PRINCIPLES OF BIOLOGY II, OL ED



Thompson Rivers University

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Principles of Biology II

This resource is designed to support a first year biology course focused on providing a survey of the kingdoms of life, emphasizing their ecology and evolutionary relationships. This version provides resources and content that is focused on a Canadian context, with an emphasis on weaving in indigenous knowledge, resources and cases.

Acknowledgements

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Detailed Licensing

Licensing

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CHAPTER OVERVIEW

Unit 1: Biology, Science, and Society

1.1: Unit 1 Introduction

1.2: Themes and Concepts of Biology

1.3: The Nature of Science

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1.1: Unit 1 Introduction

Unit 1 Introduction

Biology is the study of life and living organisms' interactions with the environment. Western science seeks to know and often follows a process of steps, known as the scientific method, to understand the nature of life and the universe. Observation, questioning, controlled experimentation, modeling, and reasoning are hallmarks of the process of science. Indigenous science recognizes the knowledge inherent in each culture and understanding nature is a process of 'coming to know' which is a journey of wisdom in action rather than a process of discovery. Science in all its forms is a hallmark of humanity and critical to culture and society worldwide. Each section of text in this Unit is reinforced through embedded media and special call-out features.

Unit 1 Learning Outcomes

By the end of this Unit, you will be able to:

- Classify living organisms;
- Understand and articulate the principles and processes of scientific inquiry;
- Think critically about the principles of biology studied; and
- Communicate your thinking clearly and concisely in speaking and in writing.

Unit 1 Table of Contents

1.1. Introduction

1.2. Themes and Concepts of Biology

1.3. The Nature of Science

1.4. The Role of Science in Society

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1.S. Summary

This unit introduces learners to the basic principles of life, the process of science, and the relationship between science and society.

Unit 1 Assessments

If you are a TRU student using this resource, all of your assessed learning activities and assignments are in your course Moodle site.

Please click on the blue arrow on the right to start Unit 1: Chapter 1.2. If you are on a mobile device, use the navigation links at the bottom of this page.

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- **Unit I: The Chemistry of Life** by OpenStax is licensed CC BY 4.0.

Unit 1.2 - Themes and Concepts of Biology

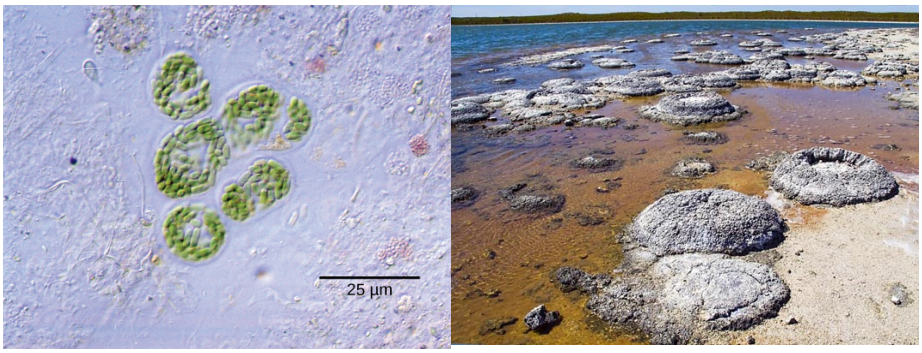
- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities and Resources are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 1.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
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Learning Objectives

- Identify and describe the properties of life
- Describe the levels of organization among living things
- Identify the shared characteristics of the natural sciences
- Identify examples of different subdisciplines in biology

What is Biology?

In simple terms, biology is the study of living organisms and their interactions with one another and their environments. This is a very broad definition because the scope of biology is vast. Biologists may study anything from the microscopic or submicroscopic view of a cell to ecosystems and the whole living planet (Figure **1.2.1**).



(a) (b)

Figure **1.2.1**: Formerly called blue-green algae, these (a) cyanobacteria, shown here at 300x magnification under a light microscope, are some of Earth's oldest life forms. These (b) stromatolites along the shores of Lake Thetis in Western Australia are ancient structures formed by the layering of cyanobacteria in shallow waters. (credit a: modification of work by NASA; credit b: modification of work by Ruth Ellison; scale-bar data from Matt Russell)

Listening to the daily news, you will quickly realize how many aspects of biology are discussed every day. For example, recent news topics include *Escherichia coli* (Figure **1.2.2**) outbreaks in spinach and *Salmonella* contamination in peanut butter. Other subjects include efforts toward finding a cure for AIDS, Alzheimer's disease, and cancer. On a global scale, many researchers are committed to finding ways to protect the planet, solve environmental issues, and reduce the effects of climate change. All of these diverse endeavors are related to different facets of the discipline of biology.

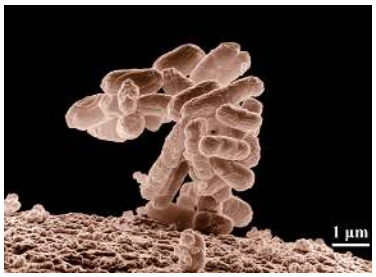


Figure **1.2.2**: Escherichia coli (*E. coli*) bacteria, seen in this scanning electron micrograph, are normal residents of our digestive tracts that aid in the absorption of vitamin K and other nutrients. However, virulent strains are sometimes responsible for disease outbreaks. (credit: Eric Erbe, digital colorization by Christopher Pooley, both of USDA, ARS, EMU)

Optional Resource

Find an example of up-to-date news on biology at Science Daily here: https://www.sciencedaily.com/news/plants_animals/biology/

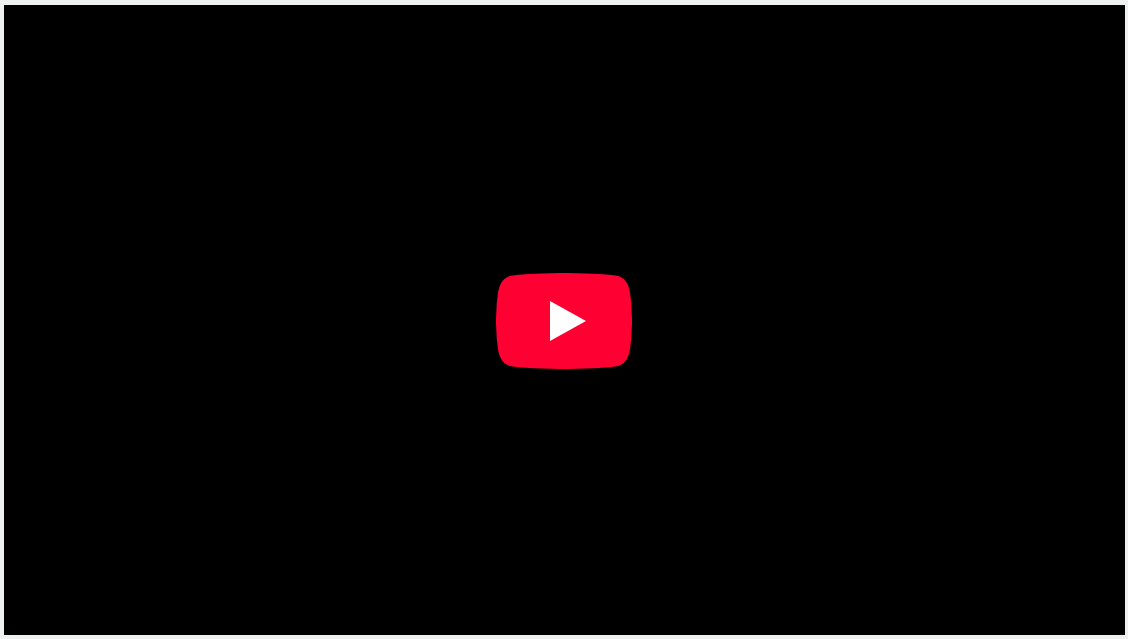
Biology is the science that studies life, but what exactly is life? This may sound like a silly question with an obvious response, but it is not always easy to define life. For example, a branch of biology called **virology** studies viruses, which exhibit some of the characteristics of living entities but lack others. It turns out that although viruses can attack living organisms, cause diseases, and even reproduce, they do not meet the criteria that biologists use to define life. Consequently, virologists are not biologists, strictly speaking. Similarly, some biologists study the early molecular evolution that gave rise to life; since the events that preceded life are not biological events, these scientists are also excluded from biology in the strict sense of the term.

From its earliest beginnings, biology has wrestled with three questions:

1. What are the shared properties that make something “alive”?
2. And once we know something is alive, how do we find meaningful levels of organization in its structure?
3. And, finally, when faced with the remarkable diversity of life, how do we organize the different kinds of organisms so that we can better understand them?

As new organisms are discovered every day, biologists continue to seek answers to these and other questions.

Video





Watch this 1.5-minute video as multiple scientists and professors describe what biology means to them.

Question after watching: What does biology mean to you?

Properties of Life

All living organisms share several key characteristics or functions: order, sensitivity or response to the environment, reproduction, adaptation, growth and development, regulation, homeostasis, energy processing, and evolution. When viewed together, these are nine characteristics that can serve to define life. However, different scientists have used varying definitions to classify matter as living (**biotic**) or non-living (**abiotic**). Some use seven or fewer of these characteristics, some use all nine. One of the most concise definitions of life is from the National Aeronautics and Space Administration "*Life is a self-sustaining chemical system capable of Darwinian evolution*" (NASA, 2022).

Order

Organisms are highly organized, coordinated structures that consist of one or more cells. Even very simple, single-celled organisms are remarkably complex: inside each cell, atoms make up molecules; these, in turn, make up cell organelles and other cellular inclusions. In multicellular organisms (Figure **1.2.1**), similar cells form tissues. Tissues, in turn, collaborate to create organs (body structures with a distinct function). Organs work together to form organ systems.



Figure **1.2.1**: A toad represents a highly organized structure consisting of cells, tissues, organs, and organ systems. (credit: "Ivengo"/Wikimedia Commons)

Sensitivity or Response to Stimuli

Organisms respond to diverse stimuli. For example, plants can bend toward a source of light (**phototaxis**), climb on fences and walls, or respond to touch (Figure **1.2.2**). Even tiny bacteria can move toward or away from chemicals (**chemotaxis**) or light.



Figure **1.2.2**: The leaves of this sensitive plant (*Mimosa pudica*) will instantly droop and fold when touched. After a few minutes, the plant returns to normal. (credit: Alex Lomas)

Video



Watch this 1-minute video to see how plants respond to a stimulus (sunlight) and what that means for their success. Question after watching: What are other types of stimuli that the plant encounters?

Reproduction

Single-celled organisms reproduce by first duplicating their DNA, and then dividing it equally as the cell prepares to divide to form two new cells. Multicellular organisms often produce specialized reproductive germline cells, such as eggs and sperm, that will form new individuals. When reproduction occurs, genes containing DNA are passed along to an organism's offspring. These genes ensure that the offspring will belong to the same species and will have similar characteristics, such as size and shape.

Growth and Development

Organisms grow and develop following specific instructions coded for by their **genes**. These genes provide instructions that will direct cellular growth and development, ensuring that a species' young will grow up to exhibit many of the same characteristics as its parents (Figure 1.2.3).



Figure 1.2.3: Although no two look alike, these kittens have inherited genes from both parents and share many of the same characteristics. (credit: Rocky Mountain Feline Rescue)

Regulation

Even the smallest organisms are complex and require multiple regulatory mechanisms to coordinate internal functions, respond to stimuli, and cope with environmental stresses. Two examples of internal functions regulated in an organism are nutrient transport and blood flow. **Organs** (groups of tissues working together) perform specific functions, such as carrying oxygen throughout the body, removing wastes, delivering nutrients to every cell, and cooling the body.

Homeostasis

In order to function properly, cells need to have appropriate conditions such as proper temperature, pH, and appropriate concentration of diverse chemicals. These conditions may, however, change from one moment to the next. Organisms are able to maintain internal conditions within a narrow range almost constantly, despite environmental changes, through **homeostasis** (literally, "steady state")—the ability of an organism to maintain constant internal conditions.

For example, an organism needs to regulate body temperature through a process known as thermoregulation. Organisms that live in cold climates, such as the polar bear (Figure 1.2.4), have body structures that help them withstand low temperatures and conserve body heat. Structures that aid in this type of insulation include fur, feathers, blubber, and fat. In hot climates, organisms have methods (such as perspiration in humans or panting in dogs) that help them to shed excess body heat.



Figure 1.2.4: Polar bears (*Ursus maritimus*) and other mammals living in ice-covered regions maintain their body temperature by generating heat and reducing heat loss through thick fur and a dense layer of fat under their skin. (credit: "longhorndave"/Flickr)

Energy Processing

All organisms use a source of energy for their metabolic activities. Some organisms capture energy from the sun and convert it into chemical energy in food; others use chemical energy in molecules they take in as food (Figure 1.2.5).

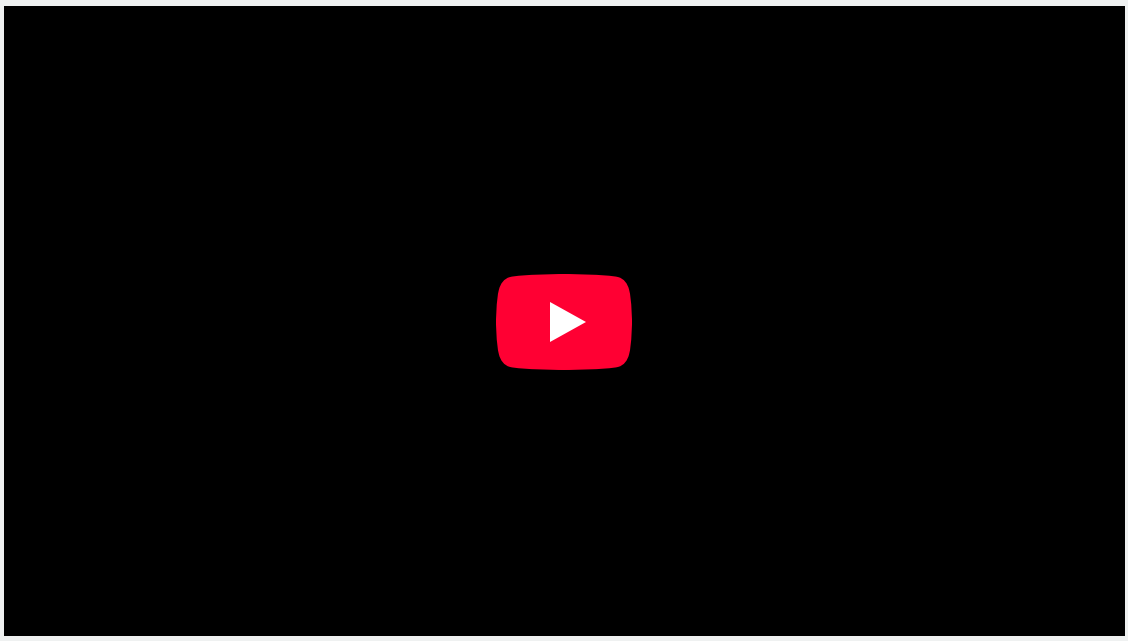


Figure 1.2.5: The California condor (*Gymnogyps californianus*) uses chemical energy derived from food to power flight. California condors are an endangered species; this bird has a wing tag that helps biologists identify the individual. (credit: Pacific Southwest Region U.S. Fish and Wildlife Service)

Evolution

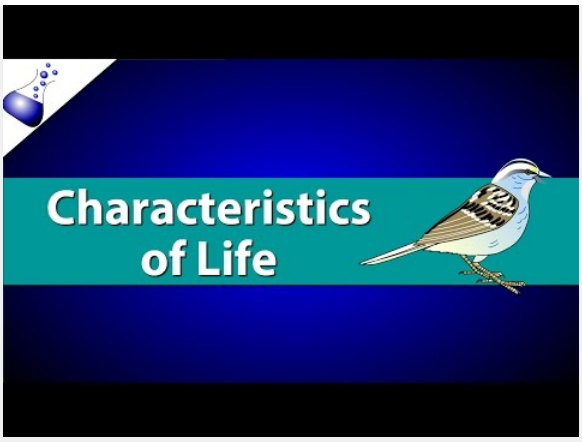
All organisms evolve. We will investigate the theory of evolution and its mechanisms thoroughly in Unit 2.

Videos









Use these two videos to help you synthesize the ideas from above about the processes of life.
Question after watching: Which features help scientists separate the biotic from the abiotic?

Levels of Organization of Living Things

Living things are highly organized and structured, following a hierarchy that can be examined on a scale from small to large. The **atom** is the smallest and most fundamental unit of matter. It consists of a nucleus surrounded by electrons. Atoms form molecules. A **molecule** is a chemical structure consisting of at least two atoms held together by one or more chemical bonds. Many molecules that are biologically important are **macromolecules**, large molecules that are typically formed by polymerization (a polymer is a large molecule that is made by combining smaller units called monomers, which are simpler than macromolecules). An example of a macromolecule is deoxyribonucleic acid (DNA) (Figure **1.2.6**), which contains the instructions for the structure and functioning of all living organisms.

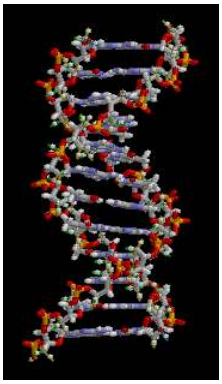


Figure **1.2.6**: All molecules, including this DNA molecule, are composed of atoms. (credit: "brian0918"/Wikimedia Commons)

Some cells contain aggregates of macromolecules surrounded by membranes; these are called **organelles**. Organelles are small structures that exist within cells. Examples of organelles include mitochondria and chloroplasts, which carry out indispensable functions: mitochondria produce energy to power the cell, while chloroplasts enable green plants to utilize the energy in sunlight to make sugars. All living things are made of **cells**; the cell itself is the smallest fundamental unit of structure and function in living organisms. (This requirement is why viruses are not considered living: they are not made of cells. To make new viruses, they have to invade and hijack the reproductive mechanism of a living cell; only then can they obtain the materials they need to reproduce.) Some organisms consist of a single cell and others are multicellular. Cells are classified as **prokaryotic** or **eukaryotic**. Prokaryotes are single-celled or colonial organisms that do not have membrane-bound nuclei; in contrast, the cells of eukaryotes do have membrane-bound organelles and a membrane-bound nucleus.

