.D.1. All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.	2.1, 2.2, 7.1, 7.4, 7.5, 7.6, 8.2, 15.2, 15.3, 17.3, 21.1, 22.4, 35.1, 37.1
2.D.2. Homeostatic mechanisms reflect both common ancestry and divergence due to adaptation in different environments.	4.3, 5.2, 6.1, 18.2, 21.1, 25.1, 32.1, 32.3, 34.1
2.D.3. Biological systems are affected by disruptions to their dynamic homeostasis.	3.2, 22.3, 22.5, 23.1, 28.3, 38.2
2.D.4. Plants and animals have a variety of chemical defenses against infections that affect dynamic homeostasis.	23.6, 33.1, 33.2
Enduring understanding 2.E. Many biological processes involved in growth, reproduction and dynamic homeostasis include temporal regulation and coordination.	**Chapter/Key Concepts**
2.E.1. Timing and coordination of specific events are necessary for the normal development of an organism, and these events are regulated by a variety of mechanisms.	10.2, 10.3, 14.3, 23.5, 30.1, 32.3, 34.1, 34.6
2.E.2. Timing and coordination of physiological events are regulated by multiple mechanisms.	6.8, 10.1, 10.2, 15.3, 22.3, 23.2, 24.1, 30.6, 36.1, 36.2, 36.3, 36.4, 36.5, 43.6, 43.7

Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce and to maintain dynamic homeostasis.

2.E.3. Timing and coordination of behavior are regulated by various mechanisms and are important in natural selection.	11.1, 21.2, 23.5, 30.6, 35.2, 45.7

Big Idea 3: Living systems store, retrieve, transmit and respond to information essential to life processes.

Enduring understanding 3.A. Heritable information provides for continuity of life.	**Chapter/Key Concepts**
3.A.1. DNA, and in some cases RNA, is the primary source of heritable information.	3.5, 10.3, 13.1, 13.2, 14.1, 14.2, 14.3, 14.5, 15.1, 15.2, 15.3, 15.4, 15.5, 16.1, 16.2, 16.3, 17.1, 17.3, 21.1, 21.2, 22.4,
3.A.2. In eukaryotes, heritable information is passed to the next generation via processes that include the cell cycle and mitosis or meiosis plus fertilization.	10.1, 10.2, 10.3, 11.1, 11.2, 13.1,
3.A.3. The chromosomal basis of inheritance provides an understanding of the pattern of passage (transmission) of genes from parent to offspring.	11.2, 12.1, 12.2, 13.1, 14.2, 17.1, 17.4,
3.A.4. The inheritance pattern of many traits cannot be explained by simple Mendelian genetics.	4.3, 12.2, 13.1
Enduring understanding 3.B. Expression of genetic information involves cellular and molecular mechanisms.	**Chapter/Key Concepts**
3.B.1. Gene regulation results in differential gene expression, leading to cell specialization.	7.3, 7.6, 16.1, 16.2, 16.3, 16.4, 16.5, 17.3
3.B.2. A variety of intercellular and intracellular signal transmissions mediate gene expression.	9.1, 9.2, 9.3, 15.3, 17.1
Enduring understanding 3.C. The processing of genetic information is imperfect and is a source of genetic variation.	**Chapter/Key Concepts**
3.C.1. Changes in genotype can result in changes in phenotype.	5.3, 11.2, 13.1, 13.2, 14.6, 15.1, 17.1, 18.1, 19.1, 19.3
3.C.2. Biological systems have multiple processes that increase genetic variation.	11.2, 13.1, 14.1, 14.6, 15.2, 17.1, 20.3, 21.2, 22.4
3.C.3. Viral replication results in genetic variation, and viral infection can introduce genetic variation into the hosts.	21.1, 21.2
Enduring understanding 3.D. Cells communicate by generating, transmitting and receiving chemical signals	**Chapter/Key Concepts**
3.D.1. Cell communication processes share common features that reflect a shared evolutionary history.	4.6, 9.1, 9.2, 9.3, 9.4, 10.4, 37.2, 37.3
3.D.2. Cells communicate with each other through direct contact with other cells or from a distance via chemical signaling.	9.1, 9.3
3.D.3. Signal transduction pathways link signal reception with cellular response.	9.1, 9.2,
3.D.4. Changes in signal transduction pathways can alter cellular response.	9.2, 9.3, 9.4

Big Idea 3: Living systems store, retrieve, transmit and respond to information essential to life processes.

Enduring understanding 3.E. Transmission of information results in changes within and between biological systems.	**Chapter/Key Concepts**
3.E.1. Individuals can act on information and communicate it to others.	9.2, 9.4, 21.2, 36.1, 36.2, 36.3, 36.4, 36.5
3.E.2. Animals have nervous systems that detect external and internal signals, transmit and integrate information, and produce responses.	6.1, 35.1, 35.2, 35.3, 35.4

Big Idea 4: Biological systems interact, and these systems and their interactions possess complex properties.

Enduring understanding 4.A Interactions within biological systems lead to complex properties.	**Chapter/Key Concepts**
4.A.1. The subcomponents of biological molecules and their sequence determine the properties of that molecule.	3.1, 3.2, 3.3, 3.4, 3.5, 5.2, 6.2, 14.1, 14.3, 14.4, 17.1
4.A.2. The structure and function of subcellular components, and their interactions, provide essential cellular processes.	3.4, 4.3, 4.4, 4.6, 10.3, 15.3
4.A.3. Interactions between external stimuli and regulated gene expression result in specialization of cells, tissues and organs.	16.1, 22.3, 43.6, 43.7
4.A.4. Organisms exhibit complex properties due to interactions between their constituent parts.	15.2, 17.1, 18.1, 22.3, 22.5, 30.5, 33.3, 34.3
4.A.5. Communities are composed of populations of organisms that interact in complex ways.	22.5, 23.5, 45.5, 45.6
4.A.6. Interactions among living systems and with their environment result in the movement of matter and energy.	3.2, 3.3, 6.2, 6.3, 6.6, 7.5, 7.6, 8.2, 10.3, 18.1, 23.1, 22.4, 45.2, 45.6, 46.2, 47.3
Enduring understanding 4.B Competition and cooperation are important aspects of biological systems.	**Chapter/Key Concepts**
4.B.1. Interactions between molecules affect their structure and function.	3.5, 5.2, 6.2, 6.5, 8.3
4.B.2. Cooperative interactions within organisms promote efficiency in the use of energy and matter.	4.3, 7.3, 7.6, 45.6
4.B.3. Interactions between and within populations influence patterns of species distribution and abundance.	45.4, 45.6
4.B.4. Distribution of local and global ecosystems changes over time.	22.4, 23.1, 46.1, 47.1, 47.3
Enduring understanding 4.C. Naturally occurring diversity among and between components within biological systems affects interactions with the environment.	**Chapter/Key Concepts**
4.C.1. Variation in molecular units provides cells with a wider range of functions.	3.4, 9.2, 10.3, 13.1, 15.5, 42.2, 49.1
4.C.2. Environmental factors influence the expression of the genotype in an organism.	14.2, 19.3, 22.3, 30.4, 43.1
4.C.3. The level of variation in a population affects population dynamics.	7.5, 7.6, 19.1, 45.6, 47.1

Big Idea 4: Biological systems interact, and these systems and their interactions possess complex properties.

4.C.4. The diversity of species within an ecosystem may influence the stability of the ecosystem.	45.6, 46.1

4 | CELL STRUCTURE

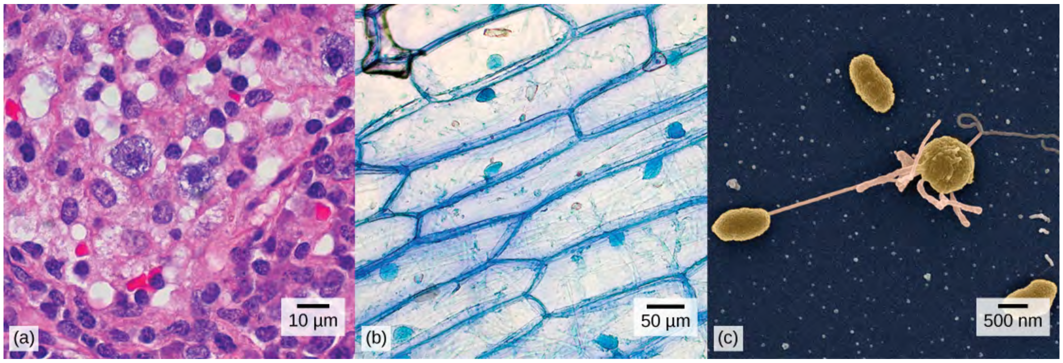


Figure 1.1 (a) Nasal sinus cells (viewed with a light microscope), (b) onion cells (viewed with a light microscope), and (c) *Vibrio tasmaniensis* bacterial cells (seen through a scanning electron microscope) are from very different organisms, yet all share certain characteristics of basic cell structure. (credit a: modification of work by Ed Uthman, MD; credit b: modification of work by Umberto Salvagnin; credit c: modification of work by Anthony D'Onofrio, William H. Fowle, Eric J. Stewart, and Kim Lewis of the Lewis Lab at Northeastern University; scale-bar data from Matt Russell)

Chapter Outline

Introduction

Close your eyes and picture a brick wall. What is the basic building block of that wall? A single brick, of course. Like a brick wall, your body is composed of basic building blocks called "cells."

Your body has many kinds of cells, each specialized for a specific purpose. Just as a home is made from a variety of building materials, the human body is constructed from many cell types. For example, epithelial cells protect the surface of the body and cover the organs and body cavities within. Bone cells help to support and protect the body. Immune system cells fight invading pathogens. Additionally, blood cells carry nutrients and oxygen throughout the body while removing carbon dioxide and other waste. Each of these cell types plays a vital role during the growth, development, and ongoing maintenance of the body. In spite of their enormous variety, however, cells from all organisms—even organisms as diverse as bacteria, onion, and human—share certain fundamental characteristics.

In humans, before a cell develops into its specialized type, it is called a stem cell. A stem cell is a cell that has not undergone the changes involved in specialization. In this state, it may differentiate to become one of many different specialized cells, and it may divide to produce more stem cells. Under normal circumstances, once a cell becomes specialized, it remains that way. However, scientists have been working on coaxing stem cells in the laboratory to become a particular specialization. For example, scientists at the Cincinnati Children's Hospital Medical Center have learned how to use stem cells to grow stomach tissue in plastic cell and tissue culture dishes. This accomplishment will enable researchers to study gastric human diseases, such as stomach cancer. You can read more about it **here (http://openstaxcollege.org/l/32cellsize)** .

4.1 | Studying Cells

In this section, you will explore the following questions:

- What is the role of cells in organisms?
- What is the difference between light microscopy and electron microscopy?
- What is the cell theory?

Connection for AP® Courses

A cell is the smallest unit of a living thing. A living thing, whether made of one cell (like bacteria) or many cells (like a human), is called an organism. Thus, cells are the basic building blocks of all organisms.

Several cells of one kind that interconnect with each other and perform a shared function form tissues, several tissues combine to form an organ (your stomach, heart, or brain), and several organs make up an organ system (such as the digestive system, circulatory system, or nervous system). Several systems that function together form an organism (like a human being). Here, we will examine the structure and function of cells.

There are many types of cells, all grouped into one of two broad categories: prokaryotic and eukaryotic. For example, both animal and plant cells are classified as eukaryotic cells, whereas bacterial cells are classified as prokaryotic. Before discussing the criteria for determining whether a cell is prokaryotic or eukaryotic, let's first examine how biologists study cells.

In addition, content from this chapter is addressed in the AP Biology Laboratory Manual in the following lab(s):

4 Prokaryotic and Eukaryotic Cells

5 Subcellular Structures

Microscopy

Cells vary in size. With few exceptions, individual cells cannot be seen with the naked eye, so scientists use microscopes (micro- = "small"; -scope = "to look at") to study them. A **microscope** is an instrument that magnifies an object. Most photographs of cells are taken with a microscope, and these images can also be called micrographs.

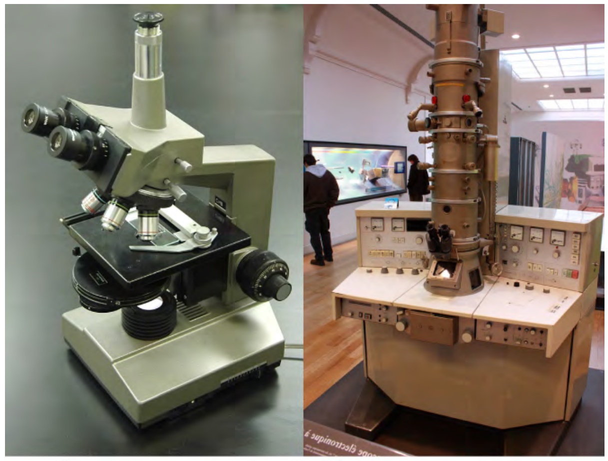
The optics of a microscope's lenses change the orientation of the image that the user sees. A specimen that is right-side up and facing right on the microscope slide will appear upside-down and facing left when viewed through a microscope, and vice versa. Similarly, if the slide is moved left while looking through the microscope, it will appear to move right, and if moved down, it will seem to move up. This occurs because microscopes use two sets of lenses to magnify the image. Because of the manner by which light travels through the lenses, this system of two lenses produces an inverted image (binocular, or dissecting microscopes, work in a similar manner, but include an additional magnification system that makes the final image appear to be upright).

Light Microscopes

To give you a sense of cell size, a typical human red blood cell is about eight millionths of a meter or eight micrometers (abbreviated as eight μm) in diameter; the head of a pin of is about two thousandths of a meter (two mm) in diameter. That means about 250 red blood cells could fit on the head of a pin.

Most student microscopes are classified as **light microscopes** (**Figure 1.2a**). Visible light passes and is bent through the lens system to enable the user to see the specimen. Light microscopes are advantageous for viewing living organisms, but since individual cells are generally transparent, their components are not distinguishable unless they are colored with special stains. Staining, however, usually kills the cells.

Light microscopes commonly used in the undergraduate college laboratory magnify up to approximately 400 times. Two parameters that are important in microscopy are magnification and resolving power. Magnification is the process of enlarging an object in appearance. Resolving power is the ability of a microscope to distinguish two adjacent structures as separate: the higher the resolution, the better the clarity and detail of the image. When oil immersion lenses are used for the study of small objects, magnification is usually increased to 1,000 times. In order to gain a better understanding of cellular structure and function, scientists typically use electron microscopes.



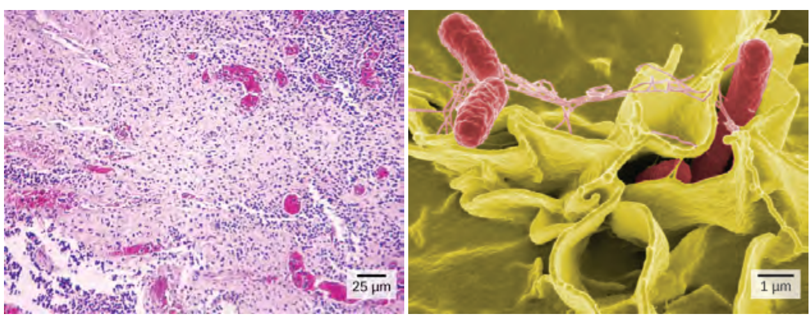
(a) (b)

Figure 1.2 (a) Most light microscopes used in a college biology lab can magnify cells up to approximately 400 times and have a resolution of about 200 nanometers. (b) Electron microscopes provide a much higher magnification, 100,000x, and a have a resolution of 50 picometers. (credit a: modification of work by "GcG"/Wikimedia Commons; credit b: modification of work by Evan Bench)

Electron Microscopes

In contrast to light microscopes, **electron microscopes** (Figure 1.2**b**) use a beam of electrons instead of a beam of light. Not only does this allow for higher magnification and, thus, more detail (Figure 1.3), it also provides higher resolving power. The method used to prepare the specimen for viewing with an electron microscope kills the specimen. Electrons have short wavelengths (shorter than photons) that move best in a vacuum, so living cells cannot be viewed with an electron microscope.

In a scanning electron microscope, a beam of electrons moves back and forth across a cell's surface, creating details of cell surface characteristics. In a transmission electron microscope, the electron beam penetrates the cell and provides details of a cell's internal structures. As you might imagine, electron microscopes are significantly more bulky and expensive than light microscopes.



(a) (b)

Figure 1.3 (a) These *Salmonella* bacteria appear as tiny purple dots when viewed with a light microscope. (b) This scanning electron microscope micrograph shows *Salmonella* bacteria (in red) invading human cells (yellow). Even though subfigure (b) shows a different *Salmonella* specimen than subfigure (a), you can still observe the comparative increase in magnification and detail. (credit a: modification of work by CDC/Armed Forces Institute of Pathology, Charles N. Farmer, Rocky Mountain Laboratories; credit b: modification of work by NIAID, NIH; scale-bar data from Matt Russell)

LINK TO LEARNING

For another perspective on cell size, try the HowBig interactive at **this site (http://openstaxcollege.org/l/cell_sizes)** .

Why are electron microscopes crucial for the study of cell biology?

a. Only electron microscopes can be used to view internal structures.

b. Some electron microscopes allow visualization of three dimensional external shapes at very high magnification in a way that is not possible with standard light microscopes.

c. Scanning electron microscopes can show internal structures clearly at very high magnifications.

d. Electron microscopes are easier to use and less expensive than light microscopes.

Cell Theory

The microscopes we use today are far more complex than those used in the 1600s by Antony van Leeuwenhoek, a Dutch shopkeeper who had great skill in crafting lenses. Despite the limitations of his now-ancient lenses, van Leeuwenhoek observed the movements of protista (a type of single-celled organism) and sperm, which he collectively termed "animalcules."

In a 1665 publication called *Micrographia*, experimental scientist Robert Hooke coined the term "cell" for the box-like structures he observed when viewing cork tissue through a lens. In the 1670s, van Leeuwenhoek discovered bacteria and protozoa. Later advances in lenses, microscope construction, and staining techniques enabled other scientists to see some components inside cells.

By the late 1830s, botanist Matthias Schleiden and zoologist Theodor Schwann were studying tissues and proposed the **unified cell theory**, which states that all living things are composed of one or more cells, the cell is the basic unit of life, and new cells arise from existing cells. Rudolf Virchow later made important contributions to this theory.

career CONNECTION

Have you ever heard of a medical test called a Pap smear (Figure 1.4)? In this test, a doctor takes a small sample of cells from the uterine cervix of a patient and sends it to a medical lab where a cytotechnologist stains the cells and examines them for any changes that could indicate abnormal cell growth or a microbial infection.

Cytotechnologists (cyto- = "cell") are professionals who study cells via microscopic examinations and other laboratory tests. They are trained to determine which cellular changes are within normal limits and which are abnormal. Their focus is not limited to cervical cells; they study cellular specimens that come from all organs. When they notice abnormalities, they consult a pathologist, who is a medical doctor who can make a clinical diagnosis.

Cytotechnologists play a vital role in saving people's lives. When abnormalities are discovered early, a patient's treatment can begin sooner, which usually increases the chances of a successful outcome.

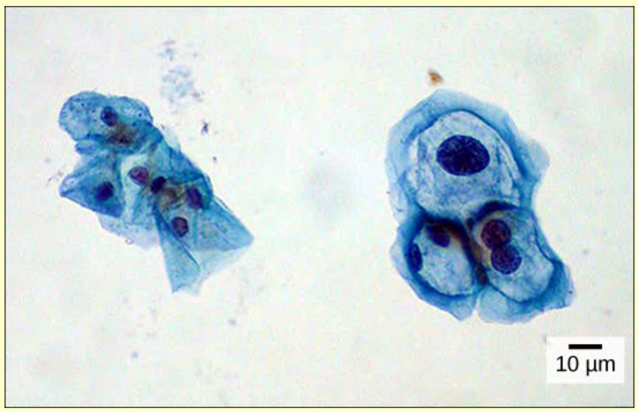


Figure 1.4 These uterine cervix cells, viewed through a light microscope, were obtained from a Pap smear. Normal cells are on the left. The cells on the right are infected with human papillomavirus (HPV). Notice that the infected cells are larger; also, two of these cells each have two nuclei instead of one, the normal number. (credit: modification of work by Ed Uthman, MD; scale-bar data from Matt Russell)

4.2 | Prokaryotic Cells

In this section, you will explore the following questions:

- What are the major structures of prokaryotic cells?
- What limits the size of a cell?

Connection for AP® Courses

According to the cell theory, all living organisms, from bacteria to humans, are composed of cells, the smallest units of living matter. Often too small to be seen without a microscope, cells come in all sizes and shapes, and their small size allows for a large surface area-to-volume ratio that enables a more efficient exchange of nutrients and wastes with the environment.

There are three basic types of cells: archaea, bacteria, and eukaryotes. Both archaea and bacteria are classified as prokaryotes, whereas cells of animals, plants, fungi, and protists are eukaryotes. Archaea are a unique group of organisms and likely evolved in the harsh conditions of early Earth and are still prevalent today in extreme environments, such as hot springs and polar regions. All cells share features that reflect their evolution from a common ancestor; these features are 1) a plasma membrane that separates the cell from its environment; 2) cytoplasm comprising the jelly-like cytosol inside the cell; 3) ribosomes that are important for the synthesis of proteins, and 4) DNA to store and transmit hereditary information.

Prokaryotes may also have a cell wall that acts as an extra layer of protection against the external environment. The term “prokaryote” means “before nucleus,” and prokaryotes do not have nuclei. Rather, their DNA exists as a single circular chromosome in the central part of the cell called the nucleoid. Some bacterial cells also have circular DNA plasmids that often carry genes for resistance to antibiotics (Chapter 17). Other common prokaryotic cell features include flagella and pili.

The content presented in this section supports the learning objectives outlined in Big Idea 1 and Big Idea 2 of the AP® Biology Curriculum Framework. The AP® Learning Objectives merge essential knowledge content with one or more of the seven Science Practices. These objectives provide a transparent foundation for the AP® Biology course, along with inquiry-based laboratory experiences, instructional activities, and AP® exam questions.

Big Idea 1	The process of evolution drives the diversity and unity of life.
Enduring Understanding 1.D	The origin of living systems is explained by natural processes.
Essential Knowledge	**1.D.2** Scientific evidence from many different disciplines supports models of the origin of life.
Science Practice	**4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question.
Learning Objective	**1.32** The student is able to justify the selection of geological, physical, chemical, and biological data that reveal early Earth conditions.
Essential Knowledge	**2.A.3** Organisms must exchange matter with the environment to grow, reproduce and maintain organization.
Science Practice	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	**2.6** The student is able to use calculated surface area-to-volume ratios to predict which cell(s) might eliminate wastes or procure nutrients faster by diffusion.
Essential Knowledge	**2.A.3** Organisms must exchange matter with the environment to grow, reproduce and maintain organization.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**2.7** The student will be able to explain how cell sizes and shapes affect the overall rate of nutrient intake and the rate of waste elimination.

Cells fall into one of two broad categories: prokaryotic and eukaryotic. Only the predominantly single-celled organisms of the domains Bacteria and Archaea are classified as prokaryotes (pro- = “before”; -kary- = “nucleus”). Cells of animals, plants, fungi, and protists are all eukaryotes (ceu- = “true”) and are made up of eukaryotic cells.

Components of Prokaryotic Cells

All cells share four common components: 1) a plasma membrane, an outer covering that separates the cell’s interior from its surrounding environment; 2) cytoplasm, consisting of a jelly-like cytosol within the cell in which other cellular components are found; 3) DNA, the genetic material of the cell; and 4) ribosomes, which synthesize proteins. However, prokaryotes differ from eukaryotic cells in several ways.

A **prokaryote** is a simple, mostly single-celled (unicellular) organism that lacks a nucleus, or any other membrane-bound organelle. We will shortly come to see that this is significantly different in eukaryotes. Prokaryotic DNA is found in a central part of the cell: the **nucleoid** (Figure 1.5).

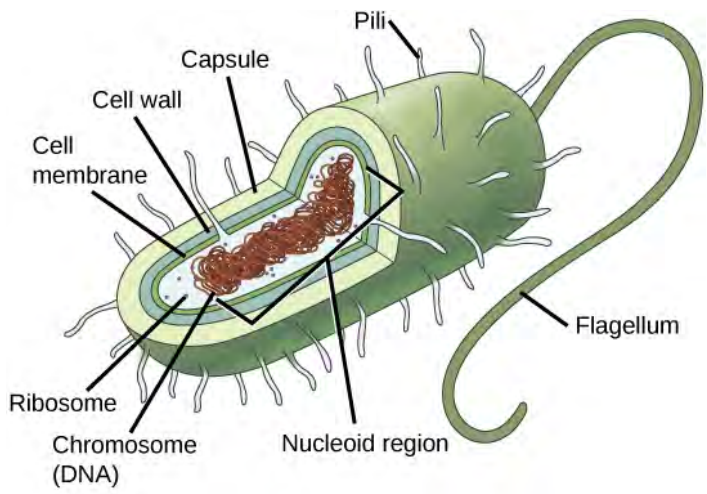


Figure 1.5 This figure shows the generalized structure of a prokaryotic cell. All prokaryotes have chromosomal DNA localized in a nucleoid, ribosomes, a cell membrane, and a cell wall. The other structures shown are present in some, but not all, bacteria.

everyday CONNECTION for AP® Courses

While the Earth is approximately 4.6 billion years old, the earliest fossil evidence for life are of microbial mats that date back to 3.5 billion years.

What type of evidence for life was most likely found in a 3.5 billion year old rock?

a. Scientists found bones buried in the rock that resemble bones of living animals.
b. Dead cells buried in the rock superficially resemble living prokaryotic cells.
c. The fossil superficially resembles living microbial mats that exist today.
d. Scientists found fossilized prokaryotic cells in the rock that are able to grow and divide.

Most prokaryotes have a peptidoglycan cell wall and many have a polysaccharide capsule (**Figure 1.5**). The cell wall acts as an extra layer of protection, helps the cell maintain its shape, and prevents dehydration. The capsule enables the cell to attach to surfaces in its environment. Some prokaryotes have flagella, pili, or fimbriae. Flagella are used for locomotion. Pili are used to exchange genetic material during a type of reproduction called conjugation. Fimbriae are used by bacteria to attach to a host cell.

career CONNECTION

Microbiologist

The most effective action anyone can take to prevent the spread of contagious illnesses is to wash his or her hands. Why? Because microbes (organisms so tiny that they can only be seen with microscopes) are ubiquitous. They live on doorknobs, money, your hands, and many other surfaces. If someone sneezes into his hand and touches a doorknob, and afterwards you touch that same doorknob, the microbes from the sneezer's mucus are now on your hands. If you touch your hands to your mouth, nose, or eyes, those microbes can enter your body and could make you sick.

However, not all microbes (also called microorganisms) cause disease; most are actually beneficial. You have microbes in your gut that make vitamin K.

Microbiologists are scientists who study microbes. Microbiologists can pursue a number of careers. Not only do they work in the food industry, they are also employed in the veterinary and medical fields. They can work in the pharmaceutical sector, serving key roles in research and development by identifying new sources of antibiotics that could be used to treat bacterial infections.

Environmental microbiologists may look for new ways to use specially selected or genetically engineered microbes for the removal of pollutants from soil or groundwater, as well as hazardous elements from contaminated sites. These uses of microbes are called bioremediation technologies. Microbiologists can also work in the field of bioinformatics, providing specialized knowledge and insight for the design, development, and specificity of computer models of, for example, bacterial epidemics.

Cell Size

At 0.1 to 5.0 μm in diameter, prokaryotic cells are significantly smaller than eukaryotic cells, which have diameters ranging from 10 to 100 μm (**Figure 1.6**). The small size of prokaryotes allows ions and organic molecules that enter them to quickly diffuse to other parts of the cell. Similarly, any wastes produced within a prokaryotic cell can quickly diffuse out. This is not the case in eukaryotic cells, which have developed different structural adaptations to enhance intracellular transport.

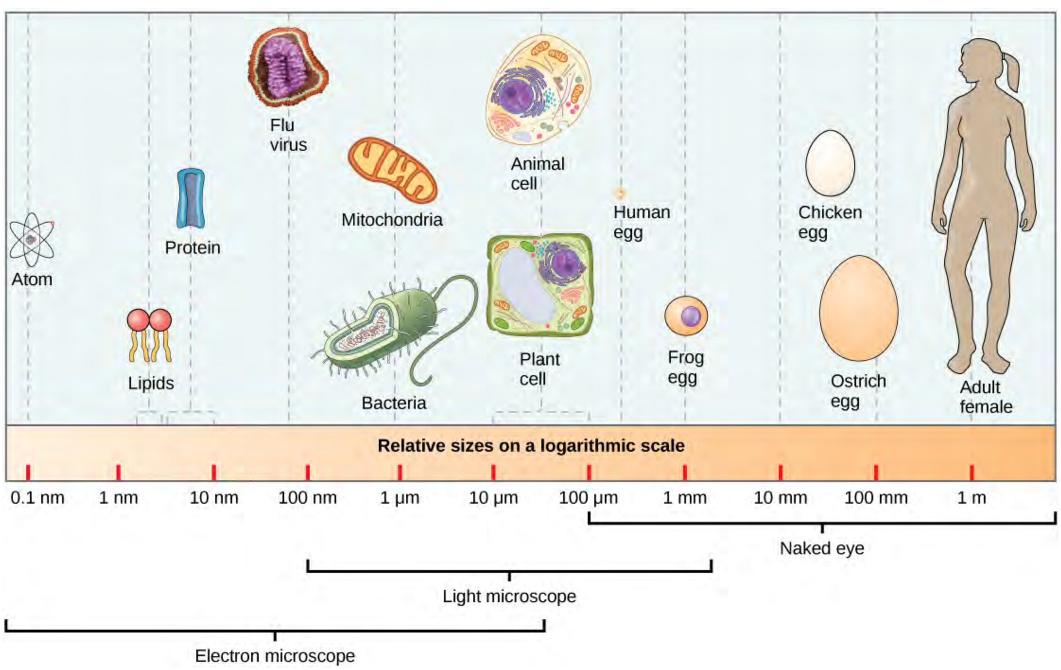


Figure 1.6 This figure shows relative sizes of microbes on a logarithmic scale (recall that each unit of increase in a logarithmic scale represents a 10-fold increase in the quantity being measured).

Small size, in general, is necessary for all cells, whether prokaryotic or eukaryotic. Let's examine why that is so. First, we'll consider the area and volume of a typical cell. Not all cells are spherical in shape, but most tend to approximate a sphere. You may remember from your high school geometry course that the formula for the surface area of a sphere is $4\pi r^2$, while the formula for its volume is $4\pi r^3/3$. Thus, as the radius of a cell increases, its surface area increases as the square of its radius, but its volume increases as the cube of its radius (much more rapidly). Therefore, as a cell increases in size, its surface area-to-volume ratio decreases. This same principle would apply if the cell had the shape of a cube (**see this figure**). If the cell grows too large, the plasma membrane will not have sufficient surface area to support the rate of diffusion required for the increased volume. In other words, as a cell grows, it becomes less efficient. One way to become more efficient is to divide; another way is to develop organelles that perform specific tasks. These adaptations lead to the development of more sophisticated cells called eukaryotic cells.

The shape of a cell is also optimized for the exchange of nutrients and waste across the cell membrane. Most cells are spherical because, for a given volume, nutrients and waste would have the least distance to travel from the cell membrane to the center of the cell. All points on a sphere are equidistant from its center. That means molecules can travel in any direction and reach a membrane over the same distance. However, if a cell were a cube, molecules at the center of the cell would travel less distance to reach a face of the cube and would travel longer distance to reach the vertex of the cube.

visual CONNECTION

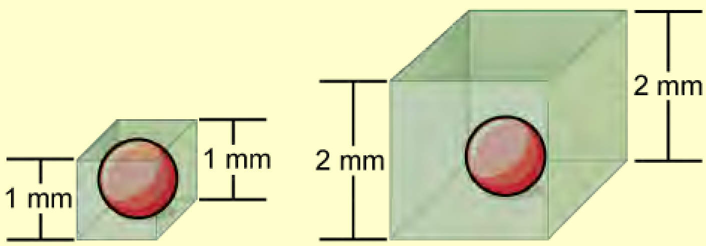


Figure 1.7 Notice that as a cell increases in size, its surface area-to-volume ratio decreases. When there is insufficient surface area to support a cell's increasing volume, a cell will either divide or die. The cell on the left has a volume of 1 mm^3 and a surface area of 6 mm^2, with a surface area-to-volume ratio of 6 to 1, whereas the cell on the right has a volume of 8 mm^3 and a surface area of 24 mm^2, with a surface area-to-volume ratio of 3 to 1.

On average, prokaryotic cells are smaller than eukaryotic cells. What are some advantages to small cell size? What are some advantages to large cell size?

a. Small, prokaryotic cells do not expend energy in intracellular transport of substances. Larger eukaryotic cells have organelles, which enable them to produce complex substances.
b. Small, prokaryotic cells easily escape the spontaneous changes in environmental conditions. Large, eukaryotic cells have complex mechanisms to cope with such changes.
c. Small, prokaryotic cells divide at a higher rate. Large, eukaryotic cells show division with genetic variations.
d. Small, prokaryotic cells have fewer phospholipids in their membrane. Large, eukaryotic cells have more transport proteins in their phospholipid bilayer, supporting efficient transport of molecules.

science practices CONNECTION for AP® Courses

Activity

Create an annotated diagram to explain how approximately 300 million alveoli in a human lung increases surface area for gas exchange to the size of a tennis court. Use the diagram to explain how the cellular structures of alveoli, capillaries, and red blood cells allow for rapid diffusion of O_2 and CO_2 among them.

Think About It

Which of the following cells would likely exchange nutrients and wastes with its environment more efficiently: a spherical cell with a diameter of 5 μm or a cubed-shaped cell with a side length of 7μm? Provide a quantitative justification for your answer based on surface area-to-volume ratios.

4.3 | Eukaryotic Cells

In this section, you will explore the following questions:

- How does the structure of the eukaryotic cell resemble as well as differ from the structure of the prokaryotic cell?
- What are structural differences between animal and plant cells?
- What are the functions of the major cell structures?

Connection for AP® Courses

Eukaryotic cells possess many features that prokaryotic cells lack, including a nucleus with a double membrane that encloses DNA. In addition, eukaryotic cells tend to be larger and have a variety of membrane-bound organelles that perform specific, compartmentalized functions. Evidence supports the hypothesis that eukaryotic cells likely evolved from prokaryotic ancestors; for example, mitochondria and chloroplasts feature characteristics of independently-living prokaryotes. Eukaryotic cells come in all shapes, sizes, and types (e.g. animal cells, plant cells, and different types of cells in the body). (Hint: This a rare instance where you should create a list of organelles and their respective functions because later you will focus on how various organelles work together, similar to how your body's organs work together to keep you healthy.) Like prokaryotes, all eukaryotic cells have a plasma membrane, cytoplasm, ribosomes, and DNA. Many organelles are bound by membranes composed of phospholipid bilayers embedded with proteins to compartmentalize functions such as the storage of hydrolytic enzymes and the synthesis of proteins. The nucleus houses DNA, and the nucleolus within the nucleus is the site of ribosome assembly. Functional ribosomes are found either free in the cytoplasm or attached to the rough endoplasmic reticulum where they perform protein synthesis. The Golgi apparatus receives, modifies, and packages small molecules like lipids and proteins for distribution. Mitochondria and chloroplasts participate in free energy capture and transfer through the processes of cellular respiration and photosynthesis, respectively. Peroxisomes oxidize fatty acids and amino acids, and they are equipped to break down hydrogen peroxide formed from these reactions without letting it into the cytoplasm where it can cause damage. Vesicles and vacuoles store substances, and in plant cells, the central vacuole stores pigments, salts, minerals, nutrients, proteins, and degradation enzymes and helps maintain rigidity. In contrast, animal cells have centrosomes and lysosomes but lack cell walls.

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 1, Big Idea 2, and Big Idea 4 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 1	The process of evolution drives the diversity and unity of life.

Enduring Understanding 1.B	Organisms are linked by lines of descent from common ancestry
Essential Knowledge	**1.B.1** Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.
Science Practice	**7.2** The student can connect concepts in and across domains to generalize or extrapolate in and/or across enduring understandings
Learning Objective	**1.15** The student is able to describe specific examples of conserved core biological processes and features shared by all domains or within one domain of life and how these shared, conserved core processes and features support the concept of common ancestry for all organisms.
Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce and to maintain dynamic homeostasis.
Enduring Understanding 2.B	Growth, reproduction and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.
Essential Knowledge	**2.B.3** Eukaryotic cells maintain internal membranes that partition the cell into specialized regions.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**2.13** The student is able to explain how internal membranes and organelles contribute to cell functions.
Essential Knowledge	**2.B.3** Eukaryotic cells maintain internal membranes that partition the cell into specialized regions.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	**2.14** The student is able to use representations and models to describe differences in prokaryotic and eukaryotic cells.
Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.2** The structure and function of subcellular components, and their interactions, provide essential cellular processes.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**4.5** The student is able to construct explanations based on scientific evidence as to how interactions of subcellular structures provide essential functions.

The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 1.15] [APLO 2.5][APLO 2.25][APLO 1.16]

Have you ever heard the phrase “form follows function?” It’s a philosophy practiced in many industries. In architecture, this means that buildings should be constructed to support the activities that will be carried out inside them. For example, a skyscraper should be built with several elevator banks; a hospital should be built so that its emergency room is easily accessible.

Our natural world also utilizes the principle of form following function, especially in cell biology, and this will become clear as we explore eukaryotic cells (Figure 1.8). Unlike prokaryotic cells, **eukaryotic cells** have: 1) a membrane-bound nucleus; 2) numerous membrane-bound **organelles** such as the endoplasmic reticulum, Golgi apparatus, chloroplasts, mitochondria, and others; and 3) several, rod-shaped chromosomes. Because a eukaryotic cell's nucleus is surrounded by a membrane, it is often said to have a "true nucleus." The word "organelle" means "little organ," and, as already mentioned, organelles have specialized cellular functions, just as the organs of your body have specialized functions.

At this point, it should be clear to you that eukaryotic cells have a more complex structure than prokaryotic cells. Organelles allow different functions to be compartmentalized in different areas of the cell. Before turning to organelles, let's first examine two important components of the cell: the plasma membrane and the cytoplasm.

visual CONNECTION

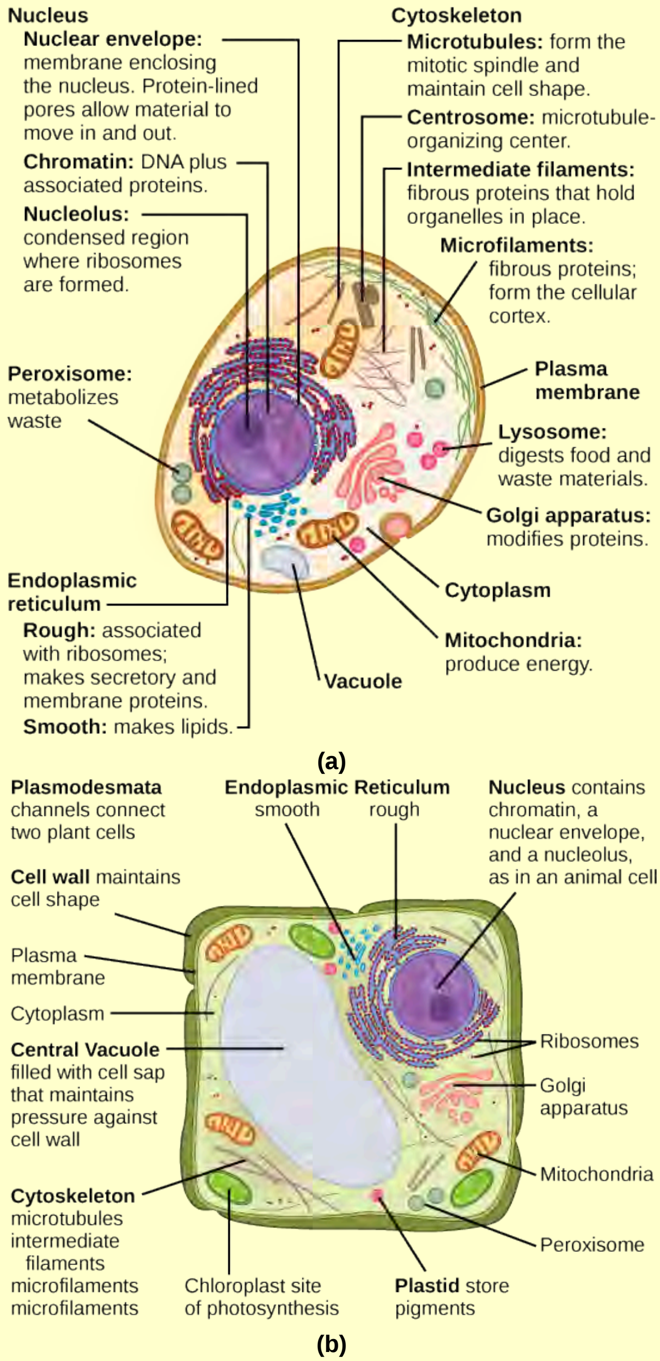


Figure 1.8 These figures show the major organelles and other cell components of (a) a typical animal cell and (b) a typical eukaryotic plant cell. The plant cell has a cell wall, chloroplasts, plastids, and a central vacuole—structures not found in animal cells. Plant cells do not have lysosomes or centrosomes.

If the nucleolus were not able to carry out its function, what other cellular organelles would be affected?

a. The structure of endoplasmic reticulum would not form.

b. The function of lysosomes would be hindered, as hydrolases are formed by nucleolus.

c. The free ribosomes and the rough endoplasmic reticulum, which contains ribosomes, would not form.

d. The Golgi apparatus will not be able to sort proteins properly.

The Plasma Membrane

Like prokaryotes, eukaryotic cells have a **plasma membrane** (**Figure 1.9**), a phospholipid bilayer with embedded proteins that separates the internal contents of the cell from its surrounding environment. A phospholipid is a lipid molecule with two fatty acid chains and a phosphate-containing group. The plasma membrane controls the passage of organic molecules, ions, water, and oxygen into and out of the cell. Wastes (such as carbon dioxide and ammonia) also leave the cell by passing through the plasma membrane.

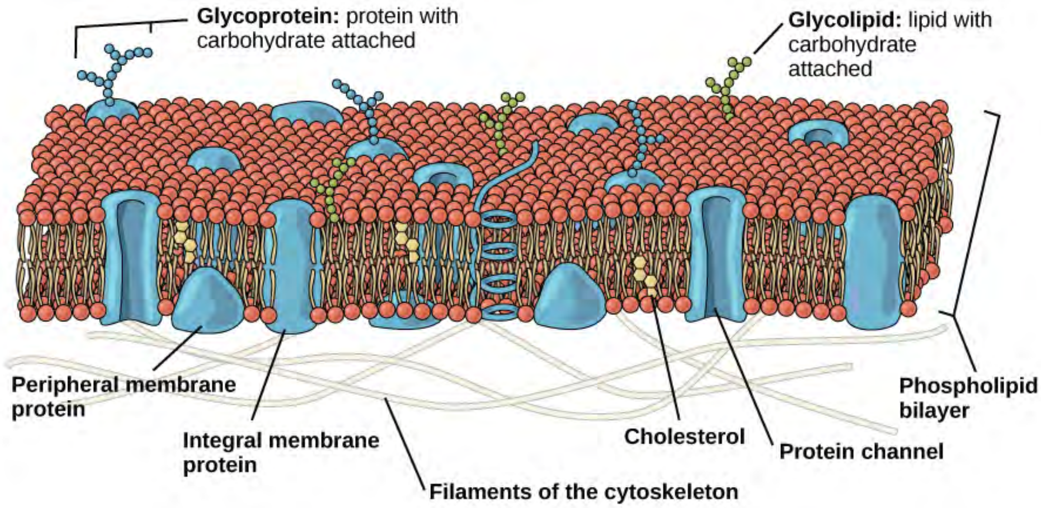


Figure 1.9 The eukaryotic plasma membrane is a phospholipid bilayer with proteins and cholesterol embedded in it.

The plasma membranes of cells that specialize in absorption are folded into fingerlike projections called microvilli (singular = microvillus); (**Figure 1.10**). Such cells are typically found lining the small intestine, the organ that absorbs nutrients from digested food. This is an excellent example of form following function. People with celiac disease have an immune response to gluten, which is a protein found in wheat, barley, and rye. The immune response damages microvilli, and thus, afflicted individuals cannot absorb nutrients. This leads to malnutrition, cramping, and diarrhea. Patients suffering from celiac disease must follow a gluten-free diet.

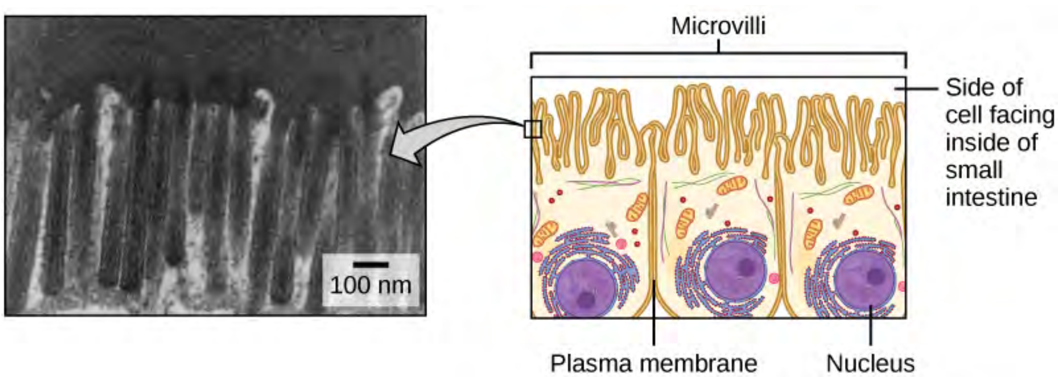


Figure 1.10 Microvilli, shown here as they appear on cells lining the small intestine, increase the surface area available for absorption. These microvilli are only found on the area of the plasma membrane that faces the cavity from which substances will be absorbed. (credit "micrograph": modification of work by Louisa Howard)

The Cytoplasm

The **cytoplasm** is the entire region of a cell between the plasma membrane and the nuclear envelope (a structure to be discussed shortly). It is made up of organelles suspended in the gel-like **cytosol**, the cytoskeleton, and various chemicals (**Figure 1.8**). Even though the cytoplasm consists of 70 to 80 percent water, it has a semi-solid consistency, which comes from the proteins within it. However, proteins are not the only organic molecules found in the cytoplasm. Glucose and other simple sugars, polysaccharides, amino acids, nucleic acids, fatty acids, and derivatives of glycerol are found there, too. Ions of sodium, potassium, calcium, and many other elements are also dissolved in the cytoplasm. Many metabolic reactions, including protein synthesis, take place in the cytoplasm.

The Nucleus

Typically, the nucleus is the most prominent organelle in a cell (**Figure 1.8**). The **nucleus** (plural = nuclei) houses the cell's DNA and directs the synthesis of ribosomes and proteins. Let's look at it in more detail (**Figure 1.11**).

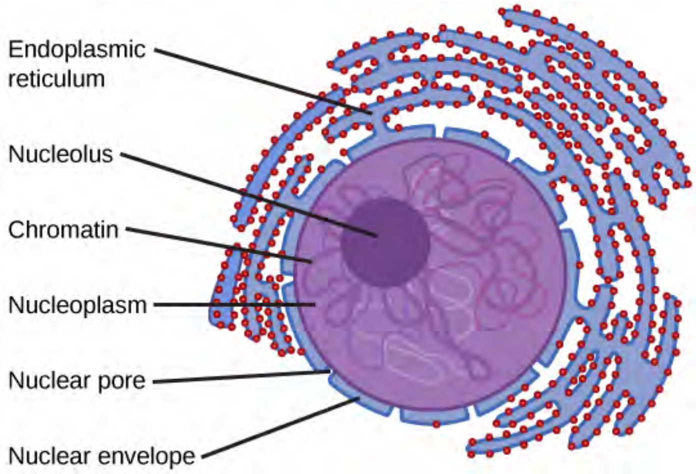


Figure 1.11 The nucleus stores chromatin (DNA plus proteins) in a gel-like substance called the nucleoplasm. The nucleolus is a condensed region of chromatin where ribosome synthesis occurs. The boundary of the nucleus is called the nuclear envelope. It consists of two phospholipid bilayers: an outer membrane and an inner membrane. The nuclear membrane is continuous with the endoplasmic reticulum. Nuclear pores allow substances to enter and exit the nucleus.

The Nuclear Envelope

The **nuclear envelope** is a double-membrane structure that constitutes the outermost portion of the nucleus (**Figure 1.11**). Both the inner and outer membranes of the nuclear envelope are phospholipid bilayers.

The nuclear envelope is punctuated with pores that control the passage of ions, molecules, and RNA between the nucleoplasm and cytoplasm. The **nucleoplasm** is the semi-solid fluid inside the nucleus, where we find the chromatin and the nucleolus.

Chromatin and Chromosomes

To understand chromatin, it is helpful to first consider chromosomes. **Chromosomes** are structures within the nucleus that are made up of DNA, the hereditary material. You may remember that in prokaryotes, DNA is organized into a single circular chromosome. In eukaryotes, chromosomes are linear structures. Every eukaryotic species has a specific number of chromosomes in the nuclei of its body's cells. For example, in humans, the chromosome number is 46, while in fruit flies, it is eight. Chromosomes are only visible and distinguishable from one another when the cell is getting ready to divide. When the cell is in the growth and maintenance phases of its life cycle, proteins are attached to chromosomes, and they resemble an unwound, jumbled bunch of threads. These unwound protein-chromosome complexes are called **chromatin** (**Figure 1.12**); chromatin describes the material that makes up the chromosomes both when condensed and decondensed.

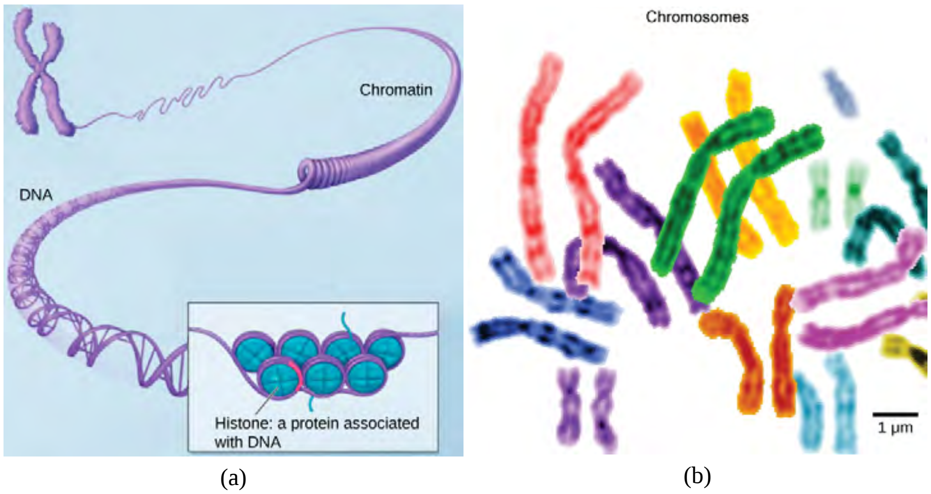


Figure 1.12 (a) This image shows various levels of the organization of chromatin (DNA and protein). (b) This image shows paired chromosomes. (credit b: modification of work by NIH; scale-bar data from Matt Russell)

The Nucleolus

We already know that the nucleus directs the synthesis of ribosomes, but how does it do this? Some chromosomes have sections of DNA that encode ribosomal RNA. A darkly staining area within the nucleus called the **nucleolus** (plural = nucleoli) aggregates the ribosomal RNA with associated proteins to assemble the ribosomal subunits that are then transported out through the pores in the nuclear envelope to the cytoplasm.

Ribosomes

Ribosomes are the cellular structures responsible for protein synthesis. When viewed through an electron microscope, ribosomes appear either as clusters (polyribosomes) or single, tiny dots that float freely in the cytoplasm. They may be attached to the cytoplasmic side of the plasma membrane or the cytoplasmic side of the endoplasmic reticulum and the outer membrane of the nuclear envelope (**Figure 1.8**). Electron microscopy has shown us that ribosomes, which are large complexes of protein and RNA, consist of two subunits, aptly called large and small (**Figure 1.13**). Ribosomes receive their "orders" for protein synthesis from the nucleus where the DNA is transcribed into messenger RNA (mRNA). The mRNA travels to the ribosomes, which translate the code provided by the sequence of the nitrogenous bases in the mRNA into a specific order of amino acids in a protein. Amino acids are the building blocks of proteins.

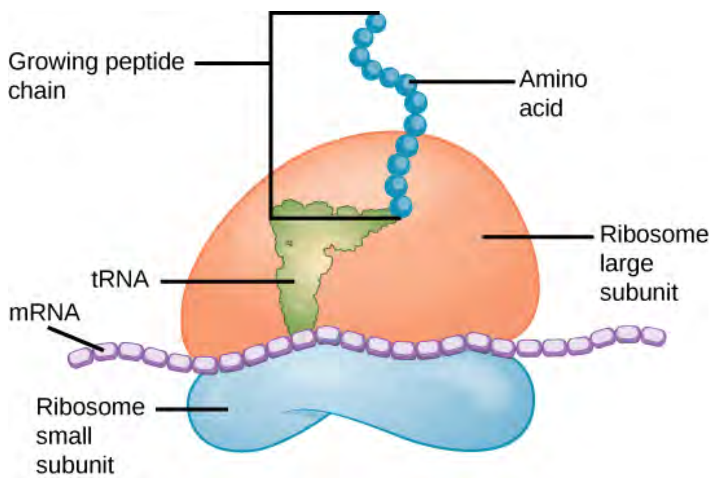


Figure 1.13 Ribosomes are made up of a large subunit (top) and a small subunit (bottom). During protein synthesis, ribosomes assemble amino acids into proteins.

Because protein synthesis is an essential function of all cells (including enzymes, hormones, antibodies, pigments, structural components, and surface receptors), ribosomes are found in practically every cell. Ribosomes are particularly abundant in cells that synthesize large amounts of protein. For example, the pancreas is responsible for creating several digestive enzymes and the cells that produce these enzymes contain many ribosomes. Thus, we see another example of form following function.

Mitochondria

Mitochondria (singular = mitochondrion) are often called the "powerhouses" or "energy factories" of a cell because they are responsible for making adenosine triphosphate (ATP), the cell's main energy-carrying molecule. ATP represents the short-term stored energy of the cell. Cellular respiration is the process of making ATP using the chemical energy found in glucose and other nutrients. In mitochondria, this process uses oxygen and produces carbon dioxide as a waste product. In fact, the carbon dioxide that you exhale with every breath comes from the cellular reactions that produce carbon dioxide as a byproduct.

In keeping with our theme of form following function, it is important to point out that muscle cells have a very high concentration of mitochondria that produce ATP. Your muscle cells need a lot of energy to keep your body moving. When your cells don't get enough oxygen, they do not make a lot of ATP. Instead, the small amount of ATP they make in the absence of oxygen is accompanied by the production of lactic acid.

Mitochondria are oval-shaped, double membrane organelles (**Figure 1.14**) that have their own ribosomes and DNA. Each membrane is a phospholipid bilayer embedded with proteins. The inner layer has folds called cristae. The area surrounded by the folds is called the mitochondrial matrix. The cristae and the matrix have different roles in cellular respiration.

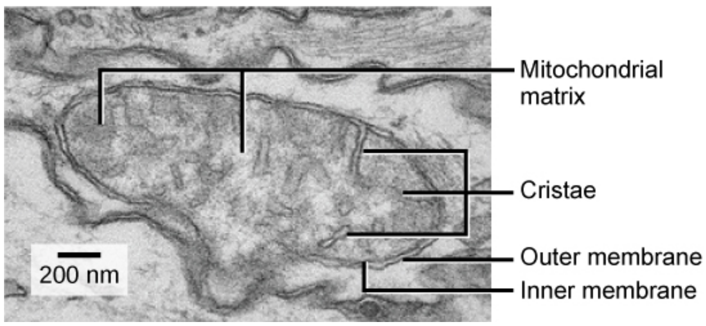


Figure 1.14 This electron micrograph shows a mitochondrion as viewed with a transmission electron microscope. This organelle has an outer membrane and an inner membrane. The inner membrane contains folds, called cristae, which increase its surface area. The space between the two membranes is called the intermembrane space, and the space inside the inner membrane is called the mitochondrial matrix. ATP synthesis takes place on the inner membrane. (credit: modification of work by Matthew Britton; scale-bar data from Matt Russell)

Peroxisomes

Peroxisomes are small, round organelles enclosed by single membranes. They carry out oxidation reactions that break down fatty acids and amino acids. They also detoxify many poisons that may enter the body. (Many of these oxidation reactions release hydrogen peroxide, H_2O_2, which would be damaging to cells; however, when these reactions are confined to peroxisomes, enzymes safely break down the H_2O_2 into oxygen and water.) Glyoxysomes, which are specialized peroxisomes in plants, are responsible for converting stored fats into sugars.

Vesicles and Vacuoles

Vesicles and **vacuoles** are membrane-bound sacs that function in storage and transport. Other than the fact that vacuoles are somewhat larger than vesicles, there is a very subtle distinction between them: The membranes of vesicles can fuse with either the plasma membrane or other membrane systems within the cell. Additionally, some agents such as enzymes within plant vacuoles break down macromolecules. The membrane of a vacuole does not fuse with the membranes of other cellular components.

Animal Cells versus Plant Cells

At this point, you know that each eukaryotic cell has a plasma membrane, cytoplasm, a nucleus, ribosomes, mitochondria, peroxisomes, and in some, vacuoles, but there are some striking differences between animal and plant cells. While both animal and plant cells have microtubule organizing centers (MTOCs), animal cells also have centrioles associated with the MTOC: a complex called the centrosome. Animal cells each have a centrosome and lysosomes, whereas plant cells do not. Plant cells have a cell wall, chloroplasts and other specialized plastids, and a large central vacuole, whereas animal cells do not.

The Centrosome

The **centrosome** is a microtubule-organizing center found near the nuclei of animal cells. It contains a pair of centrioles, two structures that lie perpendicular to each other (Figure 1.15). Each centriole is a cylinder of nine triplets of microtubules.

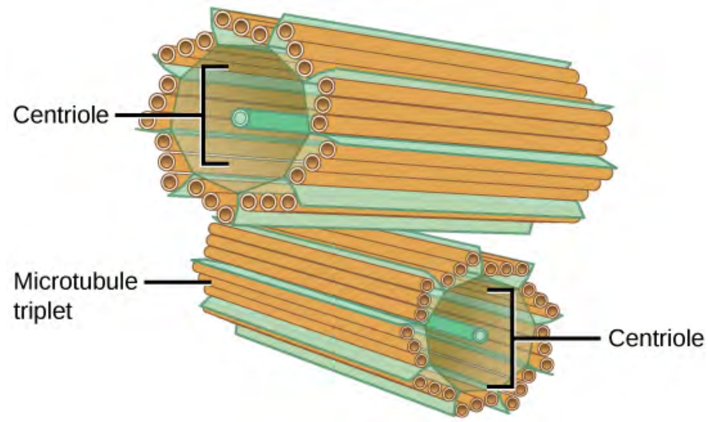


Figure 1.15 The centrosome consists of two centrioles that lie at right angles to each other. Each centriole is a cylinder made up of nine triplets of microtubules. Nontubulin proteins (indicated by the green lines) hold the microtubule triplets together.

The centrosome (the organelle where all microtubules originate) replicates itself before a cell divides, and the centrioles appear to have some role in pulling the duplicated chromosomes to opposite ends of the dividing cell. However, the exact function of the centrioles in cell division isn't clear, because cells that have had the centrosome removed can still divide, and plant cells, which lack centrosomes, are capable of cell division.

Lysosomes

Animal cells have another set of organelles not found in plant cells: lysosomes. The **lysosomes** are the cell's "garbage disposal." In plant cells, the digestive processes take place in vacuoles. Enzymes within the lysosomes aid the breakdown of proteins, polysaccharides, lipids, nucleic acids, and even worn-out organelles. These enzymes are active at a much lower pH than that of the cytoplasm. Therefore, the pH within lysosomes is more acidic than the pH of the cytoplasm. Many reactions that take place in the cytoplasm could not occur at a low pH, so again, the advantage of compartmentalizing the eukaryotic cell into organelles is apparent.

The Cell Wall

If you examine Figure 1.8**b**, the diagram of a plant cell, you will see a structure external to the plasma membrane called the cell wall. The **cell wall** is a rigid covering that protects the cell, provides structural support, and gives shape to the cell. Fungal and protistan cells also have cell walls. While the chief component of prokaryotic cell walls is peptidoglycan, the major organic molecule in the plant cell wall is cellulose (Figure 1.16), a polysaccharide made up of glucose units. Have you ever noticed that when you bite into a raw vegetable, like celery, it crunches? That's because you are tearing the rigid cell walls of the celery cells with your teeth.