In larger organisms, cells combine to make **tissues**, which are groups of similar cells carrying out similar or related functions. **Organs** are collections of tissues grouped together performing a common function. Organs are present not only in animals but also in plants. An **organ system** is a higher level of organization that consists of functionally related organs. Mammals have many organ systems. For instance, the circulatory system transports blood through the body and to and from the lungs; it includes organs such

as the heart and blood vessels. **Organisms** are individual living entities. For example, each tree in a forest is an organism. Single-celled prokaryotes and single-celled eukaryotes are also considered organisms and are typically referred to as microorganisms.

All the individuals of a species living within a specific area are collectively called a **population**. For example, a forest may include many pine trees. All of these pine trees represent the population of pine trees in this forest. Different populations may live in the same specific area. For example, the forest with pine trees includes populations of flowering plants and also insects and microbial populations. A **community** is the sum of populations inhabiting a particular area. For instance, all of the trees, flowers, insects, and other populations in a forest form the forest's community. The forest itself is an **ecosystem**. An ecosystem consists of all the living things in a particular area together with the abiotic, non-living parts of that environment such as nitrogen in the soil or rainwater. At the highest level of organization, the **biosphere** is the collection of all ecosystems, and it represents the zones of life on earth (Figure **1.2.7**). It includes land, water, and even the atmosphere to a certain extent.

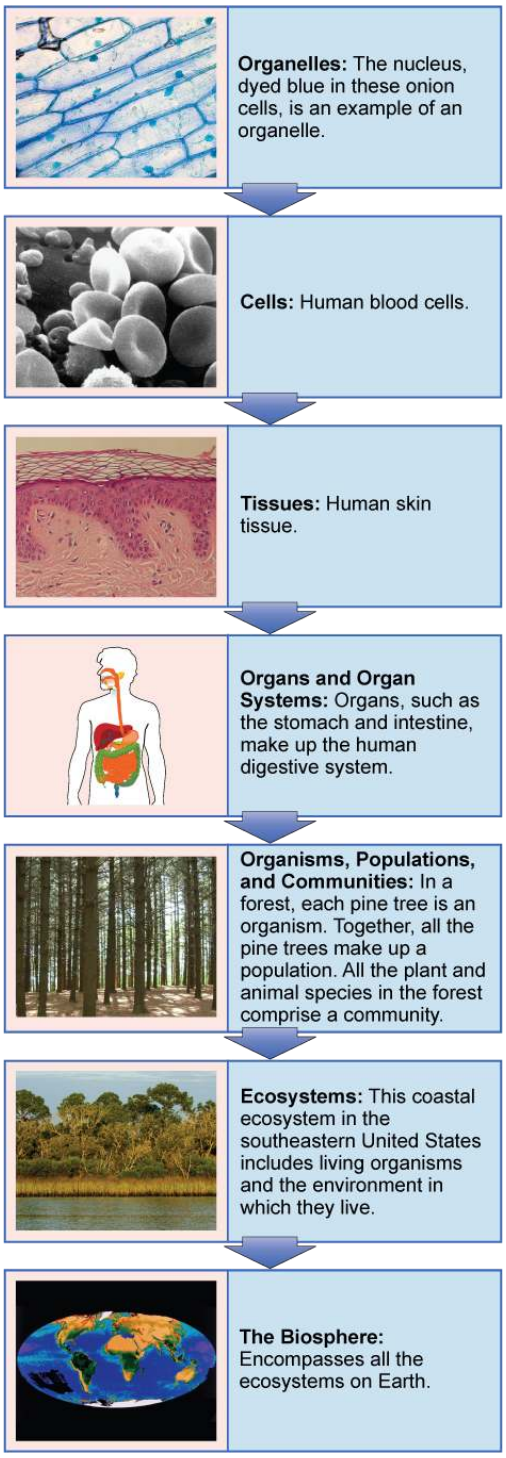
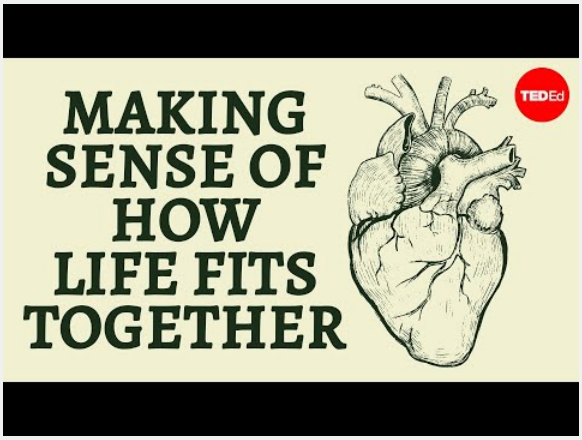


Figure **1.2.7**: The biological levels of organization of living things are shown. From a single organelle to the entire biosphere, living organisms are parts of a highly structured hierarchy. (credit “organelles”: modification of work by Umberto Salvagnin; credit “cells”: modification of work by Bruce Wetzel, Harry Schaefer/ National Cancer Institute; credit “tissues”: modification of work by Kilbad; Fama Clamosa; Mikael Häggström; credit “organs”: modification of work by Mariana Ruiz Villareal; credit “organisms”: modification of work by "Crystal"/Flickr; credit “ecosystems”: modification of work by US Fish and Wildlife Service Headquarters; credit “biosphere”: modification of work by NASA)

Video





Discover the many different levels of organization of life in this 5-minute video.
Question after watching: Many scientists specialize in a level of organization. If you were to study only one section of biological organization, which would you choose and why

Optional Activity 1.2.1

Which of the following statements is false? Refer to the text above for the correct answer.

A. Tissues exist within organs which exist within organ systems.
B. Communities exist within populations which exist within ecosystems.
C. Organelles exist within cells which exist within tissues.
D. Communities exist within ecosystems which exist in the biosphere.

Answer

B. Communities exist within populations which exist within ecosystems. This is an incorrect answer as populations ar least inclusive, then communities, then ecosystems.

The Diversity of Life

The fact that biology, as a science, has such a broad scope has to do with the tremendous diversity of life on earth. The source of this diversity is evolution, the process of gradual change during which new species arise from older species. Evolutionary biologists study the evolution of living things in everything from the microscopic world to ecosystems.

The evolution of various life forms on Earth can be summarized in a phylogenetic tree (Figure 1.2.8). A phylogenetic tree is a diagram showing the evolutionary relationships among biological species based on similarities and differences in genetic or physical traits or both. A phylogenetic tree is composed of nodes and branches. The internal nodes represent ancestors and are points in evolution when, based on scientific evidence, an ancestor is thought to have diverged to form two new species. The length of each branch is proportional to the time elapsed since the split.

We will investigate the diversity of life further in Unit 3.

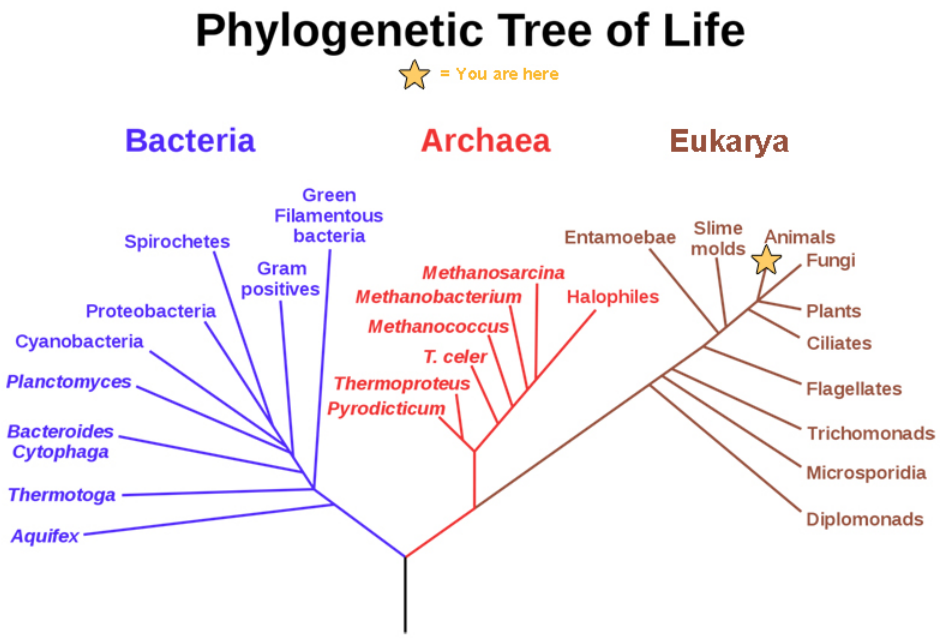


Figure 1.2.8: This phylogenetic tree was constructed by microbiologist Carl Woese using data obtained from sequencing ribosomal RNA genes. The tree shows the separation of living organisms into three domains: Bacteria, Archaea, and Eukarya. Bacteria and Archaea are prokaryotes, single-celled organisms lacking intracellular organelles. (credit: Eric Gaba; NASA Astrobiology Institute)

Evolution Connection: Carl Woese and the Phylogenetic Tree

In the past, biologists grouped living organisms into five kingdoms: animals, plants, fungi, protists, and bacteria. The organizational scheme was based mainly on physical features, as opposed to physiology, biochemistry, or molecular biology, all of which are used by modern systematics. The pioneering work of American microbiologist Carl Woese in the early 1970s has shown, however, that life on Earth has evolved along three lineages, now called domains—Bacteria, Archaea, and Eukarya. The first two are prokaryotic cells with microbes that lack membrane-enclosed nuclei and organelles. The third domain contains the eukaryotes and includes unicellular microorganisms together with the four original kingdoms (excluding bacteria). Woese defined Archaea as a new domain, and this resulted in a new taxonomic tree (Figure 1.2.8). Many organisms belonging to the Archaea domain live under extreme conditions and are called extremophiles. To construct his tree, Woese used genetic relationships rather than similarities based on morphology (shape).

Woese's tree was constructed from comparative sequencing of the genes that are universally distributed, present in every organism, and conserved (meaning that these genes have remained essentially unchanged throughout evolution). Woese's approach was revolutionary because comparisons of physical features are insufficient to differentiate between the prokaryotes that appear fairly similar in spite of their tremendous biochemical diversity and genetic variability (Figure 1.2.9). The

comparison of homologous DNA and RNA sequences provided Woese with a sensitive device that revealed the extensive variability of prokaryotes, and which justified the separation of the prokaryotes into two domains: bacteria and archaea.

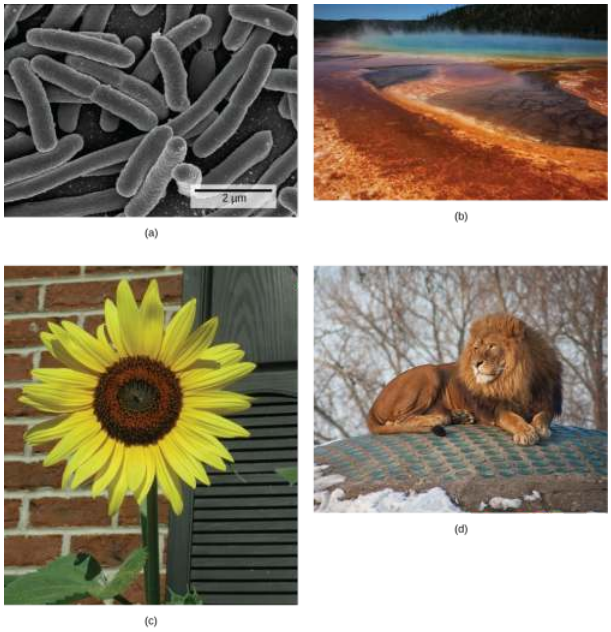
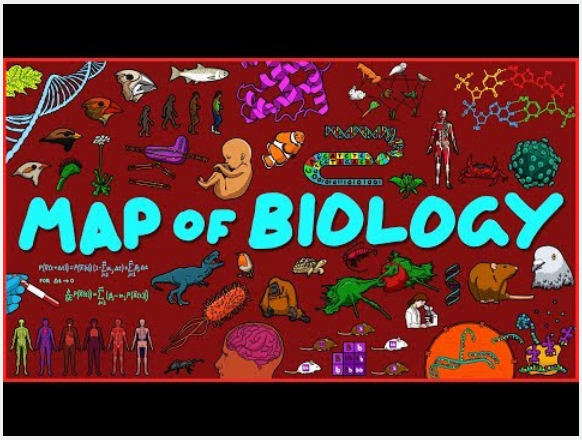


Figure **1.2.9**: These images represent different domains. The (a) bacteria in this micrograph belong to Domain Bacteria, while the (b) extremophiles (not visible) living in this hot vent belong to Domain Archaea. Both the (c) sunflower and (d) lion are part of Domain Eukarya. (credit a: modification of work by Drew March; credit b: modification of work by Steve Jurvetson; credit c: modification of work by Michael Arrighi; credit d: modification of work by Leszek Leszcynski)

Branches of Biological Study

The scope of biology is broad and therefore contains many branches and subdisciplines. Biologists may pursue one of those subdisciplines and work in a more focused field. For instance, molecular biology and biochemistry study biological processes at the molecular and chemical level, including interactions among molecules such as DNA, RNA, and proteins, as well as the way they are regulated. Microbiology, the study of microorganisms, is the study of the structure and function of single-celled organisms. It is quite a broad branch on its own, and depending on the subject of study, there are also microbial physiologists, ecologists, and geneticists, among others.

Video



This 9-minute video describes many of the fields of biology.
Question after watching: Which of the fields are new to you?

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Unit 1.3 - The Nature of Science

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2.5 hours.
- Optional Activities and Resources are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 1.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Use strategies of scientific inquiry to evaluate information, problems, and the validity of science;
- Model the scientific method;
- Compare inductive reasoning with deductive reasoning;
- Compare and contrast observational and descriptive studies;

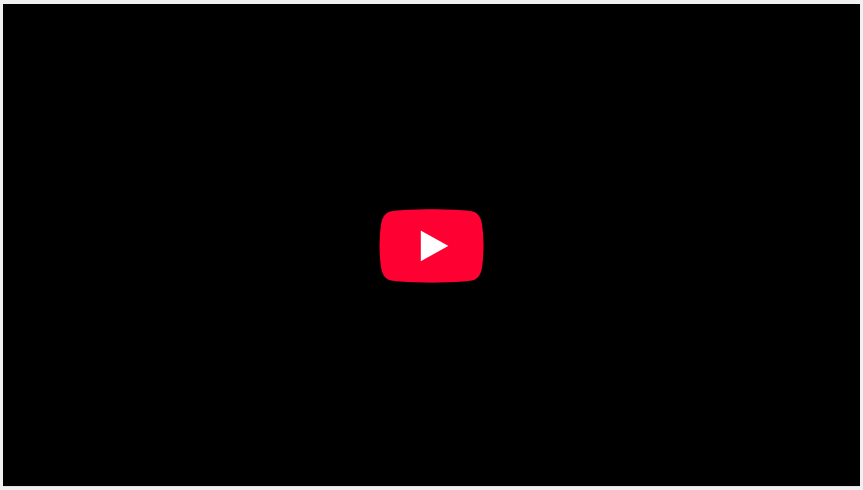
The Process of Science

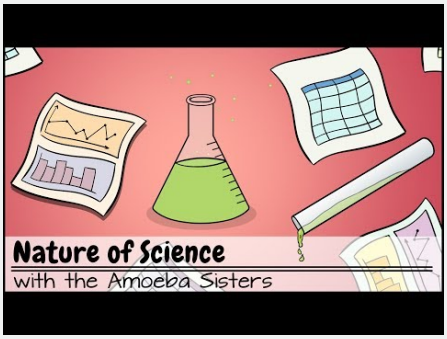
Biology is a science, but what exactly is science? What does the study of biology share with other scientific disciplines? **Science** (from the Latin *scientia*, meaning "knowledge") can be defined as a process that uses evidence, logic, and creativity to discover and explain natural and physical phenomenon while avoiding bias. The **scientific method** is a method of research with defined steps that include experiments and careful observation.

The steps of the scientific method will be examined in detail later, but one of the most important aspects of this method is the testing of hypotheses by means of repeatable experiments. A **hypothesis** is a suggested explanation for an event, which can be tested. Although using the scientific method is inherent to science, it is inadequate in determining what science is. It is relatively easy to apply the scientific method to disciplines such as physics and chemistry, but for disciplines like paleontology and geology, the scientific method is adapted to the field of study.

These areas of study are still sciences, however. Consider paleontology—even though one cannot perform repeatable experiments, hypotheses may still be supported. For instance, a paleontologist can hypothesize that an ancient organism existed based on finding a fossil. Further hypotheses could be made about various characteristics of this fossil, and these hypotheses may be found to be correct or false through continued support or contradictions from other findings. A hypothesis may become a theory with time and evidence. A **theory** is a well-tested and confirmed explanation for observations or phenomena. Science may be better defined as fields of study that attempt to comprehend the physical and natural underpinnings of the universe.

Video





This 10-minute video provides an overview of the process of science.

Question after watching: What additional characteristics/steps has this video proposed is important in the scientific process that was not mentioned in the text above?

Natural Sciences

What would you expect to see in a museum of natural sciences? Frogs? Plants? Dinosaur skeletons? Exhibits about how the brain functions? A planetarium? Gems and minerals? Or, maybe all of the above? Science includes such diverse fields as astronomy, biology, computer sciences, geology, logic, physics, chemistry, and mathematics (Figure **1.3.1**). However, those fields of science related to the physical world and its phenomena and processes are considered **natural sciences**. Thus, a museum of natural sciences might contain any of the items listed above.

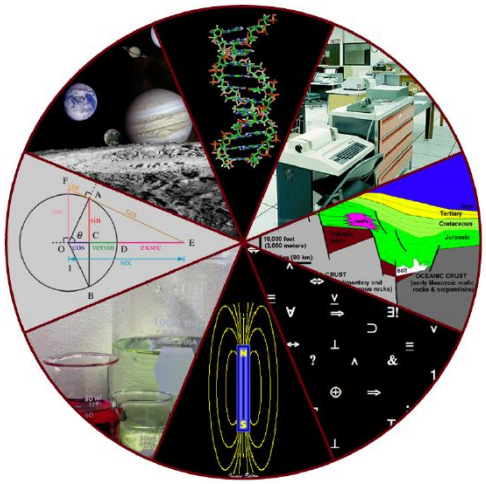
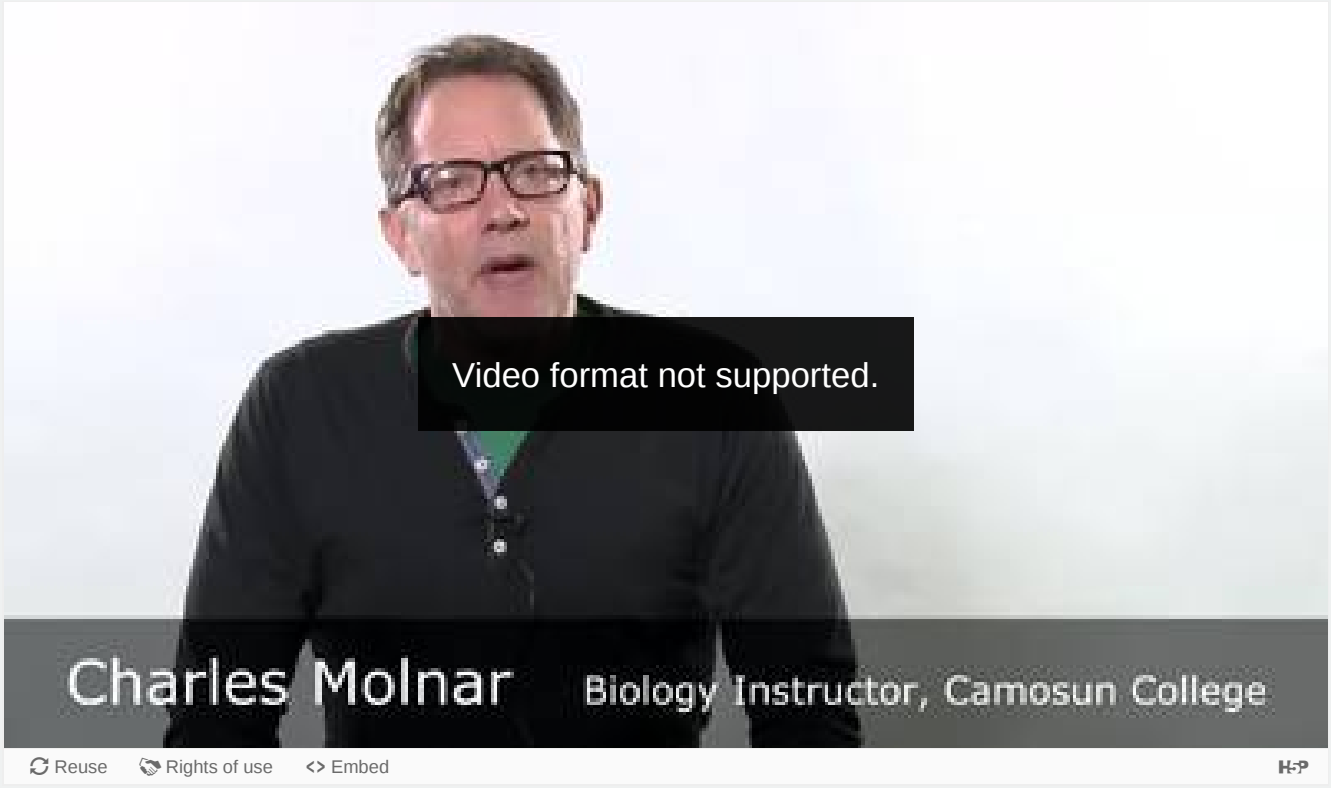


Figure **1.3.1**: The diversity of scientific fields includes astronomy, biology, computer science, geology, logic, physics, chemistry, mathematics, and many other fields. (credit: "Image Editor"/Flickr)

There is no complete agreement when it comes to defining what the natural sciences include, however. For some experts, the natural sciences are astronomy, biology, chemistry, earth science, and physics. Other scholars choose to divide natural sciences into **life sciences**, which study living things and include biology, and **physical sciences**, which study nonliving matter and include astronomy, geology, physics, and chemistry. Some disciplines such as biophysics and biochemistry build on both life and physical sciences and are **interdisciplinary**. Natural sciences often rely on the use of **quantitative**, or numeric, data although some may use **qualitative**, or non-numeric, data to support findings.

Not surprisingly, the natural science of biology has many branches or **subdisciplines**. Cell biologists study cell structure and function, while biologists who study anatomy investigate the structure of an entire organism. Those biologists studying physiology, however, focus on the internal functioning of an organism. Some areas of biology focus on only particular types of living things. For example, botanists explore plants, while zoologists specialize in animals.

Video



This 5-minute video provides the purpose of the scientific method.
Question after watching: Charles Molnar describes many ways in which human biases can influence how we observe or interpret the world around us. What steps do scientists put in place to try to remove these human biases from the process of learning about the world so that the final findings are as objective as possible?

History of Biological Science

Although modern biology is a relatively recent development, sciences related to and included within it have been studied since ancient times. Natural philosophy was studied as early as the ancient civilizations of Mesopotamia, Egypt, the Indian subcontinent, and China. However, the origins of modern biology and its approach to the study of nature are most often traced back to ancient Greece. (Biology is derived from the Greek word "bio" meaning "life" and the suffix "ology" meaning "study of.")

The scientific method was used in ancient times, but it was first documented by England's Sir Francis Bacon (1561–1626), who set up the first methodology for scientific inquiry. The scientific method is not exclusively used by biologists but can be applied to almost all fields of study as a logical, rational problem-solving method. Natural history observations and advances in microscopy have also had a profound impact on biological thinking. In the early 19th century, a number of biologists pointed to the central importance of the cell and in 1838, Schleiden and Schwann began promoting the now universal ideas of the cell theory. Jean-Baptiste Lamarck was the first to present a coherent theory of evolution, although it was the British naturalist Charles Darwin who spread the theory of natural selection throughout the scientific community. In 1953, the discovery of the double-helical structure of DNA marked the transition to the era of molecular genetics.

Video



Learn about Karl Popper and falsifiable hypotheses in this 11-minute video.
Question after watching: How does the idea of falsification change how you may have learned about science in the past?

Scientific Reasoning

One thing is common to all forms of science: an ultimate goal "to know." Curiosity and inquiry are the driving forces for the development of science. Scientists seek to understand the world and the way it operates. To do this, they use two methods of logical thinking: inductive reasoning and deductive reasoning (Figure **1.3.2**).

Inductive reasoning is a form of logical thinking that uses related observations to arrive at a general conclusion. This type of reasoning is common in descriptive science. A life scientist such as a biologist makes observations and records them. These data can be qualitative or quantitative, and the raw data can be supplemented with drawings, pictures, photos, or videos. From many observations, the scientist can infer conclusions (inductions) based on evidence. Inductive reasoning involves formulating generalizations inferred from careful observation and the analysis of a large amount of data. Brain studies provide an example. In this type of research, many live brains are observed while people are doing a specific activity, such as viewing images of food. The part of the brain that "lights up" during this activity is then predicted to be the part controlling the response to the selected stimulus, in this case, images of food. Then, researchers can stimulate that part of the brain to see if similar responses result.

Deductive reasoning or deduction is the type of logic used in hypothesis-based science. In deductive reason, the pattern of thinking moves in the opposite direction as compared to inductive reasoning. Deductive reasoning is a form of logical thinking that uses a general principle or law to forecast specific results. From those general principles, a scientist can extrapolate and predict the specific results that would be valid as long as the general principles are valid. Studies in climate change can illustrate this type of reasoning. For example, scientists may predict that if the climate becomes warmer in a particular region, then the distribution of plants and animals should change. These predictions have been made and tested, and many such changes have been found, such as the modification of arable areas for agriculture, with change based on temperature averages.

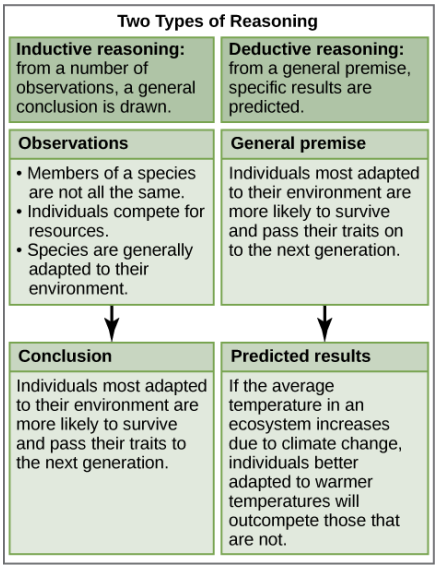


Figure **1.3.2**: Inductive vs Deductive Reasoning

? Optional Activity **1.3.1**

Decide if each of the following is an example of inductive or deductive reasoning.

1. All flying birds and insects have wings. Birds and insects flap their wings as they move through the air. Therefore, wings enable flight.
2. Insects generally survive mild winters better than harsh ones. Therefore, insect pests will become more problematic if global temperatures increase.
3. Chromosomes, the carriers of DNA, separate into daughter cells during cell division. Therefore, DNA is the genetic material.
4. Animals as diverse as humans, insects, and wolves all exhibit social behavior. Therefore, social behavior must have an evolutionary advantage.

Answer

1: inductive; 2: deductive; 3: deductive; 4: inductive.

Video



Many students confuse deductive reasoning with inductive reasoning and vice versa. Learn the difference in this 3-minute video.
Question after watching: Reflect on incidents/events in your life where you applied deductive and inductive reasoning. Describe them and why they are instances of inductive and deductive reasoning.

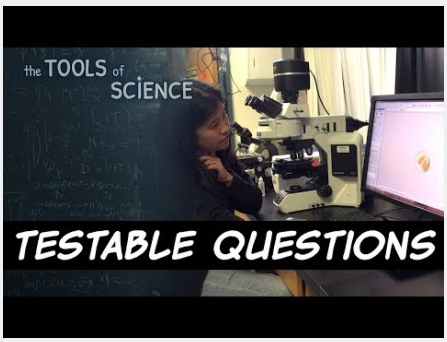
Both types of logical thinking are related to the two main pathways of scientific study: **descriptive science** and **hypothesis-based science**. Descriptive (or discovery) science, which is usually inductive, aims to observe, explore, and discover. Hypothesis-based science, which is usually deductive, begins with a specific question or problem and a potential answer or solution that can be tested. In hypothesis-based science, specific results are predicted from a general premise.

The boundary between descriptive science and hypothesis-based science is often blurred, and most scientific endeavors combine both approaches. Inductive and deductive reasoning are often used in tandem to advance scientific knowledge. The fuzzy boundary becomes apparent when thinking about how easily observation can lead to specific questions. For example, a gentleman in the 1940s observed that the burr seeds that stuck to his clothes and his dog's fur had a tiny hook structure. On closer inspection, he discovered that the burrs' gripping device was more reliable than a zipper. He eventually developed a company and produced the hook-and-loop fastener popularly known today as Velcro. Descriptive science and hypothesis-based science are in continuous dialogue.

The Scientific Method

Biologists study the living world by posing questions about it and seeking science-based responses. This approach is common to other sciences as well and is often referred to as the scientific method. The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. Let's think about a simple problem that starts with an observation and apply the scientific method to solve the problem. One Monday morning, a student arrives at class and quickly discovers that the classroom is too warm. That is an observation that also describes a problem: the classroom is too warm. The student then asks a question: "Why is the classroom so warm?"

Video



Learn about the 5 criteria that a testable question should meet in this 7.5-minute video.

? Optional Activity **1.3.2**

Read the following questions. Does the statement lend itself to investigation using the scientific method? In other words, is the hypothesis falsifiable (can be proven false)?

1. Is macaroni and cheese tastier than broccoli soup?
2. Are hummingbirds attracted to the color red?
3. Is the moon made out of green cheese?
4. Is plagiarism dishonest?

a. Questions 1 and 2 are subjective and cannot be disproven using scientific method. Questions 3 and 4 can be tested using scientific method.
b. Questions 3 and 4 are subjective and cannot be disproven using scientific method. Questions 1 and 2 can be tested using scientific method.
c. Questions 1 and 3 are subjective and cannot be disproven using scientific method. Questions 2 and 4 can be tested using scientific method.
d. Questions 1 and 4 are subjective and cannot be disproven using scientific method. Questions 2 and 3 can be tested using scientific method.

Answer

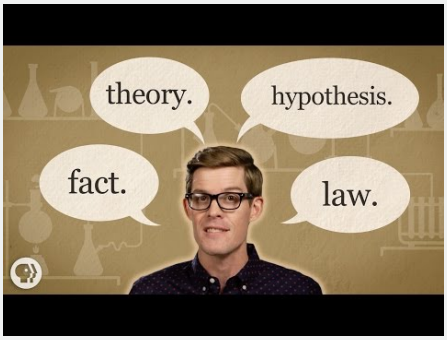
d. Questions 1 and 4 are subjective and cannot be disproven using scientific method. Questions 2 and 3 can be tested using scientific method.

Proposing a Hypothesis

Recall that a hypothesis is a suggested explanation that can be tested. To solve a problem, several hypotheses may be proposed. For example, one hypothesis might be, “The classroom is warm because no one turned on the air conditioning.” But there could be other responses to the question, and therefore other hypotheses may be proposed. A second hypothesis might be, “The classroom is warm because there is a power failure, and so the air conditioning doesn’t work.”

Once a hypothesis has been selected, the student can make a **prediction**. A prediction is similar to a hypothesis but it typically has the format “If . . . then . . . .” For example, the prediction for the first hypothesis might be, “*If* the student turns on the air conditioning, *then* the classroom will no longer be too warm.”

Video



In this 7-minute video, learn the difference between a fact, a theory, a hypothesis, and a scientific law.
Question BEFORE and AFTER watching: How would you define hypothesis and theory?

Testing a Hypothesis

A valid hypothesis must be testable. It should also be **falsifiable**, meaning that it can be disproven by experimental results. Importantly, science does not claim to "prove" anything because scientific understandings are always subject to modification with further information. This step—openness to disproving ideas—is what distinguishes sciences from non-sciences. The presence of the supernatural, for instance, is neither testable nor falsifiable. To test a hypothesis, a researcher will conduct one or more experiments designed to eliminate one or more of the hypotheses. Each experiment will have one or more variables and one or more controls. A **variable** is any part of the experiment that can vary or change during the experiment. The **control group** contains all of the same conditions experimental group EXCEPT for the variable being tested. Therefore, if the results of the **experimental group** differ from the control group, the difference must be due to the manipulation, rather than some outside factor. Identify the variables and controls in the examples from the section above.

Revisit the hypotheses from the section above:

1. The classroom is warm because no one turned on the air conditioning.
2. The classroom is warm because there is a power failure, and so the air conditioning doesn't work.

To test the first hypothesis, the student would find out if the air conditioning is on. If the air conditioning is turned on but does not work, there should be another reason, and this hypothesis should be rejected. To test the second hypothesis, the student could check if the lights in the classroom are functional. If so, there is no power failure and this hypothesis should be rejected. Each hypothesis should be tested by carrying out appropriate experiments. Be aware that rejecting one hypothesis does not determine whether or not the other hypotheses can be accepted; it simply eliminates one hypothesis that is not valid (Figure **1.3.4**). Using the scientific method, the hypotheses that are inconsistent with experimental data are rejected.

While this "warm classroom" example is based on observational results, other hypotheses and experiments might have clearer controls. For instance, a student might attend class on Monday and realize she had difficulty concentrating on the lecture. One observation to explain this occurrence might be, "When I eat breakfast before class, I am better able to pay attention." The student could then design an experiment with a control to test this hypothesis, including keeping all details of their morning the same but eating breakfast one day versus another to see how their attention holds in class.

The scientific method may seem too rigid and structured (Figure **1.3.3**). It is important to keep in mind that, although scientists often follow this sequence, there is flexibility. In fact, the scientific process is much more complex in practice. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion; instead, scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests. Notice, too, that the scientific method can be applied to solving problems that aren't necessarily scientific in nature.

Video



In this 5-minute video, explore how scientists designed and implemented a sampling and data collection plan to answer scientific questions.
Question after watching: What are important things to consider when selecting samples?

Video



In this 6-minute video, explore why data is critically important to the scientific process, what makes good data, and how to use data correctly.
Question after watching: What is the distinction and/or relationship between variables and data?

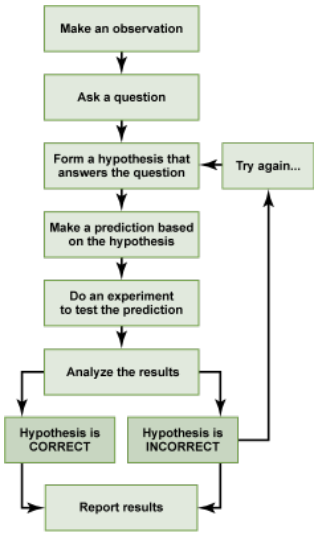


Figure **1.3.3**: The traditional view of the scientific method.

? Optional Activity 1.3.3

In the example below, the scientific method is used to solve an everyday problem. Order the scientific method steps (numbered items) with the process of solving the everyday problem (lettered items). Based on the results of the experiment, is the hypothesis correct? If it is incorrect, propose some alternative hypotheses.