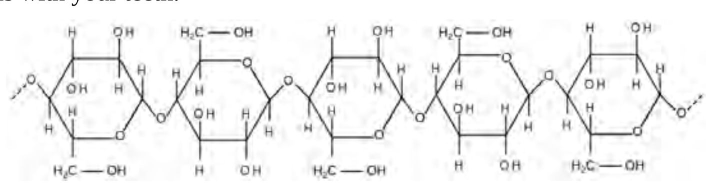


Figure 1.16 Cellulose is a long chain of β-glucose molecules connected by a 1-4 linkage. The dashed lines at each end of the figure indicate a series of many more glucose units. The size of the page makes it impossible to portray an entire cellulose molecule.

Chloroplasts

Like the mitochondria, chloroplasts have their own DNA and ribosomes, but chloroplasts have an entirely different function. **Chloroplasts** are plant cell organelles that carry out photosynthesis. Photosynthesis is the series of reactions that use carbon dioxide, water, and light energy to make glucose and oxygen. This is a major difference between plants and animals; plants (autotrophs) are able to make their own food, like sugars, while animals (heterotrophs) must ingest their food.

Like mitochondria, chloroplasts have outer and inner membranes, but within the space enclosed by a chloroplast's inner membrane is a set of interconnected and stacked fluid-filled membrane sacs called thylakoids (Figure 1.17). Each stack of thylakoids is called a granum (plural = grana). The fluid enclosed by the inner membrane that surrounds the grana is called the stroma.

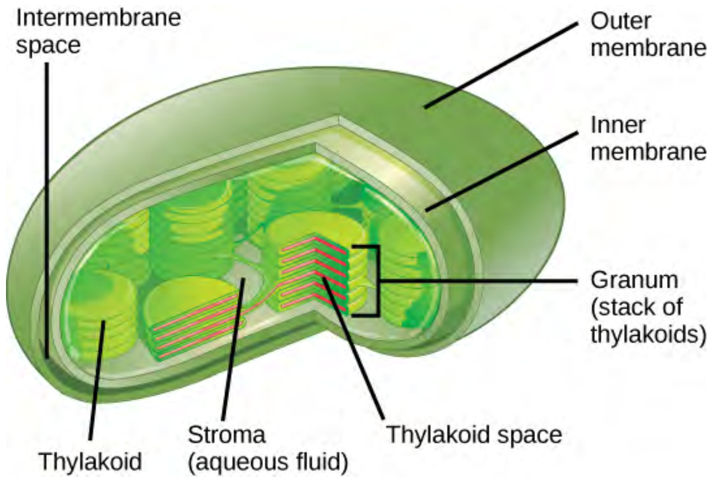


Figure 1.17 The chloroplast has an outer membrane, an inner membrane, and membrane structures called thylakoids that are stacked into grana. The space inside the thylakoid membranes is called the thylakoid space. The light harvesting reactions take place in the thylakoid membranes, and the synthesis of sugar takes place in the fluid inside the inner membrane, which is called the stroma. Chloroplasts also have their own genome, which is contained on a single circular chromosome.

The chloroplasts contain a green pigment called **chlorophyll**, which captures the light energy that drives the reactions of photosynthesis. Like plant cells, photosynthetic protists also have chloroplasts. Some bacteria perform photosynthesis, but their chlorophyll is not relegated to an organelle.

evolution CONNECTION

Endosymbiosis

We have mentioned that both mitochondria and chloroplasts contain DNA and ribosomes. Have you wondered why? Strong evidence points to endosymbiosis as the explanation.

Symbiosis is a relationship in which organisms from two separate species depend on each other for their survival. Endosymbiosis (endo- = “within”) is a mutually beneficial relationship in which one organism lives inside the other. Endosymbiotic relationships abound in nature. We have already mentioned that microbes that produce vitamin K live inside the human gut. This relationship is beneficial for us because we are unable to synthesize vitamin K. It is also beneficial for the microbes because they are protected from other organisms and from drying out, and they receive abundant food from the environment of the large intestine.

Scientists have long noticed that bacteria, mitochondria, and chloroplasts are similar in size. We also know that bacteria have DNA and ribosomes, just as mitochondria and chloroplasts do. Scientists believe that host cells and bacteria formed an endosymbiotic relationship when the host cells ingested both aerobic and autotrophic bacteria (cyanobacteria) but did not destroy them. Through many millions of years of evolution, these ingested bacteria became more specialized in their functions, with the aerobic bacteria becoming mitochondria and the autotrophic bacteria becoming chloroplasts.

Based on what you know about plant and animals cells, which of the following events are most likely to have occurred?

a. A host cell that ingested aerobic bacteria gave rise to modern animals, while ancestor of that cell that also ingested photoautotrophic bacteria that gave rise to modern plants.

b. A host cell that gave rise to modern plants ingested photoautotrophic bacteria only, while a host cell that gave rise to modern animals ingested aerobic bacteria only.

c. A host cell that gave rise to modern plants ingested both aerobic and photoautotrophic bacteria, while a host cell that gave rise to modern animals ingested photoautotrophic bacteria only.

d. A host cell that gave rise to modern plants and animals ingested both aerobic and photoautotrophic bacteria.

The Central Vacuole

Previously, we mentioned vacuoles as essential components of plant cells. If you look at **Figure 1.8b**, you will see that plant cells each have a large central vacuole that occupies most of the area of the cell. The **central vacuole** plays a key role in regulating the cell's concentration of water in changing environmental conditions. Have you ever noticed that if you forget to water a plant for a few days, it wilts? That's because as the water concentration in the soil becomes lower than the water concentration in the plant, water moves out of the central vacuoles and cytoplasm. As the central vacuole shrinks, it leaves the cell wall unsupported. This loss of support to the cell walls of plant cells results in the wilted appearance of the plant.

The central vacuole also supports the expansion of the cell. When the central vacuole holds more water, the cell gets larger without having to invest a lot of energy in synthesizing new cytoplasm.

science practices CONNECTION for AP® Courses

Activity

- Construct a concept map or Venn diagram to describe the relationships that exist among the three domains of life (Archaea, Bacteria, and Eukarya) based on cellular features. Share your diagram with other students in the class for review and revision.
- Mystery Cell ID. Using a microscope, identify several types of cells, e.g., prokaryote/eukaryote, plant/animal, based on general features and justify your identification.
- Ten-Minute Debate. Working in small teams, create a visual representation to support the claim that eukaryotes evolved from symbiotic relationships among groups of prokaryotes.

Think About It

- If the nucleolus were not able to carry out its function, what other cellular organelles would be affected? Would a human liver cell that lacked endoplasmic reticulum be able to metabolize toxins?
- Antibiotics are medicines that are used to fight bacterial infections. These medicines kill prokaryotic cells without harming human cells. What part(s) of the bacterial cell do antibiotics target and provide reasoning for your answer.

4.4 | The Endomembrane System and Proteins

In this section, you will explore the following questions:

- What is the relationship between the structure and function of the components of the endomembrane system, especially with regard to the synthesis of proteins?

Connection for AP® Courses

In addition to the presence of nuclei, eukaryotic cells are distinguished by an endomembrane system that includes the plasma membrane, nuclear envelope, lysosomes, vesicles, endoplasmic reticulum, and Golgi apparatus. These subcellular components work together to modify, tag, package, and transport proteins and lipids. The rough endoplasmic reticulum (RER) with its attached ribosomes is the site of protein synthesis and modification. The smooth endoplasmic reticulum (SER) synthesizes carbohydrates, lipids including phospholipids and cholesterol, and steroid hormones; engages in the detoxification of medications and poisons; and stores calcium ions. Lysosomes digest macromolecules, recycle worn-out organelles, and destroy pathogens. Just like your body uses different organs that work together, cells use these organelles interact to perform specific functions. For example, proteins that are synthesized in the RER then travel to the Golgi apparatus for modification and packaging for either storage or transport. If these proteins are hydrolytic enzymes, they can be stored in lysosomes. Mitochondria produce the energy needed for these processes. This functional flow through several organelles, a process which is dependent on energy produced by yet another organelle, serves as a hallmark illustration of the cell's complex, interconnected dependence on its organelles.

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in

Big Idea 2 and Big Idea 4 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.B	Growth, reproduction and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.
Essential Knowledge	**2.B.3** Eukaryotic cells maintain internal membranes that partition the cell into specialized regions.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**2.13** The student is able to explain how internal membranes and organelles contribute to cell functions.
Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.2** The structure and function of subcellular components, and their interactions, provide essential cellular processes.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**4.5** The student is able to construct explanations based on scientific evidence as to how interactions of subcellular structures provide essential functions.

The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 4.6]

The Endoplasmic Reticulum

The endomembrane system (endo = "within") is a group of membranes and organelles (**Figure 1.18**) in eukaryotic cells that works together to modify, package, and transport lipids and proteins. It includes the nuclear envelope, lysosomes, and vesicles, which we've already mentioned, and the endoplasmic reticulum and Golgi apparatus, which we will cover shortly. Although not technically *within* the cell, the plasma membrane is included in the endomembrane system because, as you will see, it interacts with the other endomembranous organelles. The endomembrane system does not include the membranes of either mitochondria or chloroplasts.

visual CONNECTION

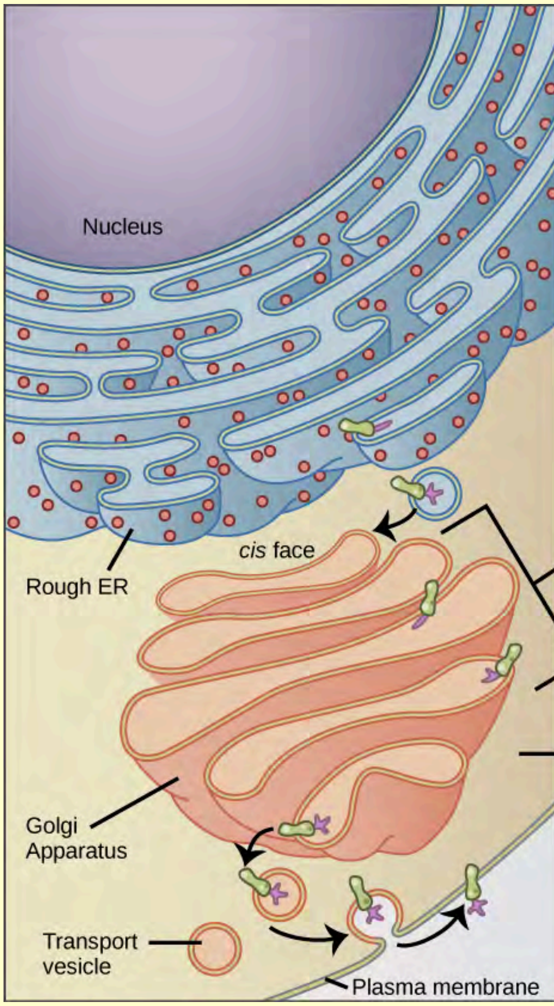


Figure 1.18 "Membrane and secretory proteins are synthesized in the rough endoplasmic reticulum (RER). The RER also sometimes modifies proteins. In this illustration, a (green) integral membrane protein in the ER is modified by attachment of a (purple) carbohydrate. Vesicles with the integral protein bud from the ER and fuse with the cis face of the Golgi apparatus. As the protein passes along the Golgi's cisternae, it is further modified by the addition of more carbohydrates. After its synthesis is complete, it exits as integral membrane protein of the vesicle that bud from the Golgi's **trans** face and when the vesicle fuses with the cell membrane the protein becomes integral portion of that cell membrane. (credit: modification of work by Magnus Manske)

If a peripheral membrane protein were synthesized inside the lumen of the ER, would it end up on the inside or outside of the plasma membrane?

a. The vesicle travels from the endoplasmic reticulum to get embedded in plasma membrane.
b. The vesicle travels from the Golgi to the plasma membrane to release the protein outside.
c. The vesicle travels from the endoplasmic reticulum to the plasma membrane, and returns to the Golgi apparatus to get modified.
d. The vesicle moves from the endoplasmic reticulum into the cytoplasmic area, remaining there.

The **endoplasmic reticulum (ER)** (Figure 1.18) is a series of interconnected membranous sacs and tubules that collectively modifies proteins and synthesizes lipids. However, these two functions are performed in separate areas of the ER: the rough ER and the smooth ER, respectively.

The hollow portion of the ER tubules is called the lumen or cisternal space. The membrane of the ER, which is a phospholipid bilayer embedded with proteins, is continuous with the nuclear envelope.

Rough ER

The **rough endoplasmic reticulum (RER)** is so named because the ribosomes attached to its cytoplasmic surface give it a studded appearance when viewed through an electron microscope (Figure 1.19).

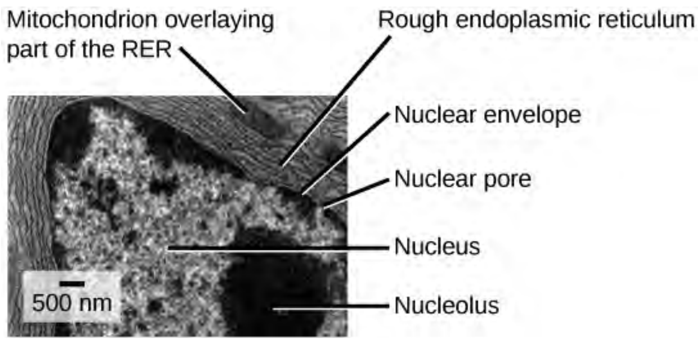


Figure 1.19 This transmission electron micrograph shows the rough endoplasmic reticulum and other organelles in a pancreatic cell. (credit: modification of work by Louisa Howard)

Ribosomes transfer their newly synthesized proteins into the lumen of the RER where they undergo structural modifications, such as folding or the acquisition of side chains. These modified proteins will be incorporated into cellular membranes—the membrane of the ER or those of other organelles—or secreted from the cell (such as protein hormones, enzymes). The RER also makes phospholipids for cellular membranes.

If the phospholipids or modified proteins are not destined to stay in the RER, they will reach their destinations via transport vesicles that bud from the RER's membrane (Figure 1.18).

Since the RER is engaged in modifying proteins (such as enzymes, for example) that will be secreted from the cell, you would be correct in assuming that the RER is abundant in cells that secrete proteins. This is the case with cells of the liver, for example.

Smooth ER

The **smooth endoplasmic reticulum (SER)** is continuous with the RER but has few or no ribosomes on its cytoplasmic surface (Figure 1.18). Functions of the SER include synthesis of carbohydrates, lipids, and steroid hormones; detoxification of medications and poisons; and storage of calcium ions.

In muscle cells, a specialized SER called the sarcoplasmic reticulum is responsible for storage of the calcium ions that are needed to trigger the coordinated contractions of the muscle cells.

LINK TO LEARNING

You can watch an excellent animation of the endomembrane system **here (http://openstaxcollege.org/l/endomembrane)**. At the end of the animation, there is a short self-assessment.

How do the nucleus and the endomembrane system work together for protein synthesis?

a. The endomembrane system processes and ships proteins specified by the nucleus. In the nucleus, DNA is used to make RNA which exits the nucleus and enters the cytoplasm of the cell. The ribosomes on the rough ER use the RNA to create the different types of protein needed by the body.

b. The endomembrane system processes and ships proteins specified by the nucleus. From the nucleus, RNA exits and enters the cytoplasm of the cell. The ribosomes on the rough ER use the RNA to create the different types of protein needed by the body.

c. The endomembrane system processes and ships proteins specified by the nucleus. In the nucleus, DNA is used to make RNA which exits the nucleus and enters the cytoplasm of the cell. The smooth ER uses the RNA to create the different types of protein needed by the body.

d. The endomembrane system processes and ships proteins specified by the nucleus. In the nucleus, DNA is used to make RNA which exits the nucleus and enters the cytoplasm of the cell. The ribosomes on the smooth ER use the RNA to create the different types of protein needed by the body.

career CONNECTION

Cardiologist

Heart disease is the leading cause of death in the United States. This is primarily due to our sedentary lifestyle and our high trans-fat diets.

Heart failure is just one of many disabling heart conditions. Heart failure does not mean that the heart has stopped working. Rather, it means that the heart can’t pump with sufficient force to transport oxygenated blood to all the vital organs. Left untreated, heart failure can lead to kidney failure and failure of other organs.

The wall of the heart is composed of cardiac muscle tissue. Heart failure occurs when the endoplasmic reticula of cardiac muscle cells do not function properly. As a result, an insufficient number of calcium ions are available to trigger a sufficient contractile force.

Cardiologists (cardi- = “heart”; -ologist = “one who studies”) are doctors who specialize in treating heart diseases, including heart failure. Cardiologists can make a diagnosis of heart failure via physical examination, results from an electrocardiogram (ECG, a test that measures the electrical activity of the heart), a chest X-ray to see whether the heart is enlarged, and other tests. If heart failure is diagnosed, the cardiologist will typically prescribe appropriate medications and recommend a reduction in table salt intake and a supervised exercise program.

The Golgi Apparatus

We have already mentioned that vesicles can bud from the ER and transport their contents elsewhere, but where do the vesicles go? Before reaching their final destination, the lipids or proteins within the transport vesicles still need to be sorted, packaged, and tagged so that they wind up in the right place. Sorting, tagging, packaging, and distribution of lipids and proteins takes place in the **Golgi apparatus** (also called the Golgi body), a series of flattened membranes (**Figure 1.20**).

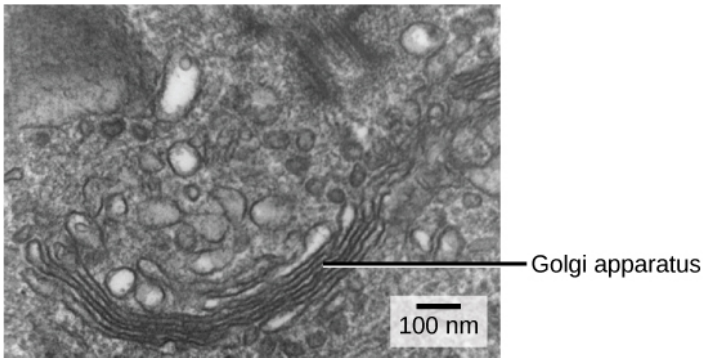


Figure 1.20 The Golgi apparatus in this white blood cell is visible as a stack of semicircular, flattened rings in the lower portion of the image. Several vesicles can be seen near the Golgi apparatus. (credit: modification of work by Louisa Howard)

The receiving side of the Golgi apparatus is called the *cis* face. The opposite side is called the *trans* face. The transport vesicles that formed from the ER travel to the *cis* face, fuse with it, and empty their contents into the lumen of the Golgi apparatus. As the proteins and lipids travel through the Golgi, they undergo further modifications that allow them to be sorted. The most frequent modification is the addition of short chains of sugar molecules. These newly modified proteins and lipids are then tagged with phosphate groups or other small molecules so that they can be routed to their proper destinations.

Finally, the modified and tagged proteins are packaged into secretory vesicles that bud from the *trans* face of the Golgi. While some of these vesicles deposit their contents into other parts of the cell where they will be used, other secretory vesicles fuse with the plasma membrane and release their contents outside the cell.

In another example of form following function, cells that engage in a great deal of secretory activity (such as cells of the salivary glands that secrete digestive enzymes or cells of the immune system that secrete antibodies) have an abundance of Golgi.

In plant cells, the Golgi apparatus has the additional role of synthesizing polysaccharides, some of which are incorporated into the cell wall and some of which are used in other parts of the cell.

career CONNECTION

Geneticist

Many diseases arise from genetic mutations that prevent the synthesis of critical proteins. One such disease is Lowe disease (also called oculocerebrorenal syndrome, because it affects the eyes, brain, and kidneys). In Lowe disease, there is a deficiency in an enzyme localized to the Golgi apparatus. Children with Lowe disease are born with cataracts, typically develop kidney disease after the first year of life, and may have impaired mental abilities.

Lowe disease is a genetic disease caused by a mutation on the X chromosome. The X chromosome is one of the two human sex chromosomes, as these chromosomes determine a person's sex. Females possess two X chromosomes while males possess one X and one Y chromosome. In females, the genes on only one of the two X chromosomes are expressed. Therefore, females who carry the Lowe disease gene on one of their X chromosomes have a 50/50 chance of having the disease. However, males only have one X chromosome and the genes on this chromosome are always expressed. Therefore, males will always have Lowe disease if their X chromosome carries the Lowe disease gene. The location of the mutated gene, as well as the locations of many other mutations that cause genetic diseases, has now been identified. Through prenatal testing, a woman can find out if the fetus she is carrying may be afflicted with one of several genetic diseases.

Geneticists analyze the results of prenatal genetic tests and may counsel pregnant women on available options. They may also conduct genetic research that leads to new drugs or foods, or perform DNA analyses that are used in forensic investigations.

Lysosomes

In addition to their role as the digestive component and organelle-recycling facility of animal cells, lysosomes are considered to be parts of the endomembrane system. Lysosomes also use their hydrolytic enzymes to destroy pathogens (disease-causing organisms) that might enter the cell. A good example of this occurs in a group of white blood cells called macrophages, which are part of your body's immune system. In a process known as phagocytosis or endocytosis, a section of the plasma membrane of the macrophage invaginates (folds in) and engulfs a pathogen. The invaginated section, with the pathogen inside, then pinches itself off from the plasma membrane and becomes a vesicle. The vesicle fuses with a lysosome. The lysosome's hydrolytic enzymes then destroy the pathogen (**Figure 1.21**).

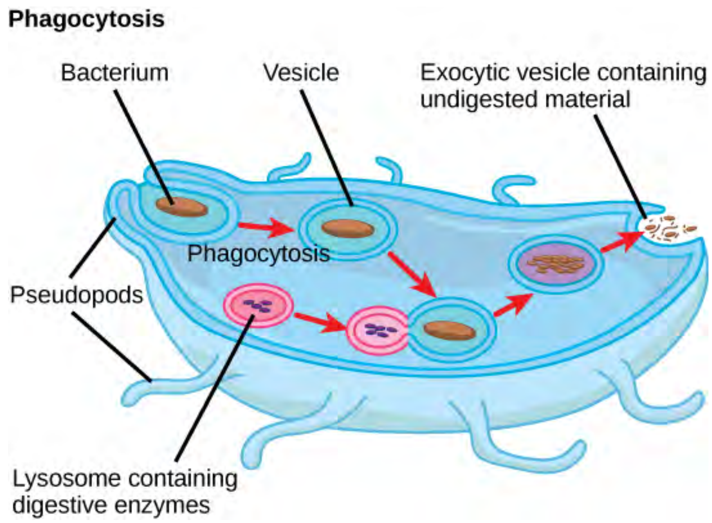


Figure 1.21 A macrophage has engulfed (phagocytized) a potentially pathogenic bacterium which then fuses with a lysosomes within the cell to destroy the pathogen. Other organelles are present in the cell but for simplicity are not shown.

science practices CONNECTION for AP® Courses

Activity

Homemade Cell Project. Using inexpensive and common household items, create a model of a specific eukaryotic cell (e.g., neuron, white blood cell, plant root cell, or *Paramecium*) that demonstrates how at least three organelles work together to perform a specific function.

Think About It

A certain cell type functions primarily to synthesize proteins for export. What is the most likely route the newly made protein takes through the cell? Justify your prediction.

4.5 | Cytoskeleton

In this section, you will explore the following questions:

- How do the various components of the cytoskeleton perform their functions?

Connection for AP® Courses

All cells, from simple bacteria to complex eukaryotes, possess a cytoskeleton composed of different types of protein elements, including microfilaments, intermediate filaments, and microtubules. The cytoskeleton serves a variety of purposes: provides rigidity and shape to the cell, facilitates cellular movement, anchors the nucleus and other organelles in place, moves vesicles through the cell, and pulls replicated chromosomes to the poles of a dividing cell. These protein elements are also integral to the movement of centrioles, flagella, and cilia.

The information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 1 of the AP Biology Curriculum Framework, as shown in the table below.

The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 1	The process of evolution drives the diversity and unity of life.
Enduring Understanding 1.B	Organisms are linked by lines of descent from common ancestry
Essential Knowledge	**1.B.1** Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.
Science Practice	**7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	**1.15** The student is able to describe specific examples of conserved core biological processes and features shared by all domains or within one domain of life and how these shared, conserved core processes and features support the concept of common ancestry for all organisms.

Microfilaments

If you were to remove all the organelles from a cell, would the plasma membrane and the cytoplasm be the only components left? No. Within the cytoplasm, there would still be ions and organic molecules, plus a network of protein fibers that help maintain the shape of the cell, secure some organelles in specific positions, allow cytoplasm and vesicles to move within the cell, and enable cells within multicellular organisms to move. Collectively, this network of protein fibers is known as the **cytoskeleton**. There are three types of fibers within the cytoskeleton: microfilaments, intermediate filaments, and microtubules (**Figure 1.22**). Here, we will examine each.

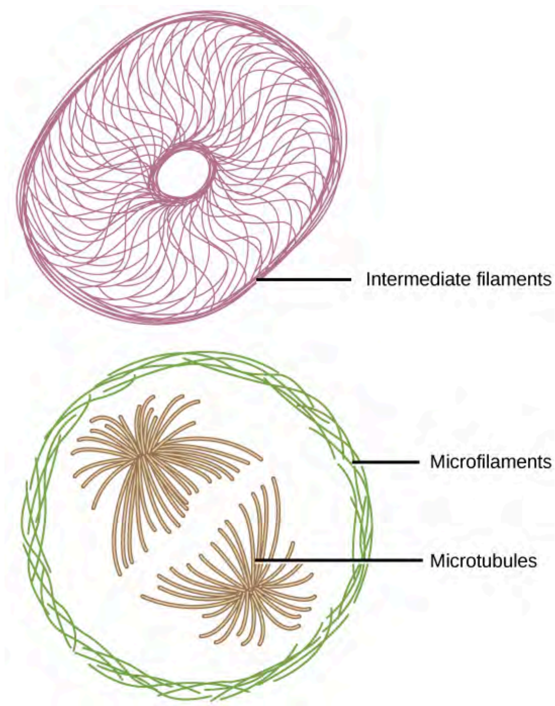


Figure 1.22 Microfilaments thicken the cortex around the inner edge of a cell; like rubber bands, they resist tension. Microtubules are found in the interior of the cell where they maintain cell shape by resisting compressive forces. Intermediate filaments are found throughout the cell and hold organelles in place.

Of the three types of protein fibers in the cytoskeleton, **microfilaments** are the narrowest. They function in cellular movement, have a diameter of about 7 nm, and are made of two intertwined strands of a globular protein called actin (**Figure 1.23**). For this reason, microfilaments are also known as actin filaments.

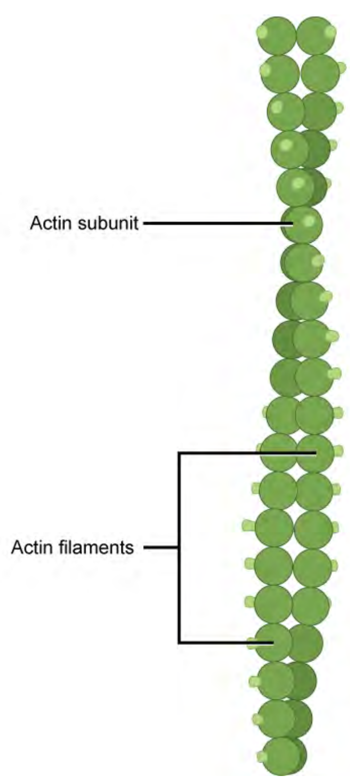


Figure 1.23 Microfilaments are made of two intertwined strands of actin.

Actin is powered by ATP to assemble its filamentous form, which serves as a track for the movement of a motor protein called myosin. This enables actin to engage in cellular events requiring motion, such as cell division in animal cells and cytoplasmic streaming, which is the circular movement of the cell cytoplasm in plant cells. Actin and myosin are plentiful in muscle cells. When your actin and myosin filaments slide past each other, your muscles contract.

Microfilaments also provide some rigidity and shape to the cell. They can depolymerize (disassemble) and reform quickly, thus enabling a cell to change its shape and move. White blood cells (your body's infection-fighting cells) make good use of this ability. They can move to the site of an infection and phagocytize the pathogen.

LINK TO LEARNING

To see an example of a white blood cell in action, click **here (http://openstaxcollege.org/l/chasing_bcteria)** and watch a short time-lapse video of the cell capturing two bacteria. It engulfs one and then moves on to the other.

The Human Immunodeficiency Virus (HIV) infects and kills white blood cells. Over time, what affect does this have on the body's immune system?

a. The body's immune system would not be affected by this.

b. The body's immune system would not be able to fight off pathogens like bacteria with fewer white blood cells. This can increase the risk of illness in HIV patients.

c. The body's immune system, in order to recoup this loss, will produce more WBC's.

d. The body's immune system will fight the pathogens more vigorously in order to compensate for the fewer white blood cells.

Intermediate Filaments

Intermediate filaments are made of several strands of fibrous proteins that are wound together (**Figure 1.24**). These elements of the cytoskeleton get their name from the fact that their diameter, 8 to 10 nm, is between those of microfilaments and microtubules.

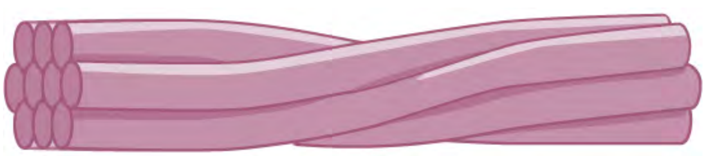


Figure 1.24 Intermediate filaments consist of several intertwined strands of fibrous proteins.

Intermediate filaments have no role in cell movement. Their function is purely structural. They bear tension, thus maintaining the shape of the cell, and anchor the nucleus and other organelles in place. **Figure 1.22** shows how intermediate filaments create a supportive scaffolding inside the cell.

The intermediate filaments are the most diverse group of cytoskeletal elements. Several types of fibrous proteins are found in the intermediate filaments. You are probably most familiar with keratin, the fibrous protein that strengthens your hair, nails, and the epidermis of the skin.

Microtubules

As their name implies, microtubules are small hollow tubes. The walls of the microtubule are made of polymerized dimers of α-tubulin and β-tubulin, two globular proteins (**Figure 1.25**). With a diameter of about 25 nm, **microtubules** are the widest components of the cytoskeleton. They help the cell resist compression, provide a track along which vesicles move through the cell, and pull replicated chromosomes to opposite ends of a dividing cell. Like microfilaments, microtubules can dissolve and reform quickly.

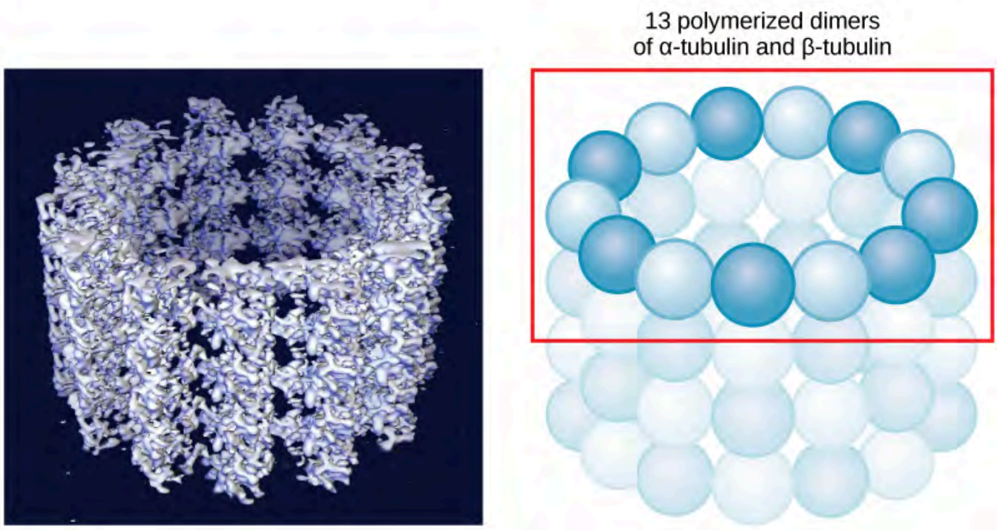


Figure 1.25 Microtubules are hollow. Their walls consist of 13 polymerized dimers of α-tubulin and β-tubulin (right image). The left image shows the molecular structure of the tube.

Microtubules are also the structural elements of flagella, cilia, and centrioles (the latter are the two perpendicular bodies of the centrosome). In fact, in animal cells, the centrosome is the microtubule-organizing center. In eukaryotic cells, flagella and cilia are quite different structurally from their counterparts in prokaryotes, as discussed below.

Flagella and Cilia

To refresh your memory, **flagella** (singular = flagellum) are long, hair-like structures that extend from the plasma membrane and are used to move an entire cell (for example, sperm, *Euglena*). When present, the cell has just one flagellum or a few flagella. When **cilia** (singular = cilium) are present, however, many of them extend along the entire surface of the plasma membrane. They are short, hair-like structures that are used to move entire cells (such as paramecia) or substances along the outer surface of the cell (for example, the cilia of cells lining the Fallopian tubes that move the ovum toward the uterus, or cilia lining the cells of the respiratory tract that trap particulate matter and move it toward your nostrils.)

Despite their differences in length and number, flagella and cilia share a common structural arrangement of microtubules called a “9 + 2 array.” This is an appropriate name because a single flagellum or cilium is made of a ring of nine microtubule doublets, surrounding a single microtubule doublet in the center (**Figure 1.26**).

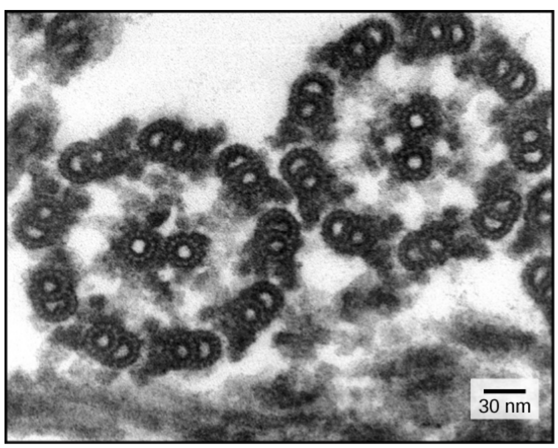


Figure 1.26 This transmission electron micrograph of two flagella shows the 9 + 2 array of microtubules: nine microtubule doublets surround a single microtubule doublet. (credit: modification of work by Dartmouth Electron Microscope Facility, Dartmouth College; scale-bar data from Matt Russell)

science practices CONNECTION for AP® Courses

Think About It

The ribosomes in bacterial cells and in human cells are made up of proteins and ribosomal RNA, suggesting that both kinds of cells share a common ancestor cell type. What are examples of other features of cells that provide evidence for common ancestry?

You have now completed a broad survey of the components of prokaryotic and eukaryotic cells. For a summary of cellular components in prokaryotic and eukaryotic cells, see **Table 1.1**.

Components of Prokaryotic and Eukaryotic Cells

Cell Component	Function	Present in Prokaryotes?	Present in Animal Cells?	Present in Plant Cells?
Plasma membrane	Separates cell from external environment; controls passage of organic molecules, ions, water, oxygen, and wastes into and out of cell	Yes	Yes	Yes
Cytoplasm	Provides turgor pressure to plant cells as fluid inside the central vacuole; site of many metabolic reactions; medium in which organelles are found	Yes	Yes	Yes
Nucleolus	Darkened area within the nucleus where ribosomal subunits are synthesized.	No	Yes	Yes
Nucleus	Cell organelle that houses DNA and directs synthesis of ribosomes and proteins	No	Yes	Yes
Ribosomes	Protein synthesis	Yes	Yes	Yes
Mitochondria	ATP production/cellular respiration	No	Yes	Yes
Peroxisomes	Oxidizes and thus breaks down fatty acids and amino acids, and detoxifies poisons	No	Yes	Yes
Vesicles and vacuoles	Storage and transport; digestive function in plant cells	No	Yes	Yes
Centrosome	Unspecified role in cell division in animal cells; source of microtubules in animal cells	No	Yes	No
Lysosomes	Digestion of macromolecules; recycling of worn-out organelles	No	Yes	No
Cell wall	Protection, structural support and maintenance of cell shape	Yes, primarily peptidoglycan	No	Yes, primarily cellulose
Chloroplasts	Photosynthesis	No	No	Yes
Endoplasmic reticulum	Modifies proteins and synthesizes lipids	No	Yes	Yes

Table 1.1

Components of Prokaryotic and Eukaryotic Cells

Cell Component	Function	Present in Prokaryotes?	Present in Animal Cells?	Present in Plant Cells?
Golgi apparatus	Modifies, sorts, tags, packages, and distributes lipids and proteins	No	Yes	Yes
Cytoskeleton	Maintains cell's shape, secures organelles in specific positions, allows cytoplasm and vesicles to move within cell, and enables unicellular organisms to move independently	Yes	Yes	Yes
Flagella	Cellular locomotion	Some	Some	No, except for some plant sperm cells.
Cilia	Cellular locomotion, movement of particles along extracellular surface of plasma membrane, and filtration	Some	Some	No

Table 1.1

4.6 | Connections between Cells and Cellular Activities

In this section, you will explore the following questions:

- What are the components of the extracellular matrix?
- What are the roles of tight junctions, gap junctions, and plasmodesmata in allowing cells to exchange materials with the environment and communicate with other cells?

Connection for AP® Courses

With the exception of gap junctions between animal cells and plasmodesmata between plant cells that facilitate the exchange of substances, the information presented in Section 4.6| Connections between Cells and Cellular Activities is not required for AP®. Concepts about cell communication and signaling processes that are required for AP®, including the features of cells that make communication possible, are covered in Chapter 9.

You already know that a group of similar cells working together is called a tissue. As you might expect that, if cells are to work together, they must communicate with one another, just as you need to communicate with others when you work on a group project. Let's take a look at how cells communicate with one another.

You already know that a group of similar cells working together is called a tissue. As you might expect, if cells are to work together, they must communicate with each other, just as you need to communicate with others if you work on a group project. Let's take a look at how cells communicate with each other.

The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 4.5][APLO 3.32][APLO 1.16][APLO 3.33][APLO 1.14][APLO 2.7][APLO 4.4]

Extracellular Matrix of Animal Cells

Most animal cells release materials into the extracellular space. The primary components of these materials are proteins, and the most abundant protein is collagen. Collagen fibers are interwoven with carbohydrate-containing protein molecules called proteoglycans. Collectively, these materials are called the **extracellular matrix** (Figure 1.27). Not only does the extracellular matrix hold the cells together to form a tissue, but it also allows the cells within the tissue to communicate with each other. How can this happen?

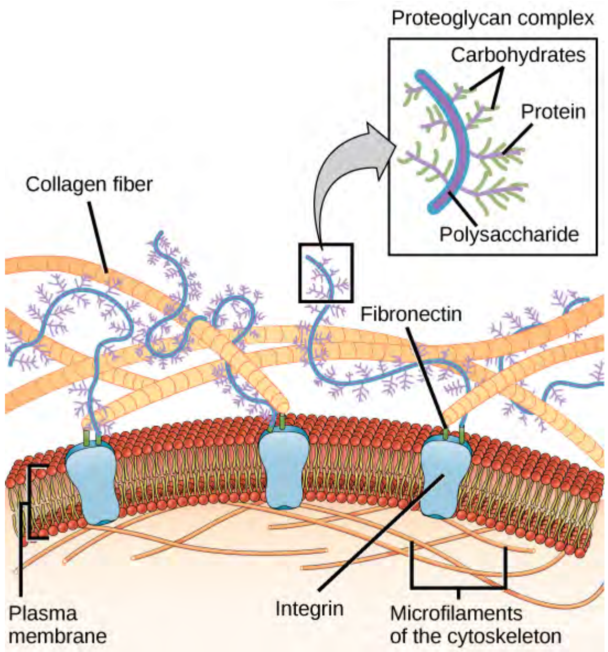


Figure 1.27 The extracellular matrix consists of a network of proteins and carbohydrates.

Cells have protein receptors on the extracellular surfaces of their plasma membranes. When a molecule within the matrix binds to the receptor, it changes the molecular structure of the receptor. The receptor, in turn, changes the conformation of the microfilaments positioned just inside the plasma membrane. These conformational changes induce chemical signals inside the cell that reach the nucleus and turn “on” or “off” the transcription of specific sections of DNA, which affects the production of associated proteins, thus changing the activities within the cell.

Blood clotting provides an example of the role of the extracellular matrix in cell communication. When the cells lining a blood vessel are damaged, they display a protein receptor called tissue factor. When tissue factor binds with another factor in the extracellular matrix, it causes platelets to adhere to the wall of the damaged blood vessel, stimulates the adjacent smooth muscle cells in the blood vessel to contract (thus constricting the blood vessel), and initiates a series of steps that stimulate the platelets to produce clotting factors.

Intercellular Junctions

Cells can also communicate with each other via direct contact, referred to as intercellular junctions. There are some differences in the ways that plant and animal cells do this. Plasmodesmata are junctions between plant cells, whereas animal cell contacts include tight junctions, gap junctions, and desmosomes.

Plasmodesmata

In general, long stretches of the plasma membranes of neighboring plant cells cannot touch one another because they are separated by the cell wall that surrounds each cell (**m64471 (http://cnx.org/content/m64471/latest/#fig-ch04-03-01) b**). How then, can a plant transfer water and other soil nutrients from its roots, through its stems, and to its leaves? Such transport uses the vascular tissues (xylem and phloem) primarily. There also exist structural modifications called **plasmodesmata** (singular = plasmodesma), numerous channels that pass between cell walls of adjacent plant cells, connect their cytoplasm, and enable materials to be transported from cell to cell, and thus throughout the plant (**Figure 1.28**).

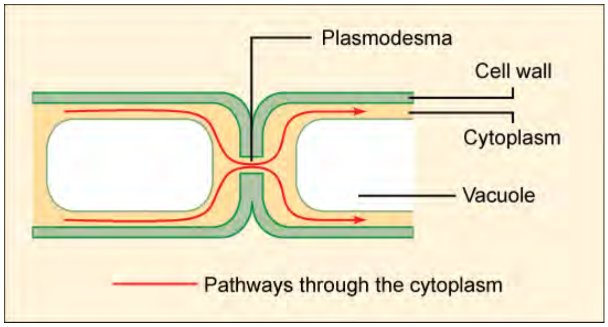


Figure 1.28 A plasmodesma is a channel between the cell walls of two adjacent plant cells. Plasmodesmata allow materials to pass from the cytoplasm of one plant cell to the cytoplasm of an adjacent cell.

Tight Junctions

A **tight junction** is a watertight seal between two adjacent animal cells (**Figure 1.29**). The cells are held tightly against each other by proteins (predominantly two proteins called claudins and occludins).

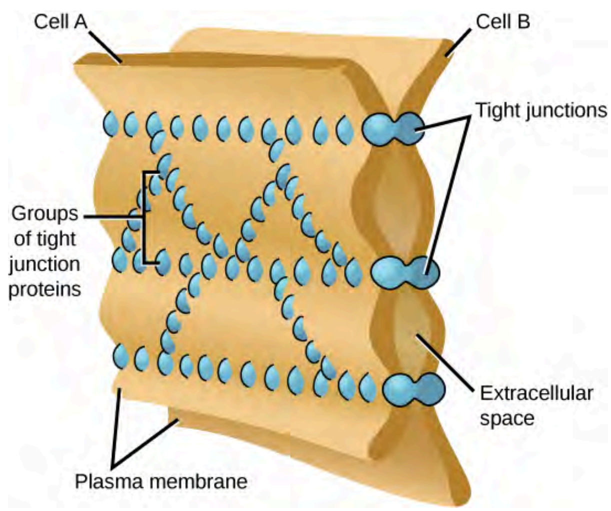


Figure 1.29 Tight junctions form watertight connections between adjacent animal cells. Proteins create tight junction adherence. (credit: modification of work by Mariana Ruiz Villareal)

This tight adherence prevents materials from leaking between the cells; tight junctions are typically found in epithelial tissues that line internal organs and cavities, and comprise most of the skin. For example, the tight junctions of the epithelial cells lining your urinary bladder prevent urine from leaking out into the extracellular space.

Desmosomes

Also found only in animal cells are **desmosomes**, which act like spot welds between adjacent epithelial cells (**Figure 1.30**). Short proteins called cadherins in the plasma membrane connect to intermediate filaments to create desmosomes. The cadherins join two adjacent cells together and maintain the cells in a sheet-like formation in organs and tissues that stretch, like the skin, heart, and muscles.

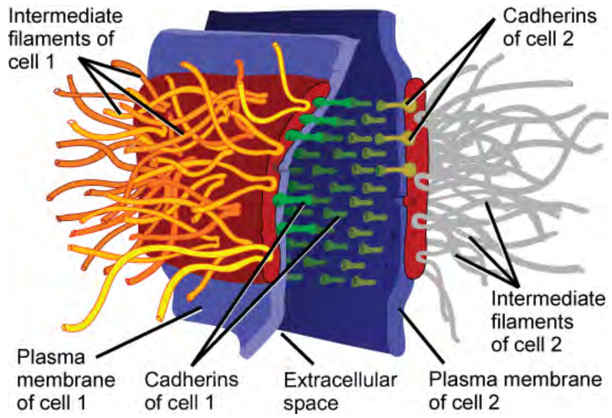


Figure 1.30 A desmosome forms a very strong spot weld between cells. It is created by the linkage of cadherins and intermediate filaments. (credit: modification of work by Mariana Ruiz Villareal)

Gap Junctions

Gap junctions in animal cells are like plasmodesmata in plant cells in that they are channels between adjacent cells that allow for the transport of ions, nutrients, and other substances that enable cells to communicate (**Figure 1.31**). Structurally, however, gap junctions and plasmodesmata differ.

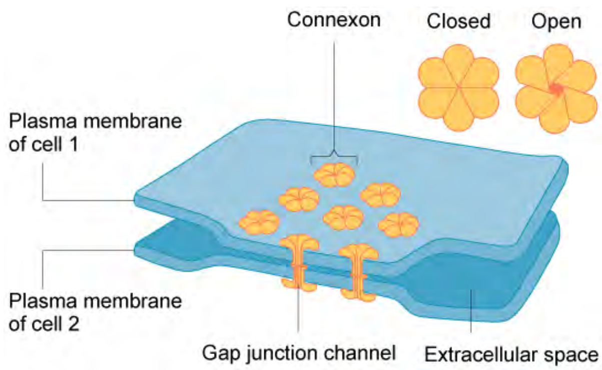


Figure 1.31 A gap junction is a protein-lined pore that allows water and small molecules to pass between adjacent animal cells. (credit: modification of work by Mariana Ruiz Villareal)

Gap junctions develop when a set of six proteins (called connexins) in the plasma membrane arrange themselves in an elongated donut-like configuration called a connexon. When the pores ("doughnut holes") of connexons in adjacent animal cells align, a channel between the two cells forms. Gap junctions are particularly important in cardiac muscle: The electrical signal for the muscle to contract is passed efficiently through gap junctions, allowing the heart muscle cells to contract in tandem.

LINK TO LEARNING

To conduct a virtual microscopy lab and review the parts of a cell, work through the steps of this **interactive assignment (http://openstaxcollege.org/l/microscopy_lab)** .

What are two similarities and two differences between plant and animal cells that can be seen under a microscope?

a. Plant cells have cell walls which provide structure to the plant and also chloroplasts which allow for photosynthesis. Animal cells do not have either of these structures. Both cells have nuclei, the command center of the cell, and cytoplasm, the gel-like solution that fills the cell.

b. Plant cells and animal cells have cell walls as well as nuclei. Plant cells have chloroplasts as well as plasmodesmata which are lacking in animal cells.

c. Plant cells have cell walls which provide structure to the plant and also chloroplasts which allow for photosynthesis. Animal cells do not have either of these structures. Animal cells and plant cells both have glyoxysomes as well cytoplasm.

d. Plant cells and animal cells both have a rigid plasma membrane as well as cytoplasm which is the gel-like solution that fills the cell. Plant cells have cell walls which provide structure to the plant and also chloroplasts which allow for photosynthesis. Animal cells do not have either of these structures.

KEY TERMS

cell theory see unified cell theory

cell wall rigid cell covering made of cellulose that protects the cell, provides structural support, and gives shape to the cell

central vacuole large plant cell organelle that regulates the cell’s storage compartment, holds water, and plays a significant role in cell growth as the site of macromolecule degradation

centrosome region in animal cells made of two centrioles

chlorophyll green pigment that captures the light energy that drives the light reactions of photosynthesis

chloroplast plant cell organelle that carries out photosynthesis

chromatin protein-DNA complex that serves as the building material of chromosomes

chromosome structure within the nucleus that is made up of chromatin that contains DNA, the hereditary material

cilium (plural = cilia) short, hair-like structure that extends from the plasma membrane in large numbers and is used to move an entire cell or move substances along the outer surface of the cell

cytoplasm entire region between the plasma membrane and the nuclear envelope, consisting of organelles suspended in the gel-like cytosol, the cytoskeleton, and various chemicals

cytoskeleton network of protein fibers that collectively maintain the shape of the cell, secure some organelles in specific positions, allow cytoplasm and vesicles to move within the cell, and enable unicellular organisms to move independently

cytosol gel-like material of the cytoplasm in which cell structures are suspended

desmosome linkages between adjacent epithelial cells that form when cadherins in the plasma membrane attach to intermediate filaments

electron microscope an instrument that magnifies an object using a beam of electrons passed and bent through a lens system to visualize a specimen

endomembrane system group of organelles and membranes in eukaryotic cells that work together modifying, packaging, and transporting lipids and proteins

endoplasmic reticulum (ER) series of interconnected membranous structures within eukaryotic cells that collectively modify proteins and synthesize lipids

eukaryotic cell cell that has a membrane-bound nucleus and several other membrane-bound compartments or sacs

extracellular matrix material (primarily collagen, glycoproteins, and proteoglycans) secreted from animal cells that provides mechanical protection and anchoring for the cells in the tissue

flagellum (plural = flagella) long, hair-like structure that extends from the plasma membrane and is used to move the cell

gap junction channel between two adjacent animal cells that allows ions, nutrients, and low molecular weight substances to pass between cells, enabling the cells to communicate

Golgi apparatus eukaryotic organelle made up of a series of stacked membranes that sorts, tags, and packages lipids and proteins for distribution

intermediate filament cytoskeletal component, composed of several intertwined strands of fibrous protein, that bears tension, supports cell-cell junctions, and anchors cells to extracellular structures

light microscope an instrument that magnifies an object using a beam visible light passed and bent through a lens system to visualize a specimen

lysosome organelle in an animal cell that functions as the cell’s digestive component; it breaks down proteins, polysaccharides, lipids, nucleic acids, and even worn-out organelles

microfilament narrowest element of the cytoskeleton system; it provides rigidity and shape to the cell and enables cellular movements

microscope an instrument that magnifies an object

microtubule widest element of the cytoskeleton system; it helps the cell resist compression, provides a track along which vesicles move through the cell, pulls replicated chromosomes to opposite ends of a dividing cell, and is the structural element of centrioles, flagella, and cilia

mitochondria (singular = mitochondrion) cellular organelles responsible for carrying out cellular respiration, resulting in the production of ATP, the cell's main energy-carrying molecule

nuclear envelope double-membrane structure that constitutes the outermost portion of the nucleus

nucleoid central part of a prokaryotic cell in which the chromosome is found

nucleolus darkly staining body within the nucleus that is responsible for assembling the subunits of the ribosomes

nucleoplasm semi-solid fluid inside the nucleus that contains the chromatin and nucleolus

nucleus cell organelle that houses the cell's DNA and directs the synthesis of ribosomes and proteins

organelle compartment or sac within a cell

peroxisome small, round organelle that contains hydrogen peroxide, oxidizes fatty acids and amino acids, and detoxifies many poisons

plasma membrane phospholipid bilayer with embedded (integral) or attached (peripheral) proteins, and separates the internal content of the cell from its surrounding environment

plasmodesma (plural = plasmodesmata) channel that passes between the cell walls of adjacent plant cells, connects their cytoplasm, and allows materials to be transported from cell to cell

prokaryote unicellular organism that lacks a nucleus or any other membrane-bound organelle

ribosome cellular structure that carries out protein synthesis

rough endoplasmic reticulum (RER) region of the endoplasmic reticulum that is studded with ribosomes and engages in protein modification and phospholipid synthesis

smooth endoplasmic reticulum (SER) region of the endoplasmic reticulum that has few or no ribosomes on its cytoplasmic surface and synthesizes carbohydrates, lipids, and steroid hormones; detoxifies certain chemicals (like pesticides, preservatives, medications, and environmental pollutants), and stores calcium ions

tight junction firm seal between two adjacent animal cells created by protein adherence

unified cell theory a biological concept that states that all organisms are composed of one or more cells; the cell is the basic unit of life; and new cells arise from existing cells

vacuole membrane-bound sac, somewhat larger than a vesicle, which functions in cellular storage and transport

vesicle small, membrane-bound sac that functions in cellular storage and transport; its membrane is capable of fusing with the plasma membrane and the membranes of the endoplasmic reticulum and Golgi apparatus

CHAPTER SUMMARY

4.1 Studying Cells

A cell is the smallest unit of life. Most cells are so tiny that they cannot be seen with the naked eye. Therefore, scientists use microscopes to study cells. Electron microscopes provide higher magnification, higher resolution, and more detail than light microscopes. The unified cell theory states that all organisms are composed of one or more cells, the cell is the basic unit of life, and new cells arise from existing cells.

4.3 Eukaryotic Cells

Like a prokaryotic cell, a eukaryotic cell has a plasma membrane, cytoplasm, and ribosomes, but a eukaryotic cell is typically larger than a prokaryotic cell, has a true nucleus (meaning its DNA is surrounded by a membrane), and has other membrane-bound organelles that allow for compartmentalization of functions. The plasma membrane is a phospholipid bilayer embedded with proteins. The nucleus's nucleolus is the site of ribosome assembly. Ribosomes are either found in the cytoplasm or attached to the cytoplasmic side of the plasma membrane or endoplasmic reticulum. They perform protein synthesis. Mitochondria participate in cellular respiration; they are responsible for the majority of ATP produced in the cell. Peroxisomes hydrolyze fatty acids, amino acids, and some toxins. Vesicles and vacuoles are storage and transport compartments. In plant cells, vacuoles also help break down macromolecules.

Animal cells also have a centrosome and lysosomes. The centrosome has two bodies perpendicular to each other, the centrioles, and has an unknown purpose in cell division. Lysosomes are the digestive organelles of animal cells.

Plant cells and plant-like cells each have a cell wall, chloroplasts, and a central vacuole. The plant cell wall, whose primary component is cellulose, protects the cell, provides structural support, and gives shape to the cell. Photosynthesis takes place in chloroplasts. The central vacuole can expand without having to produce more cytoplasm.

4.4 The Endomembrane System and Proteins

The endomembrane system includes the nuclear envelope, lysosomes, vesicles, the ER, and Golgi apparatus, as well as the plasma membrane. These cellular components work together to modify, package, tag, and transport proteins and lipids that form the membranes.

The RER modifies proteins and synthesizes phospholipids used in cell membranes. The SER synthesizes carbohydrates, lipids, and steroid hormones; engages in the detoxification of medications and poisons; and stores calcium ions. Sorting, tagging, packaging, and distribution of lipids and proteins take place in the Golgi apparatus. Lysosomes are created by the budding of the membranes of the RER and Golgi. Lysosomes digest macromolecules, recycle worn-out organelles, and destroy pathogens.

4.5 Cytoskeleton

The cytoskeleton has three different types of protein elements. From narrowest to widest, they are the microfilaments (actin filaments), intermediate filaments, and microtubules. Microfilaments are often associated with myosin. They provide rigidity and shape to the cell and facilitate cellular movements. Intermediate filaments bear tension and anchor the nucleus and other organelles in place. Microtubules help the cell resist compression, serve as tracks for motor proteins that move vesicles through the cell, and pull replicated chromosomes to opposite ends of a dividing cell. They are also the structural element of centrioles, flagella, and cilia.

REVIEW QUESTIONS

1. When viewing a specimen through a light microscope, what is a method that scientists use to make it easier to see individual components of cells?

a. a beam of electrons
b. high temperatures
c. radioactive isotopes
d. special stains

2. What is the basic unit of life?

a. cell
b. organism
c. organ
d. tissue

3. Which of the following statements is part of the cell theory?

a. All living organisms are made of cells.
b. All cells contain DNA that they pass on to daughter cells.
c. All cells depend on their surroundings to provide energy.
d. All cells have a nucleus.

4. Which of the following could most effectively be visualized with a scanning electron microscope?

a. cells swimming in a drop of pond water.
b. details of structures inside cells
c. a three-dimensional view of the surface of a membrane
d. the movement of molecules inside the cell

5. Who was the first to clearly identify and name individual cells?

a. Anton van Leeuwenhoek.
b. Matthias Schleiden
c. Robert Hooke
d. Theodore Schwann

6. Which of the following observations contributed to the cell theory?

a. Animal and plant cells have nuclei and organelles.
b. Non-living material cannot give rise to living organisms.
c. Prokaryotic and eukaryotic cells are surrounded by a plasma membrane.
d. Viruses replicate.

7. In order to obtain some materials and remove waste, what process is used by prokaryotes?

a. cell division
b. diffusion
c. flagellar motion
d. ribosomes

8. When bacteria lack fimbriae, what are they less likely to do?

a. Adhere to cell surfaces
b. retain the ability to divide
c. swim through bodily fluids
d. synthesize proteins

9. What is a difference between prokaryotic and eukaryotic cells?

a. Both cells have a nucleus but prokaryotic cells lack cytoplasm.
b. Both cells have cytoplasm but prokaryotic cells lack a nucleus.
c. Both cells have DNA but prokaryotic cells lack a cell membrane.
d. Both cells have a cell membrane but prokaryotic cells lack DNA.

10. Eukaryotic cells contain complex organelles that carry out their chemical reactions. Prokaryotes lack many of these complex organelles, although they have a variety of unique structures of their own. However, most prokaryotic cells can exchange nutrients with the outside environment faster than most eukaryotic cells. Why is this so?

a. Most prokaryotic cells are smaller, and have a higher surface-to-volume ratio, than eukaryotic cells.
b. Most prokaryotic cells are larger, and have a higher surface-to-volume ratio than eukaryotic cells.
c. Most prokaryotic cells are smaller, and have a lower surface-to-volume ratio than eukaryotic cells.
d. Prokaryotic cells are larger and have a lower surface-to-volume ratio than eukaryotic cells.

11. Which of the following is surrounded by two phospholipid bilayers?

a. lysosomes

b. ribosomes

c. nucleolus

d. nucleus

12. Peroxisomes got their name because hydrogen peroxide is:

a. a cofactor for the organelles' enzymes

b. incorporated into their membranes

c. produced during their oxidation reactions

d. used in their detoxification reactions

13. In plant cells, the function of the lysosomes is carried out by what?

a. nuclei

b. peroxisomes

c. ribosomes

d. vacuole

14. Which of the following is found both in eukaryotic and prokaryotic cells?

a. mitochondrion

b. nucleus

c. ribosomes

d. centrosomes

15. Which of the following structures is not found in prokaryotic cells?

a. plasma membrane

b. chloroplast

c. nucleoid

d. ribosome

16. Where would you find DNA, the genetic material, in an animal cell?

a. in the centriole

b. only in the mitochondria

c. in the mitochondria and the nucleus

17. Which of the following is most likely to have the greatest concentration of smooth endoplasmic reticulum (SER)?

a. a cell that secretes enzymes

b. a cell that destroys pathogens

c. a cell that makes steroid hormones

d. a cell that engages in photosynthesis

18. Which of the following sequences correctly lists in order the steps involved in the incorporation of a protein within a cell membrane?

a. synthesis of the protein on the ribosome; modification in the Golgi apparatus; packaging in the endoplasmic reticulum; modification in the vesicle
b. synthesis of the protein on the lysosome; modification in the Golgi; packaging in the vesicle; distribution in the endoplasmic reticulum
c. synthesis of the protein on the ribosome; modification in the endoplasmic reticulum; tagging in the Golgi; distribution via the vesicle
d. synthesis of the protein on the lysosome; packaging in the vesicle; distribution via the Golgi; modification in the endoplasmic reticulum

19. Which of the following is not a component of the endomembrane system?

a. endoplasmic reticulum
b. Golgi apparatus
c. lysosome
d. mitochondrion

20. Which of the following have the ability to disassemble and reform quickly?

a. intermediate filaments and microtubules
b. microfilaments and intermediate filaments
c. microfilaments and microtubules
d. only intermediate filaments

21. Which of the following do not play a role in intracellular movement?

a. intermediate filaments and microtubules
b. microfilaments and intermediate filaments
c. microfilaments and microtubules
d. only intermediate filaments

22. Which components of the cytoskeleton are responsible for the contraction of muscles?

a. intermediate filaments
b. microfilaments
c. microtubules

23. What type of junctions prevent the movement of chemicals between two adjacent animal cells?

a. desmosomes
b. gap junctions
c. plasmodesmata
d. tight junctions

24. Gap junctions are formed by ________?

a. gaps in the cell wall of plants
b. protein complexes that form channels between cells
c. tight, rivet-like regions in the membranes of adjacent cells
d. a tight knitting of membranes

25. Some animal cells produce extensive extracellular matrix. You would expect their ribosomes to synthesize large amounts of which of the following proteins?

a. actin

b. collagen

c. myosin

d. tubulin

26. Which of the following molecules are typically found in the extracellular matrix?

a. nucleic acids such as DNA

b. peptidoglycans

c. cellulose

d. proteoglycans

CRITICAL THINKING QUESTIONS

27. Which element of the cell theory has practical applications in health care because it promotes the use of sterilization and disinfection?

a. All cells come from pre-existing cells.

b. All living organisms are composed of one or more cells.

c. A cell is the basic unit of life.

d. A nucleus and organelles are found in prokaryotic cells.