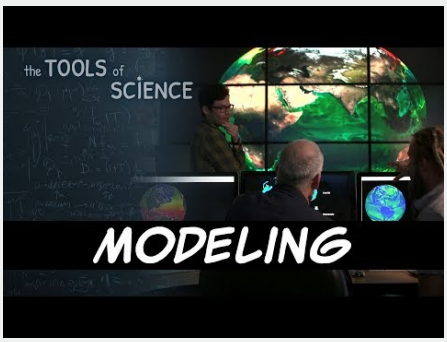
1. Observation
2. Question
3. Hypothesis (answer)
4. Prediction
5. Experiment
6. Result

A. There is something wrong with the electrical outlet.
B. If something is wrong with the outlet, my coffeemaker also won't work when plugged into it.
C. My toaster doesn't toast my bread.
D. I plug my coffee maker into the outlet.
E. My coffeemaker works.
F. Why doesn't my toaster work?

Answer

1: C; 2: F; 3: A; 4: B; 5: D; 6: E. The original hypothesis is incorrect, as the coffeemaker works when plugged into the outlet. Alternative hypotheses include that the toaster might be broken or that the toaster wasn't turned on.

Video



In this 6-minute video, the critical importance of mathematical models to the scientific process is explored.
Question: Why is modeling such a fundamentally important tool?

Video



Discover why collaboration among scientists with different backgrounds and expertise is essential for strong science investigations in this 6.5-minute video.
Question after watching: The research expedition includes several research teams. Why is that?

Video





See how science REALLY works in this 5-minute video.
Question after watching: Why do they use the pinball game analogy for describing how science works?

Optional Resource

Find a more realistic, but more complex, diagram of the scientific method from the University of California - Berkeley here: https://undsci.berkeley.edu/lessons/pdfs/complex_flow_handout.pdf

Pseudoscience

Pseudoscience is a claim, belief, or practice that is presented as scientific but does not adhere to the standards and methods of science. True science is based on repeated evidence-gathering and testing of falsifiable hypotheses. Pseudoscience does not adhere to these criteria. Pseudoscience is often known as fringe or alternative science. It usually lacks the carefully-controlled and thoughtfully-interpreted experiments which provide the foundation of the natural sciences and which contribute to their advancement. In addition to phrenology, some other examples of pseudoscience include astrology, extrasensory perception (ESP), reflexology, reincarnation, and Scientology

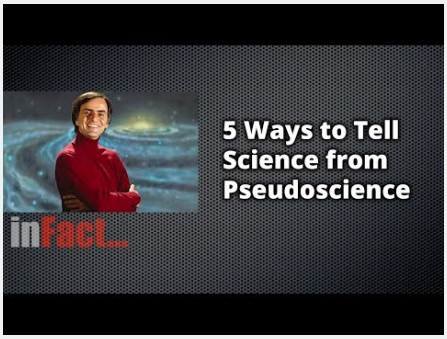
Characteristics of Pseudoscience

Whether a field is actually science or just pseudoscience is not always clear. However, pseudoscience generally exhibits certain common characteristics. Indicators of pseudoscience include:

- *The use of vague, exaggerated, or untestable claims:* Many claims made by pseudoscience cannot be tested with evidence. As a result, they cannot be falsified, even if they are not true.
- *An over-reliance on confirmation rather than refutation:* Any incident that appears to justify a pseudoscience claim is treated as proof of the claim. Claims are assumed true until proven otherwise, and the burden of disproof is placed on skeptics of the claim.
- *A lack of openness to testing by other experts:* Practitioners of pseudoscience avoid subjecting their ideas to peer review. They may refuse to share their data and justify the need for secrecy with claims of proprietary or privacy.
- *An absence of progress in advancing knowledge:* In pseudoscience, ideas are not subjected to repeated testing followed by rejection or refinement, as hypotheses are in true science. Ideas in pseudoscience may remain unchanged for hundreds — or even thousands — of years. In fact, the older an idea is, the more it tends to be trusted in pseudoscience.
- *Personalization of issues:* Proponents of pseudoscience adopt beliefs that have little or no rational basis, so they may try to confirm their beliefs by treating critics as enemies. Instead of arguing to support their own beliefs, they attack the motives and character of their critics.
- *The use of misleading language:* Followers of pseudoscience may use scientific-sounding terms to make their ideas sound more convincing. For example, they may use the formal name dihydrogen monoxide to refer to plain old water.

Video





This 3.5-minute video reviews what is considered pseudoscience.
Question after watching: What are some instances of pseudoscience that you have seen or heard recently?

Persistence of Pseudoscience

Despite failing to meet scientific standards, many pseudosciences survive. Some pseudosciences remain very popular with large numbers of believers. A good example is astrology.

Astrology claims to study the movements and relative positions of celestial objects as a means for divining information about human affairs and terrestrial events. Many ancient cultures attached importance to astronomical events, and some developed elaborate systems for predicting terrestrial events from celestial observations. Throughout most of its history in the West, astrology was actually considered a scholarly tradition and was common in academic circles. With the advent of modern Western sciences and the process of scientific inquiry, however, astrology was called into question. It was challenged on both theoretical and experimental grounds. Eventually, astrology was shown to have no scientific validity or explanatory power.

Today, astrology is considered a pseudoscience, yet it continues to have many devotees. Many people know their astrological sign, and some are familiar with the supposed personality traits associated with their "sign". Astrological readings and horoscopes are readily available online and in print media, and a lot of people read them, even if only occasionally. Some believe that astrology is scientific. Studies suggest that the persistent popularity of pseudosciences such as astrology is due to misunderstandings of

scientific principles and methodology. Alternatively, some are not convinced by scientific arguments that go against their personal beliefs and this, in the end, can do real harm to themselves or others.

Dangers of Pseudoscience

Belief in astrology is unlikely to cause a person harm, but belief in some other pseudosciences might — especially in healthcare-related areas. Treatments that seem scientific but are not may be ineffective, expensive, and even dangerous to patients. Seeking out pseudoscientific treatments may also delay or preclude patients from seeking scientifically-based medical treatments that have been tested and found safe and effective. In short, following pseudoscience instead of established health care practices may be harmful.

Scientific Hoaxes, Frauds, and Fallacies

Pseudoscience is not the only way that science may be misused. Scientific **hoaxes,** frauds, and fallacies may misdirect the pursuit of science, put patients at risk, or mislead and confuse the public. An example of each of these misuses of science and its negative effects is described below.

The Vaccine-Autism Fraud

While it is not true, you may have heard that certain vaccines put the health of young children at risk. This persistent idea is not supported by scientific evidence or accepted by the vast majority of experts in the field. It stems largely from an elaborate medical research fraud that was reported in a 1998 article published in the respected British medical journal, *The Lancet*. The main author of the article was a British physician named Andrew Wakefield. In the article, Wakefield and his colleagues described case histories of only 12 children, most of whom were reported to have developed autism soon after the administration of the MMR (measles, mumps, rubella) vaccine.

There were a whole host of problems with this study, including falsification of research, ethics violations, and experimental design problems. The paper has been retracted (a very big deal in the science community), most of the co-authors have retracted their authorship, and Wakefield lost his medical license. It also later emerged that Wakefield had received research funding from a group of people who were suing vaccine manufacturers. Thousands of follow-up studies have failed to show any association between the MMR vaccine and autism. Unfortunately, by then, the damage had already been done. Parents afraid that their children would develop autism had refrained from having them vaccinated. British MMR vaccination rates fell from nearly 100 percent to 80 percent in the years following the study. The consensus of medical experts today is that Wakefield's fraud put hundreds of thousands of children at risk because of the lower vaccination rates and also diverted research efforts and funding away from finding the true cause of autism.

Correlation-Causation Fallacy

Many statistical tests used in scientific research calculate correlations between variables. **Correlation** refers to how closely related two data sets are, which may be a useful starting point for further investigation. Correlation, however, is also one of the most misused types of evidence, primarily because of the logical fallacy that correlation implies causation. In reality, just because two variables are correlated does not *necessarily* mean that either variable causes the other.

A few simple examples, illustrated by the graphs below, can be used to demonstrate the correlation-causation fallacy. Assume a study found that both per capita consumption of mozzarella cheese and the number of Civil Engineering doctorates awarded are correlated; that is, rates of both events increase together Figure **1.3.4**. If correlation really did imply causation, then you could conclude from the second example that the increase in age of Miss America causes an increase in murders of a specific type or vice versa Figure **1.3.5**.

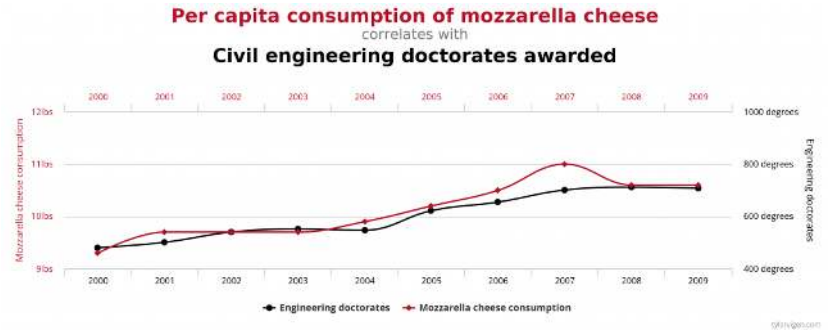


Figure **1.3.4** Spurious Correlations [Causation Fallacy] – Consumption of mozzarella cheese and awarded Doctorates

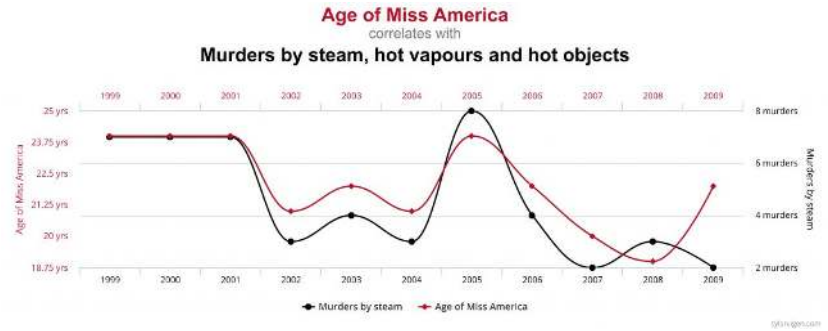


Figure **1.3.5**: Spurious Correlations (Causation Fallacy) - Miss America and Murder

Video



Watch this 4-minute video to learn how to spot a misleading graph.
Question after watching: How can graphs present an opinion?

HRT and CHD

An actual example of the correlation-causation fallacy occurred during the latter half of the 20th century. Numerous studies showed that women taking hormone replacement therapy (HRT) to treat menopausal symptoms also had a lower-than-average incidence of coronary heart disease (CHD). This correlation was misinterpreted as evidence that HRT protects women against CHD. Subsequent studies that controlled other factors related to CHD disproved this presumed causal connection. The studies found that women taking HRT were more likely to come from higher socio-economic groups, with better-than-average diets and exercise regimens. Rather than HRT causing lower CHD incidence, these studies concluded that HRT and lower CHD were both effects of higher socio-economic status and related lifestyle factors.

Video



How statistics can be misleading

Question after watching: What types of motivation could be at play when people or organizations present statistics?

Finally, read through this "Rough Guide to Spotting Bad Science" infographic from Compound Interest:



Figure **1.3.6**: A Rough Guide to Spotting Bad Science.

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Unit 1.4 - The Role of Science in Society

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1.5 hours.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to the Unit 1 Glossary and Summary, use the Contents menu at the top of the page OR the right arrow on the side of the page.
    - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Appreciate the importance of science in culture and society;
- Compare and contrast basic and applied science;
- Explain how scientists disseminate their work;
- Describe characteristics of Indigenous ways of knowing about the natural world;
- Identify how the process of science and Indigenous ways of knowing may complement one another.

Science and Culture

From the United Nations Educational, Scientific and Cultural Organization (UNESCO):

> *"Science is the greatest collective endeavor. It contributes to ensuring a longer and healthier life, monitors our health, provides medicine to cure our diseases, alleviates aches and pains, helps us to provide water for our basic needs – including our food, provides energy and makes life more fun, including sports, music, entertainment and the latest communication technology. Last but not least, it nourishes our spirit.*
>
> *Science generates solutions for everyday life and helps us to answer the great mysteries of the universe. In other words, science is one of the most important channels of knowledge. It has a specific role, as well as a variety of functions for the benefit of our society: creating new knowledge, improving education, and increasing the quality of our lives.*
>
> *Science must respond to societal needs and global challenges. Public understanding and engagement with science, and citizen participation including through the popularization of science are essential to equip citizens to make informed personal and professional choices. Governments need to make decisions based on quality scientific information on issues such as health and agriculture, and parliaments need to legislate on societal issues which necessitate the latest scientific knowledge. National governments need to understand the science behind major global challenges such as climate change, ocean health, biodiversity loss and freshwater security.*
>
> *To face sustainable development challenges, governments and citizens alike must understand the language of science and must become scientifically literate. On the other hand, scientists must understand the problems policy-makers face and endeavor to make the results of their research relevant and comprehensible to society.*
>
> *Challenges today cut across the traditional boundaries of disciplines and stretch across the lifecycle of innovation -- from research to knowledge development and its application. Science, technology and innovation must drive our pursuit of more equitable and sustainable development"* (2021).

Two Types of Science: Basic Science and Applied Science

The scientific community has been debating for the last few decades about the value of different types of science. Is it valuable to pursue science for the sake of simply gaining knowledge, or does scientific knowledge only have worth if we can apply it to solving a specific problem or to bettering our lives? This question focuses on the differences between two types of science: **basic science** and **applied science**.

Basic science or “pure” science seeks to expand knowledge regardless of the short-term application of that knowledge. It is not focused on developing a product or a service of immediate public or commercial value. The immediate goal of basic science is knowledge for knowledge’s sake, though this does not mean that, in the end, it may not result in a practical application.

In contrast, applied science or “technology,” aims to use science to solve real-world problems, making it possible, for example, to improve a crop yield, find a cure for a particular disease, or save animals threatened by a natural disaster (Figure **1.4.1**). In applied science, the problem is usually defined for the researcher.



Figure **1.4.1**: After Hurricane Ike struck the Gulf Coast in 2008, the U.S. Fish and Wildlife Service rescued this brown pelican. Thanks to applied science, scientists knew how to rehabilitate the bird. (credit: FEMA)

Some individuals may perceive applied science as “useful” and basic science as “useless.” A question these people might pose to a scientist advocating knowledge acquisition would be, “What for?” A careful look at the history of science, however, reveals that basic knowledge has resulted in many remarkable applications of great value. Many scientists think that a basic understanding of science is necessary before an application is developed; therefore, applied science relies on the results generated through basic science. Other scientists think that it is time to move on from basic science and instead to find solutions to actual problems. Both approaches are valid. It is true that there are problems that demand immediate attention; however, few solutions would be found without the help of the wide knowledge foundation generated through basic science.

One example of how basic and applied science can work together to solve practical problems occurred after the discovery of DNA structure led to an understanding of the molecular mechanisms governing DNA replication. Strands of DNA, unique in every human, are found in our cells, where they provide the instructions necessary for life. During DNA replication, DNA makes new copies of itself, shortly before a cell divides. Understanding the mechanisms of DNA replication enabled scientists to develop laboratory techniques that are now used to identify genetic diseases, pinpoint individuals who were at a crime scene, and determine paternity. Without basic science, it is unlikely that applied science would exist.

Another example of the link between basic and applied research is the Human Genome Project, a study in which each human chromosome was analyzed and mapped to determine the precise sequence of DNA subunits and the exact location of each gene. (The gene is the basic unit of heredity; an individual’s complete collection of genes is his or her genome). Other less complex organisms have also been studied as part of this project in order to gain a better understanding of human chromosomes. The Human Genome Project relied on basic research carried out with simple organisms and, later, with the human genome (Figure **1.4.2**). An important end goal eventually became using the data for applied research, seeking cures and early diagnoses for genetically related diseases.

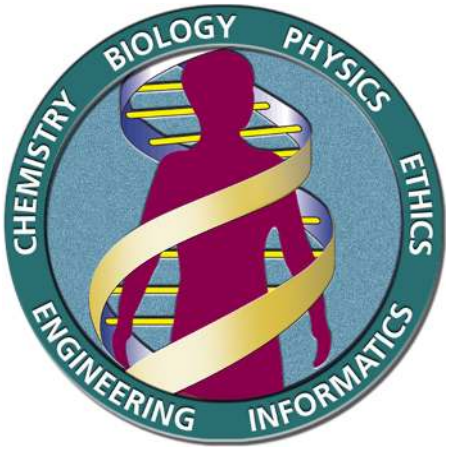


Figure **1.4.2**: The Human Genome Project was a 13-year collaborative effort among researchers working in several different fields of science. The project, which sequenced the entire human genome, was completed in 2003. (credit: the U.S. Department of Energy Genome Programs (http://genomics.energy.gov))

While research efforts in both basic science and applied science are usually carefully planned, it is important to note that some discoveries are made by **serendipity**, that is, by means of a fortunate accident or a lucky surprise. Penicillin was discovered when biologist Alexander Fleming accidentally left a petri dish of *Staphylococcus* bacteria open. An unwanted mold grew on the dish, killing the bacteria. The mold turned out to be *Penicillium*, and a new antibiotic was discovered. Even in the highly organized world of science, luck—when combined with an observant, curious mind—can lead to unexpected breakthroughs.

Video





Watch this video to see how science is playing a role in understanding Peary caribou in Canada.
Question after watching: What type of research is this? Basic or applied?

Reporting Scientific Work

Whether scientific research is basic science or applied science, scientists must share their findings in order for other researchers to expand and build upon their discoveries. Collaboration with other scientists—when planning, conducting, and analyzing results—are all important for scientific research. For this reason, important aspects of a scientist's work are communicating with peers and disseminating results to peers. Scientists can share results by presenting them at a scientific meeting or conference, but this approach can reach only the select few who are present. Instead, most scientists present their results in peer-reviewed manuscripts that are published in scientific journals. Peer-reviewed manuscripts are scientific papers that are reviewed by a scientist's colleagues, or peers. These colleagues are qualified individuals, often experts in the same research area, who judge whether or not the scientist's work is suitable for publication. The process of **peer review** helps to ensure that the research described in a scientific paper or grant proposal is original, significant, logical, and thorough. Grant proposals, which are requests for research funding, are also subject to peer review. Scientists publish their work so other scientists can reproduce their experiments under similar or different conditions to expand on the findings. The experimental results must be consistent with the findings of other scientists.