28. What are the advantages and disadvantages of light microscopes? What are the advantages and disadvantages of electron microscopes?

a. Advantage: In light microscopes, the light beam does not kill the cell. Electron microscopes are helpful in viewing intricate details of a specimen and have high resolution. Disadvantage: Light microscopes have low resolving power. Electron microscopes are costly and require killing the specimen.

b. Advantage: Light microscopes have high resolution. Electron microscopes are helpful in viewing surface details of a specimen. Disadvantage: Light microscopes kill the cell. Electron microscopes are costly and low resolution.

c. Advantage: Light microscopes have high resolution. Electron microscopes are helpful in viewing surface details of a specimen. Disadvantage: Light microscopes can be used only in the presence of light and are costly. Electron microscopes uses short wavelength of electrons and hence have lower magnification.

d. Advantage: Light microscopes have high magnification. Electron microscopes are helpful in viewing surface details of a specimen. Disadvantage: Light microscopes can be used only in the presence of light and have lower resolution. Electron microscopes can be used only for viewing ultra-thin specimens.

29. Mitochondria are observed in plant cells that contain chloroplasts. Why do you find mitochondria in photosynthetic tissue?

a. Mitochondria are not needed but are an evolutionary relic.

b. Mitochondria and chloroplasts work together to use light energy to make sugars.

c. Mitochondria participate in the Calvin cycle/light independent reactions of photosynthesis.

d. Mitochondria are required to break down sugars and other materials for energy.

30. In what situation, or situations, would the use of a light microscope be ideal? Why?

a. A light microscope is used to view the details of the surface of a cell as it cannot be viewed in detail by the transmission microscope.

b. A light microscope allows visualization of small living cells, which have been stained and cannot be viewed by scanning electron microscope.

c. A standard light microscope is used to view living organisms with little contrast to distinguish them from the background, which would be harder to see with the electron microscope.

d. A light microscope reveals the internal structures of a cell, which cannot be viewed by transmission electron microscopy.

31. The major role of the cell wall in bacteria is protecting the cell against changes in osmotic pressure, pressure caused by different solute concentrations in the environment. Bacterial cells swell, but do not burst, in low solute concentrations. What happens to bacterial cells if a compound that interferes with the synthesis of the cell wall is added to an environment with low solute concentrations?

a. Bacterial cells will shrink due to the lack of cell wall material.

b. Bacterial cells will shrink in size.

c. Bacterial cells may burst due to the influx of water.

d. Bacterial cells remain normal; they have alternative pathways to synthesize cell walls.

32. We have discussed the upper limits of cell size; yet, there is a lower limit to cell size. What determines how small a cell can be?

a. The cell should be large enough to escape detection.

b. The cell should be able to accommodate all the structures and metabolic activities necessary to survival.

c. The size of the cell should be large enough to reproduce itself.

d. The cell should be large enough to adapt to the changing environmental conditions.

33. Which of these is a possible explanation for the presence of a rigid cell wall in plants?

a. Plants remain exposed to changes in temperature and thus require rigid cell walls to protect themselves.

b. Plants are subjected to osmotic pressure and a cell wall helps them against bursting or shrinking.

c. Plant cells have a rigid cell wall to protect themselves from grazing animals.

d. Plant cells have a rigid cell wall to prevent the influx of waste material.

34. Bacteria do not have organelles; yet, the same reactions that take place on the mitochondria inner membrane, the phosphorylation of ADP to ATP, and chloroplasts, photosynthesis, take place in bacteria. Where do these reactions take place?

a. These reactions take place in the nucleoid of the bacteria.

b. These reactions occur in the cytoplasm present in the bacteria.

c. These reactions occur on the plasma membrane of bacteria.

d. These reactions take place in the mesosomes.

35. What are the structural and functional similarities and differences between mitochondria and chloroplasts?

a. Similarities: double membrane, inter-membrane space, ATP production, contain DNA. Differences: mitochondria have inner folds called cristae, chloroplast contains accessory pigments in thylakoids, which form grana and a stroma.

b. Similarities: DNA, inter-membrane space, ATP production, and chlorophyll. Differences: mitochondria have a matrix and inner folds called cristae; chloroplast contains accessory pigments in thylakoids, which form grana and a stroma.

c. Similarities: double membrane and ATP production. Differences: mitochondria have inter-membrane space and inner folds called cristae; chloroplast contains accessory pigments in thylakoids, which form grana and a stroma.

d. Similarities: double membrane and ATP production. Differences: mitochondria have inter-membrane space, inner folds called cristae, ATP synthase for ATP synthesis, and DNA; chloroplast contains accessory pigments in thylakoids, which, form grana and a stroma.

36. Is the nuclear membrane part of the endomembrane system? Why or why not?

a. The nuclear membrane is not a part of the endomembrane system as the endoplasmic reticulum is a separate organelle of the cell.
b. The nuclear membrane is considered a part of the endomembrane system as it is continuous with the Golgi body.
c. The nuclear membrane is part of the endomembrane system as it is continuous with the rough endoplasmic reticulum.
d. The nuclear membrane is not considered a part of the endomembrane system as the nucleus is a separate organelle.

37. What happens to the proteins that are synthesized on free ribosomes in the cytoplasm? Do they go through the Golgi apparatus?

a. These proteins move through the Golgi apparatus and enter in the nucleus.
b. These proteins go through the Golgi apparatus and remain in the cytosol.
c. The proteins do not go through the Golgi apparatus and move into the nucleus for processing.
d. The proteins do not go through the Golgi apparatus and remain free in the cytosol.

38. What are the similarities and differences between the structures of centrioles and flagella?

a. Centrioles and flagella are made of microtubules but show different arrangements.
b. Centrioles are made of microtubules but flagella are made of microfilaments and both show the same arrangement.
c. Centrioles and flagella are made of microfilaments. Centrioles have a 9 + 2 arrangement.
d. Centrioles are made of microtubules and flagella are made of microfilaments and both have different structures.

39. Inhibitors of microtubule assembly, vinblastine for example, are used for cancer chemotherapy. How does an inhibitor of microtubule assembly affect cancerous cells?

a. The inhibitors restrict the separation of chromosomes, thereby stopping cell division.
b. The inhibition of microtubules interferes with the synthesis of proteins.
c. The inhibitors bind the microtubule to the nuclear membrane, stopping cell division.
d. The inhibitor interferes with energy production.

40. How do cilia and flagella differ?

a. Cilia are made of microfilaments and flagella of microtubules.
b. Cilia are helpful in the process of engulfing food. Flagella are involved in the movement of the organism.
c. Cilia are short and found in large numbers on the cell surface whereas flagella are long and fewer in number.
d. Cilia are found in prokaryotic cells and flagella in eukaryotic cells.

41. In which human tissues would you find desmosomes? Think of tissues that undergo strong mechanical stress and must be held together with some flexibility.

a. bone cells and cartilage cells
b. muscle cells and skin cells
c. nerve cells and muscle cells
d. secretory cells and muscle cells

42. If there is a mutation in the gene for collagen, such as the one involved in Ehlers-Danlos syndrome, and the individual produces defective collagen, how would it affect coagulation?

a. The syndrome affects the clotting factors and platelet aggregation.
b. The disease leads to hyper-coagulation of blood.
c. Coagulation is not affected because collagen is not required for coagulation.
d. The disease occurs due to the breakdown of platelets.

43. How does the structure of a plasmodesma differ from that of a gap junction?

a. Gap junctions are essential for transportation in animal cells and plasmodesmata are essential for the movement of substances in plant cells.

b. Gap junctions are found to provide attachment in animal cells and plasmodesmata are essential for attachment of plant cells.

c. Plasmodesmata are essential for communication between animal cells and gap junctions are necessary for attachment of cells in plant cells.

d. Plasmodesmata help in transportation and gap junctions help in attachment, in plant cells.

TEST PREP FOR AP® COURSES

44. Which of the following organisms appear first in the fossil record?

a. archaea

b. fish

c. protists

d. plants

45. Why is it challenging to study bacterial fossils and determine if the fossils are members of the domain archaea, rather than bacteria?

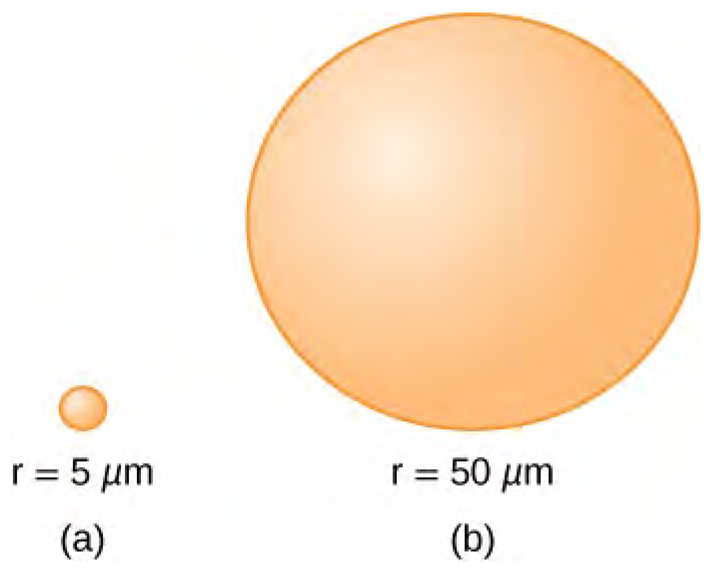
a. Bacteria lack rigid structures, thus do not form fossils.

b. Bacteria have rigid structures, but their fossil impression is scarce.

c. Fossils of bacteria are rarely found because bacteria were not abundant in the past.

d. A fossil of bacteria changes overtime due to the presence of new bacteria living on them.

46.



Pictured are two cells along with their radius. What does Cell B likely have when compared to cell A?

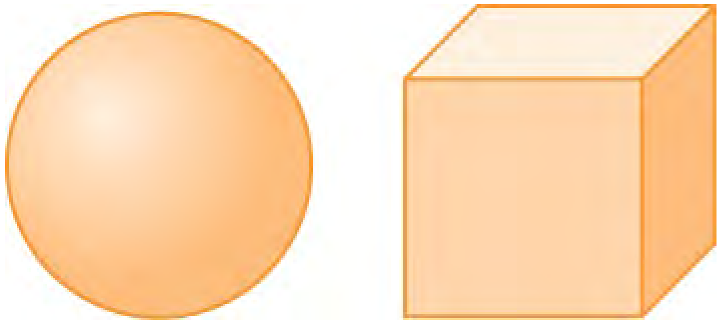
a. smaller surface area and larger volume

b. larger surface area and smaller volume

c. smaller surface area-to-volume ratio

d. larger surface area-to-volume ratio

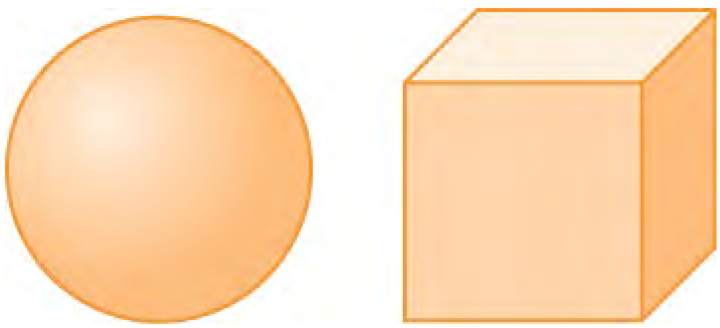
47.



Consider the shapes. The diameter of the sphere is equal to 1 mm and the side of the cube is also equal to 1 mm . What is the ratio of the surface to volume ratios for the sphere and the cube?

a. 3 : 1
b. 4 : 1
c. 1 : 1
d. 2 : 1

48.



Which of the following is true regarding the surface-to-volume ratios of the cube and the sphere?

a. The sphere will have a higher surface area than the cube.
b. The sphere will have a higher volume than the cube.
c. The sphere will have a higher surface area-to-volume ratio than the cube.
d. Their surface area-to-volume ratios will be equal.
e. The sphere will have a lower surface area-to-volume ratio than the cube.

49. What is the major consideration in setting the lower limit of cell size?

a. The cell must be large enough to fight the pathogens
b. The cell must be large enough to attach to a substrate.
c. The lower limit should be small enough, for the cell to move in the fluid efficiently.
d. The cell size must be small as to fit all the processes and structures to support life.

50. Which of the following structures has the same general structure in Archaea, Bacteria and Eukarya, pointing to a common origin?

a. centriole
b. cytoplasmic membrane
c. Golgi apparatus
d. nucleus

51. Why does the structure of the cytoplasmic membrane point to a common ancestor?

a. The presence of a cytoplasmic membrane in every organism does not point to a common ancestry.
b. The similar arrangement of phospholipids and proteins points to common ancestry.
c. The lipid nature of the membrane makes it the most primitive trait.
d. The similar effect of temperature on the membrane makes it the ancestral trait.

52. Which organelles would be present in high numbers in the leg muscles of a marathon runner?

a. centrioles
b. chloroplasts
c. mitochondria
d. peroxisome

53. Macrophages ingest and digest many pathogens. Which organelle plays a major role in the activity of macrophages?

a. chloroplast
b. lysosome
c. nucleus
d. peroxisome

54. You are looking at a sample under a light microscope and observe a new type of cell. You come to the conclusion that it is a bacterium and not a eukaryotic cell. What would you observe to come to this conclusion?

a. the cell has a cell wall
b. the cell has a flagellum
c. the cell does not have a nucleus

55. Thiomargarita namibiensis is a large single cell organism, which can reach lengths of $700\,\mu m$. The cell is classified as a bacterium. What is the main argument to justify the classification?

a. This organism shows simple diffusion for the uptake of nutrients and is thus classified as a bacterium.
b. This organism does not show presence of any cell organelles, and thus is classified as a bacterium.
c. the existence of these organisms in long chains and pearl appearance
d. The organism demonstrates characteristics of gram-negative bacteria, and thus is classified as a bacterium.

56. Radioactive amino acids are fed to a cell in culture for a short amount of time. This is called a pulse. You follow the appearance of radioactive proteins in the cell compartments. In which organelles and in what order does radioactivity appear?

a. endoplasmic reticulum - lysosomes - Golgi body - vesicle - extracellular region
b. endoplasmic reticulum - vesicles - Golgi body - vesicles - extracellular region
c. Golgi Body - vesicles - endoplasmic reticulum - vesicles - extracellular region
d. nucleus - endoplasmic reticulum - Golgi body - vesicle - extracellular region

57. With which cellular structure does the extracellular matrix interact?

a. cytoskeleton
b. nucleus
c. smooth endoplasmic reticulum

58. Which structure or structures allow bacteria to move about?

a. fimbriae only
b. flagella only
c. flagella and fimbriae
d. plasmid and capsule

59. Cells lining the intestine absorb a lot of nutrients. How did those cells adapt to their function?

a. Cells use cilia to move nutrients to their surface.
b. Cells grow much larger than adjacent cells to increase intake
c. Cells are flat and thin to absorb more nutrients.
d. Membrane folds called microvilli increase the surface area.

6 | METABOLISM

Figure 2.1 A hummingbird needs energy to maintain prolonged periods of flight. The bird obtains its energy from taking in food and transforming the nutrients into energy through a series of biochemical reactions. The flight muscles in birds are extremely efficient in energy production. (credit: modification of work by Cory Zanker)

Chapter Outline

Introduction

Virtually every task performed by living organisms requires energy. Energy is needed to perform heavy labor and exercise. Humans also use a great deal of energy while thinking and even during sleep. In fact, the living cells of every organism constantly use energy. Nutrients and other molecules are imported, metabolized (broken down), synthesized into new molecules, modified if needed, transported around the cell, and, in some cases, distributed to the entire organism. For example, the large proteins that make up muscles are actively built from smaller molecules. Complex carbohydrates are broken down into simple sugars that the cell uses for energy. Just as energy is required to both build and demolish a building, energy is required for both the synthesis and breakdown of molecules. Additionally, signaling molecules such as hormones and neurotransmitters are actively transported between cells. Pathogenic bacteria and viruses are ingested and broken down by cells. Cells must also export waste and toxins to stay healthy. Many cells swim or move surrounding materials via the beating motion of cellular appendages such as cilia and flagella.

All of the cellular processes listed above require a steady supply of energy. From where, and in what form, does this energy come? How do living cells obtain energy and how do they use it? This chapter will discuss different forms of energy and the physical laws that govern energy transfer.

How enzymes lower the activation energy required to begin a chemical reaction in the body will also be discussed in this chapter. Enzymes are crucial for life; without them the chemical reactions required to survive would not happen fast enough for an organism to survive. For example, in an individual who lacks one of the enzymes needed to break down a type of carbohydrate known as a mucopolysaccharide, waste products accumulate in the cells and cause progressive brain damage. This deadly genetic disease is called Sanfilippo Syndrome type B or Mucopolysaccharidosis III. Previously incurable, scientists have now discovered a way to replace the missing enzyme in the brain of mice. Read more about the scientists' research **here (http://openstaxcollege.org/l/32mpsiiib)** .

6.1 | Energy and Metabolism

In this section, you will explore the following questions:

- What are metabolic pathways?
- What are the differences between anabolic and catabolic pathways?
- How do chemical reactions play a role in energy transfer?

Connection for AP® Courses

All living systems, from simple cells to complex ecosystems, require free energy to conduct cell processes such as growth and reproduction.

Organisms have evolved various strategies to capture, store, transform, and transfer free energy. A cell's metabolism refers to the chemical reactions that occur within it. Some metabolic reactions involve the breaking down of complex molecules into simpler ones with a release of energy (catabolism), whereas other metabolic reactions require energy to build complex molecules (anabolism). A central example of these pathways is the synthesis and breakdown of glucose.

The content presented in this section supports the Learning Objectives outlined in Big Idea 1 and Big Idea 2 of the AP® Biology Curriculum Framework listed below. The AP® Learning Objectives merge Essential Knowledge content with one or more of the seven Science Practices. These objectives provide a transparent foundation for the AP® Biology course, along with inquiry-based laboratory experiences, instructional activities, and AP® exam questions.

Big Idea 1	The process of evolution drives the diversity and unity of life.
Enduring Understanding 1.B	Organisms are linked by lines of descent from common ancestry.
Essential Knowledge	**1.B.1** Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.
Science Practice	**3.1** The student can pose scientific questions.
Learning Objective	**1.14** The student is able to pose scientific questions that correctly identify essential properties of shared, core life processes that provide insight into the history of life on Earth.
Essential Knowledge	**1.B.1** Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.
Science Practice	**7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	**1.15** The student is able to describe specific examples of conserved core biological processes and features shared by all domains or within one domain of life, and how these shared, conserved core processes and features support the concept of common ancestry for all organisms.
Essential Knowledge	**1.B.1** Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.
Science Practice	**6.1** The student can justify claims with evidence.

Learning Objective	**1.16** The student is able to justify the scientific claim that organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.
Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.A	Growth, reproduction and maintenance of living systems require free energy and matter.
Essential Knowledge	**2.A.1** All living systems require a constant input of free energy.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**2.1** The student is able to explain how biological systems use free energy based on empirical data that all organisms require constant energy input to maintain organization, to grow and to reproduce.

The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.1][APLO 2.3][APLO 4.3][APLO 4.15][APLO 4.17][APLO 2.21]

In addition, content from this chapter is addressed in the AP Biology Laboratory Manual in the following lab(s):

7 Enzymatic Activity

Scientists use the term **bioenergetics** to discuss the concept of energy flow (**Figure 2.2**) through living systems, such as cells. Cellular processes such as the building and breaking down of complex molecules occur through stepwise chemical reactions. Some of these chemical reactions are spontaneous and release energy, whereas others require energy to proceed. Just as living things must continually consume food to replenish what has been used, cells must continually produce more energy to replenish that used by the many energy-requiring chemical reactions that constantly take place. All of the chemical reactions that take place inside cells, including those that use energy and those that release energy, are the cell's **metabolism**.

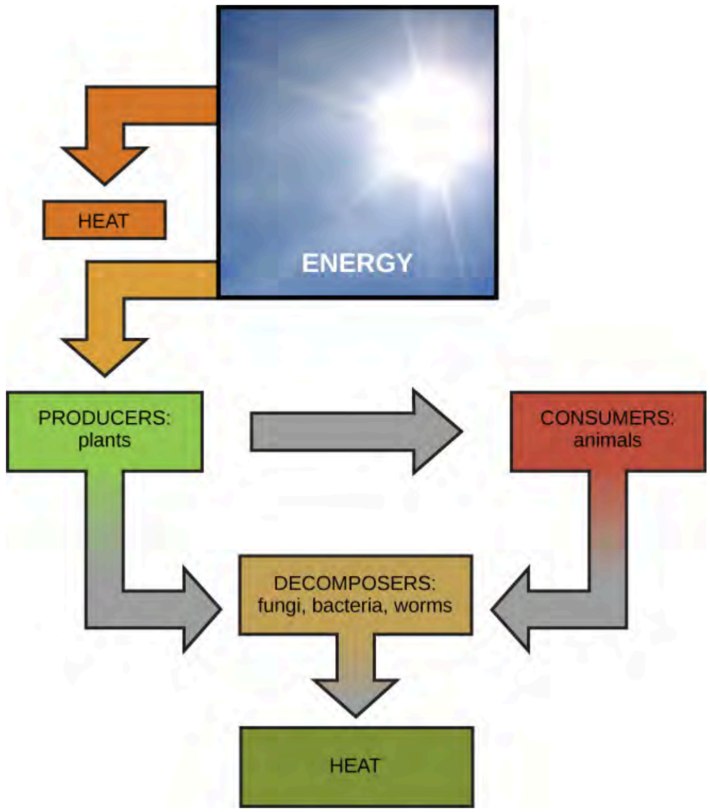


Figure 2.2 Most life forms on earth get their energy from the sun. Plants use photosynthesis to capture sunlight, and herbivores eat those plants to obtain energy. Carnivores eat the herbivores, and decomposers digest plant and animal matter.

Metabolism of Carbohydrates

The metabolism of sugar (a simple carbohydrate) is a classic example of the many cellular processes that use and produce energy. Living things consume sugar as a major energy source, because sugar molecules have a great deal of energy stored within their bonds. The breakdown of glucose, a simple sugar, is described by the equation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

Carbohydrates that are consumed have their origins in photosynthesizing organisms like plants (**Figure 2.3**). During photosynthesis, plants use the energy of sunlight to convert carbon dioxide gas (CO_2) into sugar molecules, like glucose ($C_6H_{12}O_6$). Because this process involves synthesizing a larger, energy-storing molecule, it requires an input of energy to proceed. The synthesis of glucose is described by this equation (notice that it is the reverse of the previous equation):

$$6CO_2 + 6H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

During the chemical reactions of photosynthesis, energy is provided in the form of a very high-energy molecule called ATP, or adenosine triphosphate, which is the primary energy currency of all cells. Just as the dollar is used as currency to buy goods, cells use molecules of ATP as energy currency to perform immediate work. The sugar (glucose) is stored as starch or glycogen. Energy-storing polymers like these are broken down into glucose to supply molecules of ATP.

Solar energy is required to synthesize a molecule of glucose during the reactions of photosynthesis. In photosynthesis, light energy from the sun is initially transformed into chemical energy that is temporally stored in the energy carrier molecules ATP and NADPH (nicotinamide adenine dinucleotide phosphate). The stored energy in ATP and NADPH is then used later in photosynthesis to build one molecule of glucose from six molecules of CO_2. This process is analogous to eating breakfast in the morning to acquire energy for your body that can be used later in the day. Under ideal conditions, energy from 18 molecules of ATP is required to synthesize one molecule of glucose during the reactions of photosynthesis. Glucose molecules can also be combined with and converted into other types of sugars. When sugars are consumed, molecules of glucose eventually make their way into each living cell of the organism. Inside the cell, each sugar molecule is broken down through a complex series of chemical reactions. The goal of these reactions is to harvest the energy stored inside the sugar molecules. The harvested energy is used to make high-energy ATP molecules, which can be used to perform work, powering many chemical reactions in the cell. The amount of energy needed to make one molecule of glucose from six molecules of carbon dioxide is 18 molecules of ATP and 12 molecules of NADPH (each one of which is energetically equivalent to three molecules of ATP), or a total of 54 ATP molecule equivalents required for the synthesis of one molecule of glucose. This process is a fundamental and efficient way for cells to generate the molecular energy that they require.

Figure 2.3 Plants, like this oak tree, use energy from sunlight to make sugar and other organic molecules. Both plants and animals, like this squirrel, use cellular respiration to derive energy from the organic molecules originally produced by plants.

Metabolic Pathways

The processes of making and breaking down sugar molecules illustrate two types of metabolic pathways. A metabolic pathway is a series of interconnected biochemical reactions that convert a substrate molecule or molecules, step-by-step, through a series of metabolic intermediates, eventually yielding a final product or products. In the case of sugar metabolism, the first metabolic pathway synthesized sugar from smaller molecules, and the other pathway broke sugar down into smaller molecules. These two opposite processes—the first requiring energy and the second producing energy—are referred to as anabolic (building) and catabolic (breaking down) pathways, respectively. Consequently, metabolism is composed of building (anabolism) and degradation (catabolism).

evolution CONNECTION

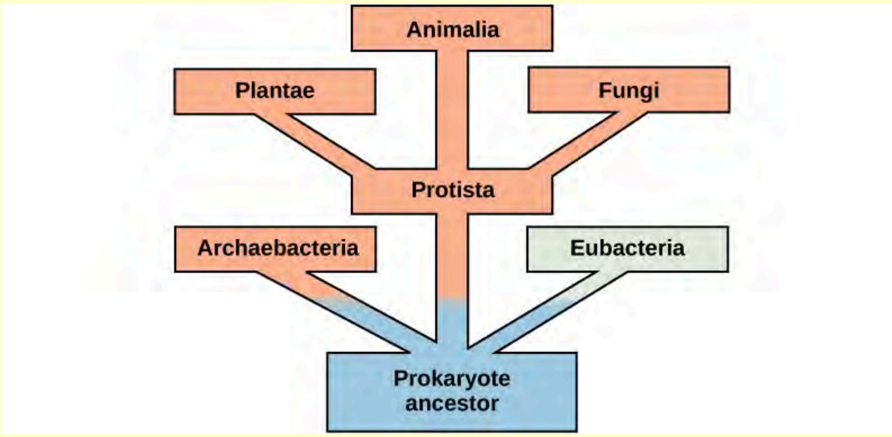


Figure 2.4 This tree shows the evolution of the various branches of life. The vertical dimension is time. Early life forms, in blue, used anaerobic metabolism to obtain energy from their surroundings.

Evolution of Metabolic Pathways

There is more to the complexity of metabolism than understanding the metabolic pathways alone. Metabolic complexity varies from organism to organism. Photosynthesis is the primary pathway in which photosynthetic organisms like plants (the majority of global synthesis is done by planktonic algae) harvest the sun's energy and convert it into carbohydrates. The by-product of photosynthesis is oxygen, required by some cells to carry out cellular respiration. During cellular respiration, oxygen aids in the catabolic breakdown of carbon compounds, like carbohydrates. Among the products of this catabolism are CO_2 and ATP. In addition, some eukaryotes perform catabolic processes without oxygen (fermentation); that is, they perform or use anaerobic metabolism.

Organisms probably evolved anaerobic metabolism to survive (living organisms came into existence about 3.8 billion years ago, when the atmosphere lacked oxygen). Despite the differences between organisms and the complexity of metabolism, researchers have found that all branches of life share some of the same metabolic pathways, suggesting that all organisms evolved from the same ancient common ancestor (**Figure 2.4**). Evidence indicates that over time, the pathways diverged, adding specialized enzymes to allow organisms to better adapt to their environment, thus increasing their chance to survive. However, the underlying principle remains that all organisms must harvest energy from their environment and convert it to ATP to carry out cellular functions.

The early atmosphere lacked oxygen. Why do you think this is the case?

a. Oxygen is a byproduct of photosynthesis, so there was very little oxygen in the atmosphere until photosynthetic organisms evolved.

b. Oxygen is a byproduct of anaerobic respiration, so there was very little oxygen in the atmosphere until anaerobic organisms evolved.

c. Oxygen is a byproduct of fermentation, so there was very little oxygen in the atmosphere until fermentative organisms evolved.

Anabolic and Catabolic Pathways

Anabolic pathways require an input of energy to synthesize complex molecules from simpler ones. Synthesizing sugar from CO_2 is one example. Other examples are the synthesis of large proteins from amino acid building blocks, and the synthesis of new DNA strands from nucleic acid building blocks. These biosynthetic processes are critical to the life of the cell, take place constantly, and demand energy provided by ATP and other high-energy molecules like NADH (nicotinamide adenine dinucleotide) and NADPH (**Figure 2.5**).

ATP is an important molecule for cells to have in sufficient supply at all times. The breakdown of sugars illustrates how a single molecule of glucose can store enough energy to make a great deal of ATP, 36 to 38 molecules. This is a **catabolic** pathway. Catabolic pathways involve the degradation (or breakdown) of complex molecules into simpler ones. Molecular energy stored in the bonds of complex molecules is released in catabolic pathways and harvested in such a way that it can be used to produce ATP. Other energy-storing molecules, such as fats, are also broken down through similar catabolic reactions to release energy and make ATP (**Figure 2.5**).

It is important to know that the chemical reactions of metabolic pathways don't take place spontaneously. Each reaction step is facilitated, or catalyzed, by a protein called an enzyme. Enzymes are important for catalyzing all types of biological reactions—those that require energy as well as those that release energy.

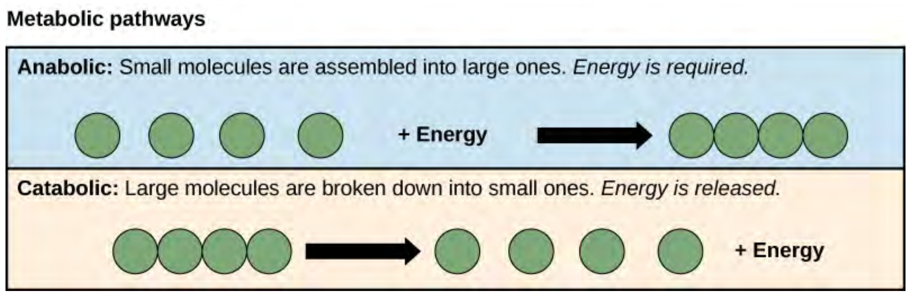


Figure 2.5 Anabolic pathways are those that require energy to synthesize larger molecules. Catabolic pathways are those that generate energy by breaking down larger molecules. Both types of pathways are required for maintaining the cell's energy balance.

science practices CONNECTION for AP® Courses

Think About It

Describe two different cellular functions in different organisms that require energy that parallel human energy-requiring functions such as physical exercise.

6.2 | Potential, Kinetic, Free, and Activation Energy

In this section, you will explore the following questions:

- What is "energy"?
- What is the difference between kinetic and potential energy?
- What is free energy, and how does free energy related to activation energy?
- What is the difference between endergonic and exergonic reactions?

Connection for AP® Courses

Although cells and organisms require free energy to survive, they cannot spontaneously create energy, as stated in the Law of Conservation of Energy. Energy is available in different forms. For example, objects in motion possess kinetic energy, whereas objects that are not in motion possess potential energy. The chemical energy in molecules, such as glucose, is potential energy because when bonds break in chemical reactions, free energy is released. Free energy is a measure of energy that is available to do work. The free energy of a system changes during energy transfers such as chemical reactions, and this change is referred to as ΔG or Gibbs free energy. The ΔG of a reaction can be negative or positive, depending on whether the reaction releases energy (exergonic) or requires energy input (endergonic). All reactions require an input of energy called activation energy in order to reach the transition state at which they will proceed. (In another section, we will explore how enzymes speed up chemical reactions by lowering activation energy barriers.)

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 2 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® Exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.A	Growth, reproduction and maintenance of living systems require free energy and matter.
Essential Knowledge	**2.A.1** All living systems require constant input of free energy.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**2.1** The student is able to explain how biological systems use free energy based on empirical data that all organisms require constant energy input to maintain organization, to grow, and to reproduce.
Essential Knowledge	**2.A.1** All living systems require constant input of free energy.
Science Practice	**6.2** The student can justify claims with evidence.
Learning Objective	**2.2** The student is able to justify a scientific claim that free energy is required for living systems to maintain organization, to grow or to reproduce, but that multiple strategies exist in different living systems.

The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.5]

Energy is defined as the ability to do work. As you've learned, energy exists in different forms. For example, electrical energy, light energy, and heat energy are all different types of energy. While these are all familiar types of energy that one can see or feel, there is another type of energy that is much less tangible. This energy is associated with something as simple as an object held above the ground. In order to appreciate the way energy flows into and out of biological systems, it is important to understand more about the different types of energy that exist in the physical world.

Types of Energy

When an object is in motion, there is energy associated with that object. In the example of an airplane in flight, there is a great deal of energy associated with the motion of the airplane. This is because moving objects are capable of enacting a change, or doing work. Think of a wrecking ball. Even a slow-moving wrecking ball can do a great deal of damage to other objects. However, a wrecking ball that is not in motion is incapable of performing work. Energy associated with objects in motion is called **kinetic energy**. A speeding bullet, a walking person, the rapid movement of molecules in the air (which produces heat), and electromagnetic radiation like light all have kinetic energy.

Now what if that same motionless wrecking ball is lifted two stories above a car with a crane? If the suspended wrecking ball is unmoving, is there energy associated with it? The answer is yes. The suspended wrecking ball has energy associated with it that is fundamentally different from the kinetic energy of objects in motion. This form of energy results from the fact that there is the *potential* for the wrecking ball to do work. If it is released, indeed it would do work. Because this type of energy refers to the potential to do work, it is called **potential energy**. Objects transfer their energy between kinetic and potential in the following way: As the wrecking ball hangs motionless, it has 0 kinetic and 100 percent potential energy. Once it is released, its kinetic energy begins to increase because it builds speed due to gravity. At the same time, as it nears the ground, it loses potential energy. Somewhere mid-fall it has 50 percent kinetic and 50 percent potential energy. Just before it hits the ground, the ball has nearly lost its potential energy and has near-maximal kinetic energy. Other examples of potential energy include the energy of water held behind a dam (**Figure 2.6**), or a person about to skydive out of an airplane.

Figure 2.6 Water behind a dam has potential energy. Moving water, such as in a waterfall or a rapidly flowing river, has kinetic energy. (credit “dam”: modification of work by "Pascal"/Flickr; credit “waterfall”: modification of work by Frank Gualtieri)

Potential energy is not only associated with the location of matter (such as a child sitting on a tree branch), but also with the structure of matter. A spring on the ground has potential energy if it is compressed; so does a rubber band that is pulled taut. The very existence of living cells relies heavily on structural potential energy. On a chemical level, the bonds that hold the atoms of molecules together have potential energy. Remember that anabolic cellular pathways require energy to synthesize complex molecules from simpler ones, and catabolic pathways release energy when complex molecules are broken down. The fact that energy can be released by the breakdown of certain chemical bonds implies that those bonds have potential energy. In fact, there is potential energy stored within the bonds of all the food molecules we eat, which is eventually harnessed for use. This is because these bonds can release energy when broken. The type of potential energy that exists within chemical bonds, and is released when those bonds are broken, is called **chemical energy** (Figure 2.7). Chemical energy is responsible for providing living cells with energy from food. The release of energy is brought about by breaking the molecular bonds within fuel molecules.

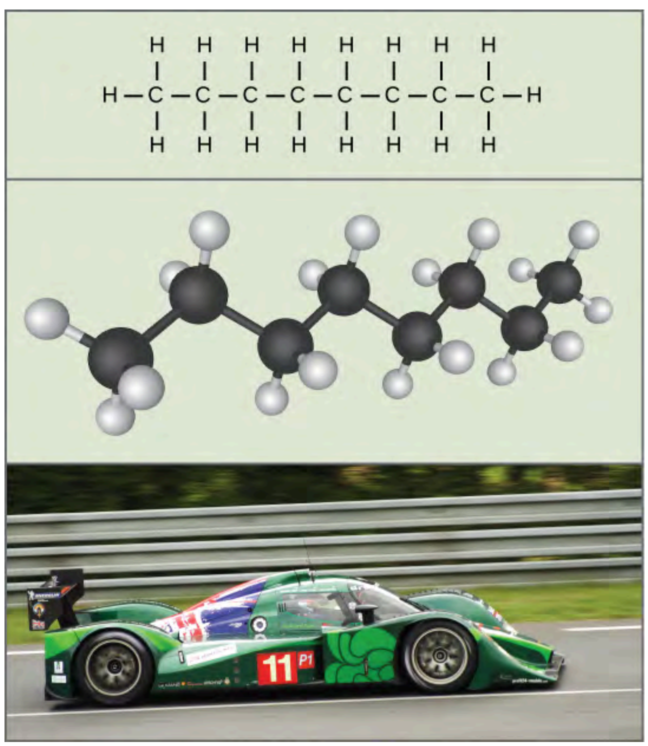


Figure 2.7 The molecules in gasoline (octane, the chemical formula shown) contain chemical energy within the chemical bonds. This energy is transformed into kinetic energy that allows a car to race on a racetrack. (credit “car”: modification of work by Russell Trow)

LINK TO LEARNING

Visit this **site (http://openstaxcollege.org/l/simple_pendulum)** and select “A simple pendulum” on the menu (under “Harmonic Motion”) to see the shifting kinetic (K) and potential energy (U) of a pendulum in motion.

Explain how the potential and kinetic energy shown in the **pendulum model (http://openstaxcollege.org/l/simple_pendulum)** relates to a child swinging on a swing set.

a. Kinetic energy increases when the child swings downward, potential energy increases when the child swings upward.

b. Kinetic energy decreases when the child swings downward, potential energy decreases when the child swings upward.

c. Kinetic energy increases when the child swings upward, potential energy increases when the child swings downward.

d. Kinetic energy increases when child swings downward, potential energy increases when the child swings downward.

Free Energy

After learning that chemical reactions release energy when energy-storing bonds are broken, an important next question is how is the energy associated with chemical reactions quantified and expressed? How can the energy released from one reaction be compared to that of another reaction? A measurement of **free energy** is used to quantitate these energy transfers. Free energy is called Gibbs free energy (abbreviated with the letter G) after Josiah Willard Gibbs, the scientist who developed the measurement. Recall that according to the second law of thermodynamics, all energy transfers involve the loss of some amount of energy in an unusable form such as heat, resulting in entropy. Gibbs free energy specifically refers to the energy associated with a chemical reaction that is available after entropy is accounted for. In other words, Gibbs free energy is usable energy, or energy that is available to do work.

Every chemical reaction involves a change in free energy, called delta G (ΔG). The change in free energy can be calculated for any system that undergoes such a change, such as a chemical reaction. To calculate ΔG, subtract the amount of energy lost to entropy (denoted as ΔS) from the total energy change of the system. This total energy change in the system is called **enthalpy** and is denoted as ΔH . The formula for calculating ΔG is as follows, where the symbol T refers to absolute temperature in Kelvin (degrees Celsius + 273):

$$\Delta G = \Delta H - T\Delta S$$

The standard free energy change of a chemical reaction is expressed as an amount of energy per mole of the reaction product (either in kilojoules or kilocalories, kJ/mol or kcal/mol; 1 kJ = 0.239 kcal) under standard pH, temperature, and pressure conditions. Standard pH, temperature, and pressure conditions are generally calculated at pH 7.0 in biological systems, 25 degrees Celsius, and 100 kilopascals (1 atm pressure), respectively. It is important to note that cellular conditions vary considerably from these standard conditions, and so standard calculated ΔG values for biological reactions will be different inside the cell.

Endergonic Reactions and Exergonic Reactions

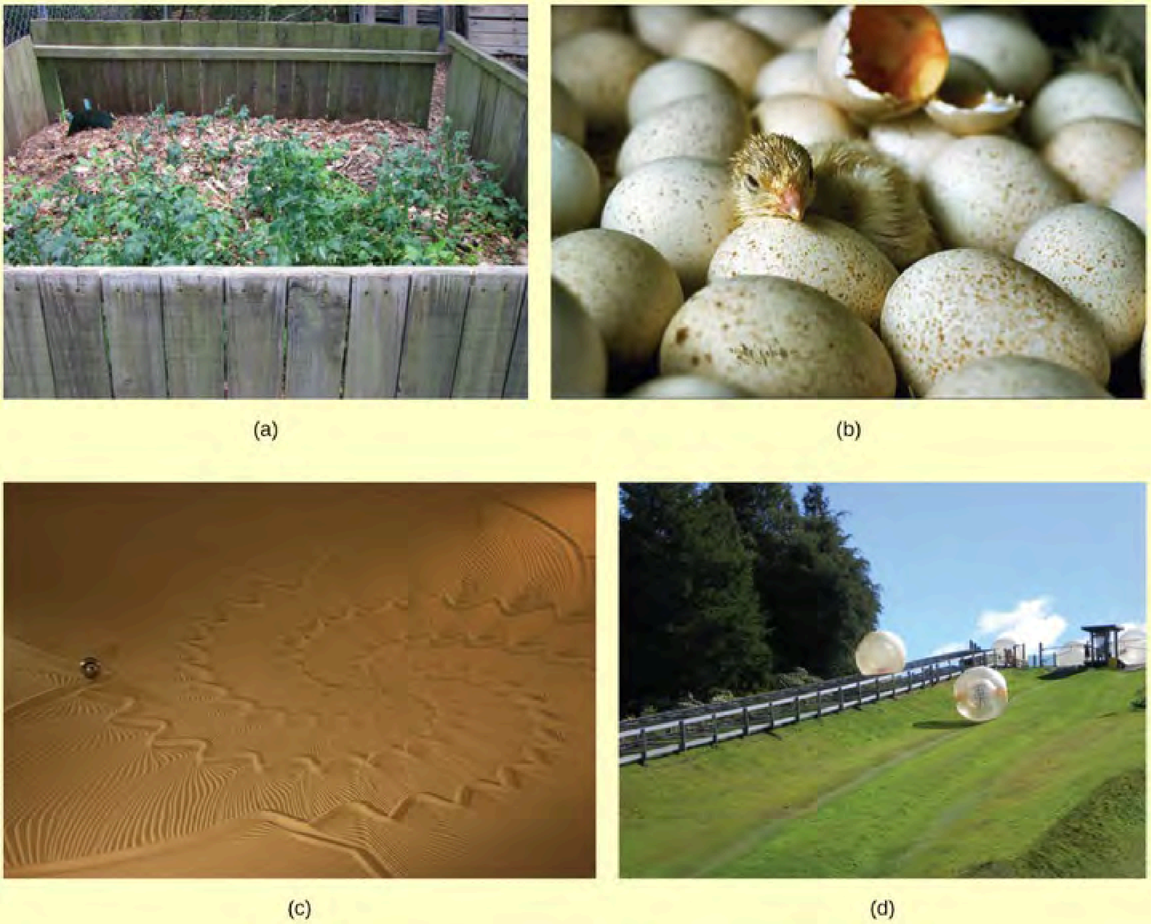
If energy is released during a chemical reaction, then the resulting value from the above equation will be a negative number. In other words, reactions that release energy have a $\Delta G < 0$. A negative ΔG also means that the products of the reaction have less free energy than the reactants, because they gave off some free energy during the reaction. Reactions that have a negative ΔG and consequently release free energy are called **exergonic reactions**. Think: *ex*ergonic means energy is *ex*iting the system. These reactions are also referred to as spontaneous reactions, because they can occur without the addition of energy into the system. Understanding which chemical reactions are spontaneous and release free energy is extremely useful for biologists, because these reactions can be harnessed to perform work inside the cell. An important distinction must be drawn between the term spontaneous and the idea of a chemical reaction that occurs immediately. Contrary to the everyday use of the term, a spontaneous reaction is not one that suddenly or quickly occurs. The rusting of iron is an example of a spontaneous reaction that occurs slowly, little by little, over time.

If a chemical reaction requires an input of energy rather than releasing energy, then the ΔG for that reaction will be a positive value. In this case, the products have more free energy than the reactants. Thus, the products of these reactions can be thought of as energy-storing molecules. These chemical reactions are called **endergonic reactions**, and they are non-spontaneous. An endergonic reaction will not take place on its own without the addition of free energy.

Let's revisit the example of the synthesis and breakdown of the food molecule, glucose. Remember that the building of complex molecules, such as sugars, from simpler ones is an anabolic process and requires energy. Therefore, the chemical reactions involved in anabolic processes are endergonic reactions. On the other hand, the catabolic process of breaking sugar down into simpler molecules releases energy in a series of exergonic reactions. Like the example of rust above, the breakdown of sugar involves spontaneous reactions, but these reactions don't occur instantaneously. **Figure 2.8** shows some other examples of endergonic and exergonic reactions. Later sections will provide more information about what else is required to make even spontaneous reactions happen more efficiently.

visual CONNECTION

Figure 2.8 Shown are some examples of endergonic processes (ones that require energy) and exergonic processes (ones that release energy). These include (a) a compost pile decomposing, (b) a chick hatching from a fertilized egg, (c) sand art being destroyed, and (d) a ball rolling down a hill. (credit a: modification of work by Natalie Maynor; credit b: modification of work by USDA; credit c: modification of work by "Athlex"/Flickr; credit d: modification of work by Harry Malsch)



Look at each of the processes shown, and decide if it is endergonic or exergonic. In each case, does enthalpy increase or decrease, and does entropy increase or decrease?

a. Compost pile decomposition is endergonic, enthalpy increases and entropy increases. A baby developing from egg is an endergonic process, enthalpy decreases and entropy decreases. Sand art being destroyed is exergonic, no change in enthalpy and entropy increases. A ball rolling downhill is exergonic process, enthalpy decreases and no change in entropy.

b. Compost pile decomposition is exergonic, enthalpy increases and entropy increases. A baby developing from egg is an endergonic process, enthalpy decreases and entropy decreases. Sand art being destroyed is exergonic, no change in enthalpy and entropy decreases. A ball rolling downhill is exergonic process, enthalpy decreases and no change in entropy.

c. Compost pile decomposition is exergonic, enthalpy increases and entropy increases. A baby developing from egg is an endergonic process, enthalpy decreases and entropy decreases. Sand art being destroyed is exergonic, no change in enthalpy and entropy increases. A ball rolling downhill is exergonic process, enthalpy decreases and entropy increases.

d. A ball rolling down the hill doesn't affect the order of system; therefore, the entropy would remain unchanged.

An important concept in the study of metabolism and energy is that of chemical equilibrium. Most chemical reactions are reversible. They can proceed in both directions, releasing energy into their environment in one direction, and absorbing it from the environment in the other direction (**Figure 2.9**). The same is true for the chemical reactions involved in cell metabolism, such as the breaking down and building up of proteins into and from individual amino acids, respectively. Reactants within a closed system will undergo chemical reactions in both directions until a state of equilibrium is reached. This state of equilibrium is one of the lowest possible free energy and a state of maximal entropy. Energy must be put into the system to push the reactants and products away from a state of equilibrium. Either reactants or products must be added, removed, or changed. If a cell were a closed system, its chemical reactions would reach equilibrium, and it would die because there would be insufficient free energy left to perform the work needed to maintain life. In a living cell, chemical reactions are constantly moving towards equilibrium, but never reach it. This is because a living cell is an open system. Materials pass in and out, the cell recycles the products of certain chemical reactions into other reactions, and chemical equilibrium is never reached. In this way, living organisms are in a constant energy-requiring, uphill battle against equilibrium and entropy. This constant supply of energy ultimately comes from sunlight, which is used to produce nutrients in the process of photosynthesis.

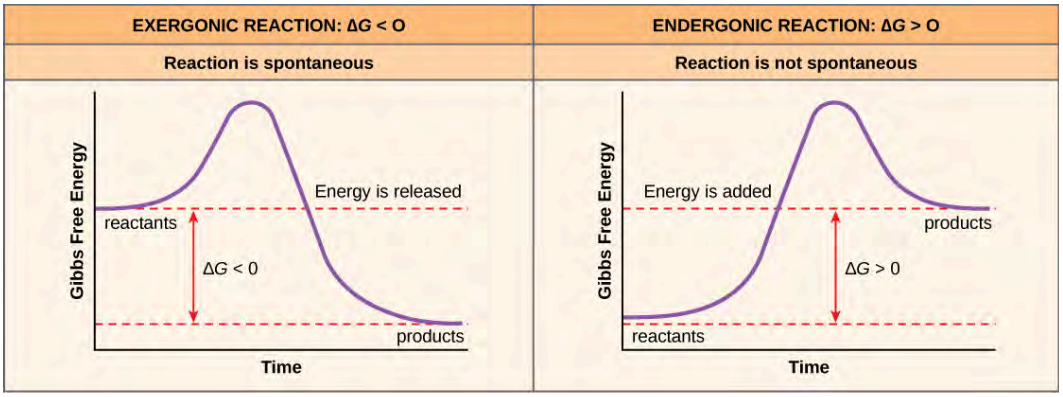


Figure 2.9 Exergonic and endergonic reactions result in changes in Gibbs free energy. Exergonic reactions release energy; endergonic reactions require energy to proceed.

Activation Energy

There is another important concept that must be considered regarding endergonic and exergonic reactions. Even exergonic reactions require a small amount of energy input to get going before they can proceed with their energy-releasing steps. These reactions have a net release of energy, but still require some energy in the beginning. This small amount of energy input necessary for all chemical reactions to occur is called the **activation energy** (or free energy of activation) and is abbreviated E_A (**Figure 2.10**).

Why would an energy-releasing, negative ΔG reaction actually require some energy to proceed? The reason lies in the steps that take place during a chemical reaction. During chemical reactions, certain chemical bonds are broken and new ones are formed. For example, when a glucose molecule is broken down, bonds between the carbon atoms of the molecule are broken. Since these are energy-storing bonds, they release energy when broken. However, to get them into a state that allows the bonds to break, the molecule must be somewhat contorted. A small energy input is required to achieve this contorted state. This contorted state is called the **transition state**, and it is a high-energy, unstable state. For this reason, reactant molecules don’t last long in their transition state, but very quickly proceed to the next steps of the chemical reaction. Free energy diagrams illustrate the energy profiles for a given reaction. Whether the reaction is exergonic or endergonic determines whether the products in the diagram will exist at a lower or higher energy state than both the reactants and the products. However, regardless of this measure, the transition state of the reaction exists at a higher energy state than the reactants, and thus, E_A is always positive.

LINK TO LEARNING

Watch an animation of the move from free energy to transition state at **this (http://openstaxcollege.org/l/energy_reaction)** site.

Explain why transitional states are unstable.

a. Molecules have relaxed molecular structure with low energy.

b. Molecules have strained molecular structure with high energy.

c. Molecules have relaxed molecular structure with high energy.

d. Molecules have strained molecular structure with low energy.

Where does the activation energy required by chemical reactants come from? The source of the activation energy needed to push reactions forward is typically heat energy from the surroundings. **Heat energy** (the total bond energy of reactants or products in a chemical reaction) speeds up the motion of molecules, increasing the frequency and force with which they collide; it also moves atoms and bonds within the molecule slightly, helping them reach their transition state. For this reason, heating up a system will cause chemical reactants within that system to react more frequently. Increasing the pressure on a system has the same effect. Once reactants have absorbed enough heat energy from their surroundings to reach the transition state, the reaction will proceed.

The activation energy of a particular reaction determines the rate at which it will proceed. The higher the activation energy, the slower the chemical reaction will be. The example of iron rusting illustrates an inherently slow reaction. This reaction occurs slowly over time because of its high E_A. Additionally, the burning of many fuels, which is strongly exergonic, will take place at a negligible rate unless their activation energy is overcome by sufficient heat from a spark. Once they begin to burn, however, the chemical reactions release enough heat to continue the burning process, supplying the activation energy for surrounding fuel molecules. Like these reactions outside of cells, the activation energy for most cellular reactions is too high for heat energy to overcome at efficient rates. In other words, in order for important cellular reactions to occur at appreciable rates (number of reactions per unit time), their activation energies must be lowered (**Figure 2.10**); this is referred to as catalysis. This is a very good thing as far as living cells are concerned. Important macromolecules, such as proteins, DNA, and RNA, store considerable energy, and their breakdown is exergonic. If cellular temperatures alone provided enough heat energy for these exergonic reactions to overcome their activation barriers, the essential components of a cell would disintegrate.

visual CONNECTION

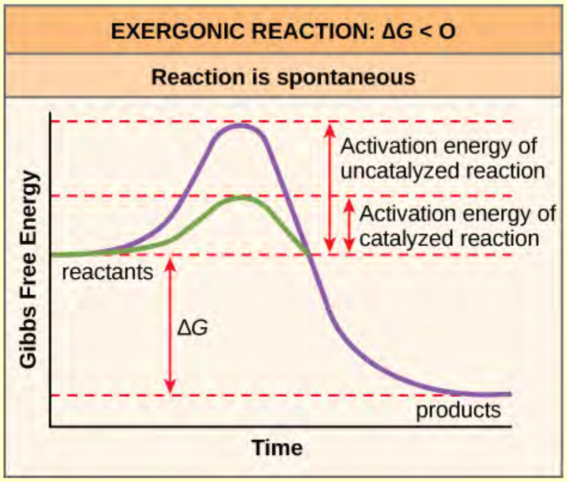


Figure 2.10 Activation energy is the energy required for a reaction to proceed, and it is lower if the reaction is catalyzed. The horizontal axis of this diagram describes the sequence of events in time.

How does the change in Gibbs free energy (ΔG) differ between the catalyzed versus uncatalyzed reaction?

a. ΔG is greater for the forward direction than for the reverse direction.

b. ΔG is greater for the uncatalyzed than the catalyzed reaction.

c. ΔG is greater for the catalyzed than the uncatalyzed reaction.

d. ΔG is the same for the catalyzed and uncatalyzed reactions.

science practices CONNECTION for AP® Courses

Think About It

All plants use water, carbon dioxide, and energy from the sun to make sugars. Think about what would happen to plants that do not have sunlight as an energy source or sufficient water. What would happen to organisms that depend on those plants for their own survival? How does depletion or destruction of forests by human activity affect free energy availability to organisms living in the rain forest? What measures can be taken to try and restore the free energy to an acceptable level?

6.3 | The Laws of Thermodynamics

In this section, you will explore the following questions:

- What is entropy?
- What is the difference between the first and second laws of thermodynamics?

Connection for AP® Courses

In studying energy, scientists use the term system to refer to the matter and its environment involved in energy transfers, such as an ecosystem. Even single cells are biological systems and all systems require energy to maintain order. The more ordered a system is, the lower its entropy. Entropy is a measure of the disorder of the system. (Think of your bedroom as a system. On Sunday evening, you throw dirty clothes in the laundry basket, put books back on the shelves, and return dirty dishes to the kitchen. Cleaning your room requires an input of energy. What gradually happens as the week progresses? You guessed it: entropy.) All biological systems obey the laws of chemistry and physics, including the laws of thermodynamics that describe the properties and processes of energy transfer in systems. The first law states that the total amount of energy in the universe is constant; energy cannot be created or destroyed, but it can be transformed and transferred. The second law states that every energy transfer involves some loss of energy in an unusable form, such as heat energy, resulting in a more disordered system (e.g., your bedroom over the course of a week). Thus, no energy transfer is completely efficient. (We will explore how free energy is stored, transferred, and used in more detail when we study photosynthesis and cellular respiration.)

Information presented and the examples highlighted in the section, support concepts and Learning Objectives outlined in Big Idea 2 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® Exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.A	Growth, reproduction and maintenance of living systems require free energy and matter.
Essential Knowledge	**2.A.1** All living systems require constant input of free energy.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**2.1** The student is able to explain how biological systems use free energy based on empirical data that all organisms require constant energy input to maintain organization, to grow, and to reproduce.

The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.1][APLO 2.2][APLO 2.4][APLO 4.16][APLO 2.3]

Thermodynamics refers to the study of energy and energy transfer involving physical matter. The matter and its environment relevant to a particular case of energy transfer are classified as a system, and everything outside of that system is called the surroundings. For instance, when heating a pot of water on the stove, the system includes the stove, the pot, and the water. Energy is transferred within the system (between the stove, pot, and water). There are two types of systems: open and closed. An open system is one in which energy can be transferred between the system and its surroundings. The stovetop system is open because heat can be lost into the air. A closed system is one that cannot transfer energy to its surroundings.

Biological organisms are open systems. Energy is exchanged between them and their surroundings, as they consume energy-storing molecules and release energy to the environment by doing work. Like all things in the physical world, energy is subject to the laws of physics. The laws of thermodynamics govern the transfer of energy in and among all systems in the universe.

The First Law of Thermodynamics

The first law of thermodynamics deals with the total amount of energy in the universe. It states that this total amount of energy is constant. In other words, there has always been, and always will be, exactly the same amount of energy in the universe. Energy exists in many different forms. According to the first law of thermodynamics, energy may be transferred from place to place or transformed into different forms, but it cannot be created or destroyed. The transfers and transformations of energy take place around us all the time. Light bulbs transform electrical energy into light energy. Gas stoves transform chemical energy from natural gas into heat energy. Plants perform one of the most biologically useful energy transformations on earth: that of converting the energy of sunlight into the chemical energy stored within organic molecules, as shown in **m64481 (http://cnx.org/content/m64481/latest/#fig-ch06_01_01)** . Some examples of energy transformations are shown in **Figure 2.11**.

The challenge for all living organisms is to obtain energy from their surroundings in forms that they can transfer or transform into usable energy to do work. Living cells have evolved to meet this challenge very well. Chemical energy stored within organic molecules such as sugars and fats is transformed through a series of cellular chemical reactions into energy within molecules of ATP. Energy in ATP molecules is easily accessible to do work. Examples of the types of work that cells need to do include building complex molecules, transporting materials, powering the beating motion of cilia or flagella, contracting muscle fibers to create movement, and reproduction.

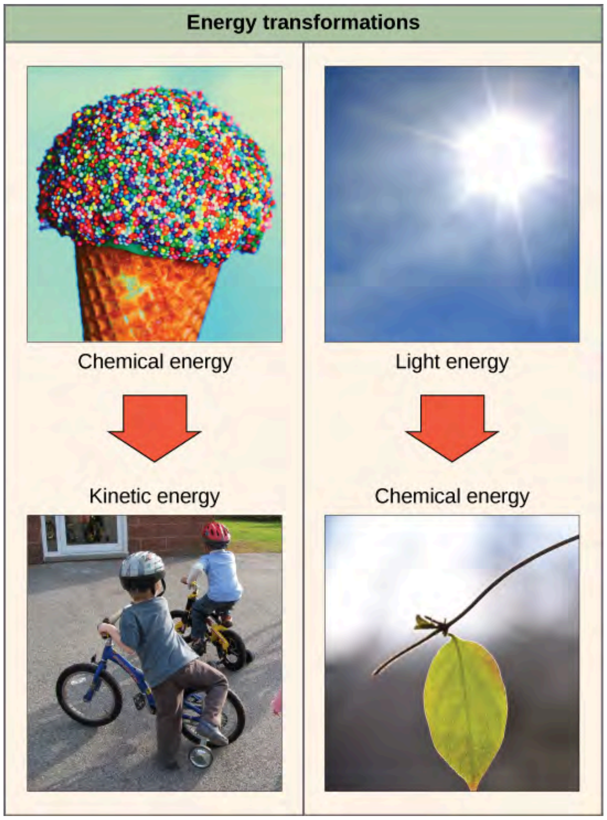


Figure 2.11 Shown are two examples of energy being transferred from one system to another and transformed from one form to another. Humans can convert the chemical energy in food, like this ice cream cone, into kinetic energy (the energy of movement to ride a bicycle). Plants can convert electromagnetic radiation (light energy) from the sun into chemical energy. (credit “ice cream”: modification of work by D. Sharon Pruitt; credit “kids on bikes”: modification of work by Michelle Riggen-Ransom; credit “leaf”: modification of work by Cory Zanker)

The Second Law of Thermodynamics

A living cell’s primary tasks of obtaining, transforming, and using energy to do work may seem simple. However, the second law of thermodynamics explains why these tasks are harder than they appear. None of the energy transfers we’ve discussed, along with all energy transfers and transformations in the universe, is completely efficient. In every energy transfer, some amount of energy is lost in a form that is unusable. In most cases, this form is heat energy. Thermodynamically, **heat energy** is defined as the energy transferred from one system to another that is not doing work. For example, when an airplane flies through the air, some of the energy of the flying plane is lost as heat energy due to friction with the surrounding air. This friction actually heats the air by temporarily increasing the speed of air molecules. Likewise, some energy is lost as heat energy during cellular metabolic reactions. This is good for warm-blooded creatures like us, because heat energy helps to maintain our body temperature. Strictly speaking, no energy transfer is completely efficient, because some energy is lost in an unusable form.

An important concept in physical systems is that of order and disorder (also known as randomness). The more energy that is lost by a system to its surroundings, the less ordered and more random the system is. Scientists refer to the measure of randomness or disorder within a system as **entropy**. High entropy means high disorder and low energy (**Figure 2.12**). To better understand entropy, think of a student's bedroom. If no energy or work were put into it, the room would quickly become messy. It would exist in a very disordered state, one of high entropy. Energy must be put into the system, in the form of the student doing work and putting everything away, in order to bring the room back to a state of cleanliness and order. This state is one of low entropy. Similarly, a car or house must be constantly maintained with work in order to keep it in an ordered state. Left alone, the entropy of the house or car gradually increases through rust and degradation. Molecules and chemical reactions have varying amounts of entropy as well. For example, as chemical reactions reach a state of equilibrium, entropy increases, and as molecules at a high concentration in one place diffuse and spread out, entropy also increases.

scientific method CONNECTION

Transfer of Energy and the Resulting Entropy

Set up a simple experiment to understand how energy is transferred and how a change in entropy results.

1. Take a block of ice. This is water in solid form, so it has a high structural order. This means that the molecules cannot move very much and are in a fixed position. The temperature of the ice is 0°C. As a result, the entropy of the system is low.
2. Allow the ice to melt at room temperature. What is the state of molecules in the liquid water now? How did the energy transfer take place? Is the entropy of the system higher or lower? Why?
3. Heat the water to its boiling point. What happens to the entropy of the system when the water is heated?

All physical systems can be thought of in this way: Living things are highly ordered, requiring constant energy input to be maintained in a state of low entropy. As living systems take in energy-storing molecules and transform them through chemical reactions, they lose some amount of usable energy in the process, because no reaction is completely efficient. They also produce waste and by-products that aren't useful energy sources. This process increases the entropy of the system's surroundings. Since all energy transfers result in the loss of some usable energy, the second law of thermodynamics states that every energy transfer or transformation increases the entropy of the universe. Even though living things are highly ordered and maintain a state of low entropy, the entropy of the universe in total is constantly increasing due to the loss of usable energy with each energy transfer that occurs. Essentially, living things are in a continuous uphill battle against this constant increase in universal entropy.

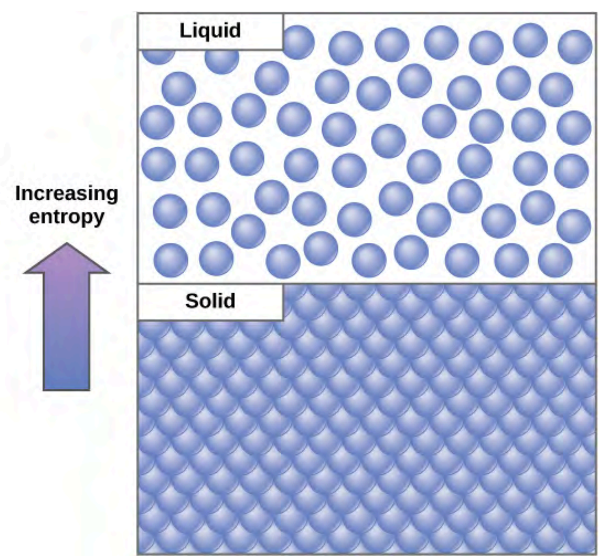


Figure 2.12 Entropy is a measure of randomness or disorder in a system. Gases have higher entropy than liquids, and liquids have higher entropy than solids.

science practices CONNECTION for AP® Courses

Think About It

- Imagine a large ant colony with an elaborate nest, containing many tunnels and passageways. Now imagine that an earthquake shakes the ground and demolishes the nest. Did the ant nest have higher entropy before or after the earthquake? What can the ants do to restore their nest to close to its original amount of entropy? Explain your answers.
- Energy transfers take place constantly in everyday activities. Think of two scenarios: cooking on a stove and driving a car. Explain how the second law of thermodynamics applies to these two scenarios.

6.4 | ATP: Adenosine Triphosphate

In this section, you will explore the following questions:

- Why is ATP considered the energy currency of the cell?
- How is energy released through the hydrolysis of ATP?

Connection for AP® Courses

Adenosine triphosphate or ATP is the energy "currency" or carrier of the cell. When cells require an input of energy, they use ATP. An ATP nucleotide molecule consists of a five-carbon sugar, the nitrogenous base adenine, and three phosphate groups. (Do not confuse ATP with the nucleotides of DNA and RNA, although they have structural similarities.) The bonds that connect the phosphate have high-energy content, and the energy released from the hydrolysis of ATP to ADP + P_i (Adenosine Diphosphate + Pyrophosphate) is used to perform cellular work, such as contracting a muscle or pumping a solute across a cell membrane in active transport. Cells use ATP by coupling the exergonic reaction of ATP hydrolysis with endergonic reactions, with ATP donating its phosphate group to another molecule via a process called phosphorylation. The phosphorylated molecule is at a higher energy state and is less stable than its unphosphorylated form and free energy is released to substrates to perform work during this process. Phosphorylation is an example of energy transfer between molecules.

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 2 of the AP® Biology Curriculum Framework. The Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® Exam questions. A Learning Objective merges required content with one or more of the seven Science Practices.

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The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.2][APLO 4.14][APLO 2.7][APLO 2.35]

Even exergonic, energy-releasing reactions require a small amount of activation energy in order to proceed. However, consider endergonic reactions, which require much more energy input, because their products have more free energy than their reactants. Within the cell, where does energy to power such reactions come from? The answer lies with an energy-supplying molecule called **adenosine triphosphate**, or **ATP**. ATP is a small, relatively simple molecule (Figure 2.13), but within some of its bonds, it contains the potential for a quick burst of energy that can be harnessed to perform cellular work. This molecule can be thought of as the primary energy currency of cells in much the same way that money is the currency that people exchange for things they need. ATP is used to power the majority of energy-requiring cellular reactions.

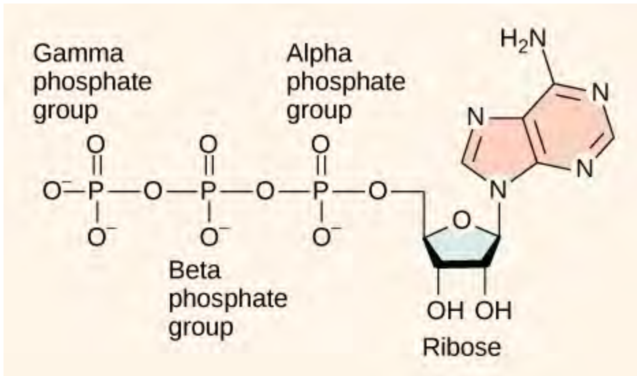


Figure 2.13 ATP is the primary energy currency of the cell. It has an adenosine backbone with three phosphate groups attached.

As its name suggests, adenosine triphosphate is comprised of adenosine bound to three phosphate groups (Figure 2.13). Adenosine is a nucleoside consisting of the nitrogenous base adenine and a five-carbon sugar, ribose. The three phosphate groups, in order of closest to furthest from the ribose sugar, are labeled alpha, beta, and gamma. Together, these chemical groups constitute an energy powerhouse. However, not all bonds within this molecule exist in a particularly high-energy state. Both bonds that link the phosphates are equally high-energy bonds (**phosphoanhydride bonds**) that, when broken, release sufficient energy to power a variety of cellular reactions and processes. These high-energy bonds are the bonds between the second and third (or beta and gamma) phosphate groups and between the first and second phosphate groups. The reason that these bonds are considered "high-energy" is because the products of such bond breaking—adenosine diphosphate (ADP) and one inorganic phosphate group (P_i)—have considerably lower free energy than the reactants: ATP and a water molecule. Because this reaction takes place with the use of a water molecule, it is considered a hydrolysis reaction. In other words, ATP is hydrolyzed into ADP in the following reaction:

$$\text{ATP} + \text{H}_2\text{O} \rightarrow \text{ADP} + \text{P}_\text{i} + \text{free energy}$$

Like most chemical reactions, the hydrolysis of ATP to ADP is reversible. The reverse reaction regenerates ATP from ADP + P_i. Indeed, cells rely on the regeneration of ATP just as people rely on the regeneration of spent money through some sort of income. Since ATP hydrolysis releases energy, ATP regeneration must require an input of free energy. The formation of ATP is expressed in this equation:

$$\text{ADP} + \text{P}_\text{i} + \text{free energy} \rightarrow \text{ATP} + \text{H}_2\text{O}$$

Two prominent questions remain with regard to the use of ATP as an energy source. Exactly how much free energy is released with the hydrolysis of ATP, and how is that free energy used to do cellular work? The calculated ΔG for the hydrolysis of one mole of ATP into ADP and P_i is −7.3 kcal/mole (−30.5 kJ/mol). Since this calculation is true under standard conditions, it would be expected that a different value exists under cellular conditions. In fact, the ΔG for the hydrolysis of one mole of ATP in a living cell is almost double the value at standard conditions: 14 kcal/mol (−57 kJ/mol).

ATP is a highly unstable molecule. Unless quickly used to perform work, ATP spontaneously dissociates into ADP + P_i, and the free energy released during this process is lost as heat. The second question posed above, that is, how the energy released by ATP hydrolysis is used to perform work inside the cell, depends on a strategy called energy coupling. Cells couple the exergonic reaction of ATP hydrolysis with endergonic reactions, allowing them to proceed. One example of energy coupling using ATP involves a transmembrane ion pump that is extremely important for cellular function. This sodium-potassium pump (Na^+/K^+ pump) drives sodium out of the cell and potassium into the cell (Figure 2.14). A large percentage of a cell's ATP is spent powering this pump, because cellular processes bring a great deal of sodium into the cell and potassium out of the cell. The pump works constantly to stabilize cellular concentrations of sodium and potassium. In order for the pump to turn one cycle (exporting three Na+ ions and importing two K^+ ions), one molecule of ATP must be hydrolyzed. When ATP is hydrolyzed, its gamma phosphate doesn't simply float away, but is actually transferred onto the pump protein. This process of a phosphate group binding to a molecule is called phosphorylation. As with most cases of ATP hydrolysis, a phosphate from ATP is transferred onto another molecule. In a phosphorylated state, the Na^+/K^+ pump has more free energy and is triggered to undergo a conformational change. This change allows it to release Na^+ to the outside of the cell. It then binds extracellular K^+, which, through another conformational change, causes the phosphate to detach from the pump. This release of phosphate triggers the K^+ to be released to the inside of the cell. Essentially, the energy released from the hydrolysis of ATP is coupled with the energy required to power the pump and transport Na^+ and K^+ ions. ATP performs cellular work using this basic form of energy coupling through phosphorylation.

visual CONNECTION

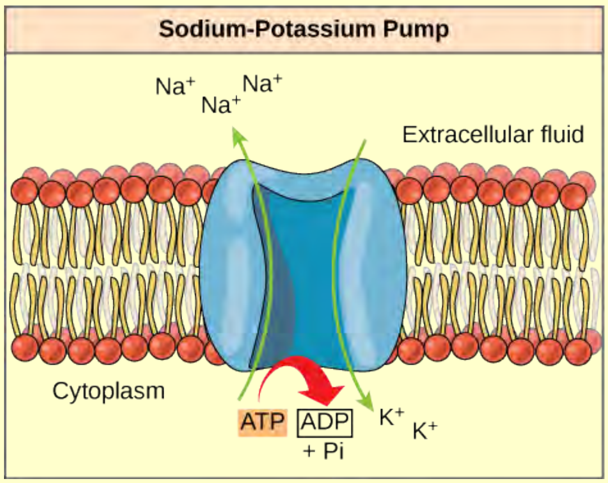


Figure 2.14 The sodium-potassium pump is an example of energy coupling. The energy derived from exergonic ATP hydrolysis is used to pump sodium and potassium ions across the cell membrane.

The hydrolysis of one ATP molecule releases 7.3 kcal/mol of energy ($\Delta G = -7.3\text{ kcal/mol}$ of energy). If it takes 2.1 kcal/mol of energy to move one Na^+ across the membrane ($\Delta G = +2.1\text{ kcal/mol}$ of energy), what is the maximum number of sodium ions that could be moved by the hydrolysis of one ATP molecule?

a. five

b. four

c. three

d. two

Often during cellular metabolic reactions, such as the synthesis and breakdown of nutrients, certain molecules must be altered slightly in their conformation to become substrates for the next step in the reaction series. One example is during the very first steps of cellular respiration, when a molecule of the sugar glucose is broken down in the process of glycolysis. In the first step of this process, ATP is required for the phosphorylation of glucose, creating a high-energy but unstable intermediate. This phosphorylation reaction powers a conformational change that allows the phosphorylated glucose molecule to be converted to the phosphorylated sugar fructose. Fructose is a necessary intermediate for glycolysis to move forward. Here, the exergonic reaction of ATP hydrolysis is coupled with the endergonic reaction of converting glucose into a phosphorylated intermediate in the pathway. Once again, the energy released by breaking a phosphate bond within ATP was used for the phosphorylation of another molecule, creating an unstable intermediate and powering an important conformational change.

LINK TO LEARNING

See an interactive animation of the ATP-producing glycolysis process at this **site (http://openstaxcollege.org/l/glycolysis_stgs)** .

Explain why the lock-and-key model does not adequately represent the relationship between hexokinase and glucose.

a. Hexokinase changes conformation in presence of glucose

b. Hexokinase induces change in the glucose structure

c. Hexokinase requires an effector molecule to bind at allosteric site

d. Hexokinase binds glucose without any conformational change

science practices CONNECTION for AP® Courses

Think About It

The hydrolysis of one ATP molecules releases 7.3 kcal/mol of energy (ΔG = –7.3 kcal/mol energy). If it takes 2.1 kcal/mol of energy to move one Na^+ across the membrane (ΔG = +2.1 kcal/mol of energy), how many sodium ions could be moved by the hydrolysis of one ATP molecule?

6.5 | Enzymes

In this section, you will explore the following questions:

- What is the role of enzymes in metabolic pathways?
- How do enzymes function as molecular catalysts?

Connection for AP® Courses

Many chemical reactions in cells occur spontaneously, but happen too slowly to meet the needs of a cell. For example, a teaspoon of sucrose (table sugar), a disaccharide, in a glass of iced tea will take time to break down into two monosaccharides, glucose and fructose; however, if you add a small amount of the enzyme sucrase to the tea, sucrose breaks down almost immediately. Sucrase is an example of an enzyme, a type of biological catalyst. Enzymes are macromolecules—most often proteins—that speed up chemical reactions by lowering activation energy barriers. Enzymes are very specific for the reactions they catalyze; because they are polypeptides, enzymes can have a variety of shapes attributed to interactions among amino acid R-groups. One part of the enzyme, the active site, interacts with the substrate via the induced fit model of interaction. Substrate binding alters the shape of the enzyme to facilitate the chemical reaction in several different ways, including bringing substrates together in an optimal orientation. After the reaction finishes, the product(s) are released, and the active site returns to its original shape.

Enzyme activity, and thus the rate of an enzyme-catalyzed reaction, is regulated by environmental conditions, including the amount of substrate, temperature, pH, and the presence of coenzymes, cofactors, activators, and inhibitors. Inhibitors, coenzymes, and cofactors can act competitively by binding to the enzyme's active site, or noncompetitively by binding to the enzyme's allosteric site. An allosteric site is an alternate part of the enzyme that can bind to non–substrate molecules. Enzymes work most efficiently under optimal conditions that are specific to the enzyme. For example, trypsin, an enzyme in the human small intestine, works most efficiently at pH 8, whereas pepsin in the stomach works best under acidic conditions. Sometimes environmental factors, especially low pH and high temperatures, alter the shape of the active site; if the shape cannot be restored, the enzyme denatures. The most common method of enzyme regulation in metabolic pathways is via feedback inhibition.

How can various factors, such as feedback inhibition, regulate enzyme activity?

Information presented and the examples highlighted in the section support concepts and Learning Objectives outlined in Big Idea 4 of the AP® Biology Curriculum Framework. The learning objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® Exam questions. A Learning Objective merges required content with one or more of the seven science practices.

Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.B	Competition and cooperation are important aspects of biological systems.
Essential Knowledge	**4.B.1** Interactions between molecules affect their structure and function.
Science Practice	**5.1** The student can analyze data to identify patterns or relationships.
Learning Objective	**4.17** The student is able to analyze data to identify how molecular interactions affect structure and function.

The Science Practices Assessment Ancillary contains additional test questions for this section that will help you prepare for the AP exam. These questions address the following standards:
[APLO 2.15][APLO 4.8][APLO 2.16]

A substance that helps a chemical reaction to occur is a catalyst, and the special molecules that catalyze biochemical reactions are called enzymes. Almost all enzymes are proteins, made up of chains of amino acids, and they perform the critical task of lowering the activation energies of chemical reactions inside the cell. Enzymes do this by binding to the reactant molecules, and holding them in such a way as to make the chemical bond-breaking and bond-forming processes take place more readily. It is important to remember that enzymes don't change the ΔG of a reaction. In other words, they don't change whether a reaction is exergonic (spontaneous) or endergonic. This is because they don't change the free energy of the reactants or products. They only reduce the activation energy required to reach the transition state (**Figure 2.15**).

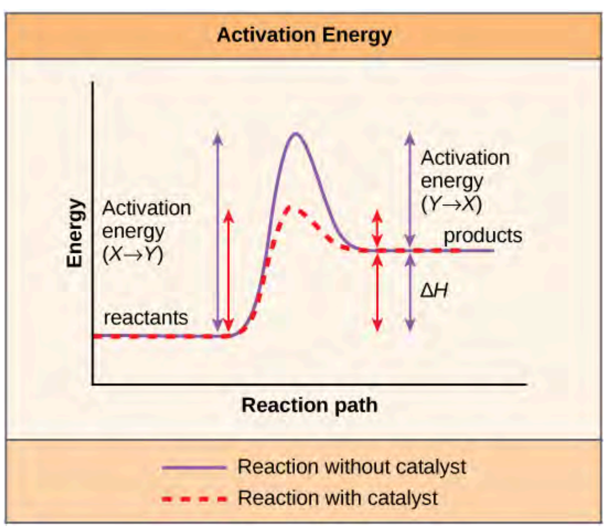


Figure 2.15 Enzymes lower the activation energy of the reaction but do not change the free energy of the reaction.

Enzyme Active Site and Substrate Specificity

The chemical reactants to which an enzyme binds are the enzyme's **substrates**. There may be one or more substrates, depending on the particular chemical reaction. In some reactions, a single-reactant substrate is broken down into multiple products. In others, two substrates may come together to create one larger molecule. Two reactants might also enter a reaction, both become modified, and leave the reaction as two products. The location within the enzyme where the substrate binds is called the enzyme's **active site**. The active site is where the "action" happens, so to speak. Since enzymes are proteins, there is a unique combination of amino acid residues (also called side chains, or R groups) within the active site. Each residue is characterized by different properties. Residues can be large or small, weakly acidic or basic, hydrophilic or hydrophobic, positively or negatively charged, or neutral. The unique combination of amino acid residues, their positions, sequences, structures, and properties, creates a very specific chemical environment within the active site. This specific environment is suited to bind, albeit briefly, to a specific chemical substrate (or substrates). Due to this jigsaw puzzle-like match between an enzyme and its substrates (which adapts to find the best fit between the transition state and the active site), enzymes are known for their specificity. The "best fit" results from the shape and the amino acid functional group's attraction to the substrate. There is a specifically matched enzyme for each substrate and, thus, for each chemical reaction; however, there is flexibility as well.

The fact that active sites are so perfectly suited to provide specific environmental conditions also means that they are subject to influences by the local environment. It is true that increasing the environmental temperature generally increases reaction rates, enzyme-catalyzed or otherwise. However, increasing or decreasing the temperature outside of an optimal range can affect chemical bonds within the active site in such a way that they are less well suited to bind substrates. High temperatures will eventually cause enzymes, like other biological molecules, to **denature**, a process that changes the natural properties of a substance. Likewise, the pH of the local environment can also affect enzyme function. Active site amino acid residues have their own acidic or basic properties that are optimal for catalysis. These residues are sensitive to changes in pH that can impair the way substrate molecules bind. Enzymes are suited to function best within a certain pH range, and, as with temperature, extreme pH values (acidic or basic) of the environment can cause enzymes to denature.

Induced Fit and Enzyme Function

For many years, scientists thought that enzyme-substrate binding took place in a simple "lock-and-key" fashion. This model asserted that the enzyme and substrate fit together perfectly in one instantaneous step. However, current research supports a more refined view called **induced fit** (**Figure 2.16**). The induced-fit model expands upon the lock-and-key model by describing a more dynamic interaction between enzyme and substrate. As the enzyme and substrate come together, their interaction causes a mild shift in the enzyme's structure that confirms an ideal binding arrangement between the enzyme and the transition state of the substrate. This ideal binding maximizes the enzyme's ability to catalyze its reaction.

LINK TO LEARNING

View an animation of induced fit at **this website (http://openstaxcollege.org/l/hexokinase)** .

Phosphofructokinase deficiency occurs when a person lacks an enzyme needed to perform glycolysis in skeletal muscles. What effect could this have on the body?

a. Production of energy by glycolysis will occur, skeletal muscles will function properly

b. Production of energy by glycolysis will not occur, skeletal muscles will function properly

c. Production of energy by glycolysis will occur, skeletal muscles will not function properly

d. Production of energy will not occur, skeletal muscles will not function properly

When an enzyme binds its substrate, an enzyme-substrate complex is formed. This complex lowers the activation energy of the reaction and promotes its rapid progression in one of many ways. On a basic level, enzymes promote chemical reactions that involve more than one substrate by bringing the substrates together in an optimal orientation. The appropriate region (atoms and bonds) of one molecule is juxtaposed to the appropriate region of the other molecule with which it must react. Another way in which enzymes promote the reaction of their substrates is by creating an optimal environment within the active site for the reaction to occur. Certain chemical reactions might proceed best in a slightly acidic or non-polar environment. The chemical properties that emerge from the particular arrangement of amino acid residues within an active site create the perfect environment for an enzyme's specific substrates to react.

You've learned that the activation energy required for many reactions includes the energy involved in manipulating or slightly contorting chemical bonds so that they can easily break and allow others to reform. Enzymatic action can aid this process. The enzyme-substrate complex can lower the activation energy by contorting substrate molecules in such a way as to facilitate bond-breaking, helping to reach the transition state. Finally, enzymes can also lower activation energies by taking part in the chemical reaction itself. The amino acid residues can provide certain ions or chemical groups that actually form covalent bonds with substrate molecules as a necessary step of the reaction process. In these cases, it is important to remember that the enzyme will always return to its original state at the completion of the reaction. One of the hallmark properties of enzymes is that they remain ultimately unchanged by the reactions they catalyze. After an enzyme is done catalyzing a reaction, it releases its product(s).

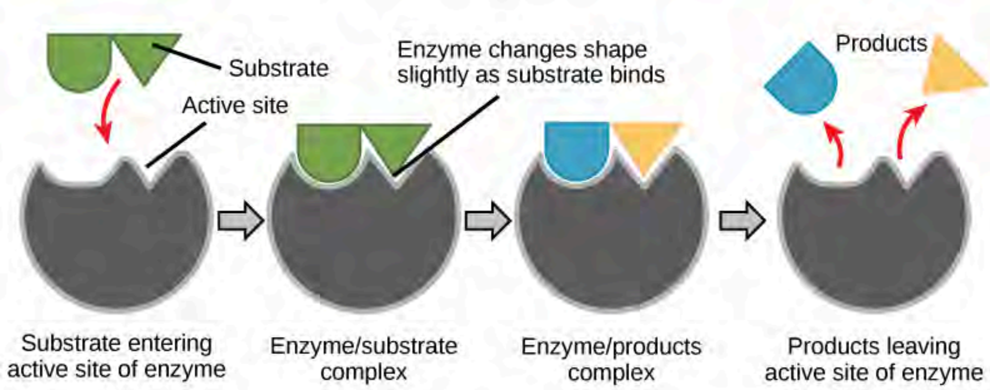


Figure 2.16 According to the induced-fit model, both enzyme and substrate undergo dynamic conformational changes upon binding. The enzyme contorts the substrate into its transition state, thereby increasing the rate of the reaction.

science practices CONNECTION for AP® Courses

Activity

AP Biology Investigation 13: Enzyme Activity. This investigation allows you to design and conduct experiments to explore the effects of environmental variables, such as temperature and pH, on the rates of enzymatic reactions.

Control of Metabolism Through Enzyme Regulation

It would seem ideal to have a scenario in which all of the enzymes encoded in an organism's genome existed in abundant supply and functioned optimally under all cellular conditions, in all cells, at all times. In reality, this is far from the case. A variety of mechanisms ensure that this does not happen. Cellular needs and conditions vary from cell to cell, and change within individual cells over time. The required enzymes and energetic demands of stomach cells are different from those of fat storage cells, skin cells, blood cells, and nerve cells. Furthermore, a digestive cell works much harder to process and break down nutrients during the time that closely follows a meal compared with many hours after a meal. As these cellular demands and conditions vary, so do the amounts and functionality of different enzymes.

Since the rates of biochemical reactions are controlled by activation energy, and enzymes lower and determine activation energies for chemical reactions, the relative amounts and functioning of the variety of enzymes within a cell ultimately determine which reactions will proceed and at which rates. This determination is tightly controlled. In certain cellular environments, enzyme activity is partly controlled by environmental factors, like pH and temperature. There are other mechanisms through which cells control the activity of enzymes and determine the rates at which various biochemical reactions will occur.

Regulation of Enzymes by Molecules

Enzymes can be regulated in ways that either promote or reduce their activity. There are many different kinds of molecules that inhibit or promote enzyme function, and various mechanisms exist for doing so. In some cases of enzyme inhibition, for example, an inhibitor molecule is similar enough to a substrate that it can bind to the active site and simply block the substrate from binding. When this happens, the enzyme is inhibited through **competitive inhibition**, because an inhibitor molecule competes with the substrate for active site binding (Figure 2.17). On the other hand, in noncompetitive inhibition, an inhibitor molecule binds to the enzyme in a location other than an allosteric site and still manages to block substrate binding to the active site.

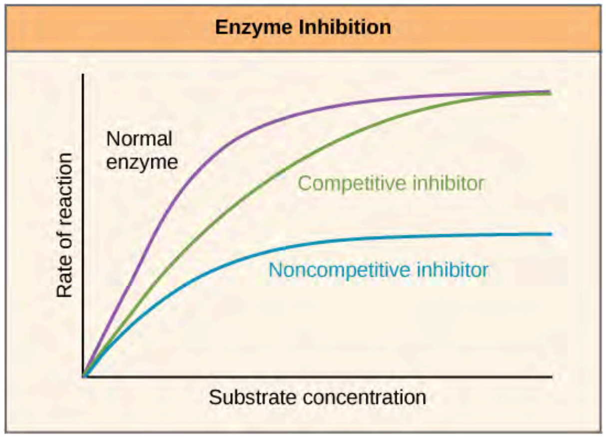


Figure 2.17 Competitive and noncompetitive inhibition affect the rate of reaction differently. Competitive inhibitors affect the initial rate but do not affect the maximal rate, whereas noncompetitive inhibitors affect the maximal rate.

Some inhibitor molecules bind to enzymes in a location where their binding induces a conformational change that reduces the affinity of the enzyme for its substrate. This type of inhibition is called **allosteric inhibition** (Figure 2.18). Most allosterically regulated enzymes are made up of more than one polypeptide, meaning that they have more than one protein subunit. When an allosteric inhibitor binds to an enzyme, all active sites on the protein subunits are changed slightly such that they bind their substrates with less efficiency. There are allosteric activators as well as inhibitors. Allosteric activators bind to locations on an enzyme away from the active site, inducing a conformational change that increases the affinity of the enzyme's active site(s) for its substrate(s).

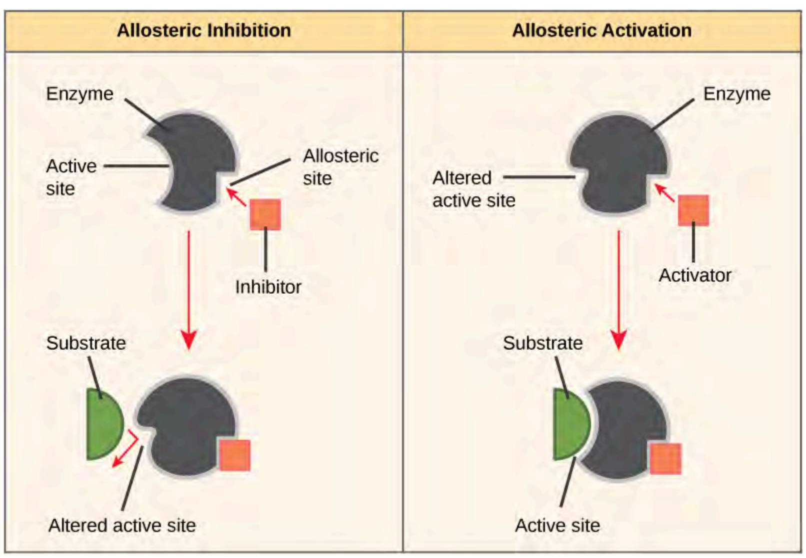


Figure 2.18 Allosteric inhibitors modify the active site of the enzyme so that substrate binding is reduced or prevented. In contrast, allosteric activators modify the active site of the enzyme so that the affinity for the substrate increases.

everyday CONNECTION

Figure 2.19 Have you ever wondered how pharmaceutical drugs are developed? (credit: Deborah Austin)

Drug Discovery by Looking for Inhibitors of Key Enzymes in Specific Pathways

Enzymes are key components of metabolic pathways. Understanding how enzymes work and how they can be regulated is a key principle behind the development of many of the pharmaceutical drugs (Figure 2.19) on the market today. Biologists working in this field collaborate with other scientists, usually chemists, to design drugs.

Consider statins for example—which is the name given to the class of drugs that reduces cholesterol levels. These compounds are essentially inhibitors of the enzyme HMG-CoA reductase. HMG-CoA reductase is the enzyme that synthesizes cholesterol from lipids in the body. By inhibiting this enzyme, the levels of cholesterol synthesized in the body can be reduced. Similarly, acetaminophen is an inhibitor of the enzyme cyclooxygenase. While it is effective in providing relief from fever and inflammation (pain), its mechanism of action is still not completely understood.

How are drugs developed? One of the first challenges in drug development is identifying the specific molecule that the drug is intended to target. In the case of statins, HMG-CoA reductase is the drug target. Drug targets are identified through painstaking research in the laboratory. Identifying the target alone is not sufficient; scientists also need to know how the target acts inside the cell and which reactions go awry in the case of disease. Once the target and the pathway are identified, then the actual process of drug design begins. During this stage, chemists and biologists work together to design and synthesize molecules that can either block or activate a particular reaction. However, this is only the beginning: both if and when a drug prototype is successful in performing its function, then it must undergo many tests from in vitro experiments to clinical trials before it can get FDA approval to be on the market.

Statins reduce the level of cholesterol in the blood. Based on the everyday connection, which of the following might also reduce cholesterol levels in the blood?

a. a drug that increases HMG-CoA reductase levels
b. a drug that reduces cyclooxygenase levels
c. a drug that reduces lipid levels in the body
d. a drug that blocks the action of acetaminophen

Many enzymes don't work optimally, or even at all, unless bound to other specific non-protein helper molecules, either temporarily through ionic or hydrogen bonds or permanently through stronger covalent bonds. Two types of helper molecules are **cofactors** and **coenzymes**. Binding to these molecules promotes optimal conformation and function for their respective enzymes. Cofactors are inorganic ions such as iron (Fe++) and magnesium (Mg++). One example of an enzyme that requires a metal ion as a cofactor is the enzyme that builds DNA molecules, DNA polymerase, which requires bound zinc ion (Zn++) to function. Coenzymes are organic helper molecules, with a basic atomic structure made up of carbon and hydrogen, which are required for enzyme action. The most common sources of coenzymes are dietary vitamins (**Figure 2.20**). Some vitamins are precursors to coenzymes and others act directly as coenzymes. Vitamin C is a coenzyme for multiple enzymes that take part in building the important connective tissue component, collagen. An important step in the breakdown of glucose to yield energy is catalysis by a multi-enzyme complex called pyruvate dehydrogenase. Pyruvate dehydrogenase is a complex of several enzymes that actually requires one cofactor (a magnesium ion) and five different organic coenzymes to catalyze its specific chemical reaction. Therefore, enzyme function is, in part, regulated by an abundance of various cofactors and coenzymes, which are supplied primarily by the diets of most organisms.

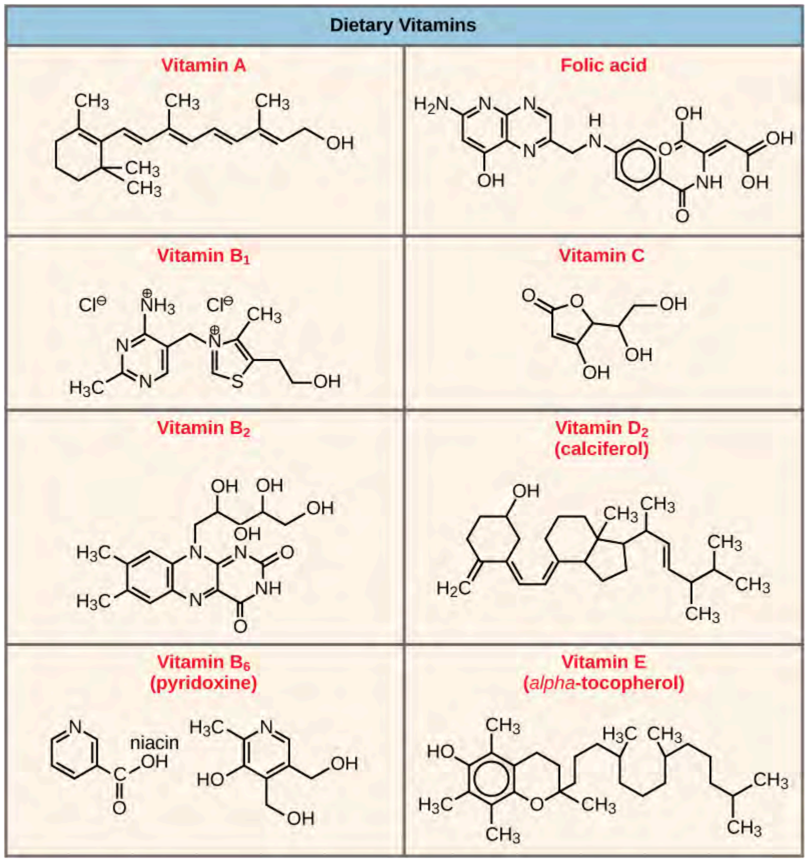


Figure 2.20 Vitamins are important coenzymes or precursors of coenzymes, and are required for enzymes to function properly. Multivitamin capsules usually contain mixtures of all the vitamins at different percentages.

Enzyme Compartmentalization

In eukaryotic cells, molecules such as enzymes are usually compartmentalized into different organelles. This allows for yet another level of regulation of enzyme activity. Enzymes required only for certain cellular processes can be housed separately along with their substrates, allowing for more efficient chemical reactions. Examples of this sort of enzyme regulation based on location and proximity include the enzymes involved in the latter stages of cellular respiration, which take place exclusively in the mitochondria, and the enzymes involved in the digestion of cellular debris and foreign materials, located within lysosomes.

Feedback Inhibition in Metabolic Pathways

Molecules can regulate enzyme function in many ways. A major question remains, however: What are these molecules and where do they come from? Some are cofactors and coenzymes, ions, and organic molecules, as you've learned. What other molecules in the cell provide enzymatic regulation, such as allosteric modulation, and competitive and noncompetitive inhibition? The answer is that a wide variety of molecules can perform these roles. Some of these molecules include pharmaceutical and non-pharmaceutical drugs, toxins, and poisons from the environment. Perhaps the most relevant sources of enzyme regulatory molecules, with respect to cellular metabolism, are the products of the cellular metabolic reactions themselves. In a most efficient and elegant way, cells have evolved to use the products of their own reactions for feedback inhibition of enzyme activity. **Feedback inhibition** involves the use of a reaction product to regulate its own further production (**Figure 2.21**). The cell responds to the abundance of specific products by slowing down production during anabolic or catabolic reactions. Such reaction products may inhibit the enzymes that catalyzed their production through the mechanisms described above.

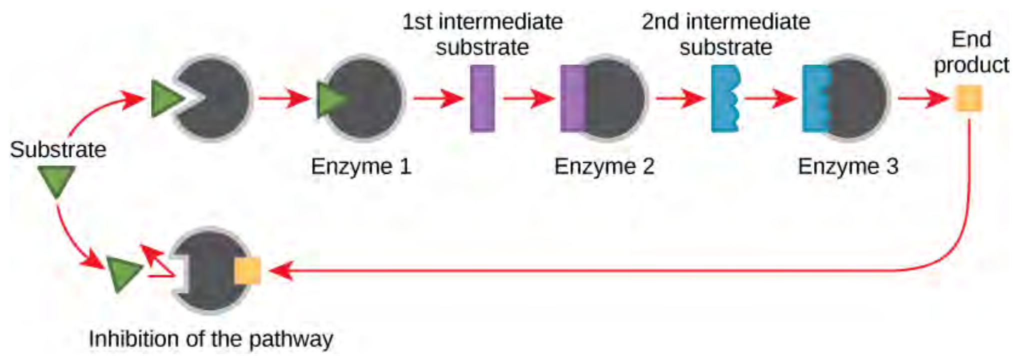


Figure 2.21 Metabolic pathways are a series of reactions catalyzed by multiple enzymes. Feedback inhibition, where the end product of the pathway inhibits an upstream step, is an important regulatory mechanism in cells.

The production of both amino acids and nucleotides is controlled through feedback inhibition. Additionally, ATP is an allosteric regulator of some of the enzymes involved in the catabolic breakdown of sugar, the process that produces ATP. In this way, when ATP is abundant, the cell can prevent its further production. Remember that ATP is an unstable molecule that can spontaneously dissociate into ADP. If too much ATP were present in a cell, much of it would go to waste. On the other hand, ADP serves as a positive allosteric regulator (an allosteric activator) for some of the same enzymes that are inhibited by ATP. Thus, when relative levels of ADP are high compared to ATP, the cell is triggered to produce more ATP through the catabolism of sugar.

KEY TERMS

activation energy energy necessary for reactions to occur

active site specific region of the enzyme to which the substrate binds

allosteric inhibition inhibition by a binding event at a site different from the active site, which induces a conformational change and reduces the affinity of the enzyme for its substrate

anabolic (also, anabolism) pathways that require an input of energy to synthesize complex molecules from simpler ones

ATP adenosine triphosphate, the cell's energy currency

bioenergetics study of energy flowing through living systems

catabolic (also, catabolism) pathways in which complex molecules are broken down into simpler ones

chemical energy potential energy in chemical bonds that is released when those bonds are broken

coenzyme small organic molecule, such as a vitamin or its derivative, which is required to enhance the activity of an enzyme

cofactor inorganic ion, such as iron and magnesium ions, required for optimal regulation of enzyme activity

competitive inhibition type of inhibition in which the inhibitor competes with the substrate molecule by binding to the active site of the enzyme

denature process that changes the natural properties of a substance

endergonic describes chemical reactions that require energy input

enthalpy total energy of a system

entropy (S) measure of randomness or disorder within a system

exergonic describes chemical reactions that release free energy

feedback inhibition effect of a product of a reaction sequence to decrease its further production by inhibiting the activity of the first enzyme in the pathway that produces it

free energy Gibbs free energy is the usable energy, or energy that is available to do work.

heat energy energy transferred from one system to another that is not work (energy of the motion of molecules or particles)

heat energy total bond energy of reactants or products in a chemical reaction

induced fit dynamic fit between the enzyme and its substrate, in which both components modify their structures to allow for ideal binding

kinetic energy type of energy associated with objects or particles in motion

metabolism all the chemical reactions that take place inside cells, including anabolism and catabolism

phosphoanhydride bond bond that connects phosphates in an ATP molecule

potential energy type of energy that has the potential to do work; stored energy

substrate molecule on which the enzyme acts

thermodynamics study of energy and energy transfer involving physical matter

transition state high-energy, unstable state (an intermediate form between the substrate and the product) occurring during a chemical reaction

CHAPTER SUMMARY

6.1 Energy and Metabolism

Cells perform the functions of life through various chemical reactions. A cell's metabolism refers to the chemical reactions that take place within it. There are metabolic reactions that involve the breaking down of complex chemicals into simpler ones, such as the breakdown of large macromolecules. This process is referred to as catabolism, and such reactions are associated with a release of energy. On the other end of the spectrum, anabolism refers to metabolic processes that build complex molecules out of simpler ones, such as the synthesis of macromolecules. Anabolic processes require energy. Glucose synthesis and glucose breakdown are examples of anabolic and catabolic pathways, respectively.

6.2 Potential, Kinetic, Free, and Activation Energy

Energy comes in many different forms. Objects in motion do physical work, and kinetic energy is the energy of objects in motion. Objects that are not in motion may have the potential to do work, and thus, have potential energy. Molecules also have potential energy because the breaking of molecular bonds has the potential to release energy. Living cells depend on the harvesting of potential energy from molecular bonds to perform work. Free energy is a measure of energy that is available to do work. The free energy of a system changes during energy transfers such as chemical reactions, and this change is referred to as ΔG.

The ΔG of a reaction can be negative or positive, meaning that the reaction releases energy or consumes energy, respectively. A reaction with a negative ΔG that gives off energy is called an exergonic reaction. One with a positive ΔG that requires energy input is called an endergonic reaction. Exergonic reactions are said to be spontaneous, because their products have less energy than their reactants. The products of endergonic reactions have a higher energy state than the reactants, and so these are nonspontaneous reactions. However, all reactions (including spontaneous $-\Delta G$ reactions) require an initial input of energy in order to reach the transition state, at which they'll proceed. This initial input of energy is called the activation energy.

6.3 The Laws of Thermodynamics

In studying energy, scientists use the term "system" to refer to the matter and its environment involved in energy transfers. Everything outside of the system is called the surroundings. Single cells are biological systems. Systems can be thought of as having a certain amount of order. It takes energy to make a system more ordered. The more ordered a system is, the lower its entropy. Entropy is a measure of the disorder of a system. As a system becomes more disordered, the lower its energy and the higher its entropy become.

A series of laws, called the laws of thermodynamics, describe the properties and processes of energy transfer. The first law states that the total amount of energy in the universe is constant. This means that energy can't be created or destroyed, only transferred or transformed. The second law of thermodynamics states that every energy transfer involves some loss of energy in an unusable form, such as heat energy, resulting in a more disordered system. In other words, no energy transfer is completely efficient and tends toward disorder.

6.4 ATP: Adenosine Triphosphate

ATP is the primary energy-supplying molecule for living cells. ATP is made up of a nucleotide, a five-carbon sugar, and three phosphate groups. The bonds that connect the phosphates (phosphoanhydride bonds) have high-energy content. The energy released from the hydrolysis of ATP into ADP + P_i is used to perform cellular work. Cells use ATP to perform work by coupling the exergonic reaction of ATP hydrolysis with endergonic reactions. ATP donates its phosphate group to another molecule via a process known as phosphorylation. The phosphorylated molecule is at a higher-energy state and is less stable than its unphosphorylated form, and this added energy from the addition of the phosphate allows the molecule to undergo its endergonic reaction.

6.5 Enzymes

Enzymes are chemical catalysts that accelerate chemical reactions at physiological temperatures by lowering their activation energy. Enzymes are usually proteins consisting of one or more polypeptide chains. Enzymes have an active site that provides a unique chemical environment, made up of certain amino acid R groups (residues). This unique environment is perfectly suited to convert particular chemical reactants for that enzyme, called substrates, into unstable intermediates called transition states. Enzymes and substrates are thought to bind with an induced fit, which means that enzymes undergo slight conformational adjustments upon substrate contact, leading to full, optimal binding. Enzymes bind to substrates and catalyze reactions in four different ways: bringing substrates together in an optimal orientation, compromising the bond structures of substrates so that bonds can be more easily broken, providing optimal environmental conditions for a reaction to occur, or participating directly in their chemical reaction by forming transient covalent bonds with the substrates.

Enzyme action must be regulated so that in a given cell at a given time, the desired reactions are being catalyzed and the undesired reactions are not. Enzymes are regulated by cellular conditions, such as temperature and pH. They are also regulated through their location within a cell, sometimes being compartmentalized so that they can only catalyze reactions under certain circumstances. Inhibition and activation of enzymes via other molecules are other important ways that enzymes are regulated. Inhibitors can act competitively, noncompetitively, or allosterically; noncompetitive inhibitors are usually allosteric. Activators can also enhance the function of enzymes allosterically. The most common method by which cells regulate the enzymes in metabolic pathways is through feedback inhibition. During feedback inhibition, the products of a metabolic pathway serve as inhibitors (usually allosteric) of one or more of the enzymes (usually the first committed enzyme of the pathway) involved in the pathway that produces them.

REVIEW QUESTIONS

1. Energy can be taken in as glucose, then has to be converted to a form that can be easily used to perform work in cells. What is the name of the latter molecule?

a. anabolic molecules
b. cholesterol
c. electrolytes
d. adenosine triphosphate

2. When cellular respiration occurs, what is the primary molecule used to store the energy that is released?

a. AMP
b. ATP
c. mRNA
d. phosphate

3. DNA replication involves unwinding two strands of parent DNA, copying each strand to synthesize complementary strands and releasing the resulting two semi-conserved strands of DNA. Which of the following accurately describes this process?

a. This is an anabolic process.
b. This is a catabolic process.
c. This is both an anabolic and a catabolic process.
d. This is a metabolic process, but is neither anabolic nor catabolic.

4. Which of the following is a catabolic process?

a. digestion of sucrose
b. dissolving sugar in water
c. DNA replication
d. RNA translation

5. What food molecule used by animals for energy and obtained from plants is most directly related to the use of sun energy?

a. glucose
b. protein
c. triglycerides
d. tRNA

6. What reaction will release the largest amount of energy to help power another reaction?

a. AMP to ATP
b. ATP to ADP
c. DNA to proteins
d. glucose to starch

7. Consider a pendulum swinging. Which type(s) of energy is/are associated with the pendulum in the following instances:

1. the moment at which it completes one cycle, just before it begins to fall back towards the other end
2. the moment that it is in the middle between the two ends
3. just before it reaches the end of one cycle (before step 1)

a. 1. potential and kinetic
   2. potential and kinetic
   3. kinetic
b. 1. potential
   2. potential and kinetic
   3. potential and kinetic
c. 1. potential
   2. kinetic
   3. potential and kinetic
d. 1. potential and kinetic
   2. kinetic
   3. kinetic

8. Which of the following best describes energy?

a. the transfer of genetic information
b. the ability to assemble a large number of functional catalysts
c. the ability to store solar output
d. the ability to do work

9. What is the ultimate source of energy on this planet?

a. glucose
b. plants
c. metabolic pathways
d. the sun

10. Which of the following molecules is likely to have the most potential energy?

a. ATP
b. ADP
c. glucose
d. sucrose

11. Which of the following is the best way to judge the relative activation energies between two given chemical reactions?

a. Compare the ΔG values between the two reactions.
b. Compare their reaction rates.
c. Compare their ideal environmental conditions.
d. Compare the spontaneity between the two reactions.

12. Which of the terms in the Gibbs free energy equation denotes enthalpy?

a. ΔG

b. ΔH

c. ΔS

d. ΔT

13. Which chemical reaction is more likely to occur?

a. dehydration synthesis

b. endergonic

c. endothermic

d. exergonic

14. Which of the following comparisons or contrasts between endergonic and exergonic reactions is false?

a. Both endergonic and exergonic reactions require a small amount of energy to overcome an activation barrier.

b. Endergonic reactions have a positive ΔG and exergonic reactions have a negative ΔG.

c. Endergonic reactions consume energy and exergonic reactions release energy.

d. Endergonic reactions take place slowly and exergonic reactions take place quickly.

15. Label each of the following systems as high or low entropy:

1. perfume the instant after it is sprayed into the air
2. an unmaintained 1950's car compared with a brand new car
3. a living cell compared with a dead cell

a. 1. low
   2. high
   3. low

b. 1. low
   2. high
   3. high

c. 1. high
   2. low
   3. high

d. 1. high
   2. low
   3. low

16. What counteracts entropy?

a. energy release

b. endergonic reactions

c. input of energy

d. time

17. Which of the following is the best example of the first law of thermodynamics?

a. a body getting warmer after exercise

b. a piece of fruit spoiling in the fridge

c. a power plant burning coal and producing electricity

d. an exothermic chemical reaction

18. What is the difference between the first and second laws of thermodynamics?

a. The first law involves creating energy while the second law involves expending it.
b. The first law involves expending energy while the second involves creating it.
c. The first law involves conserving energy while the second law involves the inability to recapture energy.
d. The first law discusses creating energy while the second law discusses the energy requirement for reactions.

19. Which best describes the effect of inputting energy into a living system?

a. It decreases entropy within the system.
b. It fuels catabolic reactions.
c. It causes enthalpy.
d. The energy is used to produce carbohydrates.

20. Why is ATP considered the energy currency of the cell?

a. It accepts energy from chemical reactions.
b. It holds energy at the site of release from substrates.
c. It is a protein.
d. It can transport energy to locations within the cell.

21. What is ATP made from?

a. adenosine + high energy electrons
b. ADP + pyrophosphate
c. AMP + ADP
d. the conversion of guanine to adenosine

22. What is true about the energy released by the hydrolosis of ATP?

a. It is equal to $-57\ \text{kJ/mol}$.
b. The cell harnesses it as heat energy in order to perform work.
c. It is primarily stored between the alpha and beta phosphates.
d. It provides energy to coupled reactions.

23. What part of ATP is broken to release energy for use in chemical reactions?

a. the adenosine molecule
b. the bond between the first and second phosphates
c. the bond between the first phosphate and the adenosine molecule
d. the bond between the second and third phosphates

24. An allosteric inhibitor does which of the following?

a. binds to an enzyme away from the active site and changes the conformation of the active site, increasing its affinity for substrate binding
b. binds to an active site and blocks it from binding substrate
c. binds to an enzyme away from the active site and changes the conformation of the active site, decreasing its affinity for the substrate
d. binds directly to the active site and mimics the substrate

25. What happens if an enzyme is not functioning in a chemical reaction in a living organism that needs it?

a. The reaction stops.
b. The reaction proceeds, but much more slowly.
c. The reaction proceeds faster without the interference.
d. There is no change in the reaction rate.

26. Which of the following is not true about enzymes?

a. They increase the ΔG of reactions.

b. They are usually made of amino acids.

c. They lower the activation energy of chemical reactions.

d. Each one is specific to the particular substrate, or substrates, to which it binds.

27. Which of the following analogies best describe the induced-fit model of enzyme-substrate binding?

a. a hug between two people

b. a key fitting into a lock

c. A square peg fitting through the square hole and a round peg fitting through the round hole of a children's toy

d. the fitting together of two jigsaw puzzle pieces

28. What is the function of enzymes?

a. to increase the ΔG of reactions

b. to increase the ΔH of reactions

c. to lower the entropy of the chemicals in the reaction

d. to lower the activation energy of a reaction

CRITICAL THINKING QUESTIONS

29. Describe the connection between anabolic and catabolic chemical reactions in a metabolic pathway.

a. Catabolic reactions produce energy and simpler compounds, whereas anabolic reactions involve the use of energy to make more complex compounds.

b. Catabolic reactions produce energy and complex compounds are formed, whereas in anabolic reactions free energy is utilized by complex compounds to make simpler molecules.

c. Catabolic reactions utilize energy and gives simpler compounds, whereas in anabolic reactions reactions, energy is produced and simpler compounds are used to make complex molecules.

d. Catabolic reactions produce energy and water molecules, whereas in anabolic reactions this free energy is utilized by simpler compounds to make only proteins and nucleic acids.

30. Does physical exercise involve anabolic processes, catabolic processes, or both? Give evidence for your answer.

a. "Physical exercise involves both catabolic and anabolic processes. Glucose is broken down into simpler compounds during physical activity. The simpler compounds are then used to provide energy to the muscles for contraction by the anabolic pathway.

b. Physical exercise is just a catabolic process. Glucose is broken down into simpler compounds during physical activity and the simpler compounds are then used to provide energy to the muscles for contraction.

c. Physical activity involves only anabolic processes. Glucose is broken down into simpler compounds during physical activity and the simpler compounds are then used to provide energy to the muscles for contraction by anabolic pathways.

d. Physical exercise involves both anabolic and catabolic processes. Cellulose is broken down into simpler compounds during physical activity. The simpler compounds are then used to provide energy to the muscles for contraction by anabolic pathways.

31. How do chemical reactions play a role in energy transfer?

a. Energy from the breakdown of glucose and other molecules in animals is released as ATP, which transfer energy to other reactions.
b. Energy from the breakdown of glucose and other molecules in animals is released in the form of NADP, which transfers energy to other reactions.
c. Energy is released in the form of glucose from the breakdown of ATP molecules. These ATP molecules transfer energy from one reaction to other.
d. Energy is released in the form of water from the breakdown of glucose. These molecules transfer energy from one reaction to other.

32. Name two different cellular functions that require energy.

a. Phagocytosis helps amoebae take up nutrients and pseudopodia help the amoebae move.
b. Phagocytosis allows amoebae to move and pseudopodia help in the uptake of nutrients.
c. Phagocytosis helps amoebae to take up nutrients and cilia help amoebae move.
d. Phagocytosis helps amoebae in cell division and pseudopodia help amoebae move.

33. Explain the conversion of energy that takes place when the sluice of a dam is opened.

a. Potential energy stored in the water held by the dam will convert to kinetic energy when it falls through the opening of the sluice.
b. Kinetic energy stored in the water held by the dam will convert to potential energy when it falls through the opening of the sluice.
c. Potential energy stored in the water held by the dam will convert to electrical energy, when it falls through the opening of the sluice.
d. Hydrothermal energy stored in the water held by the dam will convert to kinetic energy, when it falls through the opening of the sluice.

34. Explain in your own words the difference between a spontaneous reaction and one that occurs instantaneously.

a. A spontaneous reaction is one which releases free energy and moves to a more stable state. Instantaneous reactions occur rapidly with sudden release of energy.
b. A spontaneous reaction is one which utilizes free energy and moves to a more stable state. Instantaneous reactions occur rapidly with sudden release of energy.
c. A spontaneous reaction is one which releases free energy and moves to a more stable state. Instantaneous reactions occur rapidly within a system by uptake of energy.
d. A spontaneous reaction is one in which the reaction occurs rapidly with sudden release of energy. Instantaneous reaction releases free energy and moves to a more stable state.

35. Describe the position of the transition state on a vertical energy scale, from low to high, relative to the position of the reactants and products, for both endergonic and exergonic reactions.

a. The transition state of the reaction exists at a lower energy level than the reactants. Activation energy is always positive regardless of whether the reaction is exergonic or endergonic.
b. The transition state of the reaction exists at a higher energy level than the reactants. Activation energy is always positive regardless of whether the reaction is exergonic or endergonic.
c. The transition state of the reaction exists at a lower energy level than the reactants. Activation energy is always negative regardless of whether the reaction is exergonic or endergonic.
d. The transition state of the reaction exists at an intermediate energy level than that of the reactants. Activation energy is always positive regardless of whether the reaction is exergonic or endergonic.

36. Imagine an elaborate ant farm with tunnels and passageways through the sand where ants live in a large community. Now imagine that an earthquake shook the ground and demolished the ant farm. In which of these two scenarios, before or after the earthquake, was the ant farm system in a state of higher or lower entropy? Why?

a. The ant farm is in the state of high entropy after the earthquake and energy must be spent to bring the system to low entropy.

b. The ant farm is in the state of lower entropy after the earthquake and energy must be spent to bring the system to high entropy.

c. The ant farm is in the state of higher entropy before the earthquake and energy is given out of the system after the earthquake.

d. The ant farm is in the state of lower entropy before the earthquake and energy is given out of the system after the earthquake.

37. Energy transfers take place constantly in every day activities. Think of two scenarios: cooking on a stove and driving. Explain how the second law of thermodynamics applies to these scenarios.

a. Heat is lost into the room while cooking and into the metal of the engine during gasoline combustion.

b. Heat gained while cooking helps to make the food and heat released due to gasoline combustion helps the car accelerate.

c. The energy given to the system remains constant during cooking and more energy is added to the car engine when the gasoline combusts.

d. The energy given to the system for cooking helps to make food and energy in the car engine remains conserved when gasoline combustion takes place.

38. What does it mean for a system to be in a higher level of entropy? How can it be reduced?

a. Higher level of entropy refers to higher state of disorder in the system and it can be reduced by input of energy to lower the entropy.

b. Higher level of entropy refers to higher state of symmetry in the system and it can be reduced by release of energy to lower the entropy.

c. Higher level of entropy refers to low disorder in the system and it can be reduced by input of energy to increase the entropy.

d. Higher level of entropy refers to higher state of disorder in the system and it can be reduced by providing a catalyst to lower the entropy.

39. When the air temperature drops and rain turns to snow, which law of thermodynamics is exhibited?

a. first law of thermodynamics

b. second law of thermodynamics

c. third law of thermodynamics

d. zeroth law of thermodynamics

40. How does ATP supply energy to chemical reactions?

a. ATP dissociates and the energy released by breaking of a phosphate bond within ATP is used for phosphorylation of another molecule. ATP hydrolysis also provides energy to power coupling reactions.

b. ATP utilizes energy to power exergonic reactions by hydrolysis of ATP molecule. The free energy released as a result of ATP breakdown is used to carry out metabolism of products.

c. ATP utilizes energy to power endergonic reactions by dehydration of ATP molecule. The free energy released as a result of ATP breakdown is used to carry out metabolism of products.

d. ATP utilizes the energy released from the coupling reactions and that energy is used to power the endergonic and exergonic reactions.

41. Is the E_A for ATP hydrolysis relatively low or high? Explain your reasoning.

a. E_A for ATP hydrolysis is high because considerable energy is released.

b. E_A for ATP hydrolysis is high because considerable energy is released.

c. E_A for ATP hydrolysis is intermediate because considerable energy is released.

d. E_A for ATP hydrolysis is high because a low amount of energy is released.

42. What is phosphorylation as it occurs in chemical reactions?

a. Phosphorylation refers to the attachment of a phosphate to another molecule to facilitate a chemical reaction.

b. Phosphorylation is the uptake of a phosphorous molecule by an ATP molecule to power chemical reactions.

c. Phosphorylation is the release of a third phosphorous molecule of ATP during hydrolysis.

d. Phosphorylation is the breakdown of a pyrophosphate molecule which gives phosphate ions.

43. If a chemical reaction could occur without an enzyme, why is it important to have one?

a. Enzymes are important because they give the desired products only from the reaction.

b. Enzymes are important because the products are obtained consistently with time.

c. Enzymes are important because it does not disturb the concentration of the products.

d. Enzymes are important because energy remains conserved and no loss of energy occurs.

44. How does enzyme feedback inhibition benefit a cell?

a. Feedback inhibition benefits the cell by blocking the production of the products by changing the configuration of enzymes. This will prevent the cells from becoming toxic.

b. Feedback inhibition benefits the cell by blocking the production of the reactants by changing the configuration of enzymes. This will prevent the cells from becoming toxic.

c. Feedback inhibition benefits the cell by blocking the production of the products by changing the configuration of reactants. This will prevent the cells from becoming toxic.

d. Feedback inhibition benefits the cell by blocking the production of the products by reducing the reactants. This will prevent the cells from becoming toxic.

45. What type of reaction allows chemicals to be available for an organism's growth and maintenance in a timely manner?

a. enzymatically facilitated reactions

b. redox reactions

c. catabolic reactions

d. hydrolysis of ATP

TEST PREP FOR AP® COURSES

46. Cell metabolism is a complex process that uses many types of chemicals in a variety of processes. Which of the following statements is true?

a. A loss of free nucleotides would result in cancer.

b. A loss of assorted carbohydrates would result in mitosis.

c. A loss of triglycerides would result in cell death.

d. A loss of enzymes would result in cell death.

47. Which pair of descriptors of chemical reactions go together?

a. anabolic and exergonic

b. exergonic and dehydration synthesis

c. endergonic and catabolic

d. hydrolysis and exergonic

48. What is the underlying principle that supports the idea that all living organisms share the same core processes and features?

a. All organisms must harvest energy from their environment and convert it to ATP to carry out cellular functions.
b. Plants produce their own energy and pass it on to animals.
c. Herbivores, carnivores, and omnivores coexist for the survival of all.
d. Glucose is the primary source of energy for all cellular functions.

49. It has been accepted that life on the Earth started out as single celled, simple organisms, which then evolved into complex organisms. How did evolution proceed to produce such a wide variety of living organisms from a simple ancestor?

a. Prokaryotes produced the fungi, then the protists which then branches to plants and animals.
b. Protists evolved first, then the prokaryotes, which branched into the fungi, plants, and animals
c. Prokaryotes produced the protists, which branched into the fungi, plants, and animals.
d. Prokaryotes produced the protists, then the fungi, which branched into the plants and animals.