A scientific paper is very different from creative writing. Although creativity is required to design experiments, there are fixed guidelines when it comes to presenting scientific results. First, scientific writing should be concise and accurate. A scientific paper needs to be succinct but detailed enough to allow peers to reproduce the experiments.

The scientific paper consists of several specific sections—introduction, materials and methods, results, and discussion. This structure is sometimes called the "**IMRaD**" format. There are usually acknowledgment and reference sections as well as an abstract (a concise summary) at the beginning of the paper. There might be additional sections depending on the type of paper and the journal where it will be published; for example, some review papers require an outline.

The **introduction** starts with brief, but broad, background information about what is known in the field. A good introduction also gives the rationale of the work; it justifies the work carried out and is where the hypothesis or research question driving the research will be presented. The introduction may also briefly mention the results of the paper. The introduction refers to the published scientific work of others and therefore requires citations following the style of the journal. Using the work or ideas of others without proper citation is considered plagiarism.

The **materials and methods** section includes a complete and accurate description of the substances used, and the method and techniques used by the researchers to gather data. The description should be thorough enough to allow another researcher to repeat the experiment and obtain similar results, but it does not have to be verbose. This section will also include information on how measurements were made and what types of calculations and statistical analyses were used to examine raw data. Although the materials and methods section gives an accurate description of the experiments, it does not discuss them.

Some journals require a **results** section followed by a **discussion** section, but some may combine both. If the journal does not allow the combination of both sections, the results section simply narrates the findings without any further interpretation. The results are presented by means of tables or graphs, but no duplicate information should be presented. In the discussion section, the researcher

will interpret the results, describe how variables may be related, and attempt to explain the observations. It is indispensable to conduct an extensive literature search to put the results in the context of previously published scientific research. Therefore, proper **citations** are included in this section as well.

Finally, a **conclusion** section may be used to summarize the importance of the experimental findings. Most often, the conclusions are included in the discussion. While the scientific paper almost certainly answered one or more scientific questions that were stated, any good research should lead to more questions. Therefore, a well-done scientific paper leaves doors open for the researcher and others to continue and expand on the findings.

Review articles do not follow the IMRAD format because they do not present original scientific findings, or primary literature; instead, they summarize and comment on findings that were published as primary literature and typically include extensive reference sections. They follow specific methods of searching and summarizing the scientific literature, to ensure that their findings are reproducible.

Indigenous Science

The following text may be different than text that you have come across before in a science context because Indigenous Science will be woven throughout the content. You will find this content as green call-out boxes throughout this text.

Now that you have read Unit 1.3, the following piece has been included to provide you with another perspective on science and culture. Consider this not as an alternative to what you have already learned but an examination of how each can contribute to a better understanding of nature, the world, and its importance. Indigenous Science, explained below, is formally known to many biologists and ecologists as Traditional Ecological Knowledge (TEK); this text will use TEK throughout the rest of the Units.

Indigenous Connections

It is important to balance and consider Indigenous Science, that which recognizes the knowledge inherent in each culture. Yamada, a Japanese historian of Oriental science, writes that "every culture and every society has its own science, and its function is sustaining its mother society and culture" (1970, p. 585). Cultural diversity suggests that Western Science (WS) and Indigenous Science (IS) should be viewed as co-existing or parallel. Hatcher et al. (2009, p. 15) describe Indigenous Science metaphorically as a "living knowledge" that requires less dependence on knowledge transfer from books and requires "knowledge gardening with living knowledge keepers," which differs from Western Science. As you study biology, it is important to balance and consider the traditional contexts of IS with WS evidence and reason.

The traditional wisdom component of IS—the values and ways of decision-making relating to science knowledge—is particularly rich in time-tested approaches that foster sustainability and environmental integrity. WS is the most dominant science in the world today and is widely thought of as "officially sanctioned science." However, because WS has been implicated in many of the world's ecological disasters—pesticide contamination, introduced species, dams and water diversions that have impacted salmon and other indigenous species—it seems that reliance on Western Science alone can be seen as increasingly problematic and even counterproductive.

The process of generating or learning Indigenous ways of living in nature is *coming to know* (Cajete, 2000; Peat, 1994), a phrase that connotes a journey. *Coming to know* differs from a Eurocentric science process *to know* or *to discover* that connotes a destination, such as a patent or published record of discovery. Indigenous *coming to know* is a journey toward wisdom or a journey of wisdom in action, not a discovery of knowledge (Aikenhead & Ogawa, 2007). For Michell (2005), *coming to know* includes the goal of living in harmony with nature for the survival of the community. "Nature provides a blueprint of how to live well and all that is necessary to sustain life" (Michell, 2005, p. 39).

Traditional Ecological Knowledge (TEK) combines current observation with wisdom, knowledge, and experience that has been acquired over thousands of years of direct human contact with specific environments. TEK interprets how the world works from the cultural perspective unique to a particular group of Indigenous peoples. Although the term TEK came into widespread use in the 1980's, TEK itself is timeless and predates written record (Corsiglia & Snively, 1997). The stories and testimonies of Indigenous peoples are usually related to a home place or territory. TEK embodies both remembered sensory information built upon repeated observation, and formal understandings that are usually transmitted orally in story form or ceremonial form with abstract principles and important information encapsulated in metaphor (Cruikshank, 1991; Turner et al.,

2000). Perhaps the most useful way to think about Indigenous Science is that it is complementary to Western Science and not a replacement for it. Rooted in different worldviews, Indigenous and Western Science are not easy to combine, and it may not be desirable to meld the two. Each knowledge system is legitimate in its own right. The two kinds of knowledge may be pursued separately but in parallel, enriching one another as needed (Berkes, 2012). As such, *weaving TEK* with western science throughout this text will help you develop a deeper understanding of key biology concepts from multiple perspectives.

Numerous traditional peoples' scientific and technological contributions have been incorporated in modern applied sciences such as ecology, biology, medicine, architecture, engineering, geology, pharmacology, agriculture, horticulture, agronomy, metallurgy, navigation, astronomy, animal husbandry, fish and wildlife management, nautical science, plant breeding, and military and political science (Berkes, 2012; Turner & Peacock, 2005; Deur & Turner, 2005; Turner, 2014a, 2014b; Weatherford, 1988, 1991). The truth is, directly or indirectly, we are all benefiting from Indigenous scientific and technological innovations every time we dine, clothe ourselves, travel or go to the doctor.

TEK provides invaluable time-tested resource management practices that can be used alongside WS to develop more workable and effective approaches to current resource management strategies than either could accomplish alone. In fact, it has become a policy requirement in Canada, and in particular Northern Canada, that TEK be incorporated into environmental assessments affecting wildlife management including: migratory birds, species at risk, forest practices, and fisheries management (Usher, 2000).

Some of the contributions of TEK and Indigenous Science scholarship to contemporary environmental knowledge, conservation and resource management worldwide (acknowledged by Western scientists) are outlined below:

- Perceptive investigations of traditional environmental knowledge systems provide important biological and ecological insights (Berkes 2012; Houde, 2007; Turner & Peacock, 2005; Turner, 2014a, 2014b; Usher, 2000; Warren, 1997).
- Help locate rare and endangered species and provide cost-effective shortcuts for investigating the local resource bases. Local knowledge makes it possible to survey and map in a few days what would otherwise take months, for example, soil types, plant and animal species, migration pathways, and aggregation sites (Berkes, 2012; Usher, 2000; Warren, 1997).
- Provide knowledge of time-tested resource management practices and can be used to develop workable approaches to current resource management strategies (Houde, 2007; Turner & Peacock, 2005; Usher, 2000; Warren et al., 1995).
- Provides time-tested in-depth knowledge of the local area (past and present) that can be triangulated with WS resulting in more accurate environmental assessment and impact statements. People who depend on local resources for their livelihood are often able to assess the true costs and benefits of development better than any evaluator from outside (Houde, 2007; Warren, 1997; Warren et al., 1995).
- Provides experience-based value statements about appropriate and ethical behavior with respect to animals and the environment (Berkes, 2012; Deur & Turner, 2005; Turner, 2014a, 2014b; Houde, 2007; Usher, 2000).

A key point here is that scientists may be unable to understand the complexity of ecosystems, especially northern or distant ecosystems, through sporadic observations, as opposed to lived experience.

Recognition of the importance of incorporating IS and TEK in environmental planning is explicitly addressed in reports and agreements in Canada and internationally. The Brundtland Commission report, *Our Common Future* (WCED: World Commission on Environment and Development, 1987), recognized the role of TEK in sustainable development; and the *Convention on Biological Diversity*, *Agenda 21* (UN Conference on the Environment, 1993), declared that Indigenous people possess important traditional scientific knowledge. The document *Science for the Twenty-First Century: A New Commitment* (World Conference on Science, 2000), set new standards for respecting, protecting and utilizing Indigenous Knowledge. Working scientists worldwide, associated with hundreds of institutes, are collaborating with Elders and knowledge holders to collect and document examples of TEK and IS knowledge; this includes institutes in the United States, Canada, Middle and South America, Africa, Europe, Australia, New Zealand, India, Russia, China, and Japan.

To find out more about researchers working with Indigenous partners and how they are benefiting from traditional knowledge of the natural world, read "First Nations Communities Bring Expertise to Canada's Scientific Research" by Owens (2021) from *Nature*.

Source: Adapted from Snively and Corsiglia (2016).

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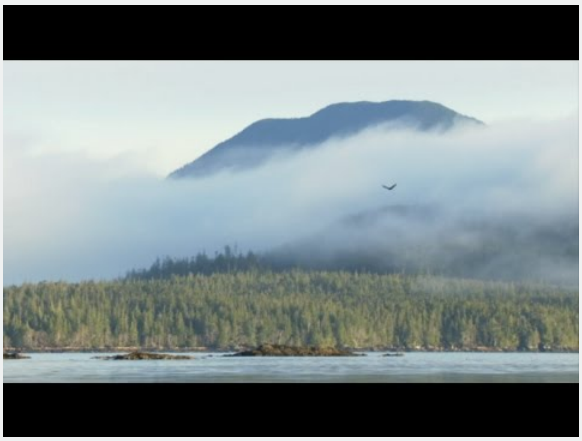
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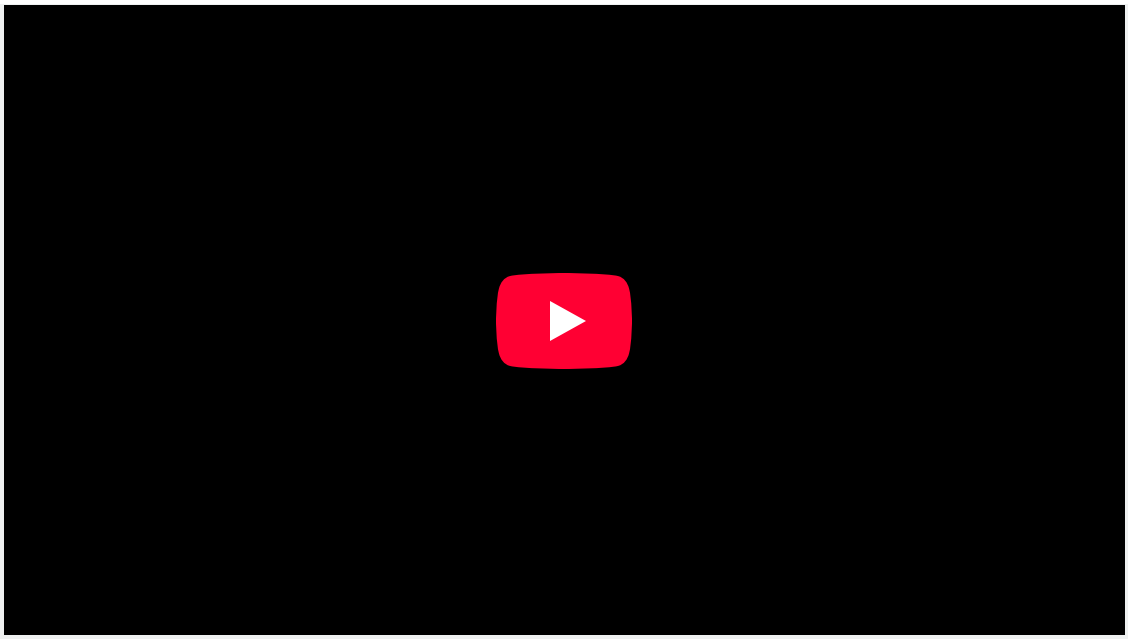
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Videos













Watch the three videos above as examples of the TEK and WS working together.
Question after watching: Do you know of other examples of TEK and IS from your province or region?

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1.G: Unit 1 Glossary

Unit 1.2

atom
smallest and most fundamental unit of matter

biochemistry
study of the chemistry of biological organisms

biosphere
collection of all the ecosystems on Earth

botany
study of plants

cell
smallest fundamental unit of structure and function in living things

community
set of populations inhabiting a particular area

ecosystem
all the living things in a particular area together with the abiotic, nonliving parts of that environment

eukaryote
organism with cells that have nuclei and membrane-bound organelles

evolution
process of gradual change during which new species arise from older species and some species become extinct

homeostasis
ability of an organism to maintain constant internal conditions

macromolecule
large molecule, typically formed by the joining of smaller molecules

microbiology
study of the structure and function of microorganisms

molecule
chemical structure consisting of at least two atoms held together by one or more chemical bonds

molecular biology
study of biological processes and their regulation at the molecular level, including interactions among molecules such as DNA, RNA, and proteins

neurobiology
study of the biology of the nervous system

organ
collection of related tissues grouped together performing a common function

organ system
level of organization that consists of functionally related interacting organs

organelle
small structures that exist within cells and carry out cellular functions

organism
individual living entity

paleontology
study of life's history by means of fossils

phylogenetic tree
diagram showing the evolutionary relationships among various biological species based on similarities and differences in genetic or physical traits or both; in essence, a hypothesis concerning evolutionary connections

population
all of the individuals of a species living within a specific area

prokaryote
single-celled organism that lacks organelles and does not have nuclei surrounded by a nuclear membrane

tissue
group of similar cells carrying out related functions

Unit 1.3

zoology
study of animals

abstract
opening section of a scientific paper that summarizes the research and conclusions

applied science
form of science that aims to solve real-world problems

basic science
science that seeks to expand knowledge and understanding regardless of the short-term application of that knowledge

biology
the study of living organisms and their interactions with one another and their environments

conclusion
section of a scientific paper that summarizes the importance of the experimental findings

control
part of an experiment that does not change during the experiment

deductive reasoning

form of logical thinking that uses a general inclusive statement to forecast specific results

descriptive science
(also, discovery science) form of science that aims to observe, explore, and investigate

discussion
section of a scientific paper in which the author interprets experimental results, describes how variables may be related, and attempts to explain the phenomenon in question

falsifiable
able to be disproven by experimental results

hypothesis
suggested explanation for an observation, which can be tested

hypothesis-based science
form of science that begins with a specific question and potential testable answers

inductive reasoning
form of logical thinking that uses related observations to arrive at a general conclusion

introduction
opening section of a scientific paper, which provides background information about what was known in the field prior to the research reported in the paper

life science
field of science, such as biology, that studies living things

materials and methods
section of a scientific paper that includes a complete description of the substances, methods, and techniques used by the researchers to gather data

natural science
field of science that is related to the physical world and its phenomena and processes

peer-reviewed manuscript
scientific paper that is reviewed by a scientist's colleagues who are experts in the field of study

physical science
field of science, such as geology, astronomy, physics, and chemistry, that studies nonliving matter

plagiarism
using other people's work or ideas without proper citation, creating the false impression that those are the author's original ideas

results
section of a scientific paper in which the author narrates the experimental findings and presents relevant figures, pictures, diagrams, graphs, and tables, without any further interpretation

review article
paper that summarizes and comments on findings that were published as primary literature

science
knowledge that covers general truths or the operation of general laws, especially when acquired and tested by the scientific method

scientific method
method of research with defined steps that include observation, formulation of a hypothesis, testing, and confirming or falsifying the hypothesis

serendipity
fortunate accident or a lucky surprise

theory
tested and confirmed explanation for observations or phenomena

variable
part of an experiment that the experimenter can vary or change

Unit 1.4

applied science
process of science to solve real-world problems

basic science
process of science for the sake of gaining knowledge

IMRaD
traditional format of a scientific paper comprised of introduction, materials and methods, results, and discussion

Indigenous Science
recognizes the knowledge inherent in each culture

peer review
ensures that research described in a scientific paper or grant proposal is original, significant, logical, and thorough

serendipity
fortunate accident

Traditional Ecological Knowledge
combines current observation with wisdom, knowledge, and experience that has been acquired over thousands of years of direct human contact with specific environments

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1.S: Unit 1 Summary

In Unit 1, we learned about the study of biology, science as a process, and the interplay of science and culture.

Unit 1.2

Biology is the science of life. All living organisms share several key properties such as order, sensitivity or response to stimuli, reproduction, growth and development, regulation, homeostasis, and energy processing. Living things are highly organized parts of a hierarchy that includes atoms, molecules, organelles, cells, tissues, organs, and organ systems. Organisms, in turn, are grouped as populations, communities, ecosystems, and the biosphere. The great diversity of life today evolved from less-diverse ancestral organisms over billions of years. A diagram called a phylogenetic tree can be used to show evolutionary relationships among organisms.

Biology is very broad and includes many branches and subdisciplines. Examples include molecular biology, microbiology, neurobiology, zoology, and botany, among others. Biology is the culmination of the achievements of the natural sciences from their inception to today. Excitingly, it is the cradle of emerging sciences, such as the biology of brain activity, genetic engineering of custom organisms, and the biology of evolution that uses the laboratory tools of molecular biology to retrace the earliest stages of life on earth. A scan of news headlines—whether reporting on immunizations, a newly discovered species, sports doping, or a genetically-modified food—demonstrates the way biology is active in and important to our everyday world.