50. Glucose is the sugar most often used in metabolism by the majority of cells on Earth. It is made and used by plants as well as other organisms. Which of the following describes the chemical breakdown of glucose, and what is the name of the chemical process involved in this breakdown?

a. cellular respiration: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$
b. photosynthesis: $6CO_2 + 6H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$
c. electrolysis: $C_4H_8O_4 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$
d. Krebs cycle: $6CO_2 + 6H_2S + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$

51. Plants make glucose through a pathway called photosynthesis. The amount of energy captured from light can be expressed as the number of energy containing molecules used to make one molecule of glucose. Which of the following best states the number of each molecule needed?

a. 54 molecules of ATP, 18 molecules of nicotinamide adenine dinucleotide phosphate (NADPH)
b. 18 molecules of ATP and 12 molecules of NADPH
c. 24 molecules of ATP and 18 molecules of NADPH
d. 12 molecules of ATP and 18 molecules of NADPH

52. What is an anabolic pathway? Which of these is an example of an anabolic pathway used by cells in their metabolism?

a. Anabolic pathways involve the breakdown of nutrient molecules into usable forms. An example is the harvesting of amino acids from dietary proteins.
b. Anabolic pathways involve the breakdown of nutrient molecules into useable forms. An example is the use of glycogen by the liver to maintain blood glucose levels.
c. Anabolic pathways build new molecules out of the products of catabolic pathways. An example is the separation of fatty acids from triglycerides to satisfy energy needs.
d. Anabolic pathways build new molecules out of the products of catabolic pathways. An example is the linkage of nucleotides to form a molecule of mRNA.

53. If glucose is broken down through aerobic respiration, a number of ATP can be made from the energy extracted. How many ATP are possible?

a. 2 to 4
b. 36 to 38
c. 10 to 12
d. 24 to 30

54. Plants must have adequate resources to complete their functions. If they do not have what they need, there are changes in the organism’s metabolism. What happens to the metabolism of a plant that does not have adequate sunlight?

a. Photosynthesis slows and less glucose is produced for energy use.

b. The plant switches to anaerobic metabolism.

c. The plant goes into a dormant state until the sunlight returns.

d. The plant flowers quickly to reproduce while it can.

55. Water deficiency is arguably the easiest deficiency to detect in plants. This is because plants that are lacking water will wilt, as water within the plant’s cells helps to supports the plant’s weight. Plant cells become water deficient because their cells use the water for metabolic processes. What happens to the metabolism of a plant that does not have adequate water?

a. Photosynthesis is inhibited, less glucose is produced, and water used by the cells is not replaced.

b. The plant increases its breakdown of glucose to create more water at the end of the process.

c. The plant will stop photosynthesizing for long periods of time until it has enough water to do so.

d. The cell will bring in more CO_2, to compensate for the lack of water, allowing glucose synthesis to continue.

56. Enzymes facilitate chemical reactions that result in changes to a substrate. How does the induced fit model of enzymes and substrates explain their function?

a. Both enzyme and substrate undergo dynamic changes, inducing the transitions state of the substrate.

b. The enzyme induces a change in the substrate, but is not changed itself during the reaction.

c. The substrates attach to the enzyme and the chemical reaction proceeds.

d. The enzyme changes shape to fit the substrate causing the transition state to occur.

57. Enzyme inhibitors play an important part in the control of enzyme functions, allowing them to continue, or inhibiting them for a period of time. Which inhibitor affects the initial rate but do not affect the maximal rate?

a. allosteric

b. competitive

c. non-competitive

d. uncompetitive

36 | POPULATION AND COMMUNITY ECOLOGY

Figure 3.1 Asian carp jump out of the water in response to electrofishing. The Asian carp in the inset photograph were harvested from the Little Calumet River in Illinois in May, 2010, using rotenone, a toxin often used as an insecticide, in an effort to learn more about the population of the species. (credit main image: modification of work by USGS; credit inset: modification of work by Lt. David French, USCG)

Chapter Outline

Introduction

Imagine sailing down a river in a small motorboat on a weekend afternoon; the water is smooth and you are enjoying the warm sunshine and cool breeze when suddenly you are hit in the head by a 20-pound silver carp. This is a risk now on many rivers and canal systems in Illinois and Missouri because of the presence of Asian carp.

This fish—actually a group of species including the silver, black, grass, and big head carp—has been farmed and eaten in China for over 1000 years. It is one of the most important aquaculture food resources worldwide. In the United States, however, Asian carp is considered a dangerous invasive species that disrupts community structure and composition to the point of threatening native species.

The Asian carp is now threatening to invade the Great Lakes. You can read more about this invasion **here (http://openstaxcollege.org/l/32asiancarp)** .

36.1 | Population Demography

In this section, you will explore the following questions:

- How do ecologists measure population size and density?
- What are three different patterns of population distribution?
- How can life tables be used to calculate mortality rates?
- What are the three types of survivorship curves and how do they relate to specific populations?

Connection for AP® Courses

By using mathematics, ecologists can study how interactions among living organisms and with their environment affect the distribution, abundance, density, and life strategies of species. A population consists of individuals of the same species living within a specific area. Populations fluctuate based on both biotic and abiotic factors. When studying a population, characteristics of that population are quantified and their change is monitored. This statistical study of these changes, **demography**, investigates how populations respond to these fluctuations. A shift in populations can affect community structure and the ecosystem as a whole.

Information presented and the examples highlighted in the section support concepts outlined in Big Idea 2 and Big Idea 4 of the AP® Biology Curriculum Framework. The AP® Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.D	Growth and dynamic homeostasis of a biological system are influenced by changes in the system's environment.
Essential Knowledge	**2.D.1** All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**2.3** The student is able to predict how changes in free energy availability affect organisms, populations, and ecosystems.
Essential Knowledge	**2.D.1** All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.
Science Practice	**1.3** The student can refine representations and models of natural or man-made phenomena and systems in the domain.
Science Practice	**3.2** The student can refine scientific questions.
Learning Objective	**2.22** The student is able to refine scientific models and questions about the effect of complex biotic and abiotic interactions on all biological systems, from cells and organisms to populations, communities and ecosystems.
Essential Knowledge	**2.D.1** All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.

Science Practice	**4.2** The student can design a plan for collecting data to answer a particular scientific question.
Science Practice	**7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	**2.23** The student is able to design a plan for collecting data to show that all biological systems, including populations, are affected by complex biotic and abiotic interactions.
Essential Knowledge	**2.D.1** All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.
Science Practice	**5.1** The student can analyze data to identify patterns or relationships.
Learning Objective	**2.24** The student is able to analyze data to identify possible patterns and relationships between a biotic or abiotic factors and a biological system, including populations.
Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Science Practice	**4.2** The student can design a plan for collecting data to answer a particular scientific question.
Learning Objective	**4.11** The student is able to justify the selection of the kind of data needed to answer scientific questions about the interaction of populations within communities.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	**4.12** The student is able to apply mathematical routines to quantities that describe communities composed of populations of organisms that interact in complex ways.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.13** The student is able to predict the effects of a change in the community's populations on the community.

In addition, content from this chapter is addressed in the AP Biology Laboratory Manual in the following lab(s):

1 Biodiversity in Leaf Litter

Populations are dynamic entities. Populations consist all of the species living within a specific area, and populations fluctuate based on a number of factors: seasonal and yearly changes in the environment, natural disasters such as forest fires and volcanic eruptions, and competition for resources between and within species. The statistical study of population dynamics, demography, uses a series of mathematical tools to investigate how populations respond to changes in their biotic and abiotic environments. Many of these tools were originally designed to study human populations. For example, **life tables**, which detail the life expectancy of individuals within a population, were initially developed by life insurance companies to set insurance rates. In fact, while the term "demographics" is commonly used when discussing humans, all living populations can be studied using this approach.

Population Size and Density

The study of any population usually begins by determining how many individuals of a particular species exist, and how closely associated they are with each other. Within a particular habitat, a population can be characterized by its **population size (*N*)**, the total number of individuals, and its **population density**, the number of individuals within a specific area or volume. Population size and density are the two main characteristics used to describe and understand populations. For example, populations with more individuals may be more stable than smaller populations based on their genetic variability, and thus their potential to adapt to the environment. Alternatively, a member of a population with low population density (more spread out in the habitat), might have more difficulty finding a mate to reproduce compared to a population of higher density. As is shown in **Figure 3.2**, smaller organisms tend to be more densely distributed than larger organisms.

visual CONNECTION

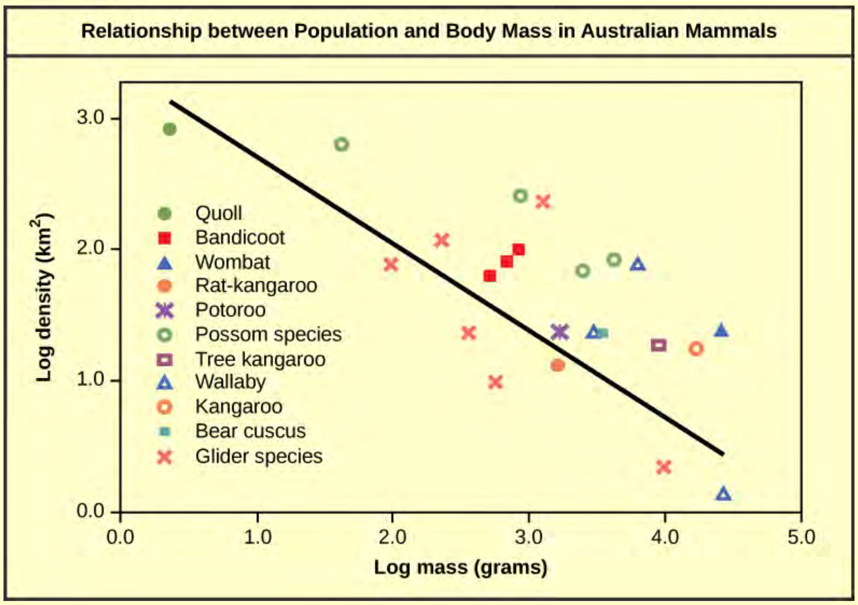


Figure 3.2 Australian mammals show a typical inverse relationship between population density and body size.

Population Research Methods

The most accurate way to determine population size is to simply count all of the individuals within the habitat. However, this method is often not logistically or economically feasible, especially when studying large habitats. Thus, scientists usually study populations by sampling a representative portion of each habitat and using this data to make inferences about the habitat as a whole. A variety of methods can be used to sample populations to determine their size and density. For immobile organisms such as plants, or for very small and slow-moving organisms, a **quadrat** may be used (**Figure 3.3**). A quadrat is a way of marking off square areas within a habitat, either by staking out an area with sticks and string, or by the use of a wood, plastic, or metal square placed on the ground. After setting the quadrats, researchers then count the number of individuals that lie within their boundaries. Multiple quadrat samples are performed throughout the habitat at several random locations. All of this data can then be used to estimate the population size and population density within the entire habitat. The number and size of quadrat samples depends on the type of organisms under study and other factors, including the density of the organism. For example, if sampling daffodils, a 1 m^2 quadrat might be used whereas with giant redwoods, which are larger and live much further apart from each other, a larger quadrat of 100 m^2 might be employed. This ensures that enough individuals of the species are counted to get an accurate sample that correlates with the habitat, including areas not sampled.

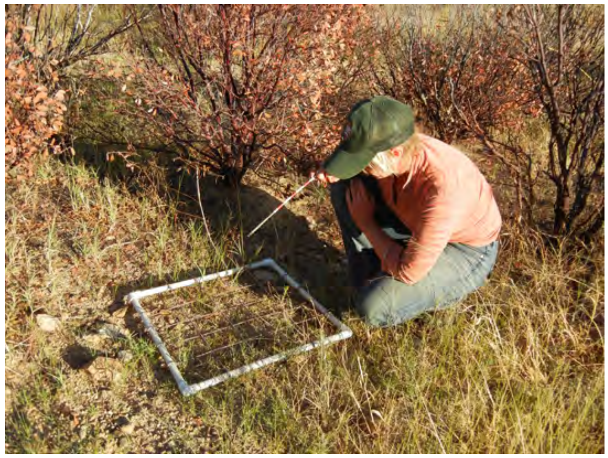
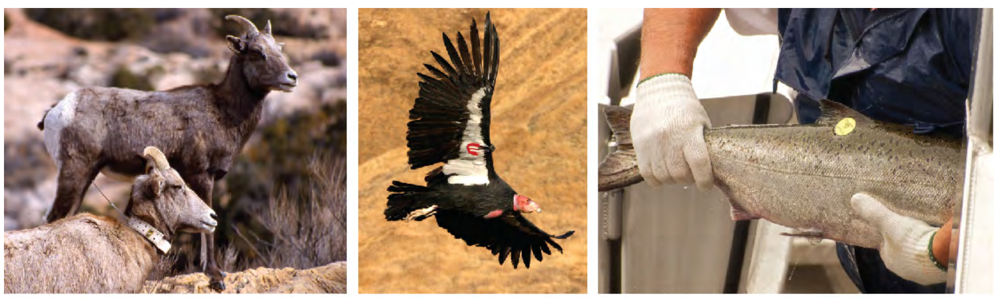


Figure 3.3 A scientist uses a quadrat to measure population size and density. (credit: NPS Sonoran Desert Network)

For mobile organisms, such as mammals, birds, or fish, a technique called **mark and recapture** is often used. This method involves marking a sample of captured animals in some way (such as tags, bands, paint, or other body markings), and then releasing them back into the environment to allow them to mix with the rest of the population; later, a new sample is collected, including some individuals that are marked (recaptures) and some individuals that are unmarked (**Figure 3.4**).



(a) (b) (c)

Figure 3.4 Mark and recapture is used to measure the population size of mobile animals such as (a) bighorn sheep, (b) the California condor, and (c) salmon. (credit a: modification of work by Neal Herbert, NPS; credit b: modification of work by Pacific Southwest Region USFWS; credit c: modification of work by Ingrid Taylar)

Using the ratio of marked and unmarked individuals, scientists determine how many individuals are in the sample. From this, calculations are used to estimate the total population size. This method assumes that the larger the population, the lower the percentage of tagged organisms that will be recaptured since they will have mixed with more untagged individuals. For example, if 80 deer are captured, tagged, and released into the forest, and later 100 deer are captured and 20 of them are already marked, we can determine the population size (N) using the following equation:

$$\frac{\text{(number marked fir t catch x total number of second catch)}}{\text{number marked second catch}} = N$$

Using our example, the population size would be estimated at 400.

$$\frac{(80 \text{ x } 100)}{20} = 400$$

Therefore, there are an estimated 400 total individuals in the original population.

There are some limitations to the mark and recapture method. Some animals from the first catch may learn to avoid capture in the second round, thus inflating population estimates. Alternatively, animals may preferentially be retrapped (especially if a food reward is offered), resulting in an underestimate of population size. Also, some species may be harmed by the marking technique, reducing their survival. A variety of other techniques have been developed, including the electronic tracking of animals tagged with radio transmitters and the use of data from commercial fishing and trapping operations to estimate the size and health of populations and communities.

Species Distribution

In addition to measuring simple density, further information about a population can be obtained by looking at the distribution of the individuals. **Species dispersion patterns** (or distribution patterns) show the spatial relationship between members of a population within a habitat at a particular point in time. In other words, they show whether members of the species live close together or far apart, and what patterns are evident when they are spaced apart.

Individuals in a population can be more or less equally spaced apart, dispersed randomly with no predictable pattern, or clustered in groups. These are known as uniform, random, and clumped dispersion patterns, respectively (**Figure 3.5**). Uniform dispersion is observed in plants that secrete substances inhibiting the growth of nearby individuals (such as the release of toxic chemicals by the sage plant *Salvia leucophylla,* a phenomenon called allelopathy) and in animals like the penguin that maintain a defined territory. An example of random dispersion occurs with dandelion and other plants that have wind-dispersed seeds that germinate wherever they happen to fall in a favorable environment. A clumped dispersion may be seen in plants that drop their seeds straight to the ground, such as oak trees, or animals that live in groups (schools of fish or herds of elephants). Clumped dispersions may also be a function of habitat heterogeneity. Thus, the dispersion of the individuals within a population provides more information about how they interact with each other than does a simple density measurement. Just as lower density species might have more difficulty finding a mate, solitary species with a random distribution might have a similar difficulty when compared to social species clumped together in groups.

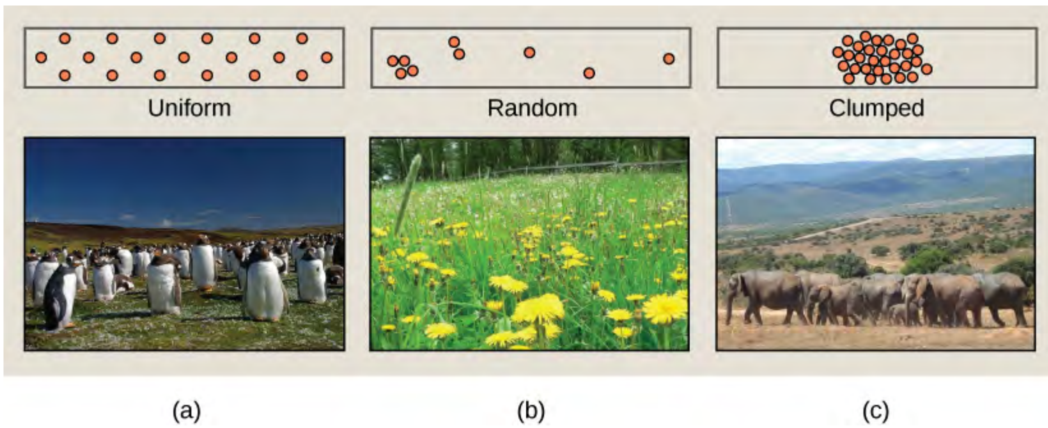


Figure 3.5 Species may have uniform, random, or clumped distribution. Territorial birds such as penguins tend to have uniform distribution. Plants such as dandelions with wind-dispersed seeds tend to be randomly distributed. Animals such as elephants that travel in groups exhibit clumped distribution. (credit a: modification of work by Ben Tubby; credit b: modification of work by Rosendahl; credit c: modification of work by Rebecca Wood)

Demography

While population size and density describe a population at one particular point in time, scientists must use demography to study the dynamics of a population. Demography is the statistical study of population changes over time: birth rates, death rates, and life expectancies. Each of these measures, especially birth rates, may be affected by the population characteristics described above. For example, a large population size results in a higher birth rate because more potentially reproductive individuals are present. In contrast, a large population size can also result in a higher death rate because of competition, disease, and the accumulation of waste. Similarly, a higher population density or a clumped dispersion pattern results in more potential reproductive encounters between individuals, which can increase birth rate. Lastly, a female-biased sex ratio (the ratio of males to females) or age structure (the proportion of population members at specific age ranges) composed of many individuals of reproductive age can increase birth rates.

In addition, the demographic characteristics of a population can influence how the population grows or declines over time. If birth and death rates are equal, the population remains stable. However, the population size will increase if birth rates exceed death rates; the population will decrease if birth rates are less than death rates. Life expectancy is another important factor; the length of time individuals remain in the population impacts local resources, reproduction, and the overall health of the population. These demographic characteristics are often displayed in the form of a life table.

Life Tables

Life tables provide important information about the life history of an organism. Life tables divide the population into age groups and often sexes, and show how long a member of that group is likely to live. They are modeled after actuarial tables used by the insurance industry for estimating human life expectancy. Life tables may include the probability of individuals dying before their next birthday (i.e., their **mortality rate**), the percentage of surviving individuals dying at a particular age interval, and their life expectancy at each interval. An example of a life table is shown in **Table 3.1** from a study of Dall mountain sheep, a species native to northwestern North America. Notice that the population is divided into age intervals (column A). The mortality rate (per 1000), shown in column D, is based on the number of individuals dying during the age interval (column B) divided by the number of individuals surviving at the beginning of the interval (Column C), multiplied by 1000.

$$\text{mortality rate} = \frac{\text{number of individuals dying}}{\text{number of individuals surviving}} \text{ x } 1000$$

For example, between ages three and four, 12 individuals die out of the 776 that were remaining from the original 1000 sheep. This number is then multiplied by 1000 to get the mortality rate per thousand.

$$\text{mortality rate} = \frac{12}{776} \text{ x } 1000 \approx 15.5$$

As can be seen from the mortality rate data (column D), a high death rate occurred when the sheep were between 6 and 12 months old, and then increased even more from 8 to 12 years old, after which there were few survivors. The data indicate that if a sheep in this population were to survive to age one, it could be expected to live another 7.7 years on average, as shown by the life expectancy numbers in column E.

Life Table of Dall Mountain Sheep[1]

Age interval (years)	Number dying in age interval out of 1000 born	Number surviving at beginning of age interval out of 1000 born	Mortality rate per 1000 alive at beginning of age interval	Life expectancy or mean lifetime remaining to those attaining age interval
0-0.5	54	1000	54.0	7.06
0.5-1	145	946	153.3	--
1-2	12	801	15.0	7.7
2-3	13	789	16.5	6.8
3-4	12	776	15.5	5.9
4-5	30	764	39.3	5.0
5-6	46	734	62.7	4.2
6-7	48	688	69.8	3.4
7-8	69	640	107.8	2.6
8-9	132	571	231.2	1.9
9-10	187	439	426.0	1.3
10-11	156	252	619.0	0.9
11-12	90	96	937.5	0.6
12-13	3	6	500.0	1.2
13-14	3	3	1000	0.7

Table 3.1 This life table of *Ovis dalli* shows the number of deaths, number of survivors, mortality rate, and life expectancy at each age interval for the Dall mountain sheep.

Survivorship Curves

Another tool used by population ecologists is a **survivorship curve**, which is a graph of the number of individuals surviving at each age interval plotted versus time (usually with data compiled from a life table). These curves allow us to compare the life histories of different populations (Figure 3.6). Humans and most primates exhibit a Type I survivorship curve because a high percentage of offspring survive their early and middle years—death occurs predominantly in older individuals. These types of species usually have small numbers of offspring at one time, and they give a high amount of parental care to them to ensure their survival. Birds are an example of an intermediate or Type II survivorship curve because birds die more or

1. Data Adapted from Edward S. Deevey, Jr., “Life Tables for Natural Populations of Animals,” *The Quarterly Review of Biology* 22, no. 4 (December 1947): 283-314.

less equally at each age interval. These organisms also may have relatively few offspring and provide significant parental care. Trees, marine invertebrates, and most fishes exhibit a Type III survivorship curve because very few of these organisms survive their younger years; however, those that make it to an old age are more likely to survive for a relatively long period of time. Organisms in this category usually have a very large number of offspring, but once they are born, little parental care is provided. Thus these offspring are "on their own" and vulnerable to predation, but their sheer numbers assure the survival of enough individuals to perpetuate the species.

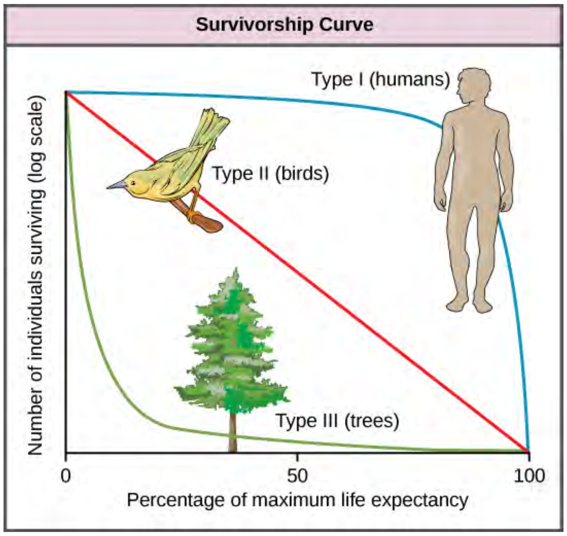


Figure 3.6 Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have a Type III survivorship curve because very few survive the younger years, but after a certain age, individuals are much more likely to survive.

science practices CONNECTION for AP® Courses

Activity

Design an investigation that a researcher might use to determine the size of a penguin population in the Antarctic using the mark and release method. What biotic or abiotic factors might influence the size of the penguin population in a given area?

36.2 | Life Histories and Natural Selection

In this section, you will explore the following questions:

- How are life history patterns influenced by natural selection?
- What are different life history patterns, and how do different reproductive strategies affect species survival?

Connection for AP® Courses

All living systems, including populations, require free energy to maintain order, to grow and to reproduce. As we learned in earlier chapters, changes in free energy availability can cause fluctuations in population. All species have an **energy budget** and must balance energy intake with their use of energy for metabolism, parental care, and energy storage.

It's amazing how much free energy is required for reproduction and the subsequent care of offspring. Fecundity describes how many offspring could be produced if an individual has as many offspring as possible. In animals, fecundity is inversely proportional to the amount of care given to an individual offspring.

Information presented and the examples highlighted in the section support concepts outlined in Big Idea 1 and Big Idea 2 of the AP® Biology Curriculum Framework. The AP® Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 1	The process of evolution drives the diversity and unity of life.
Enduring Understanding 1.A	Change in the genetic makeup of a population over time is evolution.
Essential Knowledge	**1.A.2** Natural selection acts on phenotypic variations in populations.
Science Practice	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena.
Science Practice	**5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question.
Learning Objective	**1.2** The student is able to evaluate evidence provided by data to qualitatively and quantitatively investigate the role of natural selection in evolution.
Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.A	Growth, reproduction and maintenance of living systems require free energy and matter.
Essential Knowledge	**2.A.1** All living systems require constant input of free energy.
Science Practice	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	**2.1** The student is able to explain how biological systems use free energy based on empirical data that all organisms require constant energy input to maintain organization, to grow and to reproduce.

A species' **life history** describes the series of events over its lifetime, such as how resources are allocated for growth, maintenance, and reproduction. Life history traits affect the life table of an organism. A species' life history is genetically determined and shaped by the environment and natural selection.

Life History Patterns and Energy Budgets

Energy is required by all living organisms for their growth, maintenance, and reproduction; at the same time, energy is often a major limiting factor in determining an organism's survival. Plants, for example, acquire energy from the sun via photosynthesis, but must expend this energy to grow, maintain health, and produce energy-rich seeds to produce the next generation. Animals have the additional burden of using some of their energy reserves to acquire food. Furthermore, some animals must expend energy caring for their offspring. Thus, all species have an energy budget: they must balance energy intake with their use of energy for metabolism, reproduction, parental care, and energy storage (such as bears building up body fat for winter hibernation).

Parental Care and Fecundity

Fecundity is the potential reproductive capacity of an individual within a population. In other words, fecundity describes how many offspring could ideally be produced if an individual has as many offspring as possible, repeating the reproductive cycle as soon as possible after the birth of the offspring. In animals, fecundity is inversely related to the amount of parental care given to an individual offspring. Species, such as many marine invertebrates, that produce many offspring usually provide little if any care for the offspring (they would not have the energy or the ability to do so anyway). Most of their energy budget is used to produce many tiny offspring. Animals with this strategy are often self-sufficient at a very early age. This is because of the energy tradeoff these organisms have made to maximize their evolutionary fitness. Because their energy is used for producing offspring instead of parental care, it makes sense that these offspring have some ability to be able to move within their environment and find food and perhaps shelter. Even with these abilities, their small size makes them extremely vulnerable to predation, so the production of many offspring allows enough of them to survive to maintain the species.

Animal species that have few offspring during a reproductive event usually give extensive parental care, devoting much of their energy budget to these activities, sometimes at the expense of their own health. This is the case with many mammals, such as humans, kangaroos, and pandas. The offspring of these species are relatively helpless at birth and need to develop before they achieve self-sufficiency.

Plants with low fecundity produce few energy-rich seeds (such as coconuts and chestnuts) with each having a good chance to germinate into a new organism; plants with high fecundity usually have many small, energy-poor seeds (like orchids) that have a relatively poor chance of surviving. Although it may seem that coconuts and chestnuts have a better chance of surviving, the energy tradeoff of the orchid is also very effective. It is a matter of where the energy is used, for large numbers of seeds or for fewer seeds with more energy.

Early versus Late Reproduction

The timing of reproduction in a life history also affects species survival. Organisms that reproduce at an early age have a greater chance of producing offspring, but this is usually at the expense of their growth and the maintenance of their health. Conversely, organisms that start reproducing later in life often have greater fecundity or are better able to provide parental care, but they risk that they will not survive to reproductive age. Examples of this can be seen in fishes. Small fish like guppies use their energy to reproduce rapidly, but never attain the size that would give them defense against some predators. Larger fish, like the bluegill or shark, use their energy to attain a large size, but do so with the risk that they will die before they can reproduce or at least reproduce to their maximum. These different energy strategies and tradeoffs are key to understanding the evolution of each species as it maximizes its fitness and fills its niche. In terms of energy budgeting, some species "blow it all" and use up most of their energy reserves to reproduce early before they die. Other species delay having reproduction to become stronger, more experienced individuals and to make sure that they are strong enough to provide parental care if necessary.

Single versus Multiple Reproductive Events

Some life history traits, such as fecundity, timing of reproduction, and parental care, can be grouped together into general strategies that are used by multiple species. **Semelparity** occurs when a species reproduces only once during its lifetime and then dies. Such species use most of their resource budget during a single reproductive event, sacrificing their health to the point that they do not survive. Examples of semelparity are bamboo, which flowers once and then dies, and the Chinook salmon (**Figure 3.7a**), which uses most of its energy reserves to migrate from the ocean to its freshwater nesting area, where it reproduces and then dies. Scientists have posited alternate explanations for the evolutionary advantage of the Chinook's post-reproduction death: a programmed suicide caused by a massive release of corticosteroid hormones, presumably so the parents can become food for the offspring, or simple exhaustion caused by the energy demands of reproduction; these are still being debated.

Iteroparity describes species that reproduce repeatedly during their lives. Some animals are able to mate only once per year, but survive multiple mating seasons. The pronghorn antelope is an example of an animal that goes into a seasonal estrus cycle ("heat"): a hormonally induced physiological condition preparing the body for successful mating (**Figure 3.7b**). Females of these species mate only during the estrus phase of the cycle. A different pattern is observed in primates, including humans and chimpanzees, which may attempt reproduction at any time during their reproductive years, even though their menstrual cycles make pregnancy likely only a few days per month during ovulation (**Figure 3.7c**).

(a) (b) (c)

Figure 3.7 The (a) Chinook salmon mates once and dies. The (b) pronghorn antelope mates during specific times of the year during its reproductive life. Primates, such as humans and (c) chimpanzees, may mate on any day, independent of ovulation. (credit a: modification of work by Roger Tabor, USFWS; credit b: modification of work by Mark Gocke, USDA; credit c: modification of work by "Shiny Things"/Flickr)

LINK TO LEARNING

Play this **interactive PBS evolution-based mating game (http://openstaxcollege.org/l/mating_game)** to learn more about reproductive strategies.

Explain why it is possible to make good guesses about the best mate selections in this game.

a. Organisms have reproductive strategies that are fairly easy to predict once the type of organism and the type of habitat they live in is known.

b. Organisms have nutritional strategies that are fairly easy to predict once the type of organism and the type of habitat they live in is known.

c. Organisms have reproductive strategies that are fairly easy to predict once the nutritional requirements and the type of habitat they live in is known.

d. Organisms have nutritional strategies that are fairly easy to predict once the nutritional requirements and the type of habitat they live in is known.

evolution CONNECTION

Energy Budgets, Reproductive Costs, and Sexual Selection in *Drosophila*

Research into how animals allocate their energy resources for growth, maintenance, and reproduction has used a variety of experimental animal models. Some of this work has been done using the common fruit fly, *Drosophila melanogaster*. Studies have shown that not only does reproduction have a cost as far as how long male fruit flies live, but also fruit flies that have already mated several times have limited sperm remaining for reproduction. Fruit flies maximize their last chances at reproduction by selecting optimal mates.

In a 1981 study, male fruit flies were placed in enclosures with either virgin or inseminated females. The males that mated with virgin females had shorter life spans than those in contact with the same number of inseminated females with which they were unable to mate. This effect occurred regardless of how large (indicative of their age) the males were. Thus, males that did not mate lived longer, allowing them more opportunities to find mates in the future.

More recent studies, performed in 2006, show how males select the female with which they will mate and how this is affected by previous matings (**Figure 3.8**).[2] Males were allowed to select between smaller and larger females. Findings showed that larger females had greater fecundity, producing twice as many offspring per mating as the smaller females did. Males that had previously mated, and thus had lower supplies of sperm, were termed “resource-depleted,” while males that had not mated were termed “non-resource-depleted.” The study showed that although non-resource-depleted males preferentially mated with larger females, this selection of partners was more pronounced in the resource-depleted males. Thus, males with depleted sperm supplies, which were limited in the number of times that they could mate before they replenished their sperm supply, selected larger, more fecund females, thus maximizing their chances for offspring. This study was one of the first to show that the physiological state of the male affected its mating behavior in a way that clearly maximizes its use of limited reproductive resources.

	Ratio large/small females mated
Non sperm-depleted	8 ± 5
Sperm-depleted	15 ± 5

Figure 3.8 Male fruit flies that had previously mated (sperm-depleted) picked larger, more fecund females more often than those that had not mated (non-sperm-depleted). This change in behavior causes an increase in the efficiency of a limited reproductive resource: sperm.

These studies demonstrate two ways in which the energy budget is a factor in reproduction. First, energy expended on mating may reduce an animal’s lifespan, but by this time they have already reproduced, so in the context of natural selection this early death is not of much evolutionary importance. Second, when resources such as sperm (and the energy needed to replenish it) are low, an organism’s behavior can change to give them the best chance of passing their genes on to the next generation. These changes in behavior, so important to evolution, are studied in a discipline known as behavioral biology, or ethology, at the interface between population biology and psychology.

Discuss how natural selection might influence the phenomenon revealed by this study.

a. Sperm-depleted males were successful in producing offspring when mated with small females. So, the genes that influenced the behavior of sperm-depleted males to choose larger, more fecund females were selected.

b. Sperm-depleted males were successful in producing offspring when mated with large females. So, the genes that influenced the behavior of sperm-depleted males to choose smaller, more fecund females were selected.

c. Sperm-depleted males were successful in producing offspring when mated with large females. So, the genes that influenced the behavior of sperm-depleted males to choose larger, more fecund females were selected.

d. Sperm-depleted males were successful in producing offspring when mated with smaller females. So, the genes that influenced the behavior of sperm-depleted males to choose smaller, less fecund females were selected.

science practices CONNECTION for AP® Courses

Think About It

Why is long-term parental care not associated with having many offspring during a reproductive episode?

36.3 | Environmental Limits to Population Growth

In this section, you will explore the following questions:

- What are the characteristics of and differences between exponential and logistic growth patterns?
- What are examples of exponential and logistic growth in natural populations?

Connection for AP® Courses

Population ecologists use mathematical methods to model population dynamics. These models can be used to describe changes occurring in a population and to better predict future changes. Applying mathematics to these models (and being able to manipulate the equations) is in scope for AP®. (Remember that for the AP® Exam you will have access to a formula sheet with these equations.)

Information presented and the examples highlighted in the section support concepts outlined in Big Idea 4 of the AP® Biology Curriculum Framework. The AP® Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	**4.12** The student is able to apply mathematical routines to quantities that describe communities composed of populations of organisms that interact in complex ways.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.

2. Adapted from Phillip G. Byrne and William R. Rice, “Evidence for adaptive male mate choice in the fruit fly *Drosophila melanogaster*,” Proc Biol Sci. 273, no. 1589 (2006): 917-922, doi: 10.1098/rspb.2005.3372.

Learning Objective	**4.13** The student is able to predict the effects of a change in the community's populations on the community.

Although life histories describe the way many characteristics of a population (such as their age structure) change over time in a general way, population ecologists make use of a variety of methods to model population dynamics mathematically. These more precise models can then be used to accurately describe changes occurring in a population and better predict future changes. Certain models that have been accepted for decades are now being modified or even abandoned due to their lack of predictive ability, and scholars strive to create effective new models.

Exponential Growth

Charles Darwin, in his theory of natural selection, was greatly influenced by the English clergyman Thomas Malthus. Malthus published a book in 1798 stating that populations with unlimited natural resources grow very rapidly, and then population growth decreases as resources become depleted. This accelerating pattern of increasing population size is called **exponential growth**.

The best example of exponential growth is seen in bacteria. Bacteria are prokaryotes that reproduce by prokaryotic fission. This division takes about an hour for many bacterial species. If 1000 bacteria are placed in a large flask with an unlimited supply of nutrients (so the nutrients will not become depleted), after an hour, there is one round of division and each organism divides, resulting in 2000 organisms—an increase of 1000. In another hour, each of the 2000 organisms will double, producing 4000, an increase of 2000 organisms. After the third hour, there should be 8000 bacteria in the flask, an increase of 4000 organisms. The important concept of exponential growth is that the **population growth rate**—the number of organisms added in each reproductive generation—is accelerating; that is, it is increasing at a greater and greater rate. After 1 day and 24 of these cycles, the population would have increased from 1000 to more than 16 billion. When the population size, *N*, is plotted over time, a **J-shaped growth curve** is produced (**Figure 3.9**).

The bacteria example is not representative of the real world where resources are limited. Furthermore, some bacteria will die during the experiment and thus not reproduce, lowering the growth rate. Therefore, when calculating the growth rate of a population, the **death rate (*D*)** (number organisms that die during a particular time interval) is subtracted from the **birth rate (*B*)** (number organisms that are born during that interval). This is shown in the following formula:

$$\frac{\Delta N \text{ (change in number)}}{\Delta T \text{ (change in time)}} = B \text{ (birth rate) - } D \text{ (death rate)}$$

The birth rate is usually expressed on a per capita (for each individual) basis. Thus, *B* (birth rate) = *bN* (the per capita birth rate "*b*" multiplied by the number of individuals "*N*") and *D* (death rate) =*dN* (the per capita death rate "d" multiplied by the number of individuals "*N*"). Additionally, ecologists are interested in the population at a particular point in time, an infinitely small time interval. For this reason, the terminology of differential calculus is used to obtain the "instantaneous" growth rate, replacing the *change* in number and time with an instant-specific measurement of number and time.

$$\frac{dN}{dT} = bN - dN = (b - d)N$$

Notice that the "*d*" associated with the first term refers to the derivative (as the term is used in calculus) and is different from the death rate, also called "*d*." The difference between birth and death rates is further simplified by substituting the term "*r*" (intrinsic rate of increase) for the relationship between birth and death rates:

$$\frac{dN}{dT} = rN$$

The value "*r*" can be positive, meaning the population is increasing in size; or negative, meaning the population is decreasing in size; or zero, where the population's size is unchanging, a condition known as **zero population growth**. A further refinement of the formula recognizes that different species have inherent differences in their intrinsic rate of increase (often thought of as the potential for reproduction), even under ideal conditions. Obviously, a bacterium can reproduce more rapidly and have a higher intrinsic rate of growth than a human. The maximal growth rate for a species is its **biotic potential, or r_{max}**, thus changing the equation to:

$$\frac{dN}{dT} = r_{\max} N$$

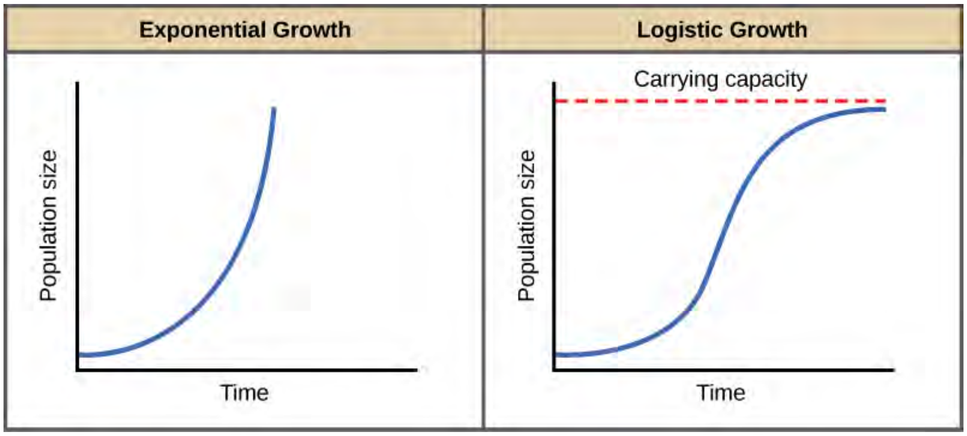


Figure 3.9 When resources are unlimited, populations exhibit exponential growth, resulting in a J-shaped curve. When resources are limited, populations exhibit logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity of the environment is reached, resulting in an S-shaped curve.

Logistic Growth

Exponential growth is possible only when infinite natural resources are available; this is not the case in the real world. Charles Darwin recognized this fact in his description of the "struggle for existence," which states that individuals will compete (with members of their own or other species) for limited resources. The successful ones will survive to pass on their own characteristics and traits (which we know now are transferred by genes) to the next generation at a greater rate (natural selection). To model the reality of limited resources, population ecologists developed the **logistic growth** model.

Carrying Capacity and the Logistic Model

In the real world, with its limited resources, exponential growth cannot continue indefinitely. Exponential growth may occur in environments where there are few individuals and plentiful resources, but when the number of individuals gets large enough, resources will be depleted, slowing the growth rate. Eventually, the growth rate will plateau or level off (**Figure 3.9**). This population size, which represents the maximum population size that a particular environment can support, is called the **carrying capacity, or *K***.

The formula we use to calculate logistic growth adds the carrying capacity as a moderating force in the growth rate. The expression "*K* – *N*" is indicative of how many individuals may be added to a population at a given stage, and "*K* – *N*" divided by "*K*" is the fraction of the carrying capacity available for further growth. Thus, the exponential growth model is restricted by this factor to generate the logistic growth equation:

$$\frac{dN}{dT} = r_{\max}\frac{dN}{dT} = r_{\max}N\frac{(K - N)}{K}$$

Notice that when N is very small, $(K\text{-}N)/K$ becomes close to K/K or 1, and the right side of the equation reduces to $r_{max}N$, which means the population is growing exponentially and is not influenced by carrying capacity. On the other hand, when N is large, $(K\text{-}N)/K$ come close to zero, which means that population growth will be slowed greatly or even stopped. Thus, population growth is greatly slowed in large populations by the carrying capacity K. This model also allows for the population of a negative population growth, or a population decline. This occurs when the number of individuals in the population exceeds the carrying capacity (because the value of (K-N)/K is negative).

A graph of this equation yields an **S-shaped curve** (**Figure 3.9**), and it is a more realistic model of population growth than exponential growth. There are three different sections to an S-shaped curve. Initially, growth is exponential because there are few individuals and ample resources available. Then, as resources begin to become limited, the growth rate decreases. Finally, growth levels off at the carrying capacity of the environment, with little change in population size over time.

Role of Intraspecific Competition

The logistic model assumes that every individual within a population will have equal access to resources and, thus, an equal chance for survival. For plants, the amount of water, sunlight, nutrients, and the space to grow are the important resources, whereas in animals, important resources include food, water, shelter, nesting space, and mates.

In the real world, phenotypic variation among individuals within a population means that some individuals will be better adapted to their environment than others. The resulting competition between population members of the same species for resources is termed **intraspecific competition** (intra- = "within"; -specific = "species"). Intraspecific competition for resources may not affect populations that are well below their carrying capacity—resources are plentiful and all individuals can obtain what they need. However, as population size increases, this competition intensifies. In addition, the accumulation of waste products can reduce an environment's carrying capacity.

Examples of Logistic Growth

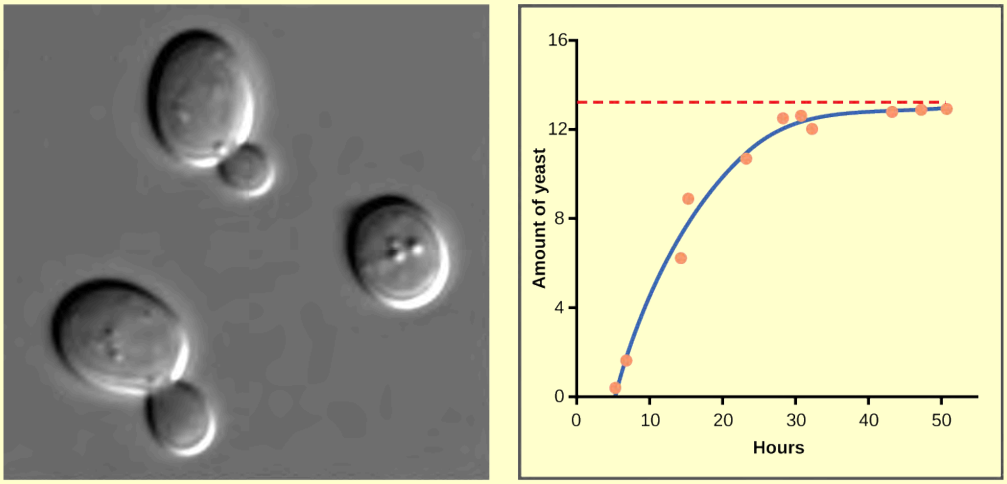
Yeast, a microscopic fungus used to make bread, exhibits the classical S-shaped curve when grown in a test tube (**Figure 3.10a**). Its growth levels off as the population depletes the nutrients that are necessary for its growth. In the real world, however, there are variations to this idealized curve. Examples in wild populations include sheep and harbor seals (**Figure 3.10b**). In both examples, the population size exceeds the carrying capacity for short periods of time and then falls below the carrying capacity afterwards. This fluctuation in population size continues to occur as the population oscillates around its carrying capacity. Still, even with this oscillation, the logistic model is confirmed.

science practices CONNECTION for AP® Courses

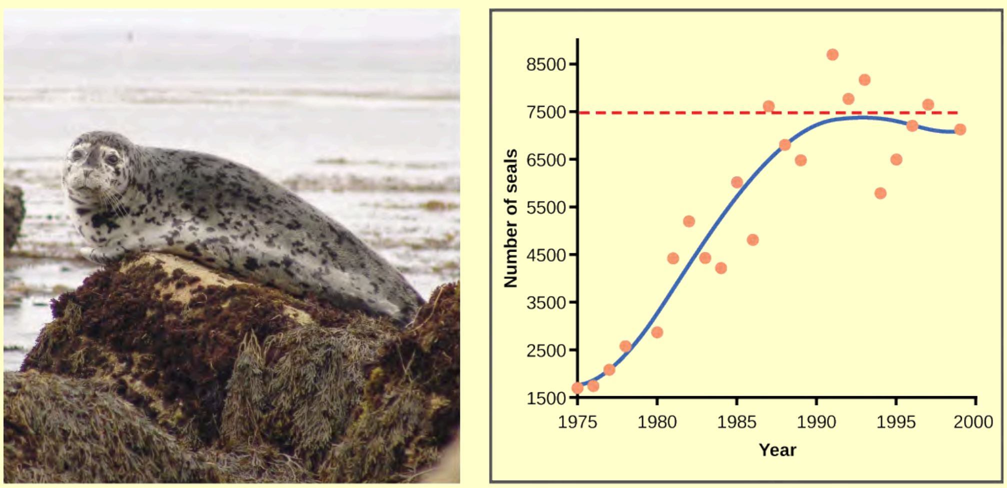
Think About It

Describe the rate of population growth that would be expected at various parts of the S-shaped curve of logistic growth.

visual CONNECTION

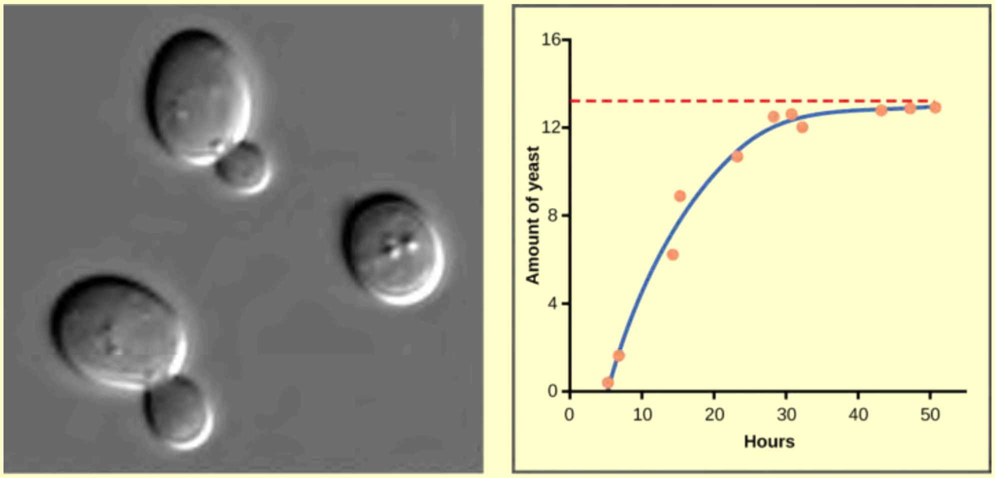


(a)

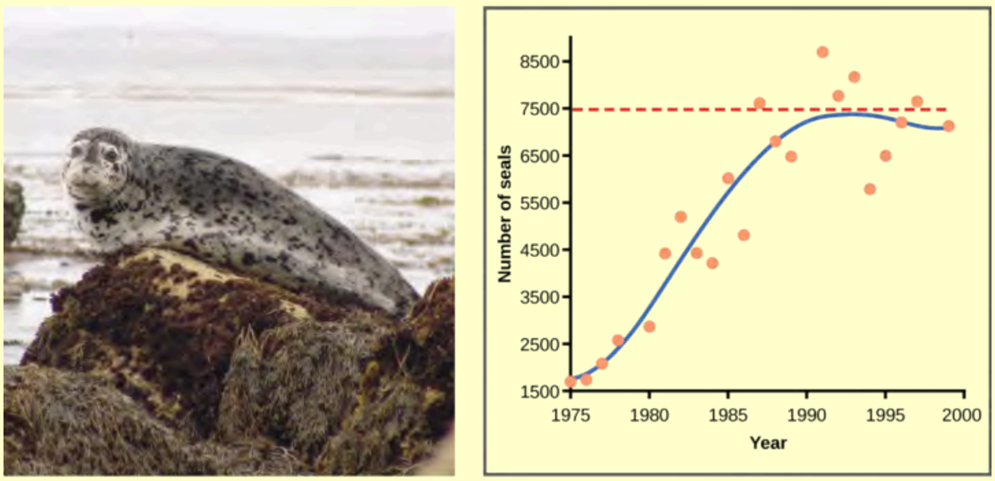


(b)

Figure 3.10 (a) Yeast grown in ideal conditions in a test tube show a classical S-shaped logistic growth curve, whereas (b) a natural population of seals shows real-world fluctuation.



(a)



(b)

Explain the underlying reasons for the differences in the two curves shown in these examples.

a. Yeast is grown under ideal conditions, so the curve reflects limitations of resources in the controlled environment. Seals live in a natural habitat where the same types of resources are limited; but, they face other pressures like migration and changing weather.

b. Yeast is grown under natural conditions, so the curve reflects limitations of resources due to the environment. Seals were also observed in natural conditions; but, there were more pressures in addition to the limitation of resources like migration and changing weather.

c. Yeast is grown under ideal conditions, so the curve reflects limitations of resources in the uncontrolled environment. Seals live in a natural environment where same types of resources are limited; but they face other pressures like migration and changing weather.

d. Yeast is grown under ideal conditions, so the curve reflects limitations of resources in the controlled environment. Seals live in a natural environment where the same types of resources are limited; but, they face another pressure of migration of seals out of the population.

36.4 | Population Dynamics and Regulation

In this section, you will investigate the following questions:

- How can the carrying capacity of a habitat change?
- What are the similarities and differences between density-dependent growth regulation and density-independent growth regulation, and what are some examples of both?
- How do natural selection and environmental adaptation lead to the evolution of particular life-history patterns?

Connection for AP® Courses

While looking at the logistic model is very useful when studying population dynamics, additional methods are used when considering more complex situations, such as changes in the carrying capacity of the environment. Abiotic and biotic factors can affect the growth and death rates of a population, so these fluctuations also require consideration when modeling a population's change over time. Sometimes, scientists need to consider how reproductive strategies play a part into the dynamics of a population over time. To consider how these different factors interact, populations are looked at from a variety of perspectives.

Information presented and the examples highlighted in the section support concepts outlined in Big Idea 4 of the AP® Biology Curriculum Framework. The AP® Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Science Practice	**4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question.
Learning Objective	**4.11** The student is able to justify the selection of the kind of data needed to answer scientific questions about the interactions of populations within communities.

The logistic model of population growth, while valid in many natural populations and a useful model, is a simplification of real-world population dynamics. Implicit in the model is that the carrying capacity of the environment does not change, which is not the case. The carrying capacity varies annually: for example, some summers are hot and dry whereas others are cold and wet. In many areas, the carrying capacity during the winter is much lower than it is during the summer. Also, natural events such as earthquakes, volcanoes, and fires can alter an environment and hence its carrying capacity. Additionally, populations do not usually exist in isolation. They engage in **interspecific competition**: that is, they share the environment with other species, competing with them for the same resources. These factors are also important to understanding how a specific population will grow.

Nature regulates population growth in a variety of ways. These are grouped into **density-dependent** factors, in which the density of the population at a given time affects growth rate and mortality, and **density-independent** factors, which influence mortality in a population regardless of population density. Note that in the former, the effect of the factor on the population depends on the density of the population at onset. Conservation biologists want to understand both types because this helps them manage populations and prevent extinction or overpopulation.

Density-dependent Regulation

Most density-dependent factors are biological in nature (biotic), and include predation, inter- and intraspecific competition, accumulation of waste, and diseases such as those caused by parasites. Usually, the denser a population is, the greater its mortality rate. For example, during intra- and interspecific competition, the reproductive rates of the individuals will usually be lower, reducing their population's rate of growth. In addition, low prey density increases the mortality of its predator because it has more difficulty locating its food source.

An example of density-dependent regulation is shown in **Figure 3.11** with results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite of humans and other mammals.[3] Denser populations of the parasite exhibited lower fecundity: they contained fewer eggs. One possible explanation for this is that females would be smaller in more dense populations (due to limited resources) and that smaller females would have fewer eggs. This hypothesis was tested and disproved in a 2009 study which showed that female weight had no influence.[4] The actual cause of the density-dependence of fecundity in this organism is still unclear and awaiting further investigation.

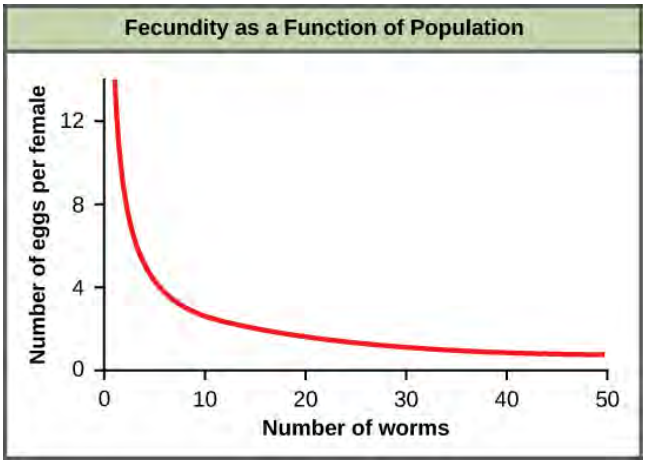


Figure 3.11 In this population of roundworms, fecundity (number of eggs) decreases with population density.[5]

3. N.A. Croll et al., "The Population Biology and Control of *Ascaris lumbricoides* in a Rural Community in Iran." *Transactions of the Royal Society of Tropical Medicine and Hygiene* 76, no. 2 (1982): 187-197, doi:10.1016/0035-9203(82)90272-3.
4. Martin Walker et al., "Density-Dependent Effects on the Weight of Female *Ascaris lumbricoides* Infections of Humans and its Impact on Patterns of Egg Production." *Parasites & Vectors* 2, no. 11 (February 2009), doi:10.1186/1756-3305-2-11.
5. N.A. Croll et al., "The Population Biology and Control of *Ascaris lumbricoides* in a Rural Community in Iran." *Transactions of the Royal Society of Tropical Medicine and Hygiene* 76, no. 2 (1982): 187-197, doi:10.1016/0035-9203(82)90272-3.

everyday CONNECTION for AP® Courses

One of the consequences of an overly dense population is the spread of disease. The brown bat pictured below has a contagious fungal infection called white nose syndrome.

Figure 3.12 (credit: U.S. Fish and Wildlife Service Headquarters)

How would infection of zebras by *Bacillus anthracis* be described—as a density-dependent or density-independent factor that regulates population growth?

a. This is an example of a density-independent factor because it becomes worse as the population density increases.
b. This is an example of a density-dependent factor because it becomes better as the population density increases.
c. This is an example of a density-dependent factor because it becomes worse as the population density increases.
d. This is an example of a density-independent factor since it becomes better as the population density increases.

Density-independent Regulation and Interaction with Density-dependent Factors

Many factors, typically physical or chemical in nature (abiotic), influence the mortality of a population regardless of its density, including weather, natural disasters, and pollution. An individual deer may be killed in a forest fire regardless of how many deer happen to be in that area. Its chances of survival are the same whether the population density is high or low. The same holds true for cold winter weather.

In real-life situations, population regulation is very complicated and density-dependent and independent factors can interact. A dense population that is reduced in a density-independent manner by some environmental factor(s) will be able to recover differently than a sparse population. For example, a population of deer affected by a harsh winter will recover faster if there are more deer remaining to reproduce.

science practices CONNECTION for AP® Courses

Think About It

Describe an example of how density-dependent and density-independent factors might interact.

evolution CONNECTION

Why Did the Woolly Mammoth Go Extinct?

(a) (b) (c)

Figure 3.13 The three photos include: (a) 1916 mural of a mammoth herd from the American Museum of Natural History, (b) the only stuffed mammoth in the world, from the Museum of Zoology located in St. Petersburg, Russia, and (c) a one-month-old baby mammoth, named Lyuba, discovered in Siberia in 2007. (credit a: modification of work by Charles R. Knight; credit b: modification of work by “Tanapon”/Flickr; credit c: modification of work by Matt Howry)

It's easy to get lost in the discussion of dinosaurs and theories about why they went extinct 65 million years ago. Was it due to a meteor slamming into Earth near the coast of modern-day Mexico, or was it from some long-term weather cycle that is not yet understood? One hypothesis that will never be proposed is that humans had something to do with it. Mammals were small, insignificant creatures of the forest 65 million years ago, and no humans existed.

Woolly mammoths, however, began to go extinct about 10,000 years ago, when they shared the Earth with humans who were no different anatomically than humans today (**Figure 3.13**). Mammoths survived in isolated island populations as recently as 1700 BC. We know a lot about these animals from carcasses found frozen in the ice of Siberia and other regions of the north. Scientists have sequenced at least 50 percent of its genome and believe mammoths are between 98 and 99 percent identical to modern elephants.

It is commonly thought that climate change and human hunting led to their extinction. A 2008 study estimated that climate change reduced the mammoth’s range from 3,000,000 square miles 42,000 years ago to 310,000 square miles 6,000 years ago.[6] It is also well documented that humans hunted these animals. A 2012 study showed that no single factor was exclusively responsible for the extinction of these magnificent creatures.[7] In addition to human hunting, climate change, and reduction of habitat, these scientists demonstrated another important factor in the mammoth’s extinction was the migration of humans across the Bering Strait to North America during the last ice age 20,000 years ago.

The maintenance of stable populations was and is very complex, with many interacting factors determining the outcome. It is important to remember that humans are also part of nature. Once we contributed to a species’ decline using primitive hunting technology only.

Explain the factors that may have contributed to the extinction of the woolly mammoth, and caused it to occur over a long period of time.

a. Deforestation affected the ability of the woolly mammoth to find adequate habitat and food, and humans contributed to declines in their population by hunting them.

b. Climate change affected the ability of the woolly mammoth to find adequate habitat and food, and humans contributed to the decline in their population by hunting them.

c. Climate change affected the ability of the woolly mammoth to find adequate food even though they had plenty of habitat, and humans contributed to declines in their population by hunting them.

d. Climate change affected the ability of the woolly mammoth to find adequate habitat and food, and a plague affected Earth during that time causing their extinction.

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6. David Nogués-Bravo et al., “Climate Change, Humans, and the Extinction of the Woolly Mammoth.” *PLoS Biol* 6 (April 2008): e79, doi:10.1371/journal.pbio.0060079.
7. G.M. MacDonald et al., “Pattern of Extinction of the Woolly Mammoth in Beringia.” *Nature Communications* 3, no. 893 (June 2012), doi:10.1038/ncomms1881.

Life Histories of *K*-selected and *r*-selected Species

While reproductive strategies play a key role in life histories, they do not account for important factors like limited resources and competition. The regulation of population growth by these factors can be used to introduce a classical concept in population biology, that of *K*-selected versus *r*-selected species.

Early Theories about Life History: K-selected and r-selected Species

By the second half of the twentieth century, the concept of K- and r-selected species was used extensively and successfully to study populations. The concept relates not only reproductive strategies, but also to a species' habitat and behavior, especially in the way that they obtain resources and care for their young. It includes length of life and survivorship factors as well. For this analysis, population biologists have grouped species into the two large categories—*K*-selected and *r*-selected—although they are really two ends of a continuum.

***K*-selected species** are species selected by stable, predictable environments. Populations of *K*-selected species tend to exist close to their carrying capacity (hence the term *K*-selected) where intraspecific competition is high. These species have few, large offspring, a long gestation period, and often give long-term care to their offspring (Table B45_04_01). While larger in size when born, the offspring are relatively helpless and immature at birth. By the time they reach adulthood, they must develop skills to compete for natural resources. In plants, scientists think of parental care more broadly: how long fruit takes to develop or how long it remains on the plant are determining factors in the time to the next reproductive event. Examples of *K*-selected species are primates (including humans), elephants, and plants such as oak trees (**Figure 3.14a**).