Unit 1.3

Biology is the science that studies living organisms and their interactions with one another and their environments. Science attempts to describe and understand the nature of the universe in whole or in part by rational means. Science has many fields; those fields related to the physical world and its phenomena are considered natural sciences. Two types of logical reasoning are used in science. Inductive reasoning uses particular results to produce general scientific principles. Deductive reasoning is a form of logical thinking that predicts results by applying general principles. The common thread throughout scientific research is the use of the scientific method, a step-based process that consists of making observations, defining a problem, posing hypotheses, testing these hypotheses, and drawing one or more conclusions. The testing uses proper controls.

Pseudoscience is a claim, belief, or practice that is presented as scientific, but does not adhere to scientific standards and methods. Indicators of pseudoscience include untestable claims, lack of openness to testing by experts, absence of progress in advancing knowledge, and attacks on the motives and character of critics. Some pseudosciences, including astrology, remain popular. This suggests that many people do not possess the scientific literacy needed to distinguish pseudoscience from true science, or to be convinced by scientific arguments against them. Belief in a pseudoscience such as astrology is unlikely to cause harm, but belief in pseudoscientific medical treatments may be harmful. In addition to pseudoscience, other examples of the misuse of science include scientific hoaxes, scientific frauds (such as the MMR vaccine-autism fraud), and scientific fallacies (such as the correlation-causation fallacy).

Unit 1.4

Science can be basic or applied. The main goal of basic science is to expand knowledge without any expectation of short-term practical application of that knowledge. The primary goal of applied research, however, is to solve practical problems. Scientists present their results in peer-reviewed scientific papers published in scientific journals. A scientific research paper consists of several well-defined sections: introduction, materials and methods, results, and, finally, a concluding discussion. Review papers summarize the research done in a particular field over a period of time.

In Unit 2, we will learn about macroevolution, speciation, and microevolution.

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CHAPTER OVERVIEW

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2.1: Unit 2 Introduction

Unit 2 Introduction

Evolution is the change in the heritable traits of biological populations over successive generations. Evolutionary processes give rise to diversity at every level of biological organization, including the levels of species, individual organisms, and molecules. The core concepts of evolution are discussed in this unit with examples illustrating evolutionary processes. Additionally, the evolutionary basis of biology is reinforced through embedded media and special call-out features highlighting specific evolution-based topics.

Unit 2 Course Learning Outcomes

By the end of this Unit, you will be able to:

- Discuss the mechanisms of evolution by natural selection.
- Explain our changing view of the evolutionary history of biological diversity.
- Discuss important processes and interactions leading to the structure of natural communities, especially natural selection, population growth, competition, nutrient cycling, and behavioural ecology.
- Think critically about the principles of biology studied
- Communicate your thinking clearly and concisely in speaking and in writing.

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2.3. The Origin of Species

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Unit 2 Assessments

If you are a TRU student using this resource, all of your assessed learning activities and assignments are in your course Moodle site.

This unit introduces learners to the evidence and mechanisms of evolution, the process of speciation, and the relationship between genes and populations.

Video



This 1.5-minute video highlights the finches that Darwin examined from the Galapagos Islands.
Question after watching: Can you spot the differences between these finches?

Please click on the blue arrow on the right to start Unit 2: Chapter 2.2. If you are on mobile, use the navigation links at the bottom of this page.

Cover Photo: "Darwin's finches" (CC-BY-SA 4.0; Kiwi Rex)

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SECTION OVERVIEW

2.2: Evolution- History, Evidence, and Mechanisms

Learning Objectives

- Explain evolution as an underlying theme in biology
- Describe adaptations as a general concept
- Describe the wide range of adaptations of individual species use to interact with and adjust to variations in their environment
- Recognize misconceptions about the theory of evolution
- Identify the major requirements of natural selection
- Explain the relationships among adaptation, natural selection, and evolution
- Compare and contrast additional mechanisms of evolution: mutation, genetic drift, gene flow, and genetic recombination.

2.2.1: Understanding Evolution

2.2.2: Evidence of Evolution

2.2.3: Natural Selection and Adaptive Evolution

2.2.4: Additional Mechanisms of Evolution

Cover photo: "Dinosaur footprint" (Greg Willis, CC BY-SA 2.0)

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Unit 2.2.1 - Understanding Evolution

- Please read and watch the following Learning Resources.
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 2.2.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe the historical influences on Darwin’s and Wallace's theory of evolution
- Explain the requirements of evolution.
- Identify the major misconceptions of evolution and why they are incorrect.

Introduction: Evolution

Video





This 12-minute video summarizes much of the material below. You may want to revisit this video at the end of the Unit. Question after watching: Darwin famously wrote that "endless forms most beautiful have been and are being evolved." In what way do we know that evolution is still taking place today?

The theory of evolution is the unifying theory of biology, meaning it is the framework within which biologists ask questions about the living world. The Ukrainian-born American geneticist Theodosius Dobzhansky famously wrote in 1964 that "nothing makes sense in biology except in the light of evolution." [1] The tenet that all species have evolved and diversified from a common ancestor is the foundation from which we approach all questions in biology. It provides a direction for predictions about living things and has been validated through extensive scientific experimentation. **Evolution** is simply a change in the gene pool of a species over time. More technically, evolution is the change in genetic composition of a population over time, specifically over generations, resulting from differential survival and reproduction of individuals. Evolution by natural selection describes one mechanism for this change. Natural selection is introduced here but is discussed in further detail in Section 2.2.3. Additional mechanisms are discussed in Section 2.2.4.

Adaptations

A heritable trait that aids the survival and reproduction of an organism in its present environment is called an **adaptation**. A population is adapted when a change in the range of genetic variation occurs over time that increases or maintains the survivability of that population in its current environmental conditions. The webbed feet of platypuses are an adaptation for swimming. The snow leopard's thick fur is an adaptation to living in the cold. The cheetah's fast speed is an adaptation for catching prey.



Figure **2.2.1.1**: All organisms are products of evolution via adaptations to their environment. (a) Saguaro (*Carnegiea gigantea*) can soak up 750 liters of water in a single rain storm, enabling these cacti to survive the dry conditions of the Sonoran desert in Mexico and the Southwestern United States. (b) The Andean semiaquatic lizard (*Potamites montanicola*), discovered in Peru in 2010, lives between 1,570 to 2,100 meters in elevation and, unlike most lizards, is nocturnal and swims. Scientists still do not know how these cold-blood animals are able to move in the cold (10 to 15°C) temperatures of the Andean night.

Whether or not an individual trait is favorable depends on the environmental conditions at the time. The same traits are not always selected because environmental conditions can change. For example, consider a species of plant that grew in a moist climate and did not need to conserve water. Large leaves were selected because they allowed the plant to obtain more energy from the sun. Large leaves require more water to maintain than small leaves, and the moist environment provided favorable conditions to support large leaves. After thousands of years, the climate changed and the area no longer had excess water. The direction of natural selection shifted so that plants with small leaves were selected because those populations were able to conserve water to survive the new environmental conditions.

Video



This video identifies the three types of adaptations organisms may possess.
Questions after watching: What sorts of adaptations might you expect to arise in a plant species or a bacterial/unicellular species? Do you expect that the three types described in the video for animals will apply to these types of species?

History of the Theory of Evolution

Well before Darwin began to explore the concept of evolution, the idea that species change over time had already been suggested and debated. The view that species are static and unchanging was grounded in the writings of Plato more than 2000 years ago, yet there were also ancient Greeks who expressed ideas about evolution. During the eighteenth century, ideas about the evolution of animals were reintroduced by the naturalist Georges-Louis Leclerc Comte de Buffon who observed that various geographic regions have different plant and animal populations, even when the environments are similar. It was also accepted that there are extinct species.

During this time, a Scottish naturalist named James Hutton proposed that geological change occurs gradually by the accumulation of small changes over long periods of time. This theory contrasted with the predominant view of the time: that the geology of the planet is a consequence of catastrophic events that occurred during a relatively brief past. During the nineteenth century, Hutton's views were popularized by the geologist Charles Lyell, who was a friend of Charles Darwin. Lyell's ideas, in turn, influenced

Darwin's concept of evolution. The greater age of the earth proposed by Lyell supported the gradual evolution that Darwin proposed, and the slow process of geological change provided an analogy for the gradual change in species.

In the early nineteenth century, Jean-Baptiste Lamarck published a book that detailed a different mechanism for evolutionary change. This mechanism is now referred to as an inheritance of acquired characteristics. This idea states that modifications in an individual are caused by its environment, or the use or disuse of a structure during its lifetime. These changes can be inherited by its offspring, bringing about change in a species. While this mechanism for evolutionary change is now known to be incorrect, Lamarck's ideas were an important influence on the initial concepts of evolution, especially in regards to epigenetics, or the influence of the environment on genetic expression.

Charles Darwin and Alfred Russell Wallace

In the mid-nineteenth century, the mechanism for evolution was independently conceived of and described by two naturalists: Charles Darwin and Alfred Russel Wallace. Importantly, each naturalist spent time exploring the natural world on expeditions to the tropics. From 1831 to 1836, Darwin traveled around the world to places like South America, Australia, and the southern tip of Africa. Wallace traveled to Brazil to collect insects in the Amazon rainforest from 1848 to 1852 and to the Malay Archipelago from 1854 to 1862. Darwin's journey, as with Wallace's later journeys to the Malay Archipelago, included stops at several island chains, the last being the Galápagos Islands west of Ecuador.

On these islands, Darwin observed that species of organisms on different islands were clearly similar, yet had distinct differences. For example, the ground finches inhabiting the Galápagos Islands comprised several species with unique beak shapes. The species on the islands had a graded series of beak sizes and shapes with very small differences between the most similar. He observed that these finches closely resembled another finch species on the mainland of South America.

Darwin imagined that the island species might be modified from one of the original mainland species. Upon further study, he realized that the varied beaks of each finch helped the birds acquire a specific type of food. For example, seed-eating finches had stronger, thicker beaks for breaking seeds, while insect-eating finches had spear-like beaks for stabbing their prey. In 1860, he wrote, "seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends."

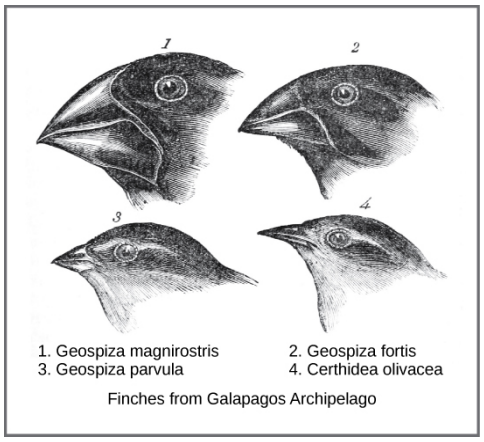


Figure **2.2.1.2**: Darwin observed that beak shape varies among finch species. He postulated that the beak of an ancestral species had adapted over time to equip the finches to acquire different food sources.

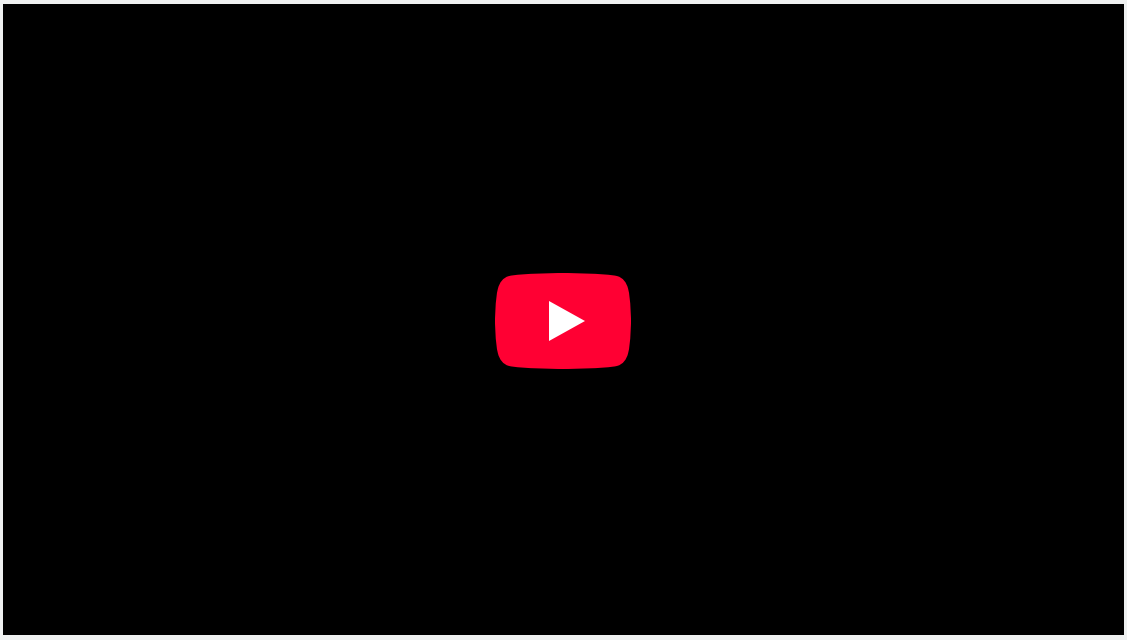
Origin of the Idea of Natural Selection

Wallace and Darwin observed similar patterns in other organisms and independently developed the same explanation for how and why such changes could take place. Darwin called this mechanism natural selection. **Natural selection**, also known as "survival of the fittest," is the more prolific reproduction of individuals with favorable traits that survive environmental change because of those traits. This leads to evolutionary change, the trait becoming predominant within a population. For example, Darwin observed that a population of giant tortoises found in the Galápagos Archipelago have longer necks than those that lived on other islands with dry lowlands. These tortoises were "selected" because they could reach more leaves and access more food than those with short necks. In times of drought, when fewer leaves would be available, those that could reach more leaves had a better chance to eat and

survive than those that could not reach the food source. Consequently, long-necked tortoises would more successfully reproduce and pass the long-necked trait to their offspring. Over time, only long-necked tortoises would be present in the population.

Natural selection, Darwin argued, was an inevitable outcome of three principles that operated in nature. First, *most characteristics of organisms are inherited*, or passed from parent to offspring, although *how* traits were inherited was unknown at the time. Second, *more offspring are produced than are able to survive*. The capacity for reproduction in all organisms outstrips the availability of resources to support their numbers. Thus, there is competition for those resources in each generation (note: when Darwin mentioned "survival of the fittest," he was referring to the competition between members of the same species for resources, not between different species, a common misconception). Both Darwin and Wallace were influenced by an essay written by economist Thomas Malthus who discussed this principle in relation to human populations. Third, Darwin and Wallace reasoned that *offspring with the inherited characteristics that allow them to best compete for limited resources will survive and have more offspring than those individuals with variations that are less able to compete*. Because characteristics are inherited, these traits will be better represented in the next generation. This will lead to change in populations over successive generations in a process that Darwin called descent with modification. Ultimately, natural selection leads to greater adaptation of the population to its local environment; it is the only mechanism known for adaptive evolution.

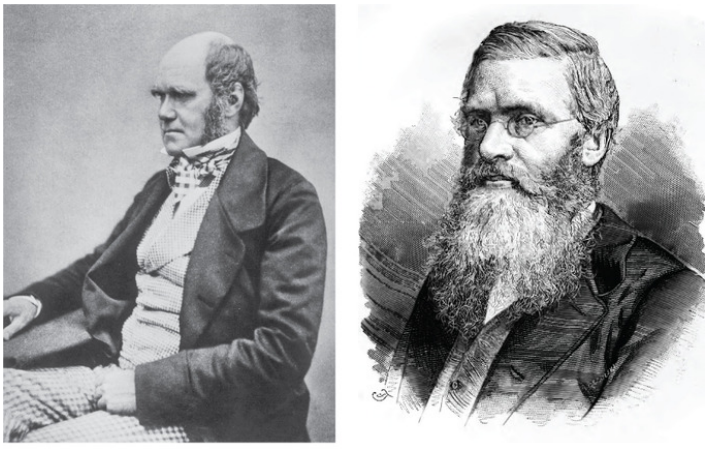
Video



This 9-minute video is an overview of Darwin's concept of natural selection which is explained in a slightly different manner than the reading. Notably, it explains how evolution by natural selection has been harnessed in agriculture and farming.

Question after watching: Which aspects of natural selection are random and which are not random?

Papers by Darwin and Wallace presenting the idea of natural selection were read together in 1858 before the Linnean Society in London. The following year, Darwin's book, *On the Origin of Species*, was published which outlined his arguments for evolution by natural selection.



(a) (b)

Figure **2.2.1.3**: Both (a) Charles Darwin and (b) Alfred Wallace wrote scientific papers on natural selection that were presented together before the Linnean Society in 1858.

? Optional Activity 2.2.1.1

Which scientific concept did Charles Darwin and Alfred Russell Wallace independently discover?

a. mutation
b. natural selection
c. overbreeding
d. sexual reproduction

Answer

b. natural selection

Requirements for Evolution

All of the following are required for evolution to occur.

Variation

One of the hallmarks of Darwin and Wallace's theory of evolution via natural selection is that it can only take place if there is **variation**, or differences, among individuals in a population. Importantly, these differences must have a genetic basis (their **genotypes**); otherwise, selection will not lead to change in the next generation. This is critical because variation among individuals can be caused by non-genetic reasons, such as an individual losing a limb due to an accident. Variations of this type would not be inherited by the next generation.

Individuals of a population often display different **phenotypes**, or physical, metabolic, or behavioral expressions of their genotypes. Populations with two or more variations of particular characteristics, or trait, are called **polymorphic**. The distribution of phenotypes among individuals, known as the **population variation**, is influenced by a number of factors, including the population's genetic structure and the environment (Figure **2.2.1.4**). Understanding the sources of a phenotypic variation in a population is important for determining how a population will evolve in response to different evolutionary pressures.