Oak trees grow very slowly and take, on average, 20 years to produce their first seeds, known as acorns. As many as 50,000 acorns can be produced by an individual tree, but the germination rate is low as many of these rot or are eaten by animals such as squirrels. In some years, oaks may produce an exceptionally large number of acorns, and these years may be on a two- or three-year cycle depending on the species of oak (*r*-selection).

As oak trees grow to a large size and for many years before they begin to produce acorns, they devote a large percentage of their energy budget to growth and maintenance. The tree's height and size allow it to dominate other plants in the competition for sunlight, the oak's primary energy resource. Furthermore, when it does reproduce, the oak produces large, energy-rich seeds that use their energy reserve to become quickly established (*K*-selection).

In contrast, ***r*-selected species** have a large number of small offspring (hence their *r* designation (**Table 3.2**). This strategy is often employed in unpredictable or changing environments. Animals that are *r*-selected do not give long-term parental care and the offspring are relatively mature and self-sufficient at birth. Examples of *r*-selected species are marine invertebrates, such as jellyfish, and plants, such as the dandelion (**Figure 3.14b**). Dandelions have small seeds that are wind dispersed long distances. Many seeds are produced simultaneously to ensure that at least some of them reach a hospitable environment. Seeds that land in inhospitable environments have little chance for survival since their seeds are low in energy content. Note that survival is not necessarily a function of energy stored in the seed itself.

Characteristics of *K*-selected and *r*-selected species

Characteristics of *K*-selected species	Characteristics of *r*-selected species
Mature late	Mature early
Greater longevity	Lower longevity
Increased parental care	Decreased parental care
Increased competition	Decreased competition
Fewer offspring	More offspring
Larger offspring	Smaller offspring

Table 3.2

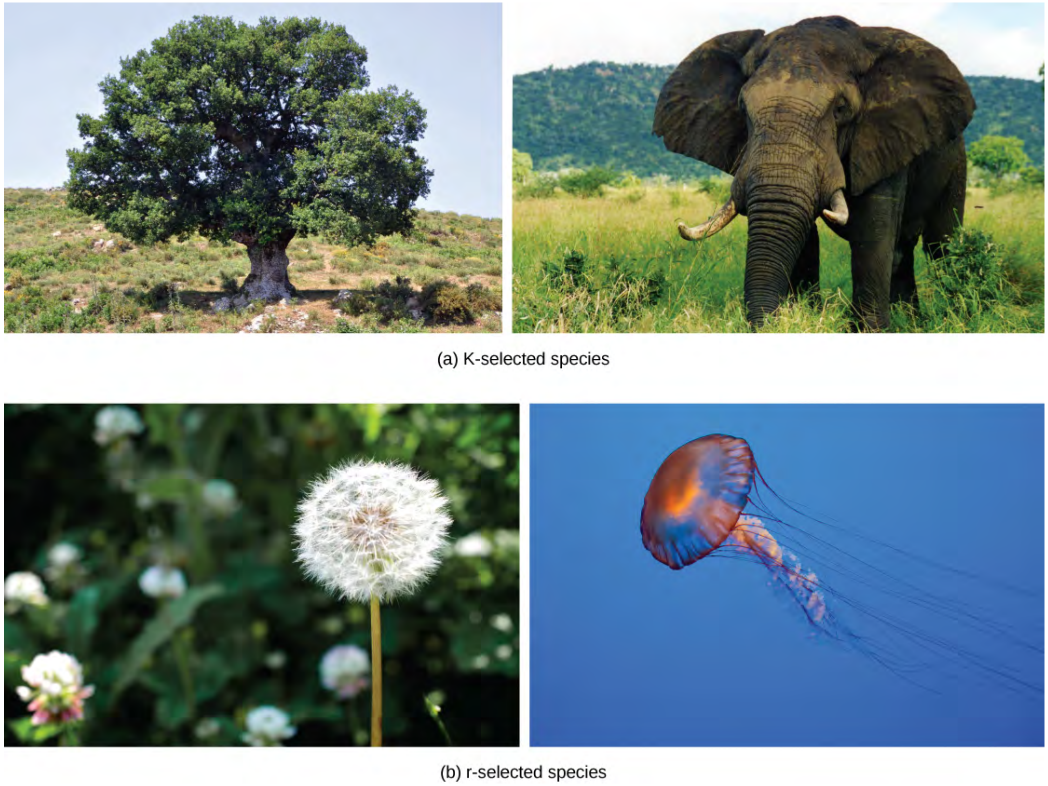


Figure 3.14 (a) Elephants are considered K-selected species as they live long, mature late, and provide long-term parental care to few offspring. Oak trees produce many offspring that do not receive parental care, but are considered K-selected species based on longevity and late maturation. (b) Dandelions and jellyfish are both considered r-selected species as they mature early, have short lifespans, and produce many offspring that receive no parental care.

Modern Theories of Life History

The *r*- and *K*-selection theory, although accepted for decades and used for much groundbreaking research, has now been reconsidered, and many population biologists have abandoned or modified it. Over the years, several studies attempted to confirm the theory, but these attempts have largely failed. Many species were identified that did not follow the theory's predictions. Furthermore, the theory ignored the age-specific mortality of the populations which scientists now know is very important. New **demographic-based models** of life history evolution have been developed which incorporate many ecological concepts included in *r*- and *K*-selection theory as well as population age structure and mortality factors.

36.5 | Human Population Growth

In this section, you will investigate the following questions:

- How can human population growth be exponential?
- How have humans expanded the carrying capacity of their habitat?
- How do population growth and age structure relate to the level of economic development in different countries?
- What are the long-term implications of unchecked human population growth?

Connection for AP® Courses

The methods used to look at animal population dynamics can also be used to look at the human populations. Like animals, humans are affected by abiotic and biotic factors. Unlike animals, humans have the ability to manipulate the factors affecting the growth of their population. As a result, additional factors come into play when studying human population dynamics. When studying projections of human population growth, ethical questions can also come to light.

Information presented and the examples highlighted in the section support concepts outlined in Big Idea 4 of the AP® Biology Curriculum Framework. The AP® Learning Objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.6** Interactions among living systems and with their environment result in the movement of matter and energy.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Science Practice	**4.1** The student is able to justify the selection of the kind of data needed to answer scientific questions about the interaction of populations within communities.
Learning Objective	**4.11** The student is able to justify the selection of the kind of data needed to answer scientific questions about the interaction of populations within communities.
Essential Knowledge	**4.A.6** Interactions among living systems and with their environment result in the movement of matter and energy.
Science Practice	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	**4.12** The student is able to apply mathematical routines to quantities that describe communities composed of populations of organisms that interact in complex ways.
Essential Knowledge	**4.A.6** Interactions among living systems and with their environment result in the movement of matter and energy.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.13** The student is able to predict the effects of a change in the community’s populations on the community.
Essential Knowledge	**4.A.6** Interactions among living systems and with their environment result in the movement of matter and energy.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.16** The student is able to predict the effects of a change of matter or energy availability on communities.

Concepts of animal population dynamics can be applied to human population growth. Humans are not unique in their ability to alter their environment. For example, beaver dams alter the stream environment where they are built. Humans, however, have the ability to alter their environment to increase its carrying capacity sometimes to the detriment of other species (e.g., via artificial selection for crops that have a higher yield). Earth’s human population is growing rapidly, to the extent that some worry about the ability of the earth’s environment to sustain this population, as long-term exponential growth carries the potential risks of famine, disease, and large-scale death.

Although humans have increased the carrying capacity of their environment, the technologies used to achieve this transformation have caused unprecedented changes to Earth’s environment, altering ecosystems to the point where some may be in danger of collapse. The depletion of the ozone layer, erosion due to acid rain, and damage from global climate change are caused by human activities. The ultimate effect of these changes on our carrying capacity is unknown. As some point out, it is likely that the negative effects of increasing carrying capacity will outweigh the positive ones—the carrying capacity of the world for human beings might actually decrease.

The world's human population is currently experiencing exponential growth even though human reproduction is far below its biotic potential (Figure 3.15). To reach its biotic potential, all females would have to become pregnant every nine months or so during their reproductive years. Also, resources would have to be such that the environment would support such growth. Neither of these two conditions exists. In spite of this fact, human population is still growing exponentially.

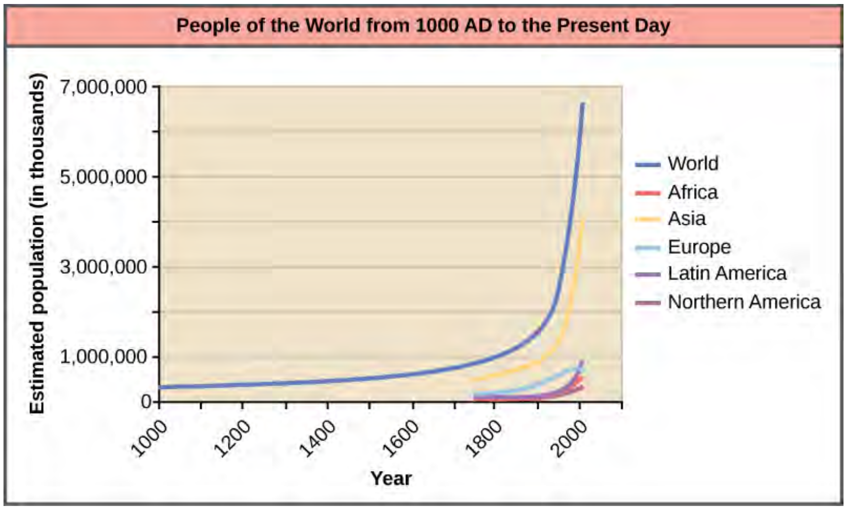


Figure 3.15 Human population growth since 1000 AD is exponential (dark blue line). Notice that while the population in Asia (yellow line), which has many economically underdeveloped countries, is increasing exponentially, the population in Europe (light blue line), where most of the countries are economically developed, is growing much more slowly.

A consequence of exponential human population growth is the time that it takes to add a particular number of humans to the Earth is becoming shorter. Figure 3.16 shows that 123 years were necessary to add 1 billion humans in 1930, but it only took 24 years to add two billion people between 1975 and 1999. As already discussed, at some point it would appear that our ability to increase our carrying capacity indefinitely on a finite world is uncertain. Without new technological advances, the human growth rate has been predicted to slow in the coming decades. However, the population will still be increasing and the threat of overpopulation remains.

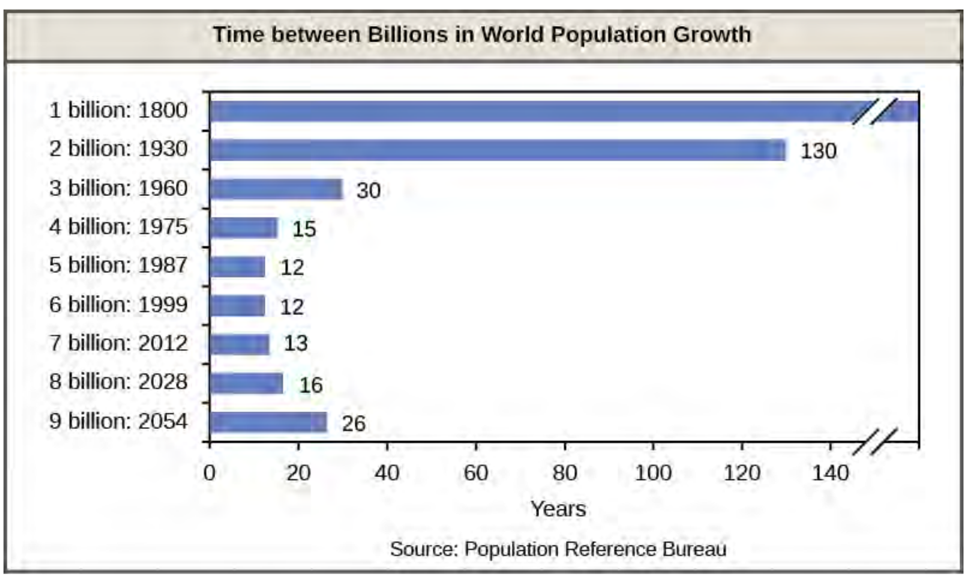


Figure 3.16 The time between the addition of each billion human beings to Earth decreases over time. (credit: modification of work by Ryan T. Cragun)

LINK TO LEARNING

Click through this **interactive view (http://openstaxcollege.org/l/human_growth)** of how human populations have changed over time.

Based on the interactive, how would you describe human population growth?

a. a decline in human population growth

b. a lag in human population growth

c. logistic growth

d. exponential growth

Overcoming Density-Dependent Regulation

Humans are unique in their ability to alter their environment with the conscious purpose of increasing its carrying capacity. This ability is a major factor responsible for human population growth and a way of overcoming density-dependent growth regulation. Much of this ability is related to human intelligence, society, and communication. Humans can construct shelter to protect them from the elements and have developed agriculture and domesticated animals to increase their food supplies. In addition, humans use language to communicate this technology to new generations, allowing them to improve upon previous accomplishments.

Other factors in human population growth are migration and public health. Humans originated in Africa, but have since migrated to nearly all inhabitable land on the Earth. Public health, sanitation, and the use of antibiotics and vaccines have decreased the ability of infectious disease to limit human population growth. In the past, diseases such as the bubonic plaque of the fourteenth century killed between 30 and 60 percent of Europe’s population and reduced the overall world population by as many as 100 million people. Today, the threat of infectious disease, while not gone, is certainly less severe. According to the World Health Organization, global death from infectious disease declined from 16.4 million in 1993 to 14.7 million in 2002. To compare to some of the epidemics of the past, the percentage of the world's population killed between 1993 and 2002 decreased from 0.30 percent of the world's population to 0.24 percent. Thus, it appears that the influence of infectious disease on human population growth is becoming less significant.

Age Structure, Population Growth, and Economic Development

The age structure of a population is an important factor in population dynamics. **Age structure** is the proportion of a population at different age ranges. Age structure allows better prediction of population growth, plus the ability to associate this growth with the level of economic development in the region. Countries with rapid growth have a pyramidal shape in their age structure diagrams, showing a preponderance of younger individuals, many of whom are of reproductive age or will be soon (**Figure 3.17**). This pattern is most often observed in underdeveloped countries where individuals do not live to old age because of less-than-optimal living conditions. Age structures of areas with slow growth, including developed countries such as the United States, still have a pyramidal structure, but with many fewer young and reproductive-aged individuals and a greater proportion of older individuals. Other developed countries, such as Italy, have zero population growth. The age structure of these populations is more conical, with an even greater percentage of middle-aged and older individuals. The actual growth rates in different countries are shown in **Figure 3.18**, with the highest rates tending to be in the less economically developed countries of Africa and Asia.

visual CONNECTION

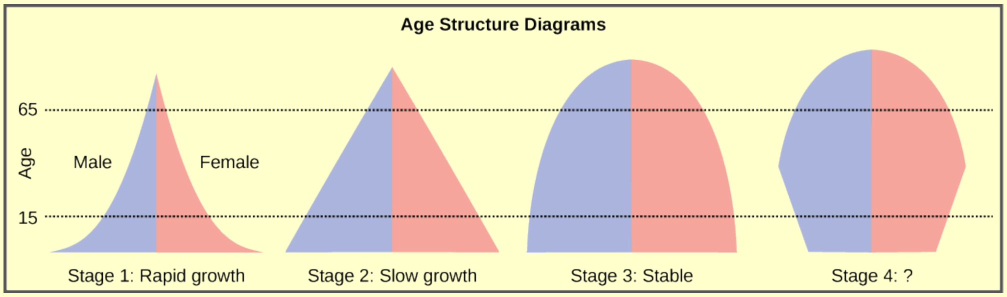


Figure 3.17 Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing that the number of individuals per age group decreases gradually, and then increases for the older part of the population.

Compare the age structure for Stage 4 to that of Stage 3. What changes in population growth would have to occur for a shift from Stage 3 to Stage 4?

a. Birth rates and death rates remains same in both Stage 3 and Stage 4.
b. Birth rates and death rates decline in Stage 4 compared to Stage 3.
c. Death rates decline in Stage 4 compared to Stage 3, but birth rates remain the same.
d. Birth rates decline in Stage 4 compared to Stage 3, but death rates remain the same.

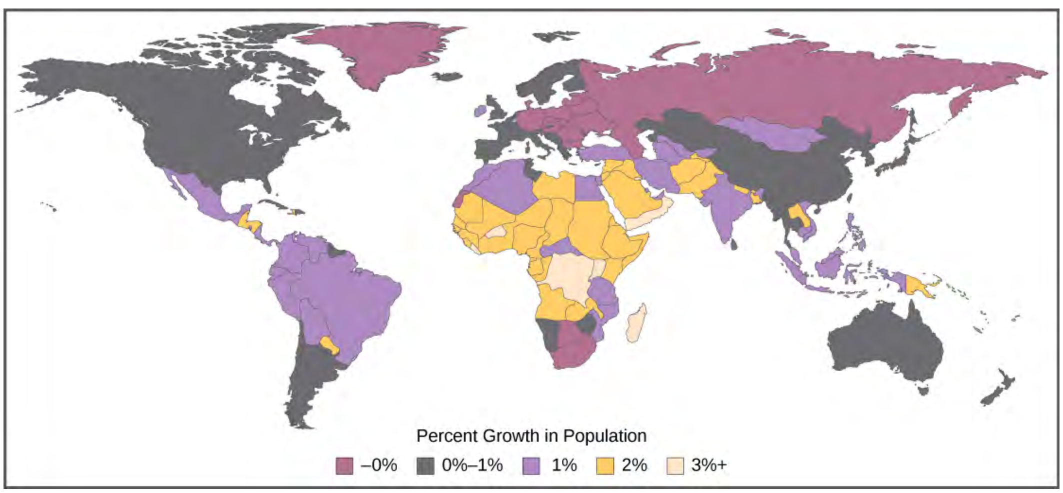


Figure 3.18 The percent growth rate of population in different countries is shown. Notice that the highest growth is occurring in less economically developed countries in Africa and Asia.

Long-Term Consequences of Exponential Human Population Growth

Many dire predictions have been made about the world's population leading to a major crisis called the "population explosion." In the 1968 book *The Population Bomb*, biologist Dr. Paul R. Ehrlich wrote, "The battle to feed all of humanity is over. In the 1970s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now. At this late date nothing can prevent a substantial increase in the world death rate."[8] While many critics view this statement as an exaggeration, the laws of exponential population growth are still in effect, and unchecked human population growth cannot continue indefinitely.

Efforts to control population growth led to the **one-child policy** in China, which used to include more severe consequences,

8. Paul R. Erlich, prologue to *The Population Bomb*, (1968; repr., New York: Ballantine, 1970).

but now imposes fines on urban couples who have more than one child. Due to the fact that some couples wish to have a male heir, many Chinese couples continue to have more than one child. The policy itself, its social impacts, and the effectiveness of limiting overall population growth are controversial. In spite of population control policies, the human population continues to grow. At some point the food supply may run out because of the subsequent need to produce more and more food to feed our population. The United Nations estimates that future world population growth may vary from 6 billion (a decrease) to 16 billion people by the year 2100. There is no way to know whether human population growth will moderate to the point where the crisis described by Dr. Ehrlich will be averted.

Another result of population growth is the endangerment of the natural environment. Many countries have attempted to reduce the human impact on climate change by reducing their emission of the greenhouse gas carbon dioxide. However, these treaties have not been ratified by every country, and many underdeveloped countries trying to improve their economic condition may be less likely to agree with such provisions if it means slower economic development. Furthermore, the role of human activity in causing climate change has become a hotly debated socio-political issue in some developed countries, including the United States. Thus, we enter the future with considerable uncertainty about our ability to curb human population growth and protect our environment.

science practices CONNECTION for AP® Courses

Think About It

Describe the age structures in rapidly growing countries, slowly growing countries, and countries with zero population growth.

LINK TO LEARNING

Visit this **website (http://openstaxcollege.org/l/populations)** and select “Launch movie” for an animation discussing the global impacts of human population growth.

36.6 | Community Ecology

In this section, you will explore the following questions:

- What is the predator-prey cycle?
- What are examples of defenses against predation and herbivory?
- What is the competitive exclusion principle?
- What are examples of symbiotic relationship among species?
- What is community structure and succession?

Connection for AP® Courses

Topics explored in this section that are in scope for AP® include mimicry, the competitive exclusion principle, symbiosis, keystone and foundation species, and primary and secondary succession. Species interact in many ways, the classical example of species interaction being the hunting of prey by its predator. In most cases, populations of predators and prey vary in cycles. Beyond predation, because resources are often limited in an environment, multiple species may compete to obtain them. Communities are complex entities defined by the types and number of species and the dynamics of how they change over time. Like populations, communities change in structure and composition, often by environmental disturbances such as fire or hurricanes.

Information presented and the examples highlighted in the section support concepts outlined in Big Idea 2 and Big Idea 4 of the AP® Biology Curriculum Framework. The learning objectives listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.D	Growth and dynamic homeostasis of a biological system are influenced by changes in the system's environment.
Essential Knowledge	**2.D.1** All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.
Science Practice	**1.3** The student can refine representations and models of natural or man-made phenomena and systems in the domain.
Science Practice	**3.2** The student can refine scientific questions.
Learning Objective	**2.22** The student is able to refine scientific models and questions about the effect of complex biotic and abiotic interactions on all biological systems, from cells and organisms to populations, communities, and ecosystems.
Essential Knowledge	**2.D.1** All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.
Science Practice	**4.2** The student can design a plan for collecting data to answer a particular scientific question.
Science Practice	**7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	**2.23** The student is able to design a plan for collecting data to show that all biological systems are affected by complex biotic and abiotic interactions.
Essential Knowledge	**2.D.1** All biological systems from cells and organisms to populations, communities and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.
Science Practice	**5.1** The student can analyze data to identify patterns or relationships.
Learning Objective	**2.24** The student is able to analyze data to identify possible patterns and relationships between a biotic or abiotic factor and a biological system.
Big Idea 4	Biological systems interact, and these systems and their interactions possess complex properties.
Enduring Understanding 4.A	Interactions within biological systems lead to complex properties.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Science Practice	**4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question.
Learning Objective	**4.11** The student is able to justify the selection of the kind of data needed to answer scientific questions about the interaction of populations within communities.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	**4.12** The student is able to apply mathematical routines to quantities that describe communities composed of populations of organisms that interact in complex ways.
Essential Knowledge	**4.A.5** Communities are composed of populations of organisms that interact in complex ways.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.13** The student is able to predict the effects of a change in the community's populations on the community.
Essential Knowledge	**4.A.6** Interactions among living systems and with their environment result in the movement of matter and energy.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.15** The student is able to predict the effects of a change of matter or energy availability on communities.

Populations rarely, if ever, live in isolation from populations of other species. In most cases, numerous species share a habitat. The interactions between these populations play a major role in regulating population growth and abundance. All populations occupying the same habitat form a community: populations inhabiting a specific area at the same time. The number of species occupying the same habitat and their relative abundance is known as species diversity. Areas with low diversity, such as the glaciers of Antarctica, still contain a wide variety of living things, whereas the diversity of tropical rainforests is so great that it cannot be counted. Ecology is studied at the community level to understand how species interact with each other and compete for the same resources.

Predation and Herbivory

Perhaps the classical example of species interaction is predation: the hunting of prey by its predator. Nature shows on television highlight the drama of one living organism killing another. Populations of predators and prey in a community are not constant over time: in most cases, they vary in cycles that appear to be related. The most often cited example of predator-prey dynamics is seen in the cycling of the lynx (predator) and the snowshoe hare (prey), using nearly 200 year-old trapping data from North American forests (**Figure 3.19**). This cycle of predator and prey lasts approximately 10 years, with the predator population lagging 1–2 years behind that of the prey population. As the hare numbers increase, there is more food available for the lynx, allowing the lynx population to increase as well. When the lynx population grows to a threshold level, however, they kill so many hares that hare population begins to decline, followed by a decline in the lynx population because of scarcity of food. When the lynx population is low, the hare population size begins to increase due, at least in part, to low predation pressure, starting the cycle anew.

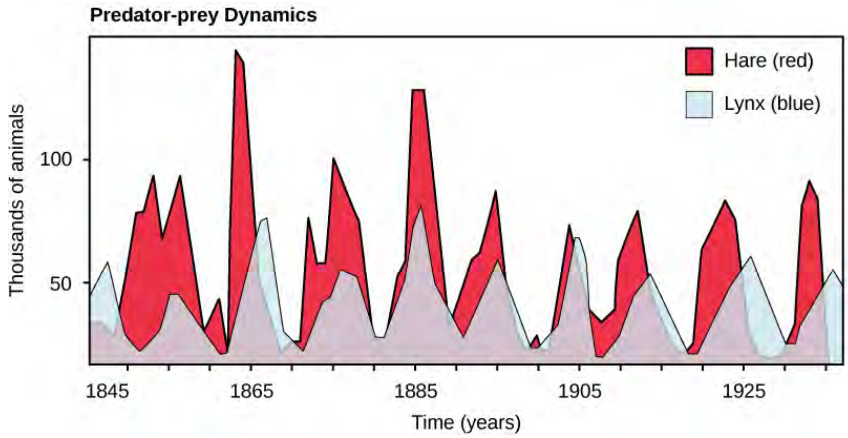


Figure 3.19 The cycling of lynx and snowshoe hare populations in Northern Ontario is an example of predator-prey dynamics.

The idea that the population cycling of the two species is entirely controlled by predation models has come under question. More recent studies have pointed to undefined density-dependent factors as being important in the cycling, in addition to predation. One possibility is that the cycling is inherent in the hare population due to density-dependent effects such as lower fecundity (maternal stress) caused by crowding when the hare population gets too dense. The hare cycling would then induce the cycling of the lynx because it is the lynxes' major food source. The more we study communities, the more complexities we find, allowing ecologists to derive more accurate and sophisticated models of population dynamics.

Herbivory describes the consumption of plants by insects and other animals, and it is another interspecific relationship that affects populations. Unlike animals, most plants cannot outrun predators or use mimicry to hide from hungry animals. Some plants have developed mechanisms to defend against herbivory. Other species have developed mutualistic relationships; for example, herbivory provides a mechanism of seed distribution that aids in plant reproduction.

Defense Mechanisms against Predation and Herbivory

The study of communities must consider evolutionary forces that act on the members of the various populations contained within it. Species are not static, but slowly changing and adapting to their environment by natural selection and other evolutionary forces. Species have evolved numerous mechanisms to escape predation and herbivory. These defenses may be mechanical, chemical, physical, or behavioral.

Mechanical defenses, such as the presence of thorns on plants or the hard shell on turtles, discourage animal predation and herbivory by causing physical pain to the predator or by physically preventing the predator from being able to eat the prey. Chemical defenses are produced by many animals as well as plants, such as the foxglove which is extremely toxic when eaten. **Figure 3.20** shows some organisms' defenses against predation and herbivory.

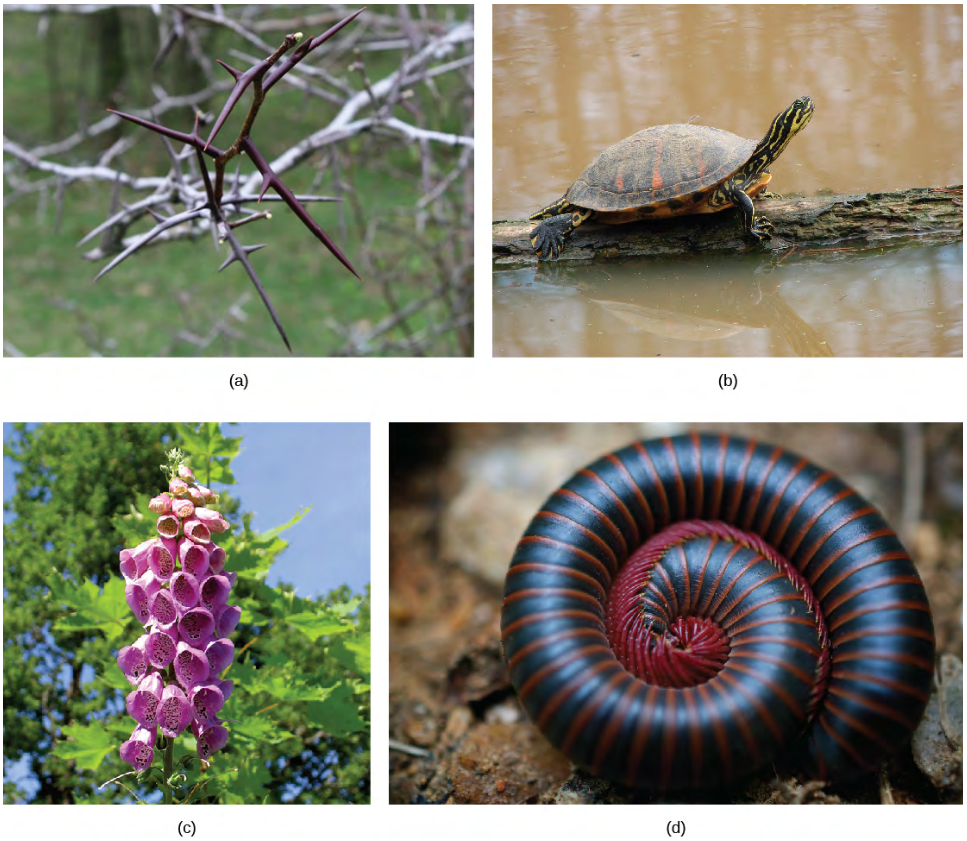
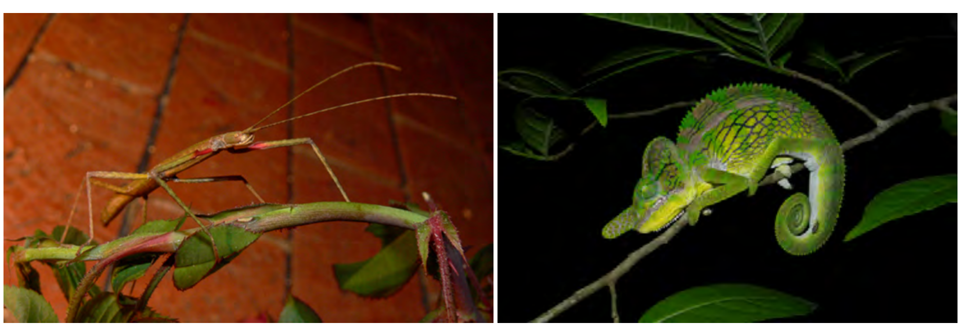


Figure 3.20 The (a) honey locust tree (*Gleditsia triacanthos*) uses thorns, a mechanical defense, against herbivores, while the (b) Florida red-bellied turtle (*Pseudemys nelsoni)* uses its shell as a mechanical defense against predators. (c) Foxglove (*Digitalis* sp.) uses a chemical defense: toxins produced by the plant can cause nausea, vomiting, hallucinations, convulsions, or death when consumed. (d) The North American millipede (*Narceus americanus*) uses both mechanical and chemical defenses: when threatened, the millipede curls into a defensive ball and produces a noxious substance that irritates eyes and skin. (credit a: modification of work by Huw Williams; credit b: modification of work by "JamieS93"/Flickr; credit c: modification of work by Philip Jägenstedt; credit d: modification of work by Cory Zanker)

Many species use their body shape and coloration to avoid being detected by predators. The tropical walking stick is an insect with the coloration and body shape of a twig which makes it very hard to see when stationary against a background of real twigs (**Figure 3.21a**). In another example, the chameleon can change its color to match its surroundings (**Figure 3.21b**). Both of these are examples of **camouflage**, or avoiding detection by blending in with the background.



(a) (b)

Figure 3.21 (a) The tropical walking stick and (b) the chameleon use body shape and/or coloration to prevent detection by predators. (credit a: modification of work by Linda Tanner; credit b: modification of work by Frank Vassen)

Some species use coloration as a way of warning predators that they are not good to eat. For example, the cinnabar moth caterpillar, the fire-bellied toad, and many species of beetle have bright colors that warn of a foul taste, the presence of toxic chemical, and/or the ability to sting or bite, respectively. Predators that ignore this coloration and eat the organisms will experience their unpleasant taste or presence of toxic chemicals and learn not to eat them in the future. This type of defensive mechanism is called **aposematic coloration**, or warning coloration (**Figure 3.22**).

(a) (b)

Figure 3.22 (a) The strawberry poison dart frog (*Oophaga pumilio*) uses aposematic coloration to warn predators that it is toxic, while the (b) striped skunk (*Mephitis mephitis*) uses aposematic coloration to warn predators of the unpleasant odor it produces. (credit a: modification of work by Jay Iwasaki; credit b: modification of work by Dan Dzurisin)

While some predators learn to avoid eating certain potential prey because of their coloration, other species have evolved mechanisms to mimic this coloration to avoid being eaten, even though they themselves may not be unpleasant to eat or contain toxic chemicals. In **Batesian mimicry**, a harmless species imitates the warning coloration of a harmful one. Assuming they share the same predators, this coloration then protects the harmless ones, even though they do not have the same level of physical or chemical defenses against predation as the organism they mimic. Many insect species mimic the coloration of wasps or bees, which are stinging, venomous insects, thereby discouraging predation (**Figure 3.23**).

(a) (b)

Figure 3.23 Batesian mimicry occurs when a harmless species mimics the coloration of a harmful species, as is seen with the (a) bumblebee and (b) bee-like robber fly. (credit a, b: modification of work by Cory Zanker)

In **Müllerian mimicry**, multiple species share the same warning coloration, but all of them actually have defenses. **Figure 3.24** shows a variety of foul-tasting butterflies with similar coloration. In **Emsleyan/Mertensian mimicry**, a deadly prey mimics a less dangerous one, such as the venomous coral snake mimicking the non-venomous milk snake. This type of mimicry is extremely rare and more difficult to understand than the previous two types. For this type of mimicry to work, it is essential that eating the milk snake has unpleasant but not fatal consequences. Then, these predators learn not to eat snakes with this coloration, protecting the coral snake as well. If the snake were fatal to the predator, there would be no opportunity for the predator to learn not to eat it, and the benefit for the less toxic species would disappear.

Figure 3.24 Several unpleasant-tasting *Heliconius* butterfly species share a similar color pattern with better-tasting varieties, an example of Müllerian mimicry. (credit: Joron M, Papa R, Beltrán M, Chamberlain N, Mavárez J, et al.)

LINK TO LEARNING

Go to this **website (http://openstaxcollege.org/l/find_the_mimic)** to view stunning examples of mimicry.

Explain the most important reason why mimicry and camouflage are so important in the animal world.

a. Mimicry and camouflage are adaptations that give these animals a advantage in finding prey over others that do not have these adaptations.

b. Mimicry and camouflage are adaptations that give these animals a survival advantage over others that do not have these adaptations.

c. Mimicry and camouflage are aposematic defense mechanisms that give these animals a survival advantage over others that do not have these mechanisms.

d. Mimicry and camouflage are aposematic defense mechanisms that give these animals a reproductive advantage over others that do not have these mechanisms.

Competitive Exclusion Principle

Resources are often limited within a habitat and multiple species may compete to obtain them. All species have an ecological niche in the ecosystem, which describes how they acquire the resources they need and how they interact with other species in the community. The **competitive exclusion principle** states that two species cannot occupy the same niche in a habitat. In other words, different species cannot coexist in a community if they are competing for all the same resources.

An example of this principle is shown in **Figure 3.25**, with two protozoan species, *Paramecium aurelia* and *Paramecium caudatum*. When grown individually in the laboratory, they both thrive. But when they are placed together in the same test tube (habitat), *P. aurelia* outcompetes *P. caudatum* for food, leading to the latter's eventual extinction.

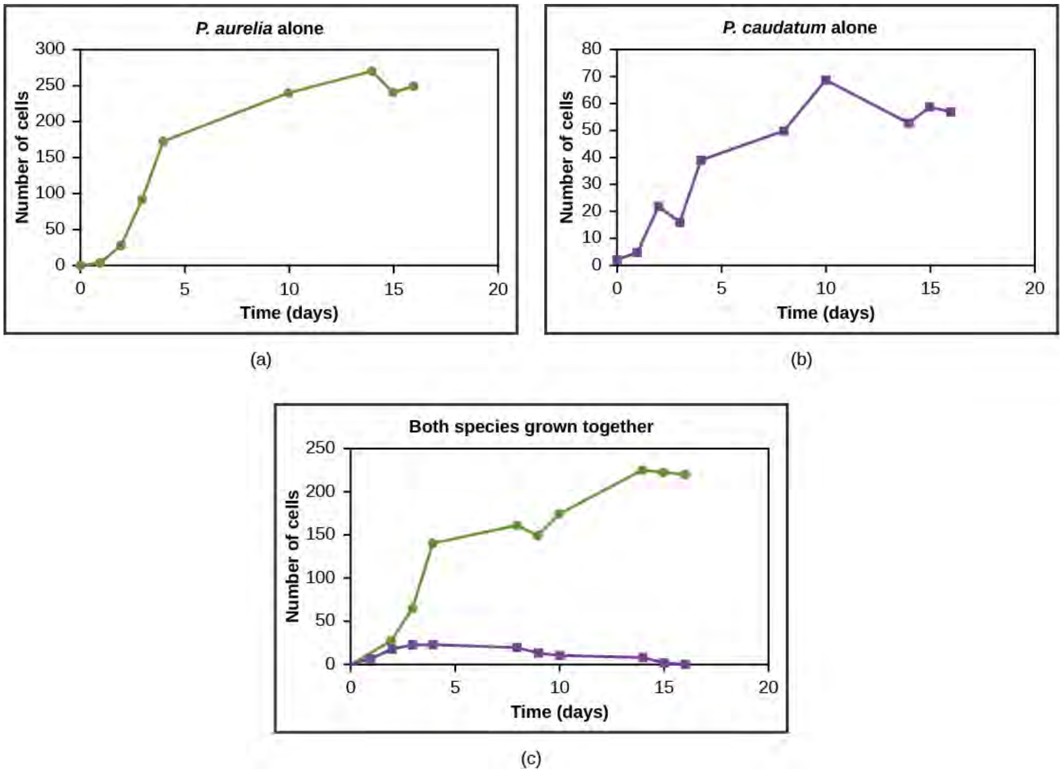


Figure 3.25 *Paramecium aurelia* and *Paramecium caudatum* grow well individually, but when they compete for the same resources, the *P. aurelia* outcompetes the *P. caudatum*.

This exclusion may be avoided if a population evolves to make use of a different resource, a different area of the habitat, or feeds during a different time of day, called resource partitioning. The two organisms are then said to occupy different microniches. These organisms coexist by minimizing direct competition.

Symbiosis

Symbiotic relationships, or **symbioses** (plural), are close interactions between individuals of different species over an extended period of time which impact the abundance and distribution of the associating populations. Most scientists accept this definition, but some restrict the term to only those species that are mutualistic, where both individuals benefit from the interaction. In this discussion, the broader definition will be used.

Commensalism

A **commensal** relationship occurs when one species benefits from the close, prolonged interaction, while the other neither benefits nor is harmed. Birds nesting in trees provide an example of a commensal relationship (**Figure 3.26**). The tree is not harmed by the presence of the nest among its branches. The nests are light and produce little strain on the structural integrity of the branch, and most of the leaves, which the tree uses to get energy by photosynthesis, are above the nest so they are unaffected. The bird, on the other hand, benefits greatly. If the bird had to nest in the open, its eggs and young would be vulnerable to predators. Another example of a commensal relationship is the clown fish and the sea anemone. The sea anemone is not harmed by the fish, and the fish benefits with protection from predators who would be stung upon nearing the sea anemone.

Figure 3.26 The southern masked-weaver bird is starting to make a nest in a tree in Zambezi Valley, Zambia. This is an example of a commensal relationship, in which one species (the bird) benefits, while the other (the tree) neither benefits nor is harmed. (credit: "Hanay"/Wikimedia Commons)

Mutualism

A second type of symbiotic relationship is called **mutualism**, where two species benefit from their interaction. Some scientists believe that these are the only true examples of symbiosis. For example, termites have a mutualistic relationship with protozoa that live in the insect's gut (**Figure 3.27a**). The termite benefits from the ability of bacterial symbionts within the protozoa to digest cellulose. The termite itself cannot do this, and without the protozoa, it would not be able to obtain energy from its food (cellulose from the wood it chews and eats). The protozoa and the bacterial symbionts benefit by having a protective environment and a constant supply of food from the wood chewing actions of the termite. Lichens have a mutualistic relationship between fungus and photosynthetic algae or bacteria (**Figure 3.27b**). As these symbionts grow together, the glucose produced by the algae provides nourishment for both organisms, whereas the physical structure of the lichen protects the algae from the elements and makes certain nutrients in the atmosphere more available to the algae.

(a) (b)

Figure 3.27 (a) Termites form a mutualistic relationship with symbiotic protozoa in their guts, which allow both organisms to obtain energy from the cellulose the termite consumes. (b) Lichen is a fungus that has symbiotic photosynthetic algae living inside its cells. (credit a: modification of work by Scott Bauer, USDA; credit b: modification of work by Cory Zanker)

Parasitism

A **parasite** is an organism that lives in or on another living organism and derives nutrients from it. In this relationship, the parasite benefits, but the organism being fed upon, the **host** is harmed. The host is usually weakened by the parasite as it siphons resources the host would normally use to maintain itself. The parasite, however, is unlikely to kill the host, especially not quickly, because this would allow no time for the organism to complete its reproductive cycle by spreading to another host.

The reproductive cycles of parasites are often very complex, sometimes requiring more than one host species. A tapeworm is a parasite that causes disease in humans when contaminated, undercooked meat such as pork, fish, or beef is consumed (**Figure 3.28**). The tapeworm can live inside the intestine of the host for several years, benefiting from the food the host is bringing into its gut by eating, and may grow to be over 50 ft long by adding segments. The parasite moves from species to species in a cycle, making two hosts necessary to complete its life cycle. Another common parasite is *Plasmodium falciparum*, the protozoan cause of malaria, a significant disease in many parts of the world. Living in human liver and red blood cells, the organism reproduces asexually in the gut of blood-feeding mosquitoes to complete its life cycle. Thus malaria is spread from human to human by mosquitoes, one of many arthropod-borne infectious diseases.

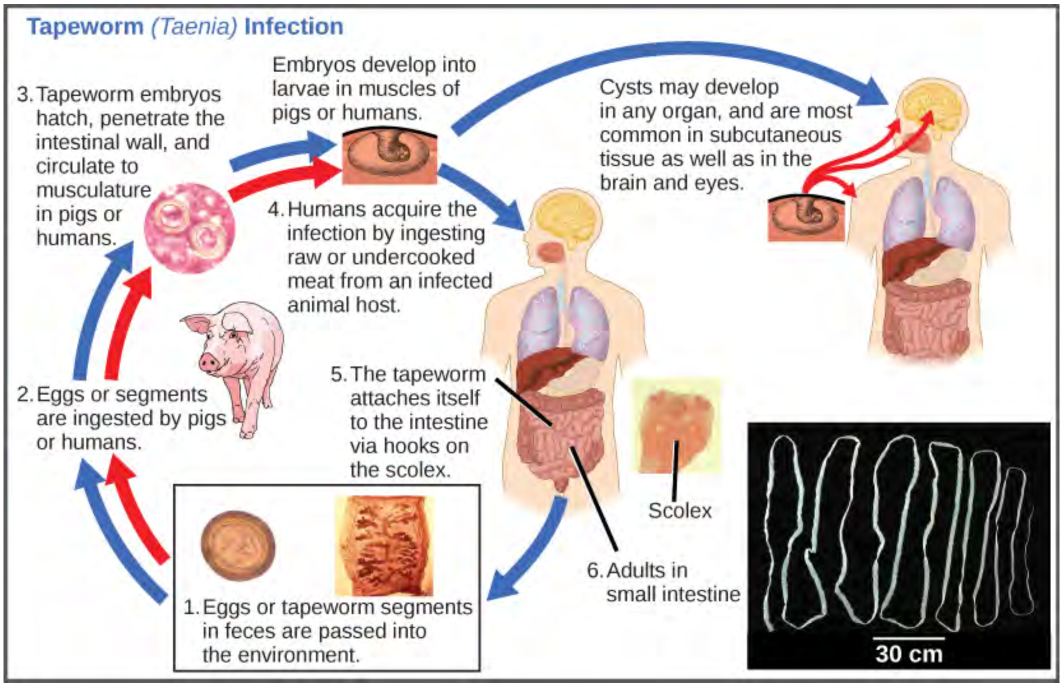


Figure 3.28 This diagram shows the life cycle of a pork tapeworm (*Taenia solium*), a human worm parasite. (credit: modification of work by CDC)

Characteristics of Communities

Communities are complex entities that can be characterized by their structure (the types and numbers of species present) and dynamics (how communities change over time). Understanding community structure and dynamics enables community ecologists to manage ecosystems more effectively.

Foundation Species

Foundation species are considered the "base" or "bedrock" of a community, having the greatest influence on its overall structure. They are usually the primary producers: organisms that bring most of the energy into the community. Kelp, brown algae, is a foundation species, forming the basis of the kelp forests off the coast of California.

Foundation species may physically modify the environment to produce and maintain habitats that benefit the other organisms that use them. An example is the photosynthetic corals of the coral reef (Figure 3.29). Corals themselves are not photosynthetic, but harbor symbionts within their body tissues (dinoflagellates called zooxanthellae) that perform photosynthesis; this is another example of a mutualism. The exoskeletons of living and dead coral make up most of the reef structure, which protects many other species from waves and ocean currents.

Figure 3.29 Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

Biodiversity, Species Richness, and Relative Species Abundance

Biodiversity describes a community's biological complexity: it is measured by the number of different species (species richness) in a particular area and their relative abundance (species evenness). The area in question could be a habitat, a biome, or the entire biosphere. **Species richness** is the term that is used to describe the number of species living in a habitat or biome. Species richness varies across the globe (**Figure 3.30**). One factor in determining species richness is latitude, with the greatest species richness occurring in ecosystems near the equator, which often have warmer temperatures, large amounts of rainfall, and low seasonality. The lowest species richness occurs near the poles, which are much colder, drier, and thus less conducive to life in Geologic time (time since glaciations). The predictability of climate or productivity is also an important factor. Other factors influence species richness as well. For example, the study of **island biogeography** attempts to explain the relatively high species richness found in certain isolated island chains, including the Galápagos Islands that inspired the young Darwin. **Relative species abundance** is the number of individuals in a species relative to the total number of individuals in all species within a habitat, ecosystem, or biome. Foundation species often have the highest relative abundance of species.

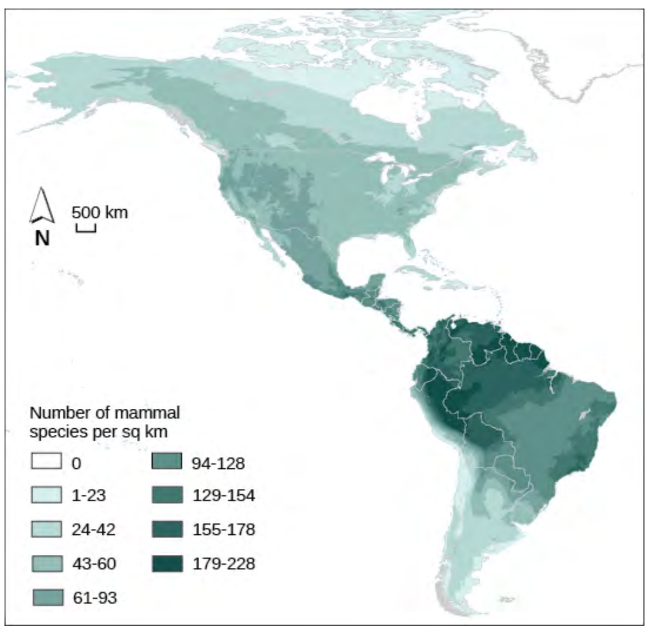


Figure 3.30 The greatest species richness for mammals in North and South America is associated with the equatorial latitudes. (credit: modification of work by NASA, CIESIN, Columbia University)

Keystone Species

A **keystone species** is one whose presence is key to maintaining biodiversity within an ecosystem and to upholding an ecological community's structure. The intertidal sea star, *Pisaster ochraceus*, of the northwestern United States is a keystone species (**Figure 3.31**). Studies have shown that when this organism is removed from communities, populations of their natural prey (mussels) increase, completely altering the species composition and reducing biodiversity. Another keystone species is the banded tetra, a fish in tropical streams, which supplies nearly all of the phosphorus, a necessary inorganic nutrient, to the rest of the community. If these fish were to become extinct, the community would be greatly affected.

Figure 3.31 The *Pisaster ochraceus* sea star is a keystone species. (credit: Jerry Kirkhart)

everyday CONNECTION

Invasive Species

Invasive species are non-native organisms that, when introduced to an area out of their native range, threaten the ecosystem balance of that habitat. Many such species exist in the United States, as shown in **Figure 3.32**. Whether enjoying a forest hike, taking a summer boat trip, or simply walking down an urban street, you have likely encountered an invasive species.

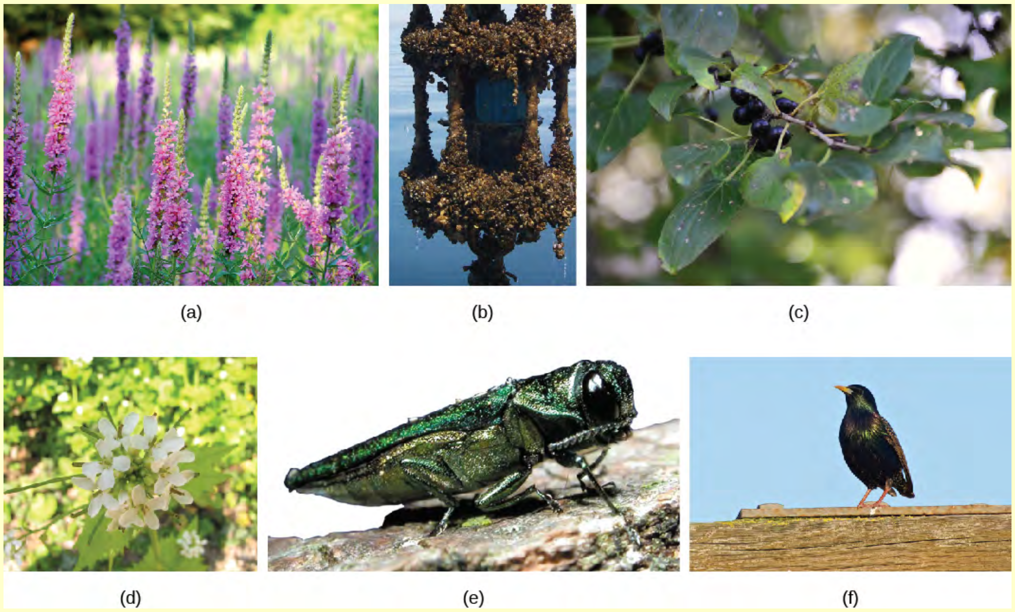


Figure 3.32 In the United States, invasive species like (a) purple loosestrife (*Lythrum salicaria*) and the (b) zebra mussel (*Dreissena polymorpha*) threaten certain aquatic ecosystems. Some forests are threatened by the spread of (c) common buckthorn (*Rhamnus cathartica*), (d) garlic mustard (*Alliaria petiolata*), and (e) the emerald ash borer (*Agrilus planipennis*). The (f) European starling (*Sturnus vulgaris*) may compete with native bird species for nest holes. (credit a: modification of work by Liz West; credit b: modification of work by M. McCormick, NOAA; credit c: modification of work by E. Dronkert; credit d: modification of work by Dan Davison; credit e: modification of work by USDA; credit f: modification of work by Don DeBold)

One of the many recent proliferations of an invasive species concerns the growth of Asian carp populations. Asian carp were introduced to the United States in the 1970s by fisheries and sewage treatment facilities that used the fish's excellent filter feeding capabilities to clean their ponds of excess plankton. Some of the fish escaped, however, and by the 1980s they had colonized many waterways of the Mississippi River basin, including the Illinois and Missouri Rivers.

Voracious eaters and rapid reproducers, Asian carp may outcompete native species for food, potentially leading to their extinction. For example, black carp are voracious eaters of native mussels and snails, limiting this food source for native fish species. Silver carp eat plankton that native mussels and snails feed on, reducing this food source by a different alteration of the food web. In some areas of the Mississippi River, Asian carp species have become the most predominant, effectively outcompeting native fishes for habitat. In some parts of the Illinois River, Asian carp constitute 95 percent of the community's biomass. Although edible, the fish is bony and not a desired food in the United States. Moreover, their presence threatens the native fish and fisheries of the Great Lakes, which are important to local economies and recreational anglers. Asian carp have even injured humans. The fish, frightened by the sound of approaching motorboats, thrust themselves into the air, often landing in the boat or directly hitting the boaters.

The Great Lakes and their prized salmon and lake trout fisheries are also being threatened by these invasive fish. Asian carp have already colonized rivers and canals that lead into Lake Michigan. One infested waterway of particular importance is the Chicago Sanitary and Ship Channel, the major supply waterway linking the Great Lakes to the Mississippi River. To prevent the Asian carp from leaving the canal, a series of electric barriers have been successfully used to discourage their migration; however, the threat is significant enough that several states and Canada have sued to have the Chicago channel permanently cut off from Lake Michigan. Local and national politicians have weighed in on how to solve the problem, but no one knows whether the Asian carp will ultimately be considered a nuisance, like other invasive species such as the water hyacinth and zebra mussel, or whether it will be the destroyer of the largest freshwater fishery of the world.

The issues associated with Asian carp show how population and community ecology, fisheries management, and politics intersect on issues of vital importance to the human food supply and economy. Socio-political issues like this make extensive use of the sciences of population ecology (the study of members of a particular species occupying a particular area known as a habitat) and community ecology (the study of the interaction of all species within a habitat).

Why are invasive species such as the Asian carp such a problem in North America?

a. They release some chemicals into the water which are toxic to the flora and fauna of the freshwater habitats in North America.

b. They kill the natural fish population native to freshwater habitats in North America by obtaining food from them. The invasive species will then reproduce rapidly.

c. They provide food and other resources to the native fish population, resulting in an over increase in their population. This decreases the amount of dissolved oxygen in the freshwater habitats of North America.

d. They are not native to freshwater habitats in North America and have no natural predators to keep their population in check. As a result, they will reproduce rapidly competing with native fish for space, food, and other resources.

Community Dynamics

Community dynamics are the changes in community structure and composition over time. Sometimes these changes are induced by **environmental disturbances** such as volcanoes, earthquakes, storms, fires, and climate change. Communities with a stable structure are said to be at equilibrium. Following a disturbance, the community may or may not return to the equilibrium state.

Succession describes the sequential appearance and disappearance of species in a community over time. In **primary succession**, newly exposed or newly formed land is colonized by living things; in **secondary succession**, part of an ecosystem is disturbed and remnants of the previous community remain.

Primary Succession and Pioneer Species

Primary succession occurs when new land is formed or rock is exposed: for example, following the eruption of volcanoes, such as those on the Big Island of Hawaii. As lava flows into the ocean, new land is continually being formed. On the Big Island, approximately 32 acres of land is added each year. First, weathering and other natural forces break down the substrate enough for the establishment of certain hearty plants and lichens with few soil requirements, known as **pioneer species** (**Figure 3.33**). These species help to further break down the mineral rich lava into soil where other, less hardy species will grow and eventually replace the pioneer species. In addition, as these early species grow and die, they add to an ever-growing layer of decomposing organic material and contribute to soil formation. Over time the area will reach an equilibrium state, with a set of organisms quite different from the pioneer species.

Figure 3.33 During primary succession in lava on Maui, Hawaii, succulent plants are the pioneer species. (credit: Forest and Kim Starr)

Secondary Succession

A classic example of secondary succession occurs in oak and hickory forests cleared by wildfire (Figure 3.34). Wildfires will burn most vegetation and kill those animals unable to flee the area. Their nutrients, however, are returned to the ground in the form of ash. Thus, even when areas are devoid of life due to severe fires, the area will soon be ready for new life to take hold.

Before the fire, the vegetation was dominated by tall trees with access to the major plant energy resource: sunlight. Their height gave them access to sunlight while also shading the ground and other low-lying species. After the fire, though, these trees are no longer dominant. Thus, the first plants to grow back are usually annual plants followed within a few years by quickly growing and spreading grasses and other pioneer species. Due to, at least in part, changes in the environment brought on by the growth of the grasses and other species, over many years, shrubs will emerge along with small pine, oak, and hickory trees. These organisms are called intermediate species. Eventually, over 150 years, the forest will reach its equilibrium point where species composition is no longer changing and resembles the community before the fire. This equilibrium state is referred to as the **climax community**, which will remain stable until the next disturbance.

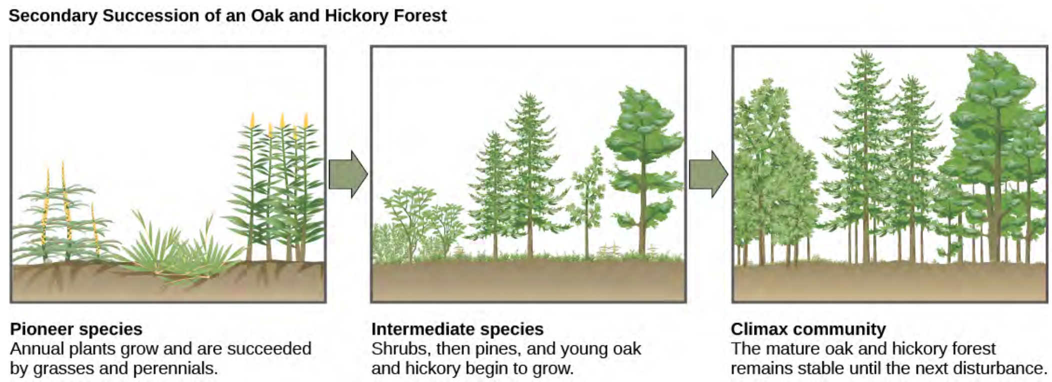


Figure 3.34 Secondary succession is shown in an oak and hickory forest after a forest fire.

science practices CONNECTION for AP® Courses

Activity

Don't Trash the Campus. Design and implement a plan to investigate the impact of school litter on a surrounding community. Based on collected data, create a proposal of short- and long-term solutions to the trash problem on campus and submit the proposal to the student council for consideration. Describes ways in which communities/ecosystems can recover from modern levels of local environmental disturbances.

36.7 | Behavioral Biology: Proximate and Ultimate

Causes of Behavior

In this section, you will explore the following questions:

- What is the difference between innate and learned behavior?
- How are movement and migration behaviors a result of natural selection?
- What are different ways members of a population communicate with each other?
- What are examples of how species use energy for mating displays and other courtship behaviors?
- What are examples of various mating systems?
- What are different ways that species learn?

Connection for AP® Courses

Behavior is the change in activity of an organism in response to a stimulus. **Innate behaviors** have a strong genetic component and are largely independent of environmental influences. In other words, these instinctive behaviors are "hard wired." Examples of innate behaviors include a human baby grabbing her mother's finger and the stork using its long beak to forage. **Learned behaviors** result from environmental conditioning and are modified by learning. For example, you likely have learned by now that reading these AP® Connections help you digest the information and that studying for a test improves your grade.

Information presented and the examples highlighted in the section support concepts outlined in Big Idea 2 and Big Idea 3 of the AP® Biology Curriculum Framework. The AP® Learning Objective listed in the Curriculum Framework provide a transparent foundation for the AP® Biology course, an inquiry-based laboratory experience, instructional activities, and AP® exam questions. A learning objective merges required content with one or more of the seven science practices.

Big Idea 2	Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.
Enduring Understanding 2.C	Organisms use feedback mechanisms to regulate growth and reproduction, and to maintain dynamic homeostasis.
Essential Knowledge	**2.C.2** Organisms respond to changes in their external environments.
Science Practice	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	**4.13** The student is able to predict the effects of a change in the community's populations on the community.
Enduring Understanding 2.E	Many biological processes involved in growth, reproduction and dynamic homeostasis include temporal regulation and coordination.
Essential Knowledge	**2.E.3** Timing and coordination of behavior are regulated by various mechanisms and are important in natural selection.
Science Practice	**4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question.
Learning Objective	**2.21** The student is able to justify the selection of the kind of data needed to answer scientific questions about the relevant mechanism that organisms use to respond to changes in their external environment.

Essential Knowledge	**2.E.3** Timing and coordination of behavior are regulated by various mechanisms and are important in natural selection.
Science Practice	**5.1** The student can analyze data to identify patterns or relationships.
Learning Objective	**2.38** The student is able to analyze data to support the claim that responses to information and communication of information affect natural selection.
Essential Knowledge	**2.E.3** Timing and coordination of behavior are regulated by various mechanisms and are important in natural selection.
Science Practice	**6.1** The student can justify claims with evidence.
Learning Objective	**2.39** The student is able to justify scientific claims, using evidence, to describe how timing and coordination of behavioral events in organisms are regulated by several mechanisms.
Essential Knowledge	**2.E.3** Timing and coordination of behavior are regulated by various mechanisms and are important in natural selection.
Science Practice	**7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	**2.40** The student is able to connect concepts in and across domain(s) to predict how environmental factors affect response to information and change behavior.
Big Idea 3	Living systems store, retrieve, transmit and respond to information essential to life processes.
Enduring Understanding 3.E	Transmission of information results in changes within and between biological systems.
Essential Knowledge	**3.E.1** Individuals can act on information and communicate it to others.
Science Practice	**5.1** The student can analyze data to identify patterns or relationships.
Learning Objective	**3.40** The student is able to analyze data that indicate how organisms exchange information in response to internal changes and external cues, and which can change behavior.
Essential Knowledge	**3.E.1** Individuals can act on information and communicate it to others.
Science Practice	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	**3.41** The student is able to create a representation that describes how organisms exchange information in response to internal changes and external cues, and which can result in changes in behavior.
Essential Knowledge	**3.E.1** Individuals can act on information and communicate it to others.
Science Practice	**7.1** The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	**3.42** The student is able to describe how organisms exchange information in response to internal changes or environmental cues.