Figure **2.2.1.4**: The distribution of phenotypes in this litter of kittens illustrates population variation. (credit: Pieter Lanser)

The theory of natural selection stems from the observation that some individuals in a population are more likely to survive longer and have more offspring than others; thus, they will pass on more of their genes to the next generation. A big, powerful male gorilla, for example, is more likely than a smaller, weaker one to become the population's silverback, the pack's leader who mates far more than the other males of the group. The pack leader will father more offspring, who share half of his genes, and are likely to also grow bigger and stronger like their father. Over time, the genes for bigger size will incase in frequency in the population, leading to a greater percentage of larger gorillas in the population. As a consequence, the average size of a gorilla in this population will increase. That is, this would occur if this particular **selection pressure**, or driving selective force, were the only one acting on the population. In other examples, better camouflage or a stronger resistance to drought might pose a selection pressure. In addition to natural selection, below are the details of five other agents of evolutionary change that are all acting in concert with natural selection.

This variation, or **genetic diversity,** within a population comes from two main mechanisms: mutation and, in those species that reproduce sexually, sexual reproduction. **Mutation**, a change in the DNA sequence, is the ultimate source of new alleles, or new genetic variation in any population. The genetic changes caused by mutation can have one of three outcomes:

- Many mutations will have no effect on the genetic contribution of an individual to future generations; these are called neutral mutations.
- A mutation may affect the phenotype of the organism in a way that gives it a lower likelihood of survival or fewer offspring.
- A mutation may produce a phenotype with a beneficial effect on survival or its genetic contribution to future generations.

Different mutations will have a range of above effects on an organism that expresses them in their phenotype, from a small to great.

Sexual reproduction also leads to genetic diversity: when two individuals of a sexually-reproducing species reproduce, unique combinations of alleles assemble to produce the unique genotypes and thus phenotypes in each of the offspring. However, sexual reproduction does not lead to *new* genes, but rather provides a new combination of genes in a given individual.

Inheritance

The trait or adaptation being selected for or against must be heritable.

Differential Reproduction and Survival

Individuals with a certain version of the trait are more likely to survive and reproduce than individuals with a different version of the trait

Time

The version of the trait that helps individuals survive and reproduce becomes more common in the population over multiple generations. Individuals do not evolve.

? Optional Activity 2.2.1.2

Which of the following situations may lead to natural selection?

a. The seeds of two plants land near each other and one grows larger faster.
b. Two types of fish eat the same kind of food but one is better able to gather food than the other.

c. In a species of fungi, one colony spreads faster through the soil to reach nutrients than another colony of the same species.
d. All of the above may lead to natural selection.

Answer

d. All of the above may lead to natural selection.

Patterns of Evolution

The evolution of species has resulted in enormous variation in form and function. Sometimes, evolution gives rise to groups of organisms that become tremendously different from each other. We call two species that evolve in diverse directions from a common point **divergent evolution**. We can see such divergent evolution in the forms of the reproductive organs of flowering plants which share the same basic anatomies (Figure **2.2.1.5**); however, they can look very different as a result of selection in different physical environments and adaptation to different kinds of pollinators.



Figure **2.2.1.5**: Flowering plants evolved from a common ancestor. Notice that the (a) dense blazing star (Liatrus spicata) and the (b) purple coneflower (Echinacea purpurea) vary in appearance, yet both share a similar basic morphology.

In other cases, similar phenotypes evolve independently in distantly related species. For example, flight has evolved in both bats and insects, and they both have structures we refer to as wings, which are adaptations to flight. However, bat and insect wings have evolved from very different original structures. We call this phenomenon **convergent evolution**, where similar traits evolve independently in species that do not share a common ancestry. The two species came to the same function, flying, but did so separately from each other.

These physical changes occur over enormous time spans and help explain how evolution occurs. Natural selection acts on individual organisms, which can then shape an entire species. Although natural selection may work in a single generation on an individual, it can take thousands or even millions of years for an entire species' genotype to evolve. It is over these large time spans that life on earth has changed and continues to change.

? Optional Activity **2.2.1.3**

Which situation is most likely an example of convergent evolution?

a. Squid and humans have eyes similar in structure.
b. Worms and snakes both move without legs.
c. Some bats and birds have wings that allow them to fly.
d. All of the above are examples of convergent evolution.

Answer

D. All of the above are examples of convergent evolution.

The Modern Synthesis: Natural Selection and Genetics

The mechanisms of inheritance, **genetics**, were not understood at the time Darwin and Wallace were developing their idea of natural selection. This lack of understanding was a stumbling block to comprehending many aspects of evolution. In fact, blending inheritance was the incorrect, but predominant, genetic theory of the time. This made it difficult to understand how natural selection might operate. Darwin and Wallace were unaware of the genetics work by Austrian monk Gregor Mendel, which was published in 1866, not long after the publication of *On the Origin of Species*. Mendel's work was rediscovered in the early twentieth century at which time geneticists were rapidly coming to an understanding of the basics of inheritance. Initially, the newly discovered particulate nature of genes made it difficult for biologists to understand how gradual evolution could occur. But over the next few decades, genetics and evolution were integrated into what became known as the **modern synthesis**—the coherent understanding of the relationship between natural selection and genetics that took shape by the 1940s and is generally accepted today. In sum, the modern synthesis describes how evolutionary pressures, such as natural selection, can affect a population's genetic makeup, and, in turn, how this can result in the gradual evolution of populations and species. The theory also connects this gradual change of a population over time, called **microevolution**, with the processes that gave rise to new species and higher taxonomic groups with widely divergent characters, called **macroevolution**.

Misconceptions about Evolution

The theory of evolution has been amply tested by researchers over the past 200 years. From this work, confidence in the theory's basic tenants has been bolstered. Today, the vast majority of scientists accept the theory of evolution by natural selection as the most plausible, supported mechanism to explain how organisms change over time.

However, certain groups, led by values other than the scientific search for evidence, have objected to the theory of evolution including as an explanation for the diversity of life. This has led to the spread of some misinformation and misconception about the theory. Below, these misconceptions are explicitly addressed.

Concept in Action

This website addresses some of the main misconceptions associated with the theory of evolution.

Misconception #1: Evolution Is Just a 'Theory'

Critics of the theory of evolution dismiss its importance by purposefully confounding the everyday usage of the word "theory" with the way scientists use the word. In science, a **theory** is understood to be a concept that has been extensively tested and supported over time. We have a theory of the atom, a theory of gravity, and the theory of relativity, each of which describes the strong evidence that scientists have to support our understanding of nature and the universe. In the same way, the theory of evolution describes our scientific understanding about life. As such, a theory in science has survived significant efforts to discredit it by scientists, who are naturally skeptical. While theories can sometimes be overturned or revised, this does not lessen their weight but simply reflects the constantly growing state of scientific understanding. In contrast, a "theory" in common vernacular means a guess or suggested explanation for something. This meaning is more along the lines of the concept of a scientific **hypothesis**, which is a tentative explanation for something that is proposed to either be supported or disproved. When critics of evolution say evolution is "just a theory," they are mischaracterizing the science and inferring that there is little evidence supporting it. This is far from accurate. Evolution is widely accepted, extensively tested, heavily supported, and can be monitored in real-time, such as with Darwin's finches.

Misconception #2: Individuals Evolve

An individual is born with the genes it has—these do not change as the individual ages. Therefore, an individual cannot evolve or adapt through natural selection. Individuals do change over their lifetime, but this is called development; it involves changes programmed by the set of genes the individual acquired at birth in coordination with the individual's environment. When thinking about the evolution of a characteristic, it is probably best to think about the change in the average value of the characteristic in the population over time. For example, when natural selection leads to a bill-size change in medium-ground finches in the Galápagos, this does not mean that individual bills on the finches are changing. If one measures the average bill size among all individuals in the population at one time, and then measures the average bill size in the population several years later after there has been a strong

selective pressure, this average value may be different as a result of evolution. Although some individuals may survive from the first time to the second, those individuals will still have the same bill size. However, there may be enough new individuals with different bill sizes to change the average bill size.

Misconception #3: Evolution Explains the Origin of Life

It is a common misunderstanding that evolution includes an explanation of life's origins. Conversely, some of the theory's critics complain that it cannot explain the origin of life. The theory of evolution explains how populations change over time and how life diversifies—the origin of species. It does not shed light on the beginnings of life including the origins of the first cells, which is how life is defined. The mechanisms of the origin of life on Earth are a particularly difficult problem because it occurred a very long time ago, over a very long time, and presumably just occurred once. Importantly, biologists believe that the presence of life on Earth precludes the possibility that the events that led to life on Earth can be repeated because the intermediate stages would immediately become food for existing living things. The early stages of life included the use or formation of organic molecules such as carbohydrates, amino acids, or nucleotides. If these were formed from inorganic precursors today, they would simply be broken down by living things. The early stages of life also probably included more complex aggregations of molecules into enclosed structures with an internal environment, a boundary layer of some form, and an external environment. Such structures, if they were formed now, would be quickly consumed or broken down by living organisms.

However, once a mechanism of inheritance was in place in the form of a molecule like DNA or RNA, either within a cell or within a pre-cell, these entities would be subject to the principle of natural selection. More effective reproducers would increase in frequency at the expense of inefficient reproducers. So while evolution does not explain the origin of life, it may have something to say about some of the processes operating once pre-living entities acquired certain properties.

Misconception #4: Organisms Evolve on Purpose

Statements such as "organisms evolve in response to a change in an environment," are quite common. There are two easy misunderstandings possible with such a statement. First of all, the statement must not be understood to mean that individual organisms evolve, as was discussed above. The statement is shorthand for "a population evolves in response to a changing environment." However, a second misunderstanding may arise by interpreting the statement to mean that the evolution is somehow intentional. A changed environment results in some individuals in the population, those with particular phenotypes, benefiting and, therefore, producing proportionately more offspring than other phenotypes. This results in a change in the population if the characters are genetically determined.

It is also important to understand that the variation that natural selection works on is already in a population and does not arise in response to an environmental change. For example, applying antibiotics to a population of bacteria will, over time, select for a population of bacteria that are resistant to antibiotics. The resistance, which is caused by a gene, did not arise by mutation because of the application of the antibiotic. The gene for resistance was already present in the gene pool of the bacteria, likely at a low frequency. The antibiotic, which kills the bacterial cells without the resistance gene, strongly selects for individuals that are resistant, since these would be the only ones that survived and divided. Experiments have demonstrated that mutations for antibiotic resistance do not arise as a result of the antibiotic application.

In a larger sense, evolution is also not goal-directed. Species do not become "better" over time; they simply track their changing environment with adaptations that maximize their reproduction in a particular environment at a particular time. Evolution has no goal of making faster, bigger, more complex, or even smarter species. This kind of language is common in popular literature. Certain organisms, ourselves included, are described as the "pinnacle" of evolution, or "perfected" by evolution. What characteristics evolve in a species are a function of the variation present and the environment, both of which are constantly changing in a non-directional way. What trait is fit in one environment at one time may well be fatal at some point in the future. This holds equally well for a species of insect as it does for the human species.

Misconception #5: Evolution Is Controversial among Scientists

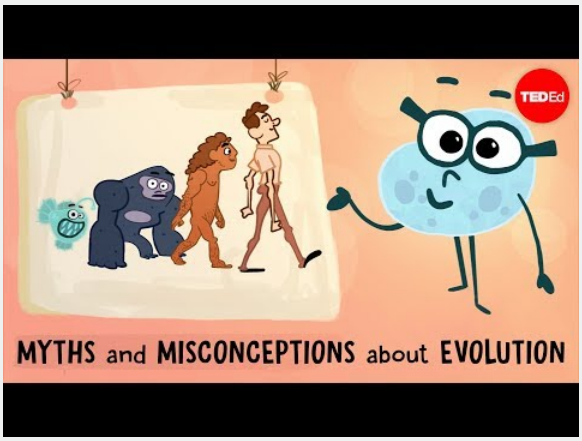
The theory of evolution was controversial when it was first proposed in 1859, yet within 20 years virtually every working biologist had accepted evolution as the explanation for the diversity of life. The rate of acceptance was extraordinarily rapid, partly because Darwin had amassed an impressive body of evidence. The early controversies involved both scientific arguments against the theory

and the arguments of religious leaders. It was the arguments of the biologists that were resolved after a short time, while the arguments of religious leaders have persisted to this day.

The number of working scientists who reject the theory of evolution, or question its validity and say so, is small. A Pew Research poll in 2009 found that 97 percent of the 2500 scientists polled believe species evolve.[2] The support for the theory is reflected in signed statements from many scientific societies such as the American Association for the Advancement of Science, which includes working scientists as members. Many of the scientists who reject or question the theory of evolution are non-biologists, such as engineers, physicians, and chemists. There are no experimental results or research programs that contradict the theory. There are no papers published in peer-reviewed scientific journals that appear to refute the theory. The latter observation might be considered a consequence of the suppression of dissent, but it must be remembered that scientists are skeptics and that there is a long history of published reports that challenged scientific orthodoxy in unpopular ways. Examples include the endosymbiotic theory of eukaryotic origins, the theory of group selection, the microbial cause of stomach ulcers, the asteroid-impact theory of the Cretaceous extinction, and the theory of plate tectonics. Research with evidence and ideas with scientific merit are considered by the scientific community. Research that does not meet these standards is rejected.

Video





This 4-minute video provides an overview of the main misconceptions about evolution, how they came to be, and what the accurate interpretation should be.

Question after watching: How can the expression "survival of the fittest" be misunderstood? Explain how it can be misunderstood and the accurate concept.

Footnotes

1. 1 Theodosius Dobzhansky. "Biology, Molecular and Organismic." *American Zoologist* 4, no. 4 (1964): 449.
2. 2 Pew Research Center for the People & the Press, *Public Praises Science; Scientists Fault Public, Media* (Washington, DC, 2009), 37.Contributors

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Unit 2.2.2 - Evidence of Evolution

- Please read and watch the following Learning Resources.
- Reading the material for understanding, and taking notes during videos, will take approximately 2.5 hours.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 2.2.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Explain how a variety of forms of evidence support the theory of evolution.

Introduction: Evolution - It's a Thing

Video



This 11-minute video describes the formation of fossils.
Question after watching: What were the forms of evidence highlighted that inform scientists about whale evolution?

Modern Studies of Darwin's Finches - Evidence of Natural Selection

Scientific studies of evolution by natural selection can be time-consuming. One of the best demonstrations has been in the very birds that helped to inspire the theory, the Galápagos finches. Peter and Rosemary Grant and their colleagues have studied Galápagos finch populations every year since 1976 and have provided important demonstrations of the operation of natural selection. The Grants found changes from one generation to the next in the beak shapes of the medium ground finches on the Galápagos island of Daphne Major. The medium-ground finch feeds on seeds. The birds have inherited variations in the bill shape with some individuals having wide, deep bills and others having thinner bills. Large-billed birds feed more efficiently on large, hard seeds, whereas smaller-billed birds feed more efficiently on small, soft seeds.

During 1977, a drought period altered vegetation on the island. After this period, the number of seeds declined dramatically: the decline in small, soft seeds was greater than the decline in large, hard seeds. The large-billed birds were able to survive better than the small-billed birds the following year. The year following the drought when the Grants measured beak sizes in the much-reduced population, they found that the average bill size was larger (Figure **2.2.2.3**). This was clear evidence for natural selection (differences in survival) of bill size caused by the availability of seeds.

The Grants had studied the inheritance of bill sizes and knew that the surviving large-billed birds would tend to produce offspring with larger bills, so the selection would lead to evolution of bill size. Subsequent studies by the Grants have demonstrated selection

on, and evolution of, bill size in this species in response to changing conditions on the island. The evolution has occurred both to larger bills, as in this case, and to smaller bills when large seeds became rare.

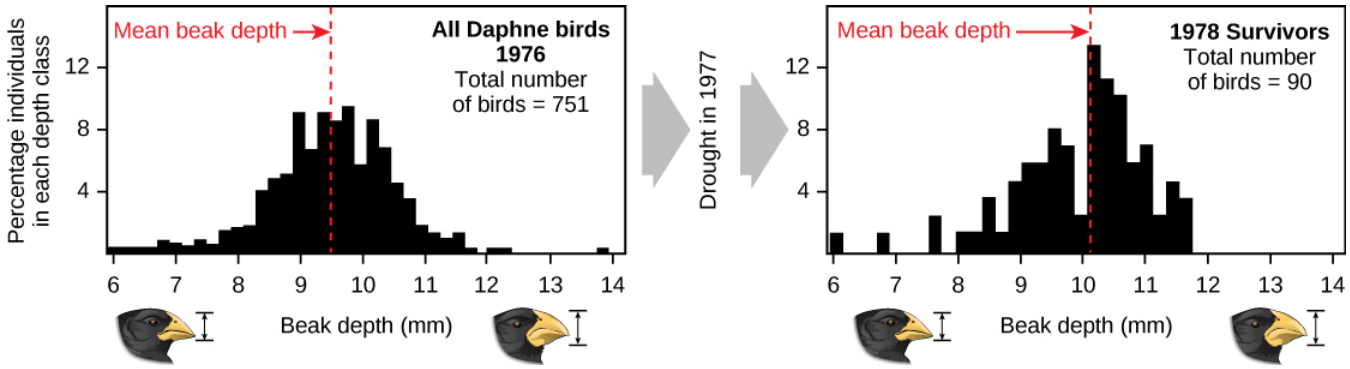


Figure 2.2.2.1: A drought on the Galápagos island of Daphne Major in 1977 reduced the number of small seeds available to finches, causing many of the small-beaked finches to die. This caused an increase in the finches' average beak size between 1976 and 1978.

The Fossil Record as Evidence for Evolution

Fossils tell us when organisms lived, as well as provide evidence for the progression and evolution of life on earth over millions of years.