Behavioral biology is the study of the biological and evolutionary bases for such changes. The idea that behaviors evolved as a result of the pressures of natural selection is not new. Animal behavior has been studied for decades, by biologists in the science of **ethology**, by psychologists in the science of comparative psychology, and by scientists of many disciplines in the study of neurobiology. Although there is overlap between these disciplines, scientists in these behavioral fields take different approaches. Comparative psychology is an extension of work done in human and behavioral psychology. Ethology is an extension of genetics, evolution, anatomy, physiology, and other biological disciplines. Still, one cannot study behavioral biology without touching on both comparative psychology and ethology.

One goal of behavioral biology is to dissect out the innate behaviors, which have a strong genetic component and are largely independent of environmental influences, from the learned behaviors, which result from environmental conditioning. Innate behavior, or instinct, is important because there is no risk of an incorrect behavior being learned. They are "hard wired" into the system. On the other hand, learned behaviors, although riskier, are flexible, dynamic, and can be altered according to changes in the environment.

Innate Behaviors: Movement and Migration

Innate or instinctual behaviors rely on response to stimuli. The simplest example of this is a **reflex action**, an involuntary and rapid response to stimulus. To test the "knee-jerk" reflex, a doctor taps the patellar tendon below the kneecap with a rubber hammer. The stimulation of the nerves there leads to the reflex of extending the leg at the knee. This is similar to the reaction of someone who touches a hot stove and instinctually pulls his or her hand away. Even humans, with our great capacity to learn, still exhibit a variety of innate behaviors.

Kinesis and Taxis

Another activity or movement of innate behavior is **kinesis**, or the undirected movement in response to a stimulus. Orthokinesis is the increased or decreased speed of movement of an organism in response to a stimulus. Woodlice, for example, increase their speed of movement when exposed to high or low temperatures. This movement, although random, increases the probability that the insect spends less time in the unfavorable environment. Another example is klinokinesis, an increase in turning behaviors. It is exhibited by bacteria such as *E. coli* which, in association with orthokinesis, helps the organisms randomly find a more hospitable environment.

A similar, but more directed version of kinesis is **taxis**: the directed movement towards or away from a stimulus. This movement can be in response to light (phototaxis), chemical signals (chemotaxis), or gravity (geotaxis) and can be directed toward (positive) or away (negative) from the source of the stimulus. An example of a positive chemotaxis is exhibited by the unicellular protozoan *Tetrahymena thermophila*. This organism swims using its cilia, at times moving in a straight line, and at other times making turns. The attracting chemotactic agent alters the frequency of turning as the organism moves directly toward the source, following the increasing concentration gradient.

Fixed Action Patterns

A **fixed action pattern** is a series of movements elicited by a stimulus such that even when the stimulus is removed, the pattern goes on to completion. An example of such a behavior occurs in the three-spined stickleback, a small freshwater fish (**Figure 3.35**). Males of this species develop a red belly during breeding season and show instinctual aggressiveness to other males during this time. In laboratory experiments, researchers exposed such fish to objects that in no way resemble a fish in their shape, but which were painted red on their lower halves. The male sticklebacks responded aggressively to the objects just as if they were real male sticklebacks.

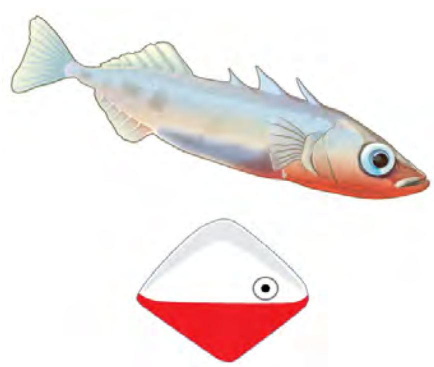


Figure 3.35 Male three-spined stickleback fish exhibit a fixed action pattern. During mating season, the males, which develop a bright red belly, react strongly to red-bottomed objects that in no way resemble fish.

Migration

Migration is the long-range seasonal movement of animals. It is an evolved, adapted response to variation in resource availability, and it is a common phenomenon found in all major groups of animals. Birds fly south for the winter to get to warmer climates with sufficient food, and salmon migrate to their spawning grounds. The popular 2005 documentary *March of the Penguins* followed the 62-mile migration of emperor penguins through Antarctica to bring food back to their breeding site and to their young. Wildebeests (**Figure 3.36**) migrate over 1800 miles each year in search of new grasslands.

Figure 3.36 Wildebeests migrate in a clockwise fashion over 1800 miles each year in search of rain-ripened grass. (credit: Eric Inafuku)

Although migration is thought of as innate behavior, only some migrating species always migrate (obligate migration). Animals that exhibit facultative migration can choose to migrate or not. Additionally, in some animals, only a portion of the population migrates, whereas the rest does not migrate (incomplete migration). For example, owls that live in the tundra may migrate in years when their food source, small rodents, is relatively scarce, but not migrate during the years when rodents are plentiful.

Foraging

Foraging is the act of searching for and exploiting food resources. Feeding behaviors that maximize energy gain and minimize energy expenditure are called optimal foraging behaviors, and these are favored by natural section. The painted stork, for example, uses its long beak to search the bottom of a freshwater marshland for crabs and other food (**Figure 3.37**).

Figure 3.37 The painted stork uses its long beak to forage. (credit: J.M. Garg)

Innate Behaviors: Living in Groups

Not all animals live in groups, but even those that live relatively solitary lives, with the exception of those that can reproduce asexually, must mate. Mating usually involves one animal signaling another so as to communicate the desire to mate. There are several types of energy-intensive behaviors or displays associated with mating, called mating rituals. Other behaviors found in populations that live in groups are described in terms of which animal benefits from the behavior. In selfish behavior, only the animal in question benefits; in altruistic behavior, one animal's actions benefit another animal; cooperative behavior describes when both animals benefit. All of these behaviors involve some sort of communication between population members.

Communication within a Species

Animals communicate with each other using stimuli known as **signals**. An example of this is seen in the three-spined stickleback, where the visual signal of a red region in the lower half of a fish signals males to become aggressive and signals females to mate. Other signals are chemical (pheromones), aural (sound), visual (courtship and aggressive displays), or tactile (touch). These types of communication may be instinctual or learned or a combination of both. These are not the same as the communication we associate with language, which has been observed only in humans and perhaps in some species of primates and cetaceans.

A pheromone is a secreted chemical signal used to obtain a response from another individual of the same species. The purpose of pheromones is to elicit a specific behavior from the receiving individual. Pheromones are especially common among social insects, but they are used by many species to attract the opposite sex, to sound alarms, to mark food trails, and to elicit other, more complex behaviors. Even humans are thought to respond to certain pheromones called axillary steroids. These chemicals influence human perception of other people, and in one study were responsible for a group of women synchronizing their menstrual cycles. The role of pheromones in human-to-human communication is still somewhat controversial and continues to be researched.

Songs are an example of an aural signal, one that needs to be heard by the recipient. Perhaps the best known of these are songs of birds, which identify the species and are used to attract mates. Other well-known songs are those of whales, which are of such low frequency that they can travel long distances underwater. Dolphins communicate with each other using a wide variety of vocalizations. Male crickets make chirping sounds using a specialized organ to attract a mate, repel other males, and to announce a successful mating.

Courtship displays are a series of ritualized visual behaviors (signals) designed to attract and convince a member of the opposite sex to mate. These displays are ubiquitous in the animal kingdom. Often these displays involve a series of steps, including an initial display by one member followed by a response from the other. If at any point, the display is performed incorrectly or a proper response is not given, the mating ritual is abandoned and the mating attempt will be unsuccessful. The mating display of the common stork is shown in **Figure 3.38**.

Aggressive displays are also common in the animal kingdom. An example is when a dog bares its teeth when it wants another dog to back down. Presumably, these displays communicate not only the willingness of the animal to fight, but also its fighting ability. Although these displays do signal aggression on the part of the sender, it is thought that these displays are actually a mechanism to reduce the amount of actual fighting that occurs between members of the same species: they allow individuals to assess the fighting ability of their opponent and thus decide whether it is “worth the fight.” The testing of certain hypotheses using game theory has led to the conclusion that some of these displays may overstate an animal’s actual fighting ability and are used to “bluff” the opponent. This type of interaction, even if “dishonest,” would be favored by natural selection if it is successful more times than not.

Figure 3.38 This stork’s courtship display is designed to attract potential mates. (credit: Linda “jinterwas”/Flickr)

Distraction displays are seen in birds and some fish. They are designed to attract a predator away from the nest that contains their young. This is an example of an altruistic behavior: it benefits the young more than the individual performing the display, which is putting itself at risk by doing so.

Many animals, especially primates, communicate with other members in the group through touch. Activities such as grooming, touching the shoulder or root of the tail, embracing, lip contact, and greeting ceremonies have all been observed in the Indian langur, an Old World monkey. Similar behaviors are found in other primates, especially in the great apes.

LINK TO LEARNING

The killdeer bird distracts predators from its eggs by faking a broken wing display in this **video (http://openstaxcollege.org/l/killdeer_bird)** taken in Boise, Idaho.

Explain why the behavior shown in the video represents both a distraction display and an altruistic type of behavior.

a. The parent creates a distraction to attract the predator away from young fledgling by pretending to have a broken wing. It is an altruistic behavior as the parent runs the risk of getting killed or harmed by predator.

b. The parent creates a distraction by being more aggressive and showing its willingness to fight. Altruistic behavior is seen as the parent runs the risk of getting attacked, killed, or harmed by the predator.

c. Parent creates distraction to attract the predator away from young fledgling by pretending to have a broken wing. It is exhibiting an altruistic behavior as in saving its fledgling; it is increasing its own fitness along with the fitness of the young bird.

d. Parent creates distraction by being more aggressive and showing its willingness to fight. It is exhibiting an altruistic behavior by saving its fledgling; it is decreasing its own fitness along with the fitness of the young bird.

Altruistic Behaviors

Behaviors that lower the fitness of the individual but increase the fitness of another individual are termed altruistic. Examples of such behaviors are seen widely across the animal kingdom. Social insects such as worker bees have no ability to reproduce, yet they maintain the queen so she can populate the hive with her offspring. Meerkats keep a sentry standing guard to warn the rest of the colony about intruders, even though the sentry is putting itself at risk. Wolves and wild dogs bring meat to pack members not present during a hunt. Lemurs take care of infants unrelated to them. Although on the surface, these behaviors appear to be altruistic, it may not be so simple.

There has been much discussion over why altruistic behaviors exist. Do these behaviors lead to overall evolutionary advantages for their species? Do they help the altruistic individual pass on its own genes? And what about such activities between unrelated individuals? One explanation for altruistic-type behaviors is found in the genetics of natural selection. In the 1976 book, *The Selfish Gene,* scientist Richard Dawkins attempted to explain many seemingly altruistic behaviors from the viewpoint of the gene itself. Although a gene obviously cannot be selfish in the human sense, it may appear that way if the sacrifice of an individual benefits related individuals that share genes that are identical by descent (present in relatives because of common lineage). Mammal parents make this sacrifice to take care of their offspring. Emperor penguins migrate miles in harsh conditions to bring food back for their young. Selfish gene theory has been controversial over the years and is still discussed among scientists in related fields.

Even less-related individuals, those with less genetic identity than that shared by parent and offspring, benefit from seemingly altruistic behavior. The activities of social insects such as bees, wasps, ants, and termites are good examples. Sterile workers in these societies take care of the queen because they are closely related to it, and as the queen has offspring, she is passing on genes from the workers indirectly. Thus, it is of fitness benefit for the worker to maintain the queen without having any direct chance of passing on its genes due to its sterility. The lowering of individual fitness to enhance the reproductive fitness of a relative and thus one’s inclusive fitness evolves through **kin selection**. This phenomenon can explain many superficially altruistic behaviors seen in animals. However, these behaviors may not be truly defined as altruism in these cases because the actor is actually increasing its own fitness either directly (through its own offspring) or indirectly (through the inclusive fitness it gains through relatives that share genes with it).

Unrelated individuals may also act altruistically to each other, and this seems to defy the “selfish gene” explanation. An example of this observed in many monkey species where a monkey will present its back to an unrelated monkey to have that individual pick the parasites from its fur. After a certain amount of time, the roles are reversed and the first monkey now grooms the second monkey. Thus, there is reciprocity in the behavior. Both benefit from the interaction and their fitness is raised more than if neither cooperated nor if one cooperated and the other did not cooperate. This behavior is still not necessarily altruism, as the "giving" behavior of the actor is based on the expectation that it will be the "receiver" of the behavior in the future, termed reciprocal altruism. Reciprocal altruism requires that individuals repeatedly encounter each other, often the result of living in the same social group, and that cheaters (those that never "give back") are punished.

Evolutionary game theory, a modification of classical game theory in mathematics, has shown that many of these so-called "altruistic behaviors" are not altruistic at all. The definition of "pure" altruism, based on human behavior, is an action that benefits another without any direct benefit to oneself. Most of the behaviors previously described do not seem to satisfy this definition, and game theorists are good at finding "selfish" components in them. Others have argued that the terms "selfish" and "altruistic" should be dropped completely when discussing animal behavior, as they describe human behavior and may not be directly applicable to instinctual animal activity. What is clear, though, is that heritable behaviors that improve the chances of passing on one's genes or a portion of one's genes are favored by natural selection and will be retained in future generations as long as those behaviors convey a fitness advantage. These instinctual behaviors may then be applied, in special circumstances, to other species, as long as it doesn't lower the animal's fitness.

Finding Sex Partners

Not all animals reproduce sexually, but many that do have the same challenge: they need to find a suitable mate and often have to compete with other individuals to obtain one. Significant energy is spent in the process of locating, attracting, and mating with the sex partner. Two types of selection occur during this process and can lead to traits that are important to reproduction called secondary sexual characteristics: **intersexual selection**, the choosing of a mate where individuals of one sex choose mates of the other sex, and **intrasexual selection**, the competition for mates between species members of the same sex. Intersexual selection is often complex because choosing a mate may be based on a variety of visual, aural, tactile, and chemical cues. An example of intersexual selection is when female peacocks choose to mate with the male with the brightest plumage. This type of selection often leads to traits in the chosen sex that do not enhance survival, but are those traits most attractive to the opposite sex (often at the expense of survival). Intrasexual selection involves mating displays and aggressive mating rituals such as rams butting heads—the winner of these battles is the one that is able to mate. Many of these rituals use up considerable energy but result in the selection of the healthiest, strongest, and/or most dominant individuals for mating. Three general mating systems, all involving innate as opposed to learned behaviors, are seen in animal populations: monogamous, polygynous, and polyandrous.

LINK TO LEARNING

Visit this **website (http://openstaxcollege.org/l/sex_selection)** for informative videos on sexual selection.

The greater sage grouse uses a mating system in which one male mates with many females. Name this mating system.

a. polyandrous
b. monogamous
c. intrasexual selection
d. polygynous

science practices CONNECTION for AP® Courses

Activity

In 1980, John Endler published his investigation into natural selection in Trinidad guppies (*Poecilia reticulata*). Some of these guppies have brighter coloration than others. Endler hypothesized that guppies with less predation have brighter colors due to sexual selection because females prefer more brightly-colored males. He then on to hypothesized that male guppies that experience greater predation become more drab-colored to camouflage themselves from predators.. In addition to a laboratory study, he tested this using a field experiment involving four areas. Area 1 had no guppies while area 2 had guppies but no predators. Area 3 had guppies and a predator (*Crenicichla alta*). Endler introduced guppies from area 3 (which were drab because of predation) to area 1 (which had no guppies). The guppies that were relocated to area 1 developed brighter colors over 2 years (enough for several guppy generations) and eventually resembled the guppies in area 2. Make a diagram showing each of the locations, all of the fish species present at the start, and the fish present at the end. Label the fish as “more conspicuous colors” or “less conspicuous colors.”

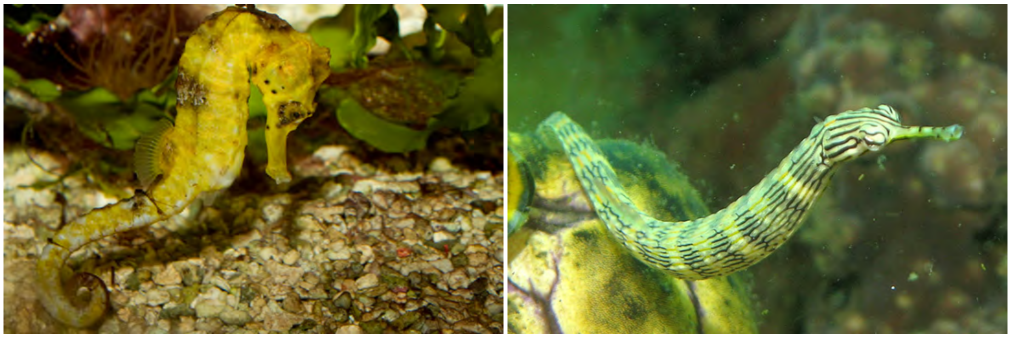
Think About It

Describe how this experiment shows that there is genetic variability in the original population. How do you know that there was genetic variability in the fish taken from area 1? Explain the tradeoff between bright colors that are attractive to female guppies and the risk of predation. What would you expect to happen if you moved fish from area 2 back to area 3? What would you expect to happen in each area if female fish began to prefer larger fish rather than more brightly colored fish?

In **monogamous** systems, one male and one female are paired for at least one breeding season. In some animals, such as the gray wolf, these associations can last much longer, even a lifetime. Several explanations have been proposed for this type of mating system. The “mate-guarding hypothesis” states that males stay with the female to prevent other males from mating with her. This behavior is advantageous in such situations where mates are scarce and difficult to find. Another explanation is the “male-assistance hypothesis,” where males that remain with a female to help guard and rear their young will have more and healthier offspring. Monogamy is observed in many bird populations where, in addition to the parental care from the female, the male is also a major provider of parental care for the chicks. A third explanation for the evolutionary advantages of monogamy is the “female-enforcement hypothesis.” In this scenario, the female ensures that the male does not have other offspring that might compete with her own, so she actively interferes with the male’s signaling to attract other mates.

Polygynous mating refers to one male mating with multiple females. In these situations, the female must be responsible for most of the parental care as the single male is not capable of providing care to that many offspring. In resourced-based polygyny, males compete for territories with the best resources, and then mate with females that enter the territory, drawn to its resource richness. The female benefits by mating with a dominant, genetically fit male; however, it is at the cost of having no male help in caring for the offspring. An example is seen in the yellow-rumped honeyguide, a bird whose males defend beehives because the females feed on their wax. As the females approach, the male defending the nest will mate with them. Harem mating structures are a type of polygynous system where certain males dominate mating while controlling a territory with resources. Elephant seals, where the alpha male dominates the mating within the group are an example. A third type of polygyny is a lek system. Here there is a communal courting area where several males perform elaborate displays for females, and the females choose their mate from this group. This behavior is observed in several bird species including the sage grouse and the prairie chicken.

In **polyandrous** mating systems, one female mates with many males. These types of systems are much rarer than monogamous and polygynous mating systems. In pipefishes and seahorses, males receive the eggs from the female, fertilize them, protect them within a pouch, and give birth to the offspring (**Figure 3.39**). Therefore, the female is able to provide eggs to several males without the burden of carrying the fertilized eggs.



(a) (b)

Figure 3.39 Polyandrous mating, in which one female mates with many males, occurs in the (a) seahorse and the (b) pipefish. (credit a: modification of work by Brian Gratwicke; credit b: modification of work by Stephen Childs)

Simple Learned Behaviors

The majority of the behaviors previously discussed were innate or at least have an innate component (variations on the innate behaviors may be learned). They are inherited and the behaviors do not change in response to signals from the environment. Conversely, learned behaviors, even though they may have instinctive components, allow an organism to adapt to changes in the environment and are modified by previous experiences. Simple learned behaviors include habituation and imprinting—both are important to the maturation process of young animals.

Habituation

Habituation is a simple form of learning in which an animal stops responding to a stimulus after a period of repeated exposure. This is a form of non-associative learning, as the stimulus is not associated with any punishment or reward. Prairie dogs typically sound an alarm call when threatened by a predator, but they become habituated to the sound of human footsteps when no harm is associated with this sound, therefore, they no longer respond to them with an alarm call. In this example, habituation is specific to the sound of human footsteps, as the animals still respond to the sounds of potential predators.

Imprinting

Imprinting is a type of learning that occurs at a particular age or a life stage that is rapid and independent of the species involved. Hatchling ducks recognize the first adult they see, their mother, and make a bond with her. A familiar sight is ducklings walking or swimming after their mothers (**Figure 3.40**). This is another type of non-associative learning, but is very important in the maturation process of these animals as it encourages them to stay near their mother so they will be protected, greatly increasing their chances of survival. However, if newborn ducks see a human before they see their mother, they will imprint on the human and follow it in just the same manner as they would follow their real mother.

Figure 3.40 The attachment of ducklings to their mother is an example of imprinting. (credit: modification of work by Mark Harkin)

LINK TO LEARNING

The International Crane Foundation has helped raise the world's population of whooping cranes from 21 individuals to about 600. Imprinting hatchlings has been a key to success: biologists wear full crane costumes so the birds never "see" humans. Watch this **video (http://openstaxcollege.org/l/whooping_crane)** to learn more.

Workers wear a special costume when interacting with whooping crane chicks. Justify the need for this process.

a. Whooping crane chicks undergo habituation in which the chicks make a bond with the objects they see in the environment. Therefore, workers must wear a special costume to fool the chick into thinking it is associating with an adult whooping crane.

b. Whooping crane chicks undergo imprinting with the first object they see. Therefore, workers must wear a special costume to fool the chick into thinking it is associating with an adult whooping crane to avoid creating the expectation it will mate with a human.

c. Whooping crane chicks undergo imprinting with the first few objects they see. Therefore, workers must wear a special costume to fool the chick into thinking it is associating with an adult whooping crane to avoid creating the expectation that it will mate with a human.

d. Whooping crane undergoes habituation in which the chicks only make a bond with the first object they see. The young chicks only trust that first object to feed them. Thus workers must wear a special costume to fool the chick into thinking it is associating with an adult whooping crane.

Conditioned Behavior

Conditioned behaviors are types of associative learning, where a stimulus becomes associated with a consequence. During operant conditioning, the behavioral response is modified by its consequences, with regards to its form, strength, or frequency.

Classical Conditioning

In **classical conditioning**, a response called the conditioned response is associated with a stimulus that it had previously not been associated with, the conditioned stimulus. The response to the original, unconditioned stimulus is called the unconditioned response. The most cited example of classical conditioning is Ivan Pavlov's experiments with dogs (**Figure 3.41**). In Pavlov's experiments, the unconditioned response was the salivation of dogs in response to the unconditioned stimulus of seeing or smelling their food. The conditioning stimulus that researchers associated with the unconditioned response was the ringing of a bell. During conditioning, every time the animal was given food, the bell was rung. This was repeated during several trials. After some time, the dog learned to associate the ringing of the bell with food and to respond by salivating. After the conditioning period was finished, the dog would respond by salivating when the bell was rung, even when the unconditioned stimulus, the food, was absent. Thus, the ringing of the bell became the conditioned stimulus and the salivation became the conditioned response. Although it is thought by some scientists that the unconditioned and conditioned responses are identical, even Pavlov discovered that the saliva in the conditioned dogs had characteristic differences when compared to the unconditioned dog.

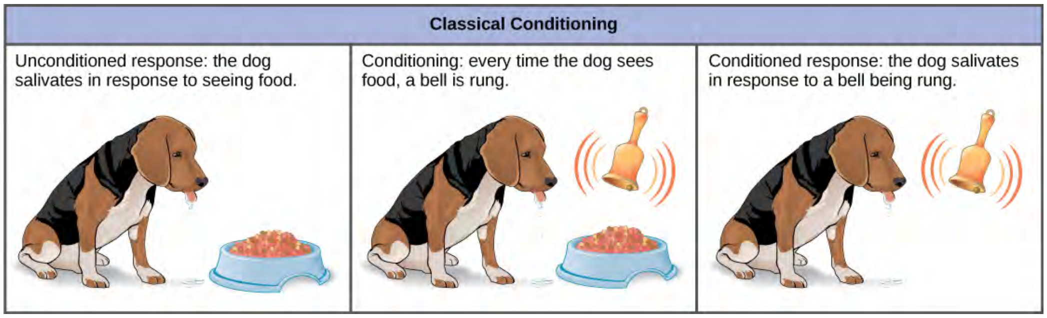


Figure 3.41 In the classic Pavlovian response, the dog becomes conditioned to associate the ringing of the bell with food.

It had been thought by some scientists that this type of conditioning required multiple exposures to the paired stimulus and response, but it is now known that this is not necessary in all cases, and that some conditioning can be learned in a single pairing experiment. Classical conditioning is a major tenet of behaviorism, a branch of psychological philosophy that proposes that all actions, thoughts, and emotions of living things are behaviors that can be treated by behavior modification and changes in the environment.

Operant Conditioning

In **operant conditioning**, the conditioned behavior is gradually modified by its consequences as the animal responds to the stimulus. A major proponent of such conditioning was psychologist B.F. Skinner, the inventor of the Skinner box. Skinner put rats in his boxes that contained a lever that would dispense food to the rat when depressed. While initially the rat would push the lever a few times by accident, it eventually associated pushing the lever with getting the food. This type of learning is an example of operant conditioning. Operant learning is the basis of most animal training. The conditioned behavior is continually modified by positive or negative reinforcement, often a reward such as food or some type of punishment, respectively. In this way, the animal is conditioned to associate a type of behavior with the punishment or reward, and, over time, can be induced to perform behaviors that they would not have done in the wild, such as the "tricks" dolphins perform at marine amusement park shows (**Figure 3.42**).

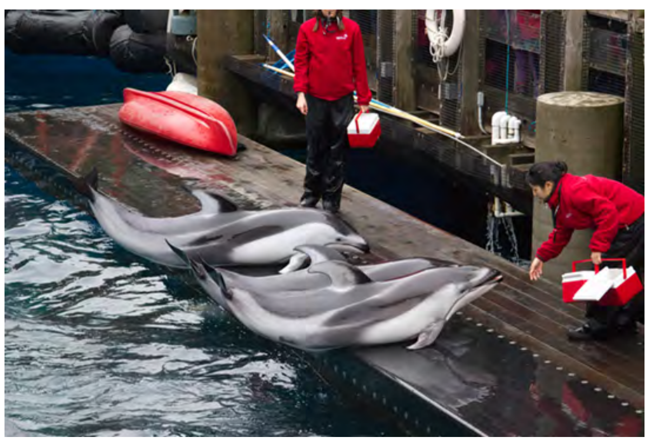


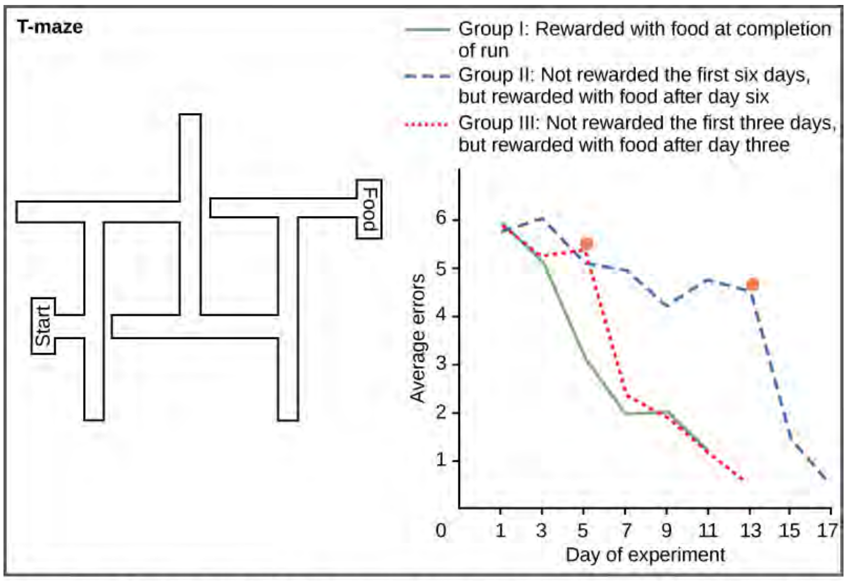
Figure 3.42 The training of dolphins by rewarding them with food is an example of positive reinforcement operant conditioning. (credit: Roland Tanglao)

Cognitive Learning

Classical and operant conditioning are inefficient ways for humans and other intelligent animals to learn. Some primates, including humans, are able to learn by imitating the behavior of others and by taking instructions. The development of complex language by humans has made **cognitive learning**, the manipulation of information using the mind, the most prominent method of human learning. In fact, that is how students are learning right now by reading this book. As students read, they can make mental images of objects or organisms and imagine changes to them, or behaviors by them, and anticipate the consequences. In addition to visual processing, cognitive learning is also enhanced by remembering past experiences, touching physical objects, hearing sounds, tasting food, and a variety of other sensory-based inputs. Cognitive learning is so powerful that it can be used to understand conditioning in detail. In the reverse scenario, conditioning cannot help someone learn about cognition.

Classic work on cognitive learning was done by Wolfgang Köhler with chimpanzees. He demonstrated that these animals were capable of abstract thought by showing that they could learn how to solve a puzzle. When a banana was hung in their cage too high for them to reach, and several boxes were placed randomly on the floor, some of the chimps were able to stack the boxes one on top of the other, climb on top of them, and get the banana. This implies that they could visualize the result of stacking the boxes even before they had performed the action. This type of learning is much more powerful and versatile than conditioning.

Cognitive learning is not limited to primates, although they are the most efficient in using it. Maze running experiments done with rats by H.C. Blodgett in the 1920s were the first to show cognitive skills in a simple mammal. The motivation for the animals to work their way through the maze was a piece of food at its end. In these studies, the animals in Group I were run in one trial per day and had food available to them each day on completion of the run (**Figure 3.43**). Group II rats were not fed in the maze for the first six days and then subsequent runs were done with food for several days after. Group III rats had food available on the third day and every day thereafter. The results were that the control rats, Group I, learned quickly, and figured out how to run the maze in seven days. Group III did not learn much during the three days without food, but rapidly caught up to the control group when given the food reward. Group II learned very slowly for the six days with no reward to motivate them, and they did not begin to catch up to the control group until the day food was given, and then it took two days longer to learn the maze.



Redrawn after H. C. Blodgett, The effect of the introduction of reward upon the maze performance of rats. Univ. Calif. Publ. Psychol., 1929, 4, No. 8, pages 117 and 120.

Figure 3.43 Group I (the green solid line) found food at the end of each trial, group II (the blue dashed line) did not find food for the first 6 days, and group III (the red dotted line) did not find food during runs on the first three days. Notice that rats given food earlier learned faster and eventually caught up to the control group. The orange dots on the group II and III lines show the days when food rewards were added to the mazes.

It may not be immediately obvious that this type of learning is different than conditioning. Although one might be tempted to believe that the rats simply learned how to find their way through a conditioned series of right and left turns, E.C. Tolman proved a decade later that the rats were making a representation of the maze in their minds, which he called a "cognitive map." This was an early demonstration of the power of cognitive learning and how these abilities were not just limited to humans.

Sociobiology

Sociobiology is an interdisciplinary science originally popularized by social insect researcher E.O. Wilson in the 1970s. Wilson defined the science as "the extension of population biology and evolutionary theory to social organization."[9] The main thrust of sociobiology is that animal and human behavior, including aggressiveness and other social interactions, can be explained almost solely in terms of genetics and natural selection. This science is controversial; noted scientists such as the late Stephen Jay Gould criticized the approach for ignoring the environmental effects on behavior. This is another example of the "nature versus nurture" debate of the role of genetics versus the role of environment in determining an organism's characteristics.

Sociobiology also links genes with behaviors and has been associated with "biological determinism," the belief that all

9. Edward O. Wilson. *On Human Nature* (1978; repr., Cambridge: Harvard University Press, 2004), xx.

behaviors are hardwired into our genes. No one disputes that certain behaviors can be inherited and that natural selection plays a role retaining them. It is the application of such principles to human behavior that sparks this controversy, which remains active today.

science practices CONNECTION for AP® Courses

Lab Investigation

AP® Biology Investigative Labs: Inquiry-Based Approach, Investigation 12: Fruit Fly Behavior. This inquiry-based investigation provides an opportunity for you to design and implement a series of experiments using choice chambers to investigate behaviors that underlie directed movement (taxis) towards or away from environmental stimuli, including chemical signals, light, and temperature, in a small population of *Drosophila*.

Activity

Animal Behavior Field Study

Animal behavior can be studied in nearly every environment. Visit a local park, zoo, athletic field, or even a location on your school campus and observe the behaviors and interactions among different animals and with their environment. Consider the following questions in your study: How do animals exchange information and alter behavior in response to stimuli? What mechanisms do animals use to communicate information? What examples of innate and learned behaviors did you observe? What predictions can you make about observed behavior(s) if environmental conditions change?

Think About It

Describe how Pavlov's dog experiments are an example of classical conditioning. How does operant conditioning that you use to train a pet to do a trick differ from classical conditioning? What type of conditioning describes how you learned that studying likely will improve your grade on an AP® test?

KEY TERMS

age structure proportion of population members at specific age ranges

aggressive display visual display by a species member to discourage other members of the same species or different species

aposematic coloration warning coloration used as a defensive mechanism against predation

Batesian mimicry type of mimicry where a non-harmful species takes on the warning colorations of a harmful one

behavior change in an organism's activities in response to a stimulus

behavioral biology study of the biology and evolution of behavior

biotic potential (r_{max}) maximal potential growth rate of a species

birth rate (*B*) number of births within a population at a specific point in time

camouflage avoid detection by blending in with the background.

carrying capacity (*K*) number of individuals of a species that can be supported by the limited resources of a habitat

classical conditioning association of a specific stimulus and response through conditioning

climax community final stage of succession, where a stable community is formed by a characteristic assortment of plant and animal species

cognitive learning knowledge and skills acquired by the manipulation of information in the mind

commensalism relationship between species wherein one species benefits from the close, prolonged interaction, while the other species neither benefits nor is harmed

competitive exclusion principle no two species within a habitat can coexist when they compete for the same resources at the same place and time

conditioned behavior behavior that becomes associated with a specific stimulus through conditioning

courtship display visual display used to attract a mate

death rate (*D*) number of deaths within a population at a specific point in time

demographic-based population model modern model of population dynamics incorporating many features of the *r*- and *K*-selection theory

demography statistical study of changes in populations over time

density-dependent regulation regulation of population that is influenced by population density, such as crowding effects; usually involves biotic factors

density-independent regulation regulation of populations by factors that operate independent of population density, such as forest fires and volcanic eruptions; usually involves abiotic factors

distraction display visual display used to distract predators away from a nesting site

Emsleyan/Mertensian mimicry type of mimicry where a harmful species resembles a less harmful one

energy budget allocation of energy resources for body maintenance, reproduction, and parental care

environmental disturbance change in the environment caused by natural disasters or human activities

ethology biological study of animal behavior

exponential growth accelerating growth pattern seen in species under conditions where resources are not limiting

fecundity potential reproductive capacity of an individual

fixed action pattern series of instinctual behaviors that, once initiated, always goes to completion regardless of changes in the environment

foraging behaviors species use to find food

foundation species species which often forms the major structural portion of the habitat

habituation ability of a species to ignore repeated stimuli that have no consequence

host organism a parasite lives on

imprinting identification of parents by newborns as the first organism they see after birth

innate behavior instinctual behavior that is not altered by changes in the environment

intersexual selection selection of a desirable mate of the opposite sex

interspecific competition competition between species for resources in a shared habitat or environment

intrasexual selection competition between members of the same sex for a mate

intraspecific competition competition between members of the same species

island biogeography study of life on island chains and how their geography interacts with the diversity of species found there

iteroparity life history strategy characterized by multiple reproductive events during the lifetime of a species

J-shaped growth curve shape of an exponential growth curve

***K*-selected species** species suited to stable environments that produce a few, relatively large offspring and provide parental care

keystone species species whose presence is key to maintaining biodiversity in an ecosystem and to upholding an ecological community's structure

kin selection sacrificing one's own life so that one's genes will be passed on to future generations by relatives

kinesis undirected movement of an organism in response to a stimulus

learned behavior behavior that responds to changes in the environment

life history inherited pattern of resource allocation under the influence of natural selection and other evolutionary forces

life table table showing the life expectancy of a population member based on its age

logistic growth leveling off of exponential growth due to limiting resources

mark and recapture technique used to determine population size in mobile organisms

migration long-range seasonal movement of animal species

monogamy mating system whereby one male and one female remain coupled for at least one mating season

mortality rate proportion of population surviving to the beginning of an age interval that die during the age interval

mutualism symbiotic relationship between two species where both species benefit

Müllerian mimicry type of mimicry where species share warning coloration and all are harmful to predators

one-child policy China’s policy to limit population growth by limiting urban couples to have only one child or face the penalty of a fine

operant conditioning learned behaviors in response to positive and/or negative reinforcement

parasite organism that uses resources from another species, the host

pioneer species first species to appear in primary and secondary succession

polyandry mating system where one female mates with many males

polygyny mating system where one male mates with many females

population density number of population members divided by the area or volume being measured

population growth rate number of organisms added in each reproductive generation

population size (*N*) number of population members in a habitat at the same time

primary succession succession on land that previously has had no life

quadrat square made of various materials used to determine population size and density in slow moving or stationary organisms

***r*-selected species** species suited to changing environments that produce many offspring and provide little or no parental care

reflex action action in response to direct physical stimulation of a nerve

relative species abundance absolute population size of a particular species relative to the population sizes of other species within the community

S-shaped growth curve shape of a logistic growth curve

secondary succession succession in response to environmental disturbances that move a community away from its equilibrium

semelparity life history strategy characterized by a single reproductive event followed by death

signal method of communication between animals including those obtained by the senses of smell, hearing, sight, or touch

species dispersion pattern (also, species distribution pattern) spatial location of individuals of a given species within a habitat at a particular point in time

species richness number of different species in a community

survivorship curve graph of the number of surviving population members versus the relative age of the member

symbiosis close interaction between individuals of different species over an extended period of time that impacts the abundance and distribution of the associating populations

taxis directed movement in response to a stimulus

zero population growth steady population size where birth rates and death rates are equal

CHAPTER SUMMARY

36.1 Population Demography

Populations are individuals of a species that live in a particular habitat. Ecologists measure characteristics of populations: size, density, dispersion pattern, age structure, and sex ratio. Life tables are useful to calculate life expectancies of individual population members. Survivorship curves show the number of individuals surviving at each age interval plotted versus time.

36.2 Life Histories and Natural Selection

All species have evolved a pattern of living, called a life history strategy, in which they partition energy for growth, maintenance, and reproduction. These patterns evolve through natural selection; they allow species to adapt to their environment to obtain the resources they need to successfully reproduce. There is an inverse relationship between fecundity and parental care. A species may reproduce early in life to ensure surviving to a reproductive age or reproduce later in life to become larger and healthier and better able to give parental care. A species may reproduce once (semelparity) or many times (iteroparity) in its life.

36.3 Environmental Limits to Population Growth

Populations with unlimited resources grow exponentially, with an accelerating growth rate. When resources become limiting, populations follow a logistic growth curve. The population of a species will level off at the carrying capacity of its environment.

36.4 Population Dynamics and Regulation

Populations are regulated by a variety of density-dependent and density-independent factors. Species are divided into two categories based on a variety of features of their life history patterns: *r*-selected species, which have large numbers of offspring, and *K*-selected species, which have few offspring. The *r*- and *K*-selection theory has fallen out of use; however, many of its key features are still used in newer, demographically-based models of population dynamics.

36.5 Human Population Growth

The world’s human population is growing at an exponential rate. Humans have increased the world’s carrying capacity through migration, agriculture, medical advances, and communication. The age structure of a population allows us to predict population growth. Unchecked human population growth could have dire long-term effects on our environment.

36.6 Community Ecology

Communities include all the different species living in a given area. The variety of these species is called species richness. Many organisms have developed defenses against predation and herbivory, including mechanical defenses, warning coloration, and mimicry, as a result of evolution and the interaction with other members of the community. Two species cannot exist in the same habitat competing directly for the same resources. Species may form symbiotic relationships such as commensalism or mutualism. Community structure is described by its foundation and keystone species. Communities respond to environmental disturbances by succession (the predictable appearance of different types of plant species) until a stable community structure is established.

36.7 Behavioral Biology: Proximate and Ultimate Causes of Behavior

Behaviors are responses to stimuli. They can either be instinctual/innate behaviors, which are not influenced by the environment, or learned behaviors, which are influenced by environmental changes. Instinctual behaviors include mating systems and methods of communication. Learned behaviors include imprinting and habituation, conditioning, and, most powerfully, cognitive learning. Although the connection between behavior, genetics, and evolution is well established, the explanation of human behavior as entirely genetic is controversial.

REVIEW QUESTIONS

1. An ecologist is planning to measure both the size and density of a population. Identify the experimental method that can best provide these data.

a. mark and recapture
b. mark and release
c. quadrat
d. life table

2. Which of the following statements can be made about the mark and recapture method of counting population numbers?

a. Using quadrats for counting individuals in a population increases the accuracy of the mark and recapture method.
b. The greater the number of individuals captured during the first round of mark and recapture, the greater is the overall population size.
c. The mark and recapture method is useful for mammals and birds, but of little use for other organisms.
d. An underestimate of population size would tend to be observed in cases of studies involving animals that learn to seek out bait.

3. Which type of dispersal pattern is characterized by even spacing between individuals in the population?

a. random
b. uniform
c. sparse
d. clumped

4. Identify the best method to show the life expectancy of an individual within a population.

a. mark and recapture
b. mark and release
c. quadrat
d. life table

5. Describe how a researcher would best collect data in order to calculate mortality rates within a population.

a. For various age groups, count the number of individuals that died and the number that survived within a defined time period.
b. For various age groups, count the number of individuals that were born and the number that died within a defined time period.
c. For each sex, count the number of individuals that were born and the number that survived within a defined time period.
d. For each sex, count the number of individuals that died and the number that were born within a defined time period.

6. What survivorship pattern can be used to describe humans?

a. by a type I survivorship curve
b. by a type II survivorship curve
c. by a type III survivorship curve
d. by a type IV survivorship curve

7. Different species have different survival curves. A Type III survival curve would most likely be observed for _____.

a. whales
b. seals
c. salmon
d. polar bears

8. Which of the following is associated with long-term parental care?

a. few offspring
b. many offspring
c. semelparity
d. fecundity

9. Which of the following conditions is inversely related with fecundity?

a. number of offspring

b. energy budget of parent

c. amount of parental care

d. age of parent

10. When studying a squash beetle native to the Everglades, scientists collected data to compare the squash beetle to another beetle native to the Great Lakes region. What data would be used to compare the beetles' reproductive potential?

a. few offspring

b. many offspring

c. semelparity

d. fecundity

11. Albatrosses are birds that can live to age 60 and older. They usually do not start breeding until they reach age 8 or 9, which is relatively late compared to other bird species. Based on this information, explain conditions that might be a risk to the survival of albatrosses.

a. increased chance of individuals dying before reproducing

b. decreased life spans of individuals

c. increased chance of offspring dying

d. decreased chances of mating between individuals

12. Frogs are animals with high fecundity. Based on this information, frogs should also have which of the following characteristics?

a. high energy budget

b. extensive energy storage for offspring

c. small numbers of offspring

d. little or no parental care

13. Species with limited resources usually exhibit a(n) ____ growth curve.

a. logistic

b. logical

c. experimental

d. exponential

14. Give an example of exponential population growth.

a. salamanders adapting to fungal infections

b. polar bears living in a warming habitat

c. bacteria growing in enriched medium in a lab

d. feral cats being trapped and neutered in a suburb

15. If the major food source of seals declines due to pollution or overfishing, how would the seal population be affected?

a. The carrying capacity of seals would decrease, as would the seal population.

b. The carrying capacity of seals would decrease, but the seal population would remain the same.

c. The number of seal deaths would increase but the number of births would also increase, so the population size would remain the same.

d. The carrying capacity of seals would remain the same, but the population of seals would decrease.

16. Define carrying capacity of a population and explain whether it changes or remains fixed for a population.

a. Carrying capacity is the amount of land needed to support a population, and it is fixed for each population.
b. Carrying capacity is the amount of water and food resources required to support a population and it is fixed for each population.
c. Carrying capacity is the maximum size of a population that can survive using the available resources and it can vary up or down.
d. Carrying capacity is the time needed for a population to reach its maximum size and it can vary up or down.

17. Suppose a pesticide used by farmers wipes out the insect population that feeds a population of bats. Predict the effects of this change on the bat population.

a. The carrying capacity of the population will increase.
b. The carrying capacity of the population will decrease.
c. The carrying capacity of the population will not change.
d. The carrying capacity of the population cannot be predicted.

18. Which explanation best defines density-dependent growth regulation.

a. a factor that affects population density but not population size
b. a factor that affects population size but not population density
c. a factor that affects population size regardless of population density
d. a factor that affects population size in ways related to population density

19. A forest fire is an example of ____ regulation.

a. density-dependent
b. density-independent
c. r-selected
d. K-selected

20. Species that have many offspring at one time are usually ________.

a. r-selected
b. K-selected
c. both r- and K-selected
d. not selected

21. The following statements compare r-selected and K-selected species. Identify the statement that makes an accurate comparison.

a. r-selected and K-selected species both have limitations in the amount of energy they can invest in reproduction, so they both use similar strategies.
b. r-selected and K-selected species both have limitations in the amount of energy they can invest in reproduction, but they use completely different strategies.
c. r-selected and K-selected species use similar reproductive strategies but r-selected species require less energy to reproduce than K-selected species.
d. r-selected and K-selected species use different reproductive strategies because r-selected species require less energy to reproduce than K-selected species.

22. If a population moves to a new environment rich in resources, what type of growth curve will it exhibit?

a. logistic
b. logical
c. experimental
d. exponential

23. Humans have altered environmental factors that have allowed the human population to grow exponentially. State an example of such a factor.

a. interspecific competition
b. age structure
c. carrying capacity
d. reproductive strategies

24. Humans have altered their own carrying capacity. Explain how humans have changed their carrying capacity and the consequences of this change.

a. By limiting their own carrying capacity, humans have enabled their population to grow rapidly.
b. By decreasing their own carrying capacity, humans have enabled their population to grow slowly.
c. By stabilizing their own carrying capacity, humans have enabled their population to grow steadily.
d. By increasing their own carrying capacity, humans have enabled their population to grow exponentially.

25. Humans have influenced their own carrying capacity in several ways. Some human activities increase carrying capacity while others decrease it. Identify a human activity that has decreased the human carrying capacity of the environment.

a. agriculture
b. using large amounts of natural resources
c. domestication of animals
d. use of language

26. Humans began developing oil as an energy source in the early part of the twentieth century. Explain the relationship between this development and the human carrying capacity of Earth.

a. Drilling for oil enabled humans to increase food production through the use of machinery, which increased the human carrying capacity of the Earth.
b. Oil production allowed new transportation methods faster than methods using animals, which decreased the human carrying capacity of the Earth.
c. Accessing oil as an energy source created increased greenhouse gas emissions, which increased the human carrying capacity of the Earth.
d. Oil as an energy source enabled humans to enjoy more recreational activities, which decreased the human carrying capacity of the Earth.

27. The greatest proportion of young individuals can be found in ___.

a. economically developed countries
b. economically underdeveloped countries
c. countries with zero population growth
d. countries in Europe

28. Explain the correlation between age structure and the level of economic development observed in many countries.

a. There is no correlation between the characteristics of age structures and the level of economic development.
b. Countries that are more economically developed tend to have fewer middle-aged individuals and more young individuals than undeveloped countries.
c. A larger ratio of very young individuals to very old individuals characterizes the age structures of countries with the highest economic development.
d. Age structures of economically undeveloped countries show greater proportions of children and fewer proportions of elderly people.

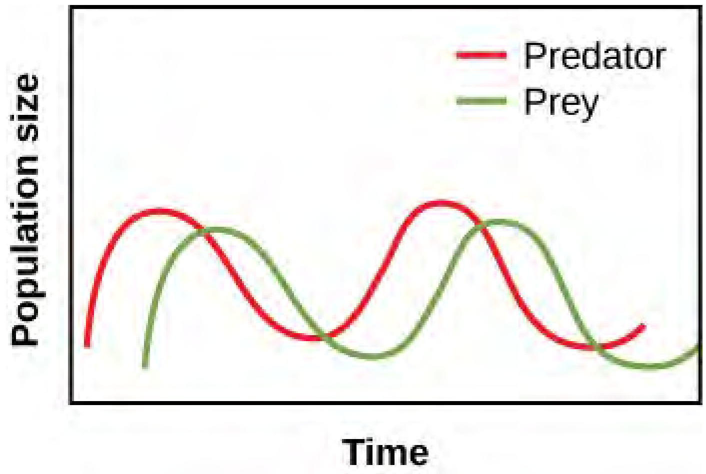
29. Which environmental characteristic is likely to increase if the human population continues growing unchecked?

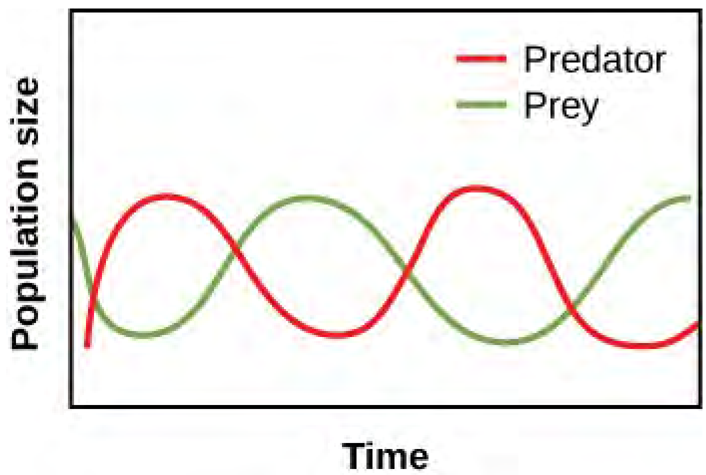
a. wilderness areas
b. fresh water supplies
c. fossil fuel reserves
d. atmospheric carbon dioxide

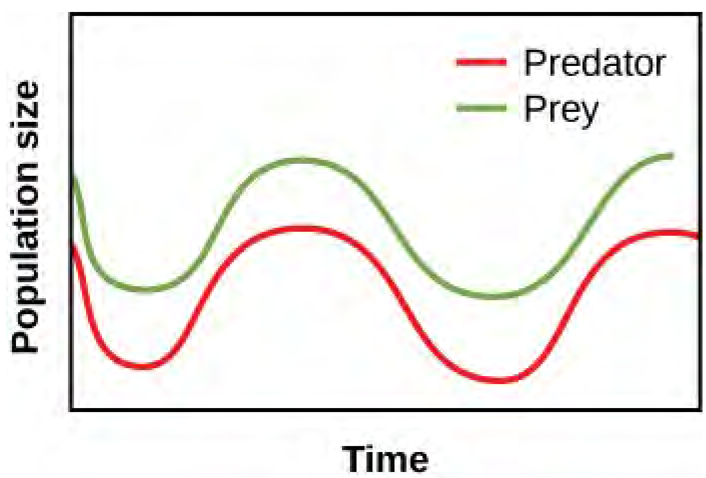
30. Predict and explain the effects of human population on biodiversity many years in the future.

a. Biodiversity will decline as human population increases because of habitat loss, increased pollution, and climate change.
b. Biodiversity will decline as human population increases because of enhanced food supplies, medical advances, and development of renewable energy sources.
c. Biodiversity will increase as human population increases because of habitat loss, increased pollution, and climate change.
d. Biodiversity will increase as human population increases because of enhanced food supplies, medical advances, and development of renewable energy sources.

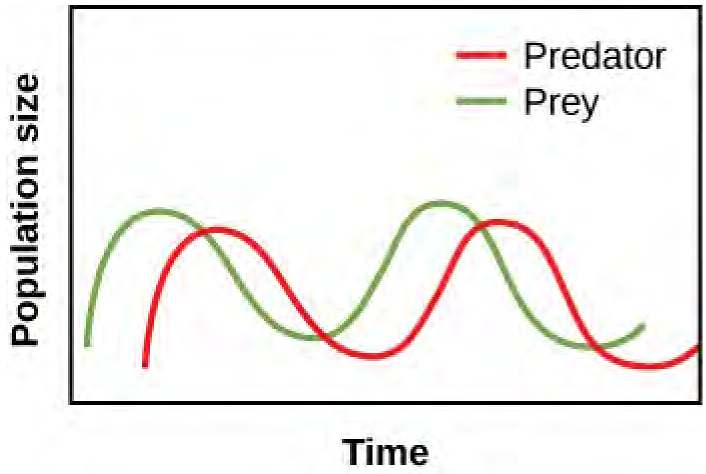
31. Analyze the predator-prey graphs to identify the graph that correctly depicts a predator-prey cycle.

a. 
Predator
Prey
Population size
Time

b. 
Predator
Prey
Population size
Time

c. 
Predator
Prey
Population size
Time

d.



32. Construct a statement to describe a predator-prey cycle.

a. Prey increase in numbers, causing an increase in the predator population, which, in turn, causes a downturn in prey numbers, and leads to a downturn in predator numbers, and then the cycle repeats.

b. The number of prey is directly related to the number of predators so that the two populations remain at the same ratio even though the total population numbers fluctuate.

c. Increasing prey numbers trigger decreases in predator numbers, which eventually causes a decrease in prey numbers as predators become too sparse, and then the cycle repeats.

d. A prey population undergoes a cyclic increasing and decreasing fluctuation in size as its predator population undergoes the same cycle but in a mirror image relationship.

33. In a region in Texas, biologists observed that two highly venomous snakes with similar markings deter owl predators. Upon closer inspection, the snakes were determined to belong to different genera and species. How would these biologists describe the mimicry in this case?

a. Batesian mimicry, because it involves nontoxic species that resembles a toxic species.

b. Emsleyan/Mertensian mimicry because an extremely toxic species resembles a less toxic species.

c. Batesian mimicry because it involves an extremely toxic species that resembles a less toxic species.

d. Mullerian mimicry because it involves different species that both produce toxins and display similar warning coloration.

34. Explain what would happen to an animal species classified as a Batesian mimic if it did not have its mimicry attributes.

a. The animal species would suffer increased loss through predation because its predators would not learn to avoid eating it.

b. The animal species would suffer decreased loss through predation because it still produces harmful toxins that would kill its predators.

c. The animal species would suffer no long-term loss through predation because it still produces foul tasting compounds that its predators would learn to avoid.

d. The animal species would suffer increased loss through predation because predators would not be deterred by its appearance and would find it to be tasty.

35. Explain how two different species can coexist in the same habitat according to the competitive exclusion principle.

a. Two species can coexist in the same habitat as long as they do not share the same trophic level.

b. Two species can coexist in the same habitat as long as they do not share the same mates.

c. Two species can coexist in the same habitat as long as they do not share the same resources.

d. Two species can coexist in the same habitat as long as they do not share the same life span.

36. Explain what would happen if the competitive exclusion principle were violated.

a. One species will prey on another species and drive it to extinction.

b. One species will adapt to another species invading its habitat.

c. One species will block another species' access to a critical resource.

d. One species will contend with another species for the same resources.

37. Describe the symbiotic relationship of mutualism.

a. Only one species benefits and the other derives no benefit or harm from the relationship.

b. One species benefits and the other is harmed by the relationship.

c. Both species benefit from the relationship.

d. Neither species benefits nor is either species harmed.

38. Construct a sentence that describes the symbiotic relationships of mutualism, commensalism, and parasitism.

a. Symbiotic relationships always benefit both species involved.

b. Symbiotic relationships never harm either of the species involved.

c. Symbiotic relationships always benefit at least one of the species involved.

d. Symbiotic relationships always harm at least one of the species involved.

39. Identify the statement that best describes a pioneer species.

a. A pioneer species is a species that is transported out of its native habitat into a non-native habitat, where there are few or no natural predators to keep the population in check.

b. A pioneer species is a species that maintains the community structure in an ecosystem, and whose loss causes the ecosystem to fail.

c. A pioneer species is a species that has the greatest influence over the ecosystem usually by bringing most of the energy into the system.

d. A pioneer species is a species that can colonize landscapes that are devoid of soil and begin the process of succession.

40. Explain what happens to a forest community after a forest fire.

a. The same community is quickly re-established just as it existed before the disturbance.

b. Another mature community with different species grows quickly in place of the original community.

c. Groups of species grow and then are replaced by other groups through a sequential series of changes as the community matures over time.

d. The landscape remains barren for many years until trees grow large enough to provide the shade needed for smaller plants to grow.

41. What is innate behavior?

a. Innate behavior results from practice and conditioning.

b. Innate behavior occurs spontaneously without any learning component.

c. Innate behavior results from thought processes.

d. Innate behavior results from interactions within a social group.

42. What is the difference between innate and learned behaviors?

a. Innate behaviors can change based on previous experiences, whereas learned behaviors remain the same throughout an organism's life.

b. Innate behaviors are controlled by genes, whereas genes play no role in learned behaviors.

c. Innate behaviors allow an organism to adapt to new situations by applying previous experiences, whereas learned behaviors allow an organism to respond quickly.

d. Innate behaviors are involuntary responses to stimuli, whereas learned behaviors change based on an organism's experiences.

43. Describe phototaxis.

a. Phototaxis is the directed movement of an organism in response to gravity.
b. Phototaxis is the long-range movement of an organism in response to a change in season.
c. Phototaxis is the movement of an organism in search of food.
d. Phototaxis is the directed movement of an organism in response to light.

44. Monarch butterflies in the eastern regions of North America migrate thousands of miles to an area in Mexico in the fall and then back to northern regions in the spring. Explain how this migration behavior came to be established in this species.

a. Each new generation learned the migration behavior by observing older generations and mimicking their behavior patterns.
b. In very early generations of this species, a few individuals found that migration improved their chances for survival and taught their young to carry on the behavior.
c. Individuals that migrated survived through the winter, whereas individuals that did not migrate died, leading to selection for migration in later generations.
d. When this butterfly emerged as a new species, by chance it inherited the genetic material that underlies long-distance migration behavior from its ancestor.

45. Pheromones are used in communication between some organisms. What is a pheromone?

a. A pheromone is a type of chemical compound.
b. A pheromone is a type of display.
c. A pheromone is a type of language.
d. A pheromone is a type of song.

46. Construct a statement to describe the type of signal used by birds to communicate the presence of a predator to other birds.

a. Birds release chemical compounds into the air that other birds rapidly recognize as signals of the presence of a predator.
b. Birds flash visual signals such as wing flapping to communicate warnings to other birds whenever a predator is present.
c. Birds physically touch other birds using tactile signals when they observe a predator entering their location.
d. Birds make aural signals such as calls that other birds can hear and learn about a predator that has been observed in the area.

47. The sacrifice of the life of an individual so that the genes of relatives may be passed on is called ____.

a. operant conditioning
b. kin selection
c. kinesis
d. imprinting

48. Cite an example that describes how an animal expends energy in finding, selecting, or winning a mate.

a. Female swallows engage in aggressive harassment of a hawk during breeding season.
b. Male cardinals harass and peck at other male cardinals in their territory.
c. Both male and female squirrels build nests out of leaves, twigs, and other plant material.
d. Female black widow spiders eat males following copulation.

49. The term polyandry comes from the Greek words for ‘many’ and ‘man.’ Based on these word origins, describe a polyandrous mating system.

a. One male mates with many females.

b. One female mates with one male.

c. One female mates with many males.

d. Many females mate with one male.

50. Describe an advantage of a monogamous relationship.

a. Having a lot of males around to provide assistance with protecting and feeding offspring ensures that offspring have the best chance of surviving.

b. When very few males are available in a population, this mating system makes sure that each male has a mating partner.

c. In populations where very few females are available, this mating system ensures that no eggs are wasted.

d. The constant presence of one male throughout the offspring rearing process makes it more likely that offspring will survive and be healthier.

51. The ability of rats to learn how to run a maze is an example of cognitive learning. Describe what happens during cognitive learning.

a. Cognitive learning is a type of learning that occurs early in an animal’s development when it learns to bond to an object or animal.

b. Cognitive learning occurs when an animal learns to associate a stimulus with a behavior not normally associated with that stimulus.

c. Cognitive learning occurs when an animal learns a behavior in response to a positive stimulus or negative stimulus.

d. Cognitive learning is the most complex type of learning that involves multiple types of brain processes to carry out.

52. Contrast classical conditioning and operant conditioning.

a. In operant conditioning, the animal learns to associate a voluntary behavior with its consequences, whereas in classical conditioning, the animal learns to associate a non-voluntary behavior with an unusual stimulus.

b. In operant conditioning, the animal does not learn a new behavior in response to a stimulus, whereas in classical conditioning, the animal learns to associate a non-voluntary behavior with an unusual stimulus.

c. In operant conditioning, the animal learns to associate a voluntary behavior with its consequences, whereas in classical conditioning, the animal does not learn a new behavior in response to a stimulus.

d. In operant conditioning, the animal learns to associate a non-voluntary behavior with an unusual stimulus, whereas in classical conditioning, the animal learns to associate a voluntary behavior with its consequences.

CRITICAL THINKING QUESTIONS

53. Describe how a researcher could determine the population size and density of a bird population on one of the Hawaiian islands.

a. Population size can be determined by life tables. The area of the island in square kilometers is divided by the population size to determine the density of the bird population.

b. Population size can be determined by the mark and recapture method. The population size is divided by the area of the island in square kilometers to determine the density of the bird population.

c. Population size can be determined by life tables. The population size is divided by the area of the island in square kilometers to determine the density of the bird population.

d. Population size can be determined by the mark and recapture method. The area of the island in square kilometers is divided by the population size to determine the density of the bird population.

54. Give examples of how two different populations of organisms might have the same population density, but different dispersal patterns.

a. Two populations could occupy the same range with the same number of individuals, giving different dispersal patterns. However, both the populations may be dispersed randomly throughout the range, giving identical population densities.
b. Two populations could occupy the different range with the different number of individuals, giving different dispersal patterns. However, both the populations may move over this range in a herd, giving identical population densities.
c. Two populations could occupy the same range with the different number of individuals, giving identical population densities. However, one population may move over this range in a herd while the other population may be dispersed randomly throughout the range.
d. Two populations could occupy the same range with the same number of individuals, giving identical population densities. However, one population may move over this range in a herd while the other population may be dispersed randomly throughout the range.

55. A population is observed to have very large numbers of very young individuals, but very low numbers of sexually mature individuals. What hypothesis might a researcher propose about mortality patterns in this population and how would a researcher follow up to test their hypothesis?

a. A researcher might propose the mortality rate of this species is very high during the developmental period after sexual maturity is reached. This hypothesis can be tested by constructing a life table and calculating mortality rates at different age intervals.
b. A researcher might propose the mortality rate of this species is very high during the developmental period before sexual maturity is reached. This hypothesis can be tested by using the mark and recapture method and calculating population densities.
c. A researcher might propose the mortality rate of this species is very high during the developmental period before sexual maturity is reached. This hypothesis can be tested by constructing a life table and calculating mortality rates at different age intervals.
d. A researcher might propose the mortality rate of this species is very low during the developmental period before sexual maturity is reached. This hypothesis can be tested by constructing a quadrat and calculating mortality rates at different age intervals.

56. An organism, such as an elephant, that invests in long-term care of its offspring faces risks to its survival as a result of this investment. Explain those risks.

a. Organisms that invest in long-term parental care have many offspring. Having many offspring means there is greater risk of rapid increase in population.
b. Organisms that invest in long-term parental care have few offspring. Having a limited number of offspring means there is greater risk to the survival of the species when a single offspring dies.
c. Organisms that invest in long-term parental care have many offspring. Having many offspring means there is greater risk to the survival of the species when a single offspring dies.
d. Organisms that invest in long-term parental care have few offspring. Having a limited number of offspring means there is greater risk of rapid increase in population.

57. A honey bee colony contains one queen, hundreds of drones, and many thousands of worker bees. The queen produces eggs, the drones produce sperm, and the workers are sterile. Explain how the reproductive strategy of honey bees benefits the survival of the species. (credit: Food and Agriculture Organization of the United Nations)

a. The fertile queen and drones produce many offspring while sterile worker bees do not benefit the survival of the species.
b. Worker bees produce many offspring while the sterile queen and drones do not benefit the survival of the species.
c. The sterile queen and drones use the energy taken in by them for their own growth, growth and maintenance of the hive, and protection and nurturing of offspring.
d. Sterile worker bees use the energy taken in by them for their own growth, growth and maintenance of the hive, and protection and nurturing of offspring.

58. Two different plant species expend approximately the same amount of energy on reproduction, yet one produces many seeds in a season and the other produces very few. Explain what is likely to be true of the seeds of these two species.

a. In the plant species that produces many seeds, most of the energy is used to produce seeds, of which only a few will germinate and produce another plant. In the species that produces few seeds, most of the energy is used to increase the chances of seeds produced to germinate and grow into an adult plant.

b. In a plant species that produces many seeds, most of the energy is used to produce seeds, most of which will germinate and produce another plant. In a species that produces few seeds, most of the energy is used to increase the chances of seeds produced to germinate and grow into an adult plant.

c. In a plant species that produces many seeds, most of the energy is used to produce seeds, of which only a few will germinate and produce another plant. In a species that produces few seeds, most of the energy is used to reduce the chances of seeds produced to germinate and grow into an adult plant.

d. In a plant species that produces many seeds, most of the energy is used to increase the chances of seeds produced to germinate and grow into an adult plant. In a species that produces few seeds, most of the energy is used to produce those seeds, which will germinate and produce another plant.

59. Explain how rmax would be expected to differ for an elephant and a flea, and how that changes the time scale over which populations of these two animals would be studied.

a. rmax would be greater for an elephant as elephant reproduces at a faster rate than flea. A shorter time scale would be used to study changes over several elephant generations.

b. rmax would be greater for a flea as flea reproduces at a faster rate than elephant. A shorter time scale would be used to study changes over several flea generations than over several elephant generations.

c. rmax would be greater for a flea as flea reproduces at a faster rate than elephant. A longer time scale would be used to study changes over several flea generations than over several elephant generations.

d. rmax would be greater for an elephant as the elephants grow at an exponential rate so the population growth rate is greatly increased. A shorter time scale would be used to study changes over several elephant generations.

60.

Date	*N*
5/1/12	56
6/1/12	98
7/2/12	203
8/10/12	421

This data were collected on a population of beetles in Florida. Based on the data, how would you describe population growth in this case and what do you predict about growth of this population in the future? Explain your reasoning.

a. Population shows logistic growth, as number of individuals doubles every month and will likely continue to grow logistically until its resources become depleted. At that point, the population growth rate will slow down and level off to zero.
b. The population shows exponential growth, as the number of individuals doubles every month and will likely grow logistically in the future when the resources become limited. At that point, the population growth rate will slow down and level off to zero.
c. The population shows exponential growth, as number of individuals doubles every month and will likely continue to grow exponentially until its resources become limited. At that point, the growth will become logistic; the population growth rate will slow down and level off to zero.
d. The population shows logistic growth and is likely to grow exponentially as the resources are probably increasing. The population growth rate will increase in the future as well.

61. Explain how climate change might lead to a decrease in one population's carrying capacity and an increase in the carrying capacity of a different population.

a. Plant species that are drought-resistant would decline in warm temperatures whereas other species would thrive in number in such a climate.
b. Plant species that are pest-resistant would thrive in warm temperatures whereas other species would decline in number in such a climate.
c. Plant species that are drought-resistant would decline in cold temperatures whereas other species would thrive in number in such a climate.
d. Plant species that are drought-resistant would thrive in warm temperatures whereas other species would decline in number in such a climate.

62. Compare and contrast density-dependent growth regulation with density-independent growth regulation. Give an example of each as they might affect a caterpillar population.

a. Both are environmental conditions that result in changes in population numbers. Density-independent factors have different effects on population densities whereas density-dependent factors have the same effect. An example of the former is a caterpillar population being kept low by a pesticide because it kills them regardless of their numbers. In the case of the latter, a large caterpillar population leads to a decrease in food availability, which will cause the caterpillar population to decline.
b. Both are environmental conditions that result in changes in population numbers. Density-independent factors have the same effect at all population densities whereas density-dependent factors have different effects. An example of the former is of a caterpillar population being kept low by a pesticide because it kills them regardless of their numbers. In the case of the latter, a large caterpillar population leads to a decrease in food availability, which will cause the caterpillar population to decline.
c. Both are environmental conditions that result in changes in population numbers. Density-independent factors have the same effect at all population densities whereas density-dependent factors have different effects. An example of the former is of a caterpillar population being kept low by a pesticide because it kills them when their numbers are low. In the case of the latter, a large caterpillar population leads to a decrease in food availability, which will cause the caterpillar population to decline.
d. Both are environmental conditions that result in changes in population numbers. Density-independent factors have the same effect at all population densities whereas density-dependent factors have different effects. An example of the former is of a caterpillar population being kept low by a pesticide because it kills them regardless of their numbers. In the case of the latter, a large caterpillar population leads to a decrease in food availability, which will cause the caterpillar population to increase.

63. Why doesn’t a frog, which is an r-selected species, care for its offspring in the way a wolf, which is a K-selected species, cares for its offspring?

a. Frogs have been selected by stable, predictable environments, therefore they do not feel the need to care for their offspring like wolves.
b. Frogs use very little energy to produce large numbers of offspring, therefore they do not have enough remaining to nurture them.
c. Smaller animals like frogs do not care for their offspring as a lot of them are produced whereas larger animals like wolves only produce a few.
d. Frogs expend a lot of energy to produce large numbers of offspring, therefore they do not have enough to nurture them.

64. Explain which features of a logistic growth curve are the same for every population exhibiting logistic growth and which features might vary from one population to another.

a. The overall S-shape would be the same for all populations. The actual x-y values on the graphs, population numbers corresponding to starting populations, and the ending carrying capacities could differ.
b. The overall carrying capacities would be the same for all populations. The actual x-y values on the graph and population numbers corresponding to the starting populations could differ.
c. The overall S-shape would be the same for all populations showing logistic growth. The only factor that could differ is the actual x-y values on the graphs indicating the time frames for the growth curves.
d. The x-y values on the graphs indicating the time frames for the growth curves would be the same. Overall S shape and population numbers corresponding to the starting populations could differ.

65. Explain why the concept of carrying capacity is important when discussing human population growth.

a. Humans can decrease the carrying capacity of their environment by developing food production methods and engineering high quality shelters, which enables more people to live than would otherwise be possible.

b. Humans have been able to change the carrying capacity of their environment, which enables more people survive. By decreasing their own carrying capacity, humans are responsible for their population boom.

c. Humans have been able to change the carrying capacity of their environment, which enables more people to live. By increasing their own carrying capacity, humans are responsible for their population boom.

d. Humans can increase the carrying capacity of their environment by developing food production methods and engineering high quality shelters, which enables fewer people to live than would otherwise be possible. This would result in population collapse.

66. The Industrial Revolution began with the invention of the steam engine. At about the same time, human population began increasing exponentially. Explain how these two events are linked to the idea that humans are able to change the carrying capacity of their environment.

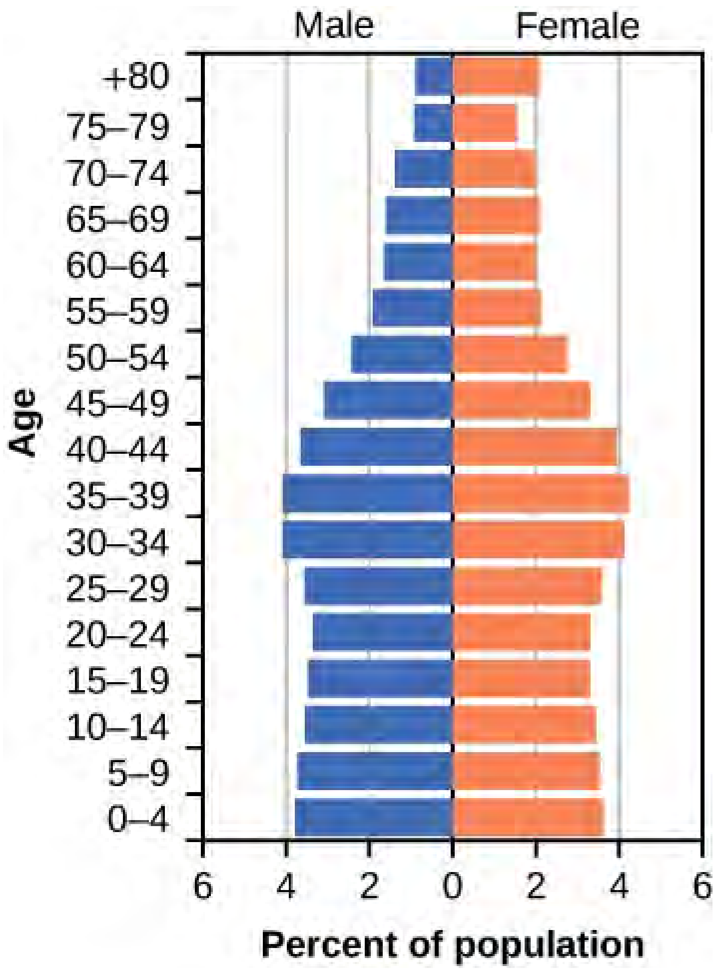
a. The invention of the steam engine enabled people to use machines to carry out farming activities. The amount of available resources needed to sustain human life increased with the invention of machines. This increase in resources spurred exponential population growth.

b. The invention of the steam engine enabled people to develop pest-resistant crop varieties. The amount of available resources needed to sustain human life increased with the invention of machines. This increase in resources spurred exponential population growth.

c. The amount of available resources needed to sustain human life decreased with the invention of machines, but the carrying capacity increased. This increase in carrying capacity spurred exponential population growth.

d. The invention of the steam engine enables the environment to be changed according to the needs of the people. This regulation of environmental conditions spurred exponential population growth.

67.



(credit: Quia)

This diagram shows the age structure for a country. Analyze the age structure and use it to predict the economic status of this country. Explain your reasoning.

a. This country is likely to be an economically developing country because it has a fairly even distribution of individuals in all age groups.

b. This country is likely to be an economically developed country because it has many more very young people and very few old people.

c. This country is likely to be an economically developed country because it has a fairly even distribution of individuals in all age groups.

d. This country is likely to be an economically undeveloped country because it has many more very young people and very few old people.

68.

(credit: EPA Victoria)

The global ecological footprint is defined as the total land area needed to supply all of the resources consumed by all humans. This graph shows the relationship between time and the global human footprint measured in number of planet Earths. Analyze the graph, and use it to explain what has been the consequence of human population change so far. Then, predict the consequences of continued population change in the future.

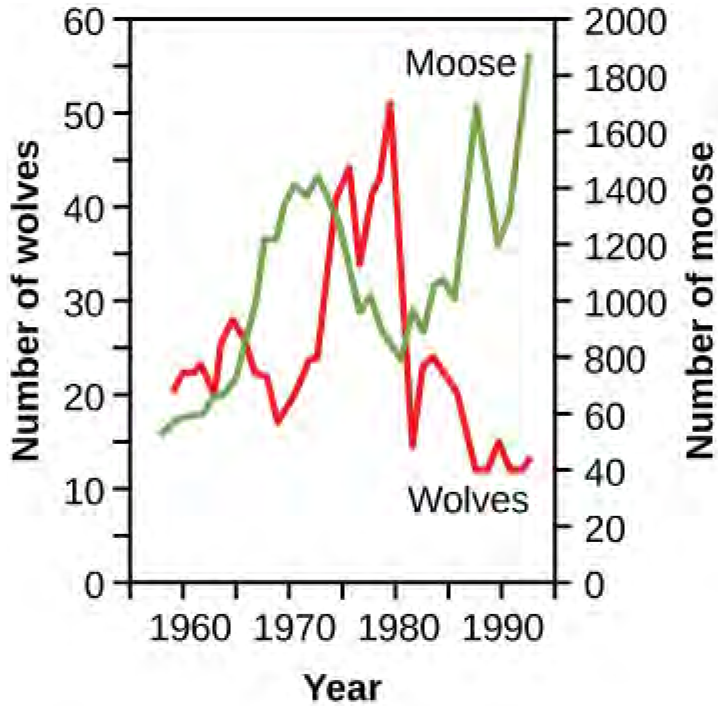
a. The water resources present on Earth has been exceeded by the human population. If the human population keeps increasing, the ecological footprint of humans will increase far beyond the ability of Earth to support human population and our population could crash.

b. The land area present on Earth to supply our resources has been exceeded by the human population. If the human population keeps increasing, the ecological footprint of humans will increase far beyond the ability of Earth to support human population and our population could crash.

c. The land area present on Earth to supply our resources has been exceeded by the human population. If the human population keeps increasing, the birth and death rates will decrease and our population could crash.

d. The water resources present on Earth has been exceeded by the human population. If the human population keeps increasing, the birth and death rates will decrease and our population could crash.

69.



This graph shows a predator-prey cycle for wolves and moose. Explain why the graphs do not resemble the idealized graphs used as models of the predator-prey cycle.

a. This graph reflects all of the influences on both populations in addition to the predator-prey influences.

b. This graph reflects all of the influences on both populations, but not the predator-prey influences.

c. This graph reflects just the influence of predator-prey interactions on both populations.

d. This graph reflects some of the influences on both populations other than the predator-prey influences.

70. Suppose a population of lizards becomes divided into two groups on two different islands after a devastating tsunami. No predators of the lizard are present on one island, and on the other island is a fierce predator that uses the lizard as its primary source of food. Assuming both populations encounter similar environments in every other way, and both survive and grow over the next 100 years, how do you predict any of the characteristics of the two lizard populations to differ at the end of that time? Give specific examples to explain your prediction.

a. The lizards on the island with no predators will likely evolve adaptations such as camouflaged coloration, sharp spines, or toxins to defend against this predator. These adaptations will likely be absent in the other population because they are adapted to other predators.

b. The lizards that survive the fierce predator will likely evolve adaptations such as camouflaged coloration, sharp spines, or toxins to defend against this predator. These adaptations will likely be absent in the other population because they are adapted to other predators.

c. The lizards that survive the fierce predator will likely evolve adaptations such as camouflaged coloration, sharp spines, or toxins to defend against this predator. These adaptations will likely be absent in the other population because this predator is not a factor in their survival.

d. The lizards on the island with no predators will likely evolve adaptations such as camouflaged coloration, sharp spines, or toxins to defend against this predator. These adaptations will likely be absent in the other population because they have survived this predator.

71. The downy woodpecker and the hairy woodpecker are two species that live in the same habitats. The downy woodpecker is slightly smaller and has a smaller beak than the hairy woodpecker. The downy woodpecker uses its bill to search for food on small twigs and branches while the hairy woodpecker is most often observed searching for food on tree trunks. Explain how the competitive exclusion principle relates to this example.

a. Both woodpeckers have identical bill structure, but do not access their food from the same places in the habitat. They do not directly compete with one another for food and thus, can coexist in the same habitat.

b. Both live in the same habitat and have some similarities, but access their food from the same places in the habitat. In this way, the two species can coexist in the same habitat.

c. Both woodpeckers share similarities in their bill structures. So, they directly compete with one another for food. This directly relates to competitive exclusion principle.

d. Both live in the same habitat and have some similarities, but do not access their food from the same places in the habitat. In this way, the two species can coexist in the same habitat.

72. Honey bees are pollinators. Identify the type of symbiotic relationship that exists between honey bees and flowering plants, and explain why your reasoning.

a. This is commensalism because bees help plants pollinate and, in turn, obtain nectar from the plants.

b. This is a mutualistic relationship, because bees obtain nectar from the plants, but do not provide any benefits to the plants.

c. This is commensalism, because bees obtain nectar from the plants, but do not provide any benefits to the plants.

d. This is a mutualistic relationship, because bees help plants pollinate and, in turn, obtain nectar from the plants.

73. Prairie dogs are considered a keystone species in the western U.S. because of their extensive burrowing activities and their role as a prey animal. Explain why these characteristics would result in the keystone role of prairie dogs in their ecosystem.

a. Prairie dogs provide protection and shelter for small animals and harm predator animals in the ecosystem.

b. Without the prairie dogs, the ecosystem might collapse due to lack of protection and shelter for small animals and lack of prey to sustain large predator animals.

c. Prairie dogs dig underground burrows, reducing aeration in the soil and preventing excessive growth of plants above ground.

d. The burrows prairie dogs dig underground provide shelter for other species of animals as well as protection from predators, but prevent growth of plants above ground.

74.

Raised by parents of species A	Contact calls made to other members of the flock	Alarm calls made in response to predator sighting
Species A chicks	Species A call	Species A call
Species B chicks	Species A call	Species B call

Mating pairs of two different species of parrots sometimes lay their eggs in the same nest. When this happens, only one mating pair ends up parenting the chicks even though chicks of both species may be present. The chicks in such mixed nesting groups displayed some interesting behaviors summarized in the table below. Classify these behaviors as innate or learned, and explain how they compare.

a. An alarm call is an innate behavior and a contact call is a learned behavior. Innate behavior comes out automatically in response to a stimulus whereas learned behavior develops over time after observing other birds carrying out the behavior.
b. The alarm call is a learned behavior and contact call is an innate behavior. Learned behavior develops over time after observing birds carrying out the behavior whereas innate behavior comes out automatically in response to a certain stimulus.
c. The alarm call is an innate behavior and contact call is a learned behavior. Innate behavior develops over time in response to stimulus after continuous exposure. Learned behavior develops over time after observing other birds carrying out their behavior.
d. The alarm call is a learned behavior and contact call is an innate behavior. Learned behavior comes out automatically whereas innate behavior develops over time in response to stimulus after continuous exposure.

75. Mammals such as humans show a behavior known as the flight or fight response. Explain how natural selection was likely involved in the development of this behavior that can be observed in humans today.

a. Individuals showing fight or flight behavior was more likely to survive than individuals lacking the trait. This trait got randomly selected by natural selection, thus became preferentially incorporated into the human lineage.
b. Individuals showing fight or flight behavior were more likely to survive than individuals lacking the trait. Sudden, inheritable changes were naturally selected, which included the fight or flight behavior. Thus, this response was incorporated into the human lineage.
c. Individuals showing fight or flight behavior were more likely to survive than individuals lacking this trait. Therefore surviving individuals passed on their trait to offspring while non-surviving individuals do not. Thus, this response became incorporated into human lineage.
d. Individuals showing fight or flight behavior were not more fit than individuals lacking this trait. However, the trait was selected by natural selection due to a random chance event in the gene frequency of individuals showing fight or flight behavior.

76. A researcher studying minnows, a type of fish, kept two groups of 20 fish in separate containers. The containers were linked by a pair of small tubes outfitted with a pump that constantly circulated water between both tanks. The researcher observed both groups of fish after placing a larger fish known to be a predator of minnows into one of the tanks. Fish in both tanks demonstrated alarm behavior. How can you explain these observations?

a. Fish in the tank that received the predator released alarm signals in chemical form. These compounds circulated and reached the other tank, eliciting an alarm response from the fish there nonetheless.

b. Fish in the tank that received the predator released alarm signals in the form of electrical signals. These compounds circulated and reached the other tank, eliciting an alarm response from the fish there nonetheless.

c. The predator introduced in one tank of fish released alarm signals in chemical form. These compounds circulated and reached the other tank, eliciting an alarm response from the fish there nonetheless.

d. Fish in the tank that did not receive the predator released alarm signals in the chemical form. These compounds circulated and reached the other tank and elicited an alarm response from the fish.

77. In some species, males expend a lot of energy in courtship rituals, whereas in other species, males expend much less energy in other ways of attracting mates such as producing colorful plumage. What does this mean for any energy that left over males of these species might have to devote to care for offspring?

a. Males of species carrying out courtship rituals assist in parental care whereas males that use colorful plumage to attract mates do not assist with the parental care.

b. Males of species carrying out courtship rituals do not assist in parental care whereas males that use colorful plumage to attract mates have energy available to assist with parental care.

c. Males of species carrying out courtship rituals as well as species of males that use colorful plumage to attract mates, both would assist with the parental care.

d. Males of species carrying out courtship rituals as well as species of males that use colorful plumage to attract mates would not assist in parental care as the females would be involved.

78. Female spotted sandpipers fight each other for resource-rich territories on their beach breeding grounds. Based on this, which mating type would most likely be operating in this species? Explain your reasoning.

a. Polyandrous mating is most likely operating as the females are establishing territories apart from other females. The females will then attract males to the resources they control which will result in many males attracted to few females with the richest territories.

b. Polygynous mating is most likely operating as the females are establishing territories apart from other females. The females from all territories would attract males to the resources they control, which would result in few males attracted to many females in each territory.

c. Polyandrous mating is most likely operating as the females are establishing territories apart from other females. The females from all territories would attract males to the resources they control, which would result in few males attracted to many females in each territory.

d. Polygynous mating is most likely operating as the females are establishing territories apart from other females. The females will then attract males to the resources they control which would result in many males attracted to few females with the richest territories.

79. Describe Pavlov's dog experiments as an example of classical conditioning.

a. Pavlov demonstrated classical conditioning through a maze running experiment with the dog. The motivation for the dog to work its way through the maze was a piece of food at the end of the maze. The dog ran in one trial per day and had food available at the end of the run.

b. Pavlov hung a chicken piece in a cage too high for the dog to reach and several boxes were placed randomly on the floor. Eventually the dog was able to stack the boxes and climb on top to get the chicken piece through classical conditioning.

c. Pavlov put a dog in a large box that contained a lever that would dispense food to the dog when pressed. While initially the dog would push the lever a few times by accident, it eventually associated pushing the lever with getting the food through classical conditioning.

d. Pavlov sounded a bell whenever food was presented to a dog, which produced saliva in response to the sight or smell of the food. Through classical conditioning, the dog started responding to the bell ringing with salivation as the dog came to associate the bell sound with the arrival of food.

TEST PREP FOR AP® COURSES

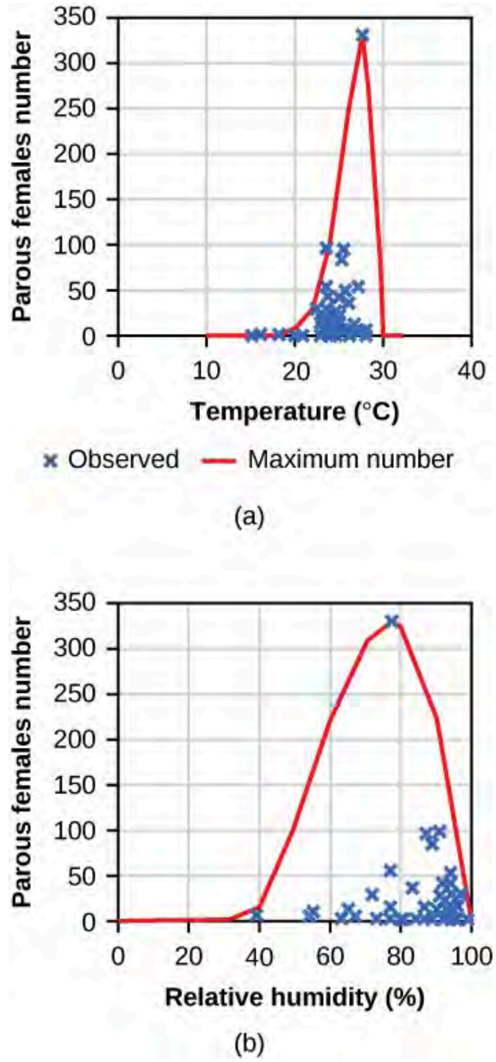
80. A researcher has been tracking a population of turtles. The researcher marked 200 young turtles just after hatching. A year later, collection data reveal that about 80% survived. A year after that, collection data revealed that about 60% of the original group was still living. After a third year, about 40% could be found alive. What do these data say about the survivorship curve that would best describe this population? Explain your reasoning.

a. Type II survivorship curve because the number of survivors decreases by the same value (20%) every year.
b. Type I survivorship curve because the number of survivors decreases by the same value (20%) every year.
c. Type II survivorship curve because the number of survivors increases by the same value (20%) every year.
d. Type IV survivorship curve because the number of survivors decreases by the same value (20%) every year.

81. After discovering a new species of salamander in a forest ecosystem, a researcher set traps at many different locations within the forest and collects data from his traps. The researcher’s goal was to determine which types of environments within the forest the salamander is most likely to be found. Construct another scientific question the researcher can answer using the data he has already collected to further refine his study of this species.

a. What is the population distribution of this salamander species in this ecosystem?
b. What is the rate of population growth of this salamander species in this ecosystem?
c. Which animal species prey on this salamander species in this ecosystem?
d. What abiotic resources are essential for the survival of this salamander species in this ecosystem?

82.



(credit: Revista da Sociedade Brasileira de Medicina Tropical)

These graphs summarize data collected in an area of Brazil between 2005 and 2006. Researchers captured mosquitos and counted the number of parous females. Parous females are females that produced viable offspring. Based on the information given, how would mosquito populations change in Brazil if the climate shifted to very hot (above 30°C) and very dry (below 60% humidity) conditions for an extended period of time? Explain your reasoning.

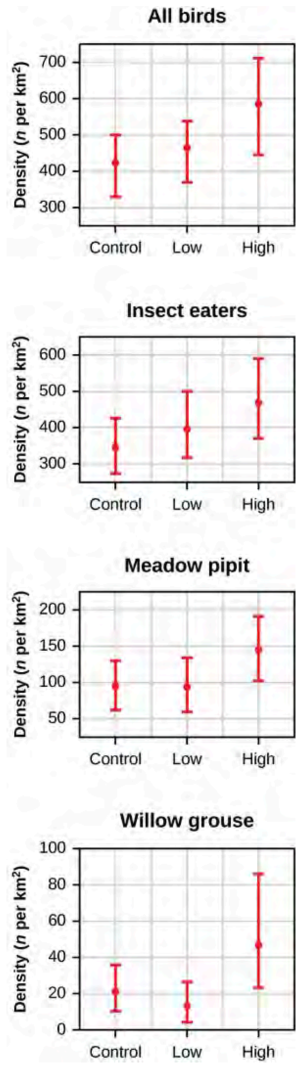
a. The mosquito populations would decrease at temperatures above 30°C, as this is the upper limit for parous females, leading to a drop in offspring production. Below 60% humidity not much change would be seen in the population of mosquitoes.

b. The mosquito populations would decrease, possibly reaching zero. As temperatures above 30°C are the upper limit for parous females, offspring production would drop. Drier conditions would do the same.

c. The mosquito populations would stay the same. This would be because temperature above 30°C and humidity below 60% is close to the favorable conditions of offspring production by parous females.

d. The mosquito populations would stay the same at temperatures above 30°C as higher temperatures will not affect the production of viable offspring by parous females. Drier conditions, below 60% humidity, would cause a drop in the population, as it is the lower limit for offspring production.

83.



(credit: The Royal Society Publishing: Biology Letters)

Researchers were interested in answering the question, “How does sheep grazing affect the population densities of wild mountain birds?” To answer this question, the researchers counted population numbers of various birds in areas of low intensity sheep grazing and in areas of high intensity sheep grazing. A third set of data was collected from control areas in which no sheep grazing occurred. The results of this study are shown in these graphs. All of the bird species eat insects as their primary source of nutrition. The group labeled “insect eaters” combines many species because the numbers for individual species were too small to show separately as shown for the meadow pipit and willow grouse, which are both highly abundant. Because all of the birds are insect eaters, construct a scientific question related to this fact that the researchers could ask to refine their study even further. Explain your reasoning.

a. Does sheep grazing make insects more available to birds? This question refines the question about how sheep grazing affects bird populations because it asks more specifically how sheep grazing changes the food availability for the birds.

b. How does sheep grazing make insects more available to birds? This question refines the question about how sheep grazing affects insect populations because it asks more specifically how sheep grazing changes the food availability for the insects.

c. Does sheep grazing make insects more available to birds? This question refines the question about how sheep grazing affects bird populations because it asks more specifically how sheep grazing changes the food availability for the insects.

d. How does sheep grazing make insects more available to birds? This question refines the question about how sheep grazing affects bird populations because it asks more specifically how sheep grazing changes the food availability for the insects.

84. A pond ecosystem in an open field begins to be shaded by the growth of trees around its perimeter. Predict changes in this pond after the trees grow large enough to completely shade the pond.

a. The population sizes of all organisms will decrease in response to lower energy flowing into the pond.

b. The population densities of all organisms will increase in response to lower temperatures in the pond.

c. The population distributions of large organisms will shift from clumped to random in response to lower energy flowing into the pond.

d. The population distributions of small organisms will shift from uniform to clumped in response to lower temperatures in the pond.

85. A researcher has been studying a wildflower population growing in a large meadow. The researcher counted individual plants and mapped their locations. Analysis of the data revealed that the wildflower has a uniform population distribution. This result prompts the researcher to ask a new scientific question to further refine his understanding of the ecology of this plant species. Construct a scientific question the researcher might ask that is directly prompted by his first set of findings.

a. When does this plant species flower and how does it attract pollinators?

b. Does this wildflower species have any adaptations that function to defend the plant against herbivores?

c. Which species of insects and/or birds are pollinators for this wildflower species?

d. Does this wildflower species secrete any chemical compounds that inhibit growth of others of its species?

86. Fruit flies are found in many different areas in the world. Fruit flies that are resistant to cold temperatures tend to have decreased fecundity at early ages compared to flies that are not capable of surviving the cold. Explain a likely reason for why this set of traits is observed. (credit: Anthony Zera Publications)

a. Flies having traits that traded early reproductive energy for greater storage of energy in their bodies were favored via natural selection because they survived the cold better than flies that did not have these traits.

b. In cold conditions, flies have less need for reproduction than in warm conditions and so energy normally used for reproduction is diverted to other survival functions.

c. Flies respond to weather conditions to shift their energy resources to either storage in their bodies in the cold or to reproduction when conditions become warm again.

d. All fruit flies have the same genetic makeup, but express different patterns of genes under different conditions, which results in expression of certain genes for cold conditions and others for warm conditions.

87.

	% Females laying eggs in host	% Viability of young	Longevity of female parent (days)
Species A			
Mated females without food	23.5	92.5	2.6
Mated females with food	83.5	95.2	7.8
Species B			
Mated females without food	0.0	–	2.0
Mated females with food	68.9	95.3	6.9

(credit: Brazilian Archives of Biology and Technology)

Female parasitoid wasps lay their eggs inside the bodies of caterpillars. The caterpillars die when the eggs hatch, and the young wasps feed on the body of the caterpillar. Egg-laying females of two species of parasitoid wasps were studied in special growth chambers in which a food source was either provided or omitted. This table summarizes some of the data collected. Identify the statement most consistent with these data.

a. When energy availability is low, females put more energy than normal into producing offspring.

b. When energy availability is high, females produce offspring with higher viability.

c. When energy availability is low, females shift energy away from reproduction and toward their own survival.

d. When energy availability is high, females cannot both produce viable offspring and maintain their own survival.

88. During breeding season, many female elk mate with males, but not all mated females become pregnant. Female elk having body fat less than 6% were found to have greatly reduced chances of becoming pregnant than female elk having body fat above 10%. Explain how natural selection was likely involved in establishing this trait in elk. (credit: USGS Northern Prairie Wildlife Research Center)

a. Through natural selection, female elk that did not have the energy reserves to carry a pregnancy to term and did not become pregnant died whereas those which became pregnant anyway were favored.

b. Natural selection favored the selection of traits preventing pregnancies in female elk with low fat reserves, so this trait has become predominant in natural elk herds observed today.

c. Natural selection randomly changes the frequency of genes allowing traits preventing pregnancies in female elk with low fat reserves to be favored.

d. Natural selection leads to a sudden inheritable change in the genome of the female elk, ensuring female elk with very high fat reserves to effectively carry out pregnancy.

89. Research on elk in Yellowstone National Park was conducted to determine how body condition affects survival of the elk over the winter months. It was found that the probability of survival of female elk is greater when they have accumulated 15% or more body fat by the end of fall. Female elk with body fat less than 10% in late fall were found to be at high risk of not surviving the winter. Explain why this pattern is likely to be observed. (credit: USGS Northern Prairie Wildlife Research Center)

a. In winter, the availability of food decreases. So, there needs to be a certain threshold level of energy their bodies store in the form of fat to ensure their survival.

b. In winter, the availability of food increases. So, there should be a certain threshold level of energy in their bodies stored in the form of fat to ensure their survival.

c. In winter, elk's requirement for food increases due to increase in metabolic activities. So, there should be a certain threshold level of energy in their bodies stored in the form of fat to ensure their survival.

d. Elk release more energy in winter. So, there should be a certain threshold level of energy in their bodies stored in the form of fat to ensure their survival.

90.

Species	Birth rate (*N*/year)	Death rate (*N*/year)
A	1845	1467
B	43	79
C	2800	2115
D	16	16
E	933	1351

The table contains birth rates and death rates for populations of several species living in the same ecosystem. Analyze the data to identify the population(s) experiencing a negative change in population size.

a. species A only

b. species A and species C

c. species B and species D

d. species B and species E

91.

Year after flood	Number of individuals
1	5
2	10
3	16
4	25
5	36
6	58
7	82
8	99
9	110
10	116
11	120
12	122
13	121
14	122

These data were collected on the population size of a species of plant growing in a region during the years after a flood destroyed the area. Explain what the data indicate about this population.

a. The plant population grew exponentially throughout the years as the numbers of individuals increased at an exponential rate. The population eventually became stable after reaching a maximum number of 120 individuals, which could be the carrying capacity of the environment.

b. The population grew exponentially in the first few years and later became logistic as the rate slowed down. The population eventually became stable after reaching a maximum number of 120 individuals, which could be the carrying capacity of the local environment.

c. The plant population grew logistically throughout the years as the growth rate of the population slowed down. The population eventually became stable after reaching a maximum number of 120 individuals, which could be the carrying capacity of the environment.

d. The population grew exponentially in the first few years and later became logistic as the rate slowed down. The population eventually became stable after reaching a number of 116 individuals, which could be the carrying capacity of the environment.

92. It has been suggested a population of a flowering plant is being jeopardized by population declines in a butterfly species thought to be the primary pollinator of the plant. Identify data that could best be used to either justify or refute this suggestion.

a. nectar energy provided to the butterfly species per visit to a flower of the plant species in a field
b. number of fruits produced per flower of plants in a section of a field screened off from access by the butterfly species
c. number of butterfly visits per flower per day in various fields throughout the growing range of the plant
d. species of flowers visited by individual butterflies in a field and frequency of visits to each flower species

93. A conservation group has claimed that the introduction of logging into a forest ecosystem will decrease the carrying capacity of trout living in a stream within the ecosystem. Describe data that could be used to either justify or refute this claim. Explain your reasoning.

a. The growth rate of trout in the stream before and after logging will give an indication as to whether the claim is justified or not.
b. Evaluate the death rate of trout in the stream after the introduction of logging, which will be used to justify or refute the claim.
c. Collect data on number of trout in the stream after the introduction of logging, which will give an indication as to whether the claim is justified or not.
d. Collect data on the number of trout in the stream before and after logging, which will give an indication as to whether the claim is justified or not.

94. Predict how human population change in the next 50 years is likely to affect marine ecosystems.

a. Humans will decrease their own carrying capacity, which will also decrease the carrying capacities of marine ecosystems.
b. Decreased fishing can be expected, which will lead to rebounds in fish populations and healthier marine ecosystems.
c. Increases in greenhouse gas emissions are likely, with increases in ocean temperatures that trigger shifts in marine populations.
d. Biodiversity of marine ecosystems will increase as humans use engineering to increase food production in the oceans.

95. Describe how the quantity of waste from human activities can be expected to change in the next 50 years and why. Explain how that change could impact a specific ecosystem.

a. The amount of waste generated by human activities will increase exponentially as the human population continues to increase exponentially. Removal of waste would require a decrease in habitats, which will lead to decrease in populations of species dependent on those habitats.
b. The amount of waste generated by human activities will increase exponentially as the human population continues to increase exponentially. Removal of waste will require an increase in habitats, which will lead to exponential increase in populations of species dependent on those habitats.
c. The amount of waste generated by human activities will decrease exponentially as the human population continues to increase exponentially. Removal of waste would require an increase in habitats, which will lead to exponential increase in populations of species dependent on those habitats.
d. The amount of waste generated by human activities will decrease exponentially as the human population continues to increase exponentially. Removal of waste will require a decrease in habitats, which will lead to decrease in populations of species dependent on those habitats.

96. A company wants to establish suspended cultures of mussels in a natural estuary from which they can farm mussels in a sustainable enterprise. The suspended cultures would keep the mussels contained for easy capture, but would allow free flow of estuary waters in and out of the cultures. The company wants to know the maximum number of mussels they can farm each month and maintain a sustainable system. A biologist has suggested that the limiting factor for mussels is the amount of phytoplankton that the mussels feed on. Identify data that could best be used to either justify or refute this suggestion.

a. rates of growth of newly established mussel cultures in a lab under different phytoplankton concentrations
b. phytoplankton population changes in the estuary as a function of intensity and duration of sunlight exposure
c. biomasses of natural mussel populations and phytoplankton populations in the estuary determined at many different times
d. lab measurements of phytoplankton biomass in response to added mussel population numbers

97. A non-venomous species of snake has a wide geographical range. In one region, the species has dull coloration and in another region, the species exhibits bright coloration that resembles a local venomous species of snake. A hypothesis has been proposed that the bright coloration is an adaptation to defend against predation, an example of Batesian mimicry. Describe an experimental design that could be used to test this hypothesis.

a. Run field tests in which dull individuals and brightly colored individuals are captured and switched into the other’s territory to see how many of each survive.
b. Run field tests in which video cameras are set up to record predators capturing dull individuals and brightly colored individuals in their native territories.
c. Run laboratory tests in which predators familiar with the poisonous snake are offered dull individuals and brightly colored individuals to see if the predators show a preference.
d. Run laboratory tests in which predators familiar with the dull colored non-poisonous snake are offered poisonous brightly colored individuals and non-poisonous brightly colored individuals to see if the predators show a preference.

98. Frogs are amphibians and spend time both on land and in water. Female frogs are vulnerable to predation by fish when they enter the water to lay eggs. A hypothesis has been proposed that frogs rely on chemical detection of predators in addition to visual detection. In other words, frogs detect the presence of predator fish by chemicals released by fish into the water. Design an experiment to test this hypothesis.

a. Arrange containers of water in which water can be freely shared between two compartments. Fish are contained within one compartment and frogs in another such that the frogs on one side cannot see or hear fish on other side. Observe and compare the egg laying behavior of female frogs in the presence and absence of predator fish in the fish tank.
b. Arrange containers of water in which water can be freely shared between two compartments. Fish and frogs are contained within one compartment such that frogs cannot see or hear fish. Observe and compare the egg laying behavior of female frogs in the presence and absence of predator fish.
c. Arrange containers of water in which water can be freely shared between two compartments. Fish and frogs are contained within one compartment such that frogs can see or hear fish. Observe and compare the egg laying behavior of female frogs in the presence and absence of predator fish in the fish tank.
d. Arrange containers of water in which water can be freely shared between two compartments. Fish are contained within one compartment and frogs in another such that frogs on one side can see or hear fish on other side. Observe and compare the egg laying behavior of female frogs in the presence and absence of predator fish in the fish tank.

99.

	Unspotted males	Spotted males
1998		
Upstream	244	742
Downstream	368	1165
2008		
Upstream	298	791
Downstream	1086	205

A biologist studied two populations of the same species of a small fish living in different locations in the same tropical stream. He noticed that adult male fish were either spotted or unspotted and made careful counts of the two variants in the two stream locations in 1998. He repeated his population studies ten years later. Construct a hypothesis that accounts for these data.

a. A new prey species of the fish established itself only in the downstream portion of the stream between 1998 and 2008.

b. A new prey species of the fish established itself only in the upstream portion of the stream between 1998 and 2008.

c. A new predator of the fish established itself only in the downstream portion of the stream between 1998 and 2008.

d. A new predator of the fish established itself in both the upstream and downstream portions of the stream between 1998 and 2008.

100.

	Survival Rate	
	Released into mottled snail region	Released into solid snail region
Mottled snails	95%	5%
Solid snails	22%	93%

A species of marine snail is found in shallow waters near coastlines. This snail feeds on detritus on the ocean bottom. Researchers noticed that snails in one area had a mottled appearance, while snails in another area were solid in color. The researchers set up areas in each region for study and then released both mottled and solid snails into the solid snail region and released both mottled and solid snails into the mottled snail region. The survival rate of each variant was measured. Results are summarized in this table. Construct a possible hypothesis that accounts for these data. Explain your reasoning.

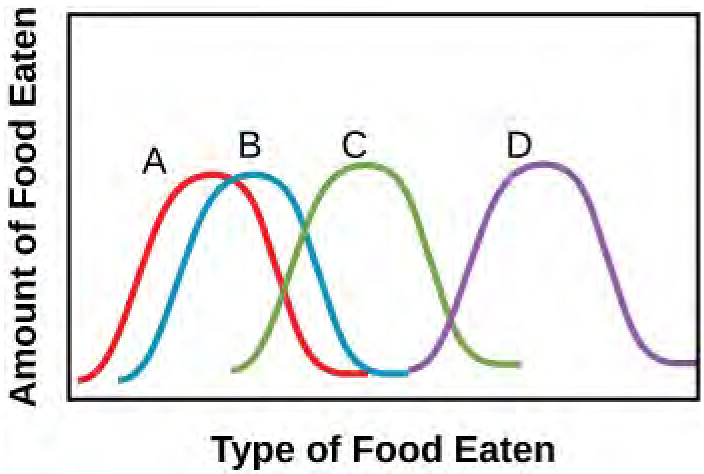
a. A possible hypothesis is that the coloration of the snail is dependent on environmental conditions. Camouflage in both mottled and solid snails is best during optimum environmental conditions and does not change according to the region in which they are placed.

b. A possible hypothesis is that the coloration of the snail is an adaptation in the form of camouflage to protect the snail from predators in the region it is invading. Mottled snails are best camouflaged in the solid snail region and stand out to predators and suffer greater predation when placed in their native region.

c. A possible hypothesis is that the coloration of the snail is an adaptation in the form of camouflage to protect the snail from predators in its native region. Mottled snails are best camouflaged in their native region and stand out to predators and suffer greater predation when placed in the region normally occupied by solid snails.

d. A possible hypothesis is that the coloration of the snail is an adaptation in the form of camouflage to protect the snail from predators in its native region. Solid snails are best camouflaged in mottled snail region and are more obvious to predators when placed in their native region.

101.



The graph below summarizes data concerning four different species of lizards that inhabit tropical habitats. Predict how these species will be able to coexist if they inhabit the same region of a tropical habitat.

a. All species will coexist with one another because they consume the same amounts of food.

b. Species A, B, and C will best coexist because of their similarities in amount and type of food eaten.

c. Species A and B will best coexist because they have the most overlap in diet.

d. Species D will best coexist with any one of the other species because this species eats completely different types of food.

102.

	Insects	Nectar	Worms
Species A	95%	5%	0%
Species B	92%	3%	5%

Warblers are a group of small songbirds consisting of many species. The table below summarizes data collected on the diets of two species of warblers. In addition, both species A and B use the same types of nesting materials and sites for building nests.

A biologist observes that Species A and Species B primarily inhabit different regions of a forest in western Canada. During a forest fire that wiped out the region it inhabited, Species B fled to the region inhabited by Species A. Predict what is likely to happen to these two species in the future. Explain your reasoning.

a. Both the species will survive because of difference in needs for food and nesting space.

b. Species A will increase in population whereas species B will remain same due to the overlapping needs for food and nesting space.

c. Only one of these species will survive in this region due to the difference in needs for food and nesting space. The species that loses will either die off or migrate to another region.

d. Only one of these species will survive in this region due to the overlapping needs for food and nesting space. The species that loses will either die off or migrate to another region.

103. Himalayan blackberries are an invasive species that has spread in the forest of the Pacific Northwest. The plants develop thick tangles of cane covered with thorns that cover ground with a tight mat. Ecologists hypothesized that Himalayan blackberries displace native species of shrubs by reproducing faster and reducing areas available for growth. They recorded the density of blackberries and native salmonberries, a native shrub, along a creek for several years. The percentage areas of ground covered by blackberries and native shrubs were plotted over time. Based on the graph, what statement best explain the role of blackberries on the ecosystem studied?

a. Blackberries promote the growth of salmonberry shrubs.
b. Blackberries and salmonberry shrubs do not interfere with each other's growth.
c. Salmonberry shrubs prevent the growth of blackberries.
d. Blackberries displaced salmonberry shrubs.

104. Predict how ecosystems in the northernmost land regions will be affected by human population change in the next 50 years.

a. Biodiversity of these northernmost regions will remain constant as humans will find other more habitable locations to house their growing numbers.
b. The populations of organisms presently inhabiting these regions will shift as global warming causes many species to decline and new species to move in.
c. The carrying capacity of these regions for humans will decrease as the human population increases exponentially.
d. Ecosystems can be expected to remain untouched by humans as new technologies are developed to sustain a growing population.

105. A researcher is interested in investigating whether the croaking pattern produced by males in a frog species is a learned behavior or an innate behavior. Which of the following would best help the researcher answer this question?

a. genetic analyses of adult male frogs raised in isolation and in multigenerational frog communities
b. field observations of adult frogs in their native habitat during mating season
c. video recordings of individual frogs raised in large multigenerational frog communities
d. audio recordings of individual frogs at sexual maturity after being raised in total isolation

106. A biologist hypothesizes birds of various species recognize the predator warning calls of other bird species. The biologist has established several feeders in a forest where birds come to feed regularly. They are spread out over a wide area, making it difficult to observe all of the boxes at the same time. Describe how the biologist can use this site to collect data to test his hypothesis.

a. The biologist can use video cameras to record the behavior of birds coming to the feeders.
b. The biologist can leave an audio recorder near the feeders.
c. The biologist can record the behavior of birds by comparing them with other birds using video cameras.
d. The biologist could observe the birds continually for one month.

107.

	Yellow bunting encountered and fled	Yellow bunting encountered and attacked	Total encounters
Butterflies with eyespot	9	19	28
Butterflies without eyespot	0	18	18

Yellow buntings are birds that feed on butterflies, including Aglaisurticae, a species of butterfly that has bright circular coloring on its wing called an eyespot. Biologists have hypothesized that eyespots mimic owl eyes. Owls are predators of yellow buntings.

In laboratory experiments using yellow buntings captured from the wild and held in captivity, individual birds were observed during sessions in which they were given butterflies that had either not be treated or had been treated to remove their eyespots. Yellow buntings were scored according to whether they showed fleeing behavior when they encountered butterflies of both types. The data were compiled into a table. How do these data support the claim that one species' response to information can affect natural selection in another species?

a. Comparison of the total number of encounters shows that more birds responded to the eyespot, a trait that will likely be selected against in natural populations of the butterfly.

b. Comparison of the number of birds attacking butterflies with and without eyespots suggests that the presence of an eyespot makes butterflies more visible to predators resulting in selection against the trait.

c. Comparison of the number of birds fleeing from butterflies with and without eyespots indicates that the eyespot trait has been disfavored because this trait makes the butterflies stand out to predators.

d. Comparison of the number of birds fleeing from butterflies with and without eyespots suggests that selection has occurred in butterflies in favor of the eyespot trait, which mimics a predator of the bird.

108.

Calls made by small bird	Call sound frequency	Small bird hearing range (1–10 kHz)	Large bird hearing range (1–4 kHz)
Mobbing call	4.5 kHz	Yes	Yes
Scolding call	4 kHz	Yes	Yes
Warning call	7–8 kHz	Yes	No

(credit: Behavioral Ecology and Sociobiology)

Biologists analyzed the sound frequencies of different calls made by a small bird species that serve as prey for a much larger predator bird species. The small bird makes three different kinds of calls: a mobbing call that a group of adults make when mobbing a single predator bird in defense of their nests, a scolding call that a single bird makes to scold a predator bird perched nearby, and a warning call that a single bird makes to warn other birds when a predator bird flies into the vicinity. A table was created to summarize the data from this analysis and also show the range of sound frequencies audible to the prey and predator species. Explain how these data support the claim that communication of information affects natural selection in the small bird species.

a. A scolding call made by small birds can be heard by large predator birds, which is required to scold away the birds; therefore, this trait is favorable and has been naturally selected.

b. As the mobbing call made by small birds can be heard by large predator birds, therefore small birds cannot defend their nests without the predators knowing. This unfavorable trait is thus naturally selected.

c. The warning call made by small birds cannot be heard by large predator birds, giving the small birds an advanced warning. This is an unfavorable trait that gives birds a survival disadvantage.

d. The warning call made by small birds cannot be heard by large predator birds, giving the small birds an advanced warning. This is a favorable trait that gives birds a survival advantage.

109. Which of the following statements most directly supports the claim that Monarch butterfly migration is a regulated event?

a. Monarch butterflies fly up to 3,000 miles from their summer habitat in North America to their winter habitat in Mexico.

b. Because the life span of a Monarch butterfly is so short, not every generation of Monarchs migrates.

c. Monarch caterpillars feed on milkweed while adult butterflies feed on flower nectar.

d. Changes in day length trigger hormonal and nervous system changes in Monarchs that result in behavioral changes.

110. What evidence can you cite to support the claim that the timing of entry into hibernation by grizzly bears is regulated? Justify why this evidence supports the claim.

a. Grizzly bears go into hibernation at the end of winters. This observation provides evidence that there is some environmental cue that triggers physiological changes in bears.

b. Grizzly bears do not go into hibernation at the beginning of autumn. This observation provides evidence that there is some environmental cue that triggers physiological changes in bears.

c. Grizzly bears go into hibernation at random times during the year. This observation provides evidence that there is some environmental cue that triggers physiological changes in bears.

d. Grizzly bears do not go into hibernation at random times during the year. This observation provides evidence that there is some environmental cue that triggers physiological changes in bears.

111. Some animal behaviors can be modified by experience. Which of the following accurately predicts how an experiential factor is likely to affect an animal’s behavior?

a. A species of salmon will migrate up the same river regardless of increases in predators that visit these waterways from one year to the next.

b. Female elk that had difficult deliveries of calves will continue to mate with males in succeeding mating seasons.

c. Bears that receive food from humans are later more likely to break into human habitations than bears that are not approached by humans.

d. A bird raised from an egg isolated in a lab environment will give the same alarm call as birds of the same species raised in the wild.

112. Estivation is a type of dormancy that some animals enter during hot, dry periods. Typically, the metabolisms of these animals slow down, their bodies retain water and some shift to altered nitrogen metabolism. Predict how the behavior of an animal such as a lizard would change in response to environmental factors that trigger the lizard into entering estivation.

a. The lizard would sit on a rock to remain protected from predation and water loss. The breathing and heart rate would slow as it begins estivating. Then it would only do critical activities needed to sustain its living state.

b. The lizard would live in a shaded spot to remain protected from predation and water loss. The breathing and heart rate would slow as it begins estivating. This way a lizard can perform all activities.

c. The lizard would stay in a shaded spot to remain protected from predation and water loss. Its breathing and heart rate would slow as it begins estivating. Then it would only do critical activities needed to sustain its living state.

d. The lizard would live in a shaded spot to remain protected from predation and water loss. The breathing and heart rate would increase as it begins estivating. Then it would only do critical activities needed to sustain its living state.

113.

	Number of trials where test animals spent the majority of time		
Treatment of paper towels	**Stimulus**	**Control**	***P***
Non-injured	12	8	0.504
Injured	3	17	0.002

Many animals produce chemical compounds that function as alarm cues. Researchers interested in determining whether salamanders fall into this group performed the following experiment. Long-toed salamanders were captured from the wild. A few were injured and tissue from their injuries was collected and ground up with water. This solution was used to moisten a paper towel. Others were not injured and placed on moistened paper towels for 48 hours. The moistened paper towels were placed at one end of a rectangular box (stimulus end) and a paper towel moistened with water was placed at the other end (control end). In each test, a salamander was placed in the center and the researchers observed the direction in which the salamander moved. Multiple trials were performed using paper towels moistened with chemicals from injured and non-injured salamanders and the data was compiled into a table. Which of the following statements is an accurate analysis of the data?

a. This salamander releases chemical compounds during injury that elicit avoidance behavior in members of its own species.

b. Chemical compounds released from this salamander species during injury elicit attractant behavior in members of its own species.

c. Both injured and non-injured salamanders produce chemical compounds that elicit avoidance behavior in non-injured salamanders.

d. There was a significant difference between stimulus and control results from treatment involving non-injured salamanders.

114.

Food dispersion	Presence of species B	Number of species A giving alarm calls	Number of species A not giving alarm calls
Concentrated	Present	10	2
Concentrated	Absent	1	11
Dispersed	Present	2	10
Dispersed	Absent	0	12

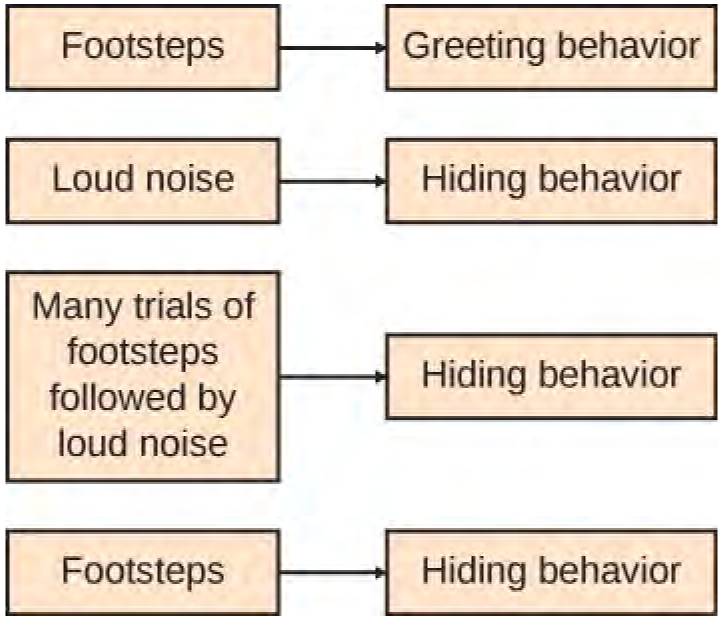
(credit: Ethology)

Biologists have observed some animal species making predator warning calls when no predator is in the area. In one species of bird, for example, individuals appeared to perform this behavior as a means for deceiving other birds into fleeing from a food source that the bird making the call was then better able to access.

In investigating the possibility that this bird species uses false alarm calls to improve its access to food, the following experiment was conducted. Researchers set up a bird feeding table in a protected area to attract two species of birds, species A and B. They either clumped food in one concentrated pile on the table or dispersed the food in a much wider area under and around the table. They then observed the number of times an individual in species A gave a predator warning call when no predator was in sight as well as the presence or absence of species B at the feeding table. The data collected by the researchers are shown here. What do the data suggest about the use of deception by species A? Explain your reasoning.

a. Species A uses deception in cases when food is plentiful, but concentrated, so access is limited to a small group of birds. A bird that had restricted access to the food has open access because of the alarm. Only in cases where it’s necessary does the bird carry out this deceptive behavior.
b. Species A uses deception in cases when food is plentiful, but concentrated, so that access is limited to a large group of birds. A bird that had restricted access to the food has open access because of the alarm. Only in cases where it’s necessary does the bird carry out this deceptive behavior.
c. Species A uses deception in cases when food is plentiful, but dispersed, so that access is limited to a small group of birds. A bird that had restricted access to the food has open access because of the alarm. Only in cases where it’s necessary does the bird carry out this deceptive behavior.
d. Species A uses deception in cases when food is plentiful, but concentrated, so that access is limited to a small group of birds. A bird that had unrestricted access to the food has open access because of the alarm. Deceptive behavior is carried out regardless of whether it is needed or not.

115.



This representation was created to describe how the behavior of a cat was affected as it was exposed to different stimuli. Identify the term that should be used for the process represented by this diagram.

a. innate behavior
b. classical conditioning
c. operant conditioning
d. cognitive learning

116. Elk migrate from summer feeding grounds in high mountain meadows down into lower valleys during winter. Using the words behavioral changes, physiological changes, seasonal changes, and migration, write the order of events that occur to bring about this migration.

a. seasonal changes, physiological changes, migration, and behavioral changes, respectively
b. physiological changes, seasonal changes, behavioral changes, and migration, respectively
c. seasonal changes, behavioral changes, physiological changes, and migration, respectively
d. seasonal changes, physiological changes, behavioral changes, and migration, respectively

117. Some fish swim in schools, which can respond rapidly by moving quickly away from predator threats. In schools, fish swim in a coordinated pattern without moving chaotically and bumping into one another. Which type of communication between individuals could account for the precisely coordinated movements of all of the fish in a school in response to a threat?

a. aural signals
b. pheromone signals
c. tactile signals
d. visual signals

118. Describe a situation in which animals of the same species exchange information in response to an approaching predator. Include a description of how the information flows between individuals.

a. Herring gulls have a brightly colored bill. When a predator approaches, the parent gull stands over its chick and taps the bill on the ground in front of it, which elicits a begging response from a hungry chick.
b. Prairie dogs live in underground burrows. If a look-out observes an approaching predator, they give an aural alarm cry communicating the information to the foraging individuals who then run back to safety.
c. Herring gulls have a brightly colored bill. When a predator approaches, the parent gull stands over its nest and taps the bill on the ground, thus exchanging information of the approaching predator.
d. Prairie dogs live inside the bark of trees. If a look-out observes an approaching predator, they give an aural alarm cry communicating the information to the foraging individuals who then run back to safety.

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