Fossils are preserved remains or traces of animals, plants, and other organisms from the past. Fossils range in age from 10,000 to 3.48 billion years old. The observation that certain fossils were associated with certain rock strata led 19th-century geologists to recognize a geological timescale. Like extant organisms, fossils vary in size from microscopic, like single-celled bacteria, to gigantic, like dinosaurs and trees.



Figure 2.2.2.2: "Sue": The bones of this *Tyrannosaurus rex* were preserved through the process of permineralization, which suggests that this organism was covered by sediment soon after death.

Permineralization

Permineralization is a process of fossilization that occurs when an organism is buried. Small-scale permineralization can produce very detailed fossils. For permineralization to occur, the organism must be covered by sediment soon after death, or soon after the initial decay process.

It would not be an exaggeration to say that the typical vertebrate fossil consists of a single bone, or tooth, or fish scale. The preservation of an intact skeleton with the bones in the relative positions they had in life requires remarkable circumstances. The mineralization of soft parts is even less common and is seen only in exceptionally rare chemical and biological conditions.

Some of the best fossil beds in the world are located in Canada, due to the vast age of the rocks in the shield formations there. Alberta is well known for its *T. rex*, *Albertasaurus*, and *Edmontonsaurus* specimens. Fossils in the Burgess Shale, located between Alberta and British Columbia, date back even further to before the Cambrian Explosion more than 550 million years ago.



a b

Figure 2.2.2.3: Dinosaur National Park in Alberta. (a) Scientists must be careful with their footing as small fossils abound.(b) A trilobite fossil. (Copyright; CC-BY-SA 4.0 Annie Prud'homme Genereux)

Video



This 4-minute video humorously describes the formation of fossils.
Question after watching: If you were a paleontologist, where would you go to look for a fossil?

Trace Fossils

Fossils may also consist of the marks left behind by the organism while it was alive, such as footprints or feces. These types of fossils are called **trace fossils**, or ichnofossils, as opposed to body fossils. Past life may also leave some markers that cannot be seen but can be detected in the form of biochemical signals; these are known as chemofossils or biomarkers.



Figure **2.2.2.4**: These dinosaur footprints, examples of trace fossils, are located in Denver, Colorado's Dino Ridge. Similar footprints can be seen in Grande Prarie in Northern Alberta and Northern British Columbia (CC-BY-SA 4.0 Annie Prud'homme Genereux).

The Fossil Record

The totality of fossils, both discovered and undiscovered, and their placement in fossiliferous (fossil-containing) rock formations and sedimentary layers (strata) is known as the **fossil record**. The fossil record was one of the early sources of data underlying the study of evolution and continues to be relevant to the history of life on Earth. The development of radiometric dating techniques in the early 20th-century allowed geologists to determine the numerical or “absolute” age of various strata and their included fossils.

Each fossil discovery represents a snapshot of the process of evolution. Because of the specialized and rare conditions required for a biological structure to fossilize, many important species or groups may never leave fossils at all. Even if they do leave fossils, humans may never find them—for example, if they are buried under hundreds of feet of ice in Antarctica. The number of species discovered through the fossil record is less than 5% of the number of species alive today. Fossilized species may represent less than 1% of all the species that have ever lived.

The fossil record is very uneven and is mostly comprised of fossils of organisms with hard body parts, leaving most groups of soft-bodied organisms with little to no fossil record. Groups considered to have a good fossil record, including transitional fossils between these groups, are the vertebrates, the echinoderms, the brachiopods, and some groups of arthropods. Their hard bones and shells fossilize easily, unlike the bodies of organisms like cephalopods or jellyfish.

Romer’s gap is an example of an apparent gap in the tetrapod fossil record used in the study of evolutionary biology. These gaps represent periods from which no relevant fossils have been found. Romer’s gap is named after paleontologist Alfred Romer, who first recognized it. Romer’s gap spanned from approximately 360 to 345 million years ago, corresponding to the first 15 million years of the Carboniferous Period. There has been much debate over why there are so few fossils from this time period. Some scientists have suggested that the geochemistry of the time period caused bad conditions for fossil formation, so few organisms were fossilized. Another hypothesis suggests that scientists have simply not yet discovered an excavation site for these fossils, due to inaccessibility or random chance.



Figure 2.2.2.5: The bank of the Whiteadder Water in Scotland is one of the few known localities bearing fossils of tetrapods from Romer's gap.

Determining Fossil Ages

Paleontology seeks to map out how life evolved across geologic time. A substantial hurdle is in the difficulty of working out fossil ages. There are several different methods for estimating the ages of fossils, including:

1. stratigraphy
2. biostratigraphy
3. carbon dating

Stratigraphy

Paleontologists rely on stratigraphy to date fossils. **Stratigraphy** is the science of understanding the strata, or layers, that form the sedimentary record. Strata are differentiated from each other by their different colors or compositions and are exposed in cliffs, quarries, and river banks. These rocks normally form relatively horizontal, parallel layers, with younger layers forming on top.

If a fossil is found between two layers of rock whose ages are known, the fossil's age is thought to be between those two known ages. Because rock sequences are not continuous but may be broken up by faults or periods of erosion, it is difficult to match up rock beds that are not directly adjacent.



Figure 2.2.2.6: The layers of sedimentary rock, or strata, can be seen as horizontal bands of differently colored or differently structured materials exposed in this cliff. The deeper layers are older than the layers found at the top, which aids in determining the relative age of fossils found within the strata.

Biostratigraphy

Fossils of species that survived for a relatively short time can be used to match isolated rocks: this technique is called **biostratigraphy**. For instance, the extinct chordate *Eoplacognathus pseudoplanus* is thought to have existed for a short time in the Middle Ordovician period. If rocks of unknown age have traces of *E. pseudoplanus*, they have a mid-Ordovician age. Such index fossils must be distinctive, globally distributed, and occupy a short time range to be useful. Misleading results can occur if the index fossils are incorrectly dated.

Relative Dating

Stratigraphy and biostratigraphy can in general provide only relative dating (A was before B), which is often sufficient for studying evolution. This is difficult for some time periods, however, because of the barriers involved in matching rocks of the same age across continents. Family-tree relationships can help to narrow down the date when lineages first appeared. For example, if fossils of B date to X million years ago and the calculated "family tree" says A was an ancestor of B, then A must have evolved earlier.

It is also possible to estimate how long ago two living branches of a family tree diverged by assuming that DNA mutations accumulate at a constant rate. However, these "**molecular clocks**" are sometimes inaccurate and provide only approximate timing. For example, they are not sufficiently precise and reliable for estimating when the groups that feature in the Cambrian explosion first evolved, and estimates produced by different approaches to this method may vary as well.

Carbon Dating

Together with stratigraphic principles, radioactive elements are used in geochronology to establish the geological time scale. Beds that preserve fossils typically lack these traditional radioactive elements. Instead, **radiocarbon dating**, or simply "carbon dating", is used Figure **2.2.2.7**. The principle of radiocarbon dating is simple: the rates at which various radioactive elements decay are known, and the ratio of the radioactive element to its decay products shows how long the radioactive element has existed in the rock. This rate is represented by the half-life, which is the time it takes for half of a sample to decay.

The half-life of carbon-14 is 5,730 years, so carbon dating is only relevant for dating fossils less than 60,000 years old. Radioactive elements are common only in rocks with a volcanic origin, so the only fossil-bearing rocks that can be dated using traditional elements are volcanic ash layers. Carbon dating uses the decay of carbon-14 to estimate the age of organic materials, such as wood and leather.

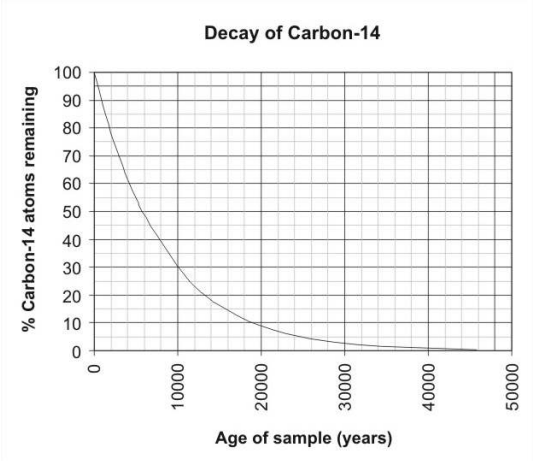


Figure **2.2.2.7**: Radiocarbon dating is a technique used to date carbon in rocks or fossils usually based on a comparison between the observed abundance of a naturally occurring radioactive isotope (in this case, carbon-14) and its decay products, using known decay rates.

Case Study: The Fossil Record and the Evolution of the Modern Horse

Highly detailed fossil records have been recovered for sequences in the evolution of modern horses. The fossil record of horses in North America is especially rich and contains transition fossils: fossils that show intermediate stages between earlier and later forms. The fossil record extends back to a dog-like ancestor some 55 million years ago, which gave rise to the first horse-like species 55 to 42 million years ago in the genus *Eohippus*.

The first *Equid* fossil was found in the gypsum quarries in Montmartre, Paris in the 1820s. The tooth was sent to the Paris Conservatory, where Georges Cuvier identified it as browsing equine, related to the tapir. His sketch of the entire animal matched later skeletons found at the site. During the H.M.S. Beagle survey expedition, Charles Darwin had remarkable success with fossil hunting in Patagonia. In 1833 in Santa Fe, Argentina, he was "filled with astonishment" when he found a horse's tooth in the same stratum as fossils of giant armadillos and wondered if it might have been washed down from a later layer, but concluded this was "not very probable." In 1836, the anatomist Richard Owen confirmed the tooth was from an extinct species, which he subsequently named *Equus curvidens*.

The original sequence of species believed to have evolved into the horse was based on fossils discovered in North America in the 1870s by paleontologist Othniel Charles Marsh. The sequence, from *Eohippus* to the modern horse (*Equus*), was popularized by Thomas Huxley and became one of the most widely known examples of a clear evolutionary progression. The sequence of transitional fossils was assembled by the American Museum of Natural History into an exhibit that emphasized the gradual, "straight-line" evolution of the horse.

Video



This video explains how fossils show dramatic changes in horse morphology over nearly 60 million years of evolution.

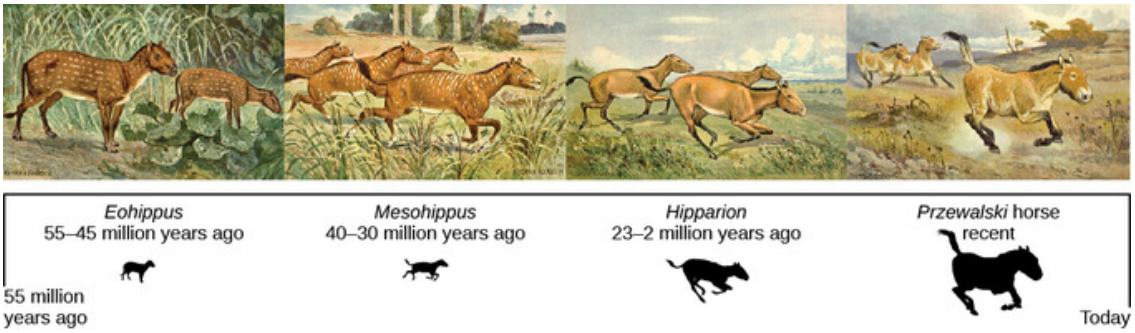


Figure **2.2.2.8**: This illustration shows an artist's renderings of species derived from fossils of the evolutionary history of the horse and its ancestors. The species depicted are only four from a very diverse lineage that contains many branches, dead ends, and adaptive radiations. One of the trends, depicted here, is the evolutionary tracking of a drying climate and increase in prairie versus forest habitat reflected in forms that are more adapted to grazing and predator escape through running.

Since then, as the number of *Equid* fossils has increased, the actual evolutionary progression from *Eohippus* to *Equus* has been discovered to be much more complex and multi-branched than was initially supposed. Detailed fossil information on the rate and distribution of new *Equid* species has also revealed that the progression between species was not as smooth and consistent as was once believed.

Although some transitions were indeed gradual progressions, a number of others were relatively abrupt in geologic time, taking place over only a few million years. Both **anagenesis**, a gradual change in an entire population's gene frequency, and **cladogenesis**, a population "splitting" into two distinct evolutionary branches, occurred, and many species coexisted with "ancestor" species at various times.

Adaptation for Grazing

The series of fossils tracks the change in anatomy resulting from a gradual drying trend that changed the landscape from a forested habitat to a prairie habitat. Early horse ancestors were originally specialized for tropical forests, while modern horses are now adapted to life on drier land. Successive fossils show the evolution of teeth shapes and foot and leg anatomy to a grazing habit with adaptations for escaping predators.

The horse belongs to the order Perissodactyla (odd-toed ungulates), the members of which all share hoofed feet and an odd number of toes on each foot, as well as mobile upper lips and a similar tooth structure. This means that horses share a common ancestry with tapirs and rhinoceroses. Later species showed gains in size, such as those of *Hipparion*, which existed from about 23 to 2 million years ago. The fossil record shows several adaptive radiations, or periods of cladogenesis, in the horse lineage, which is now much reduced to only one genus, *Equus*, with several species. Paleozoologists have been able to piece together a more complete outline of the modern horse's evolutionary lineage than that of any other animal.

Additional Evidence for Evolution

Homologous Structures vs Analogous Structures

Homology is the relationship between structures or DNA derived from the most recent common ancestor. A common example of **homologous structures** in evolutionary biology is the wings of bats and the arms of primates. Although these two structures do not look similar or have the same function, genetically, they come from the same structure from the last common ancestor. Homologous traits of organisms are therefore explained by descent from a common ancestor. In genetics, homology is measured by comparing protein or DNA sequences. Homologous gene sequences share a high similarity, supporting the hypothesis that they share a common ancestor. It's important to note that defining two structures or sequences as homologous depends on what ancestor is being described as the common ancestor.

Homology can also be partial: new structures can evolve through the combination of developmental pathways or parts of them. As a result, hybrid or mosaic structures can evolve that exhibit partial homologies. For example, certain compound leaves of flowering plants are partially homologous both to leaves and shoots because they combine some traits of leaves and some of shoots.

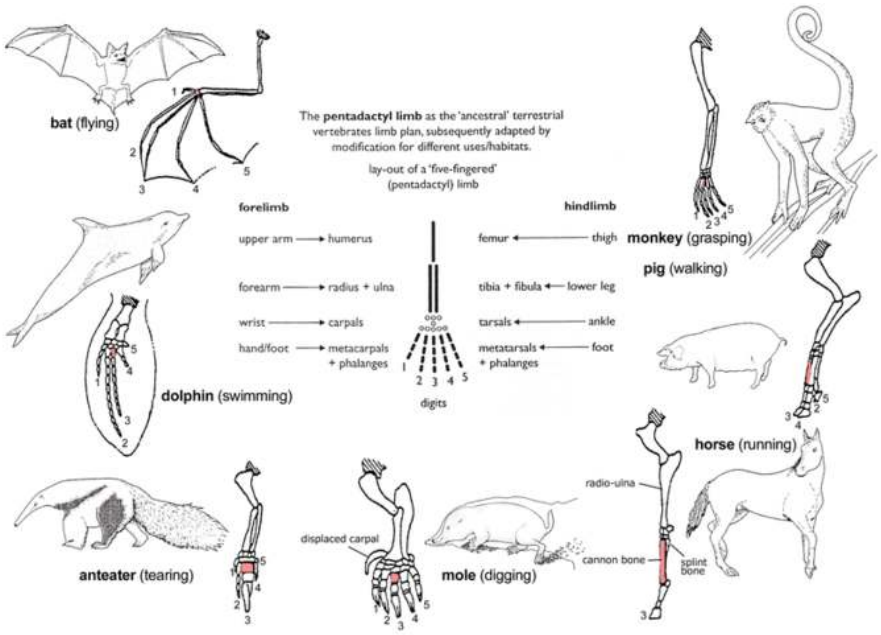


Figure **2.2.2.9**: The principle of homology illustrated by the adaptive radiation of the forelimb of mammals. All conform to the basic pentadactyl pattern but are modified for different usages. The third metacarpal is shaded throughout; the shoulder is crossed-hatched.

The opposite of homologous structures is **analogous structures**, which are physically similar structures between two taxa that evolved separately (rather than being present in the last common ancestor). Bat wings and bird wings evolved independently and are considered analogous structures. Genetically, a bat wing and a bird wing have very little in common; the last common ancestor of bats and birds did not have wings like either bats or birds. Wings evolved independently in each lineage after diverging from ancestors with forelimbs that were not used as wings (terrestrial mammals and theropod dinosaurs, respectively).

It is important to distinguish between different hierarchical levels of homology in order to make informative biological comparisons. In the above example, the bird and bat wings are analogous as wings, but homologous as forelimbs because the organ served as a forearm (not a wing) in the last common ancestor of tetrapods.

Analogy is different than homology. Although analogous characteristics are superficially similar, they are not homologous because they are phylogenetically independent. The wings of a maple seed and the wings of an albatross are analogous but not homologous (they both allow the organism to travel on the wind, but they did not both develop from the same structure).

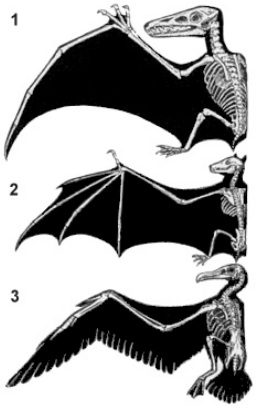


Figure **2.2.2.10**: The wings of pterosaurs (1), bats (2), and birds (3) are analogous as wings, but homologous as forelimbs. This is because they are similar characteristically and even functionally, but evolved from different ancestral roots.

Vestigial Structures

Some organisms possess structures with no apparent function which appear to be residual parts from a past ancestor. For example, some snakes have pelvic bones despite having no legs because they descended from reptiles that did have legs. Another example of a structure with no function is the human vermiform appendix. These unused structures without function are called **vestigial structures**. Other examples of vestigial structures are wings (which may have other functions) on flightless birds like the ostrich, leaves on some cacti, traces of pelvic bones in whales, and the sightless eyes of cave animals.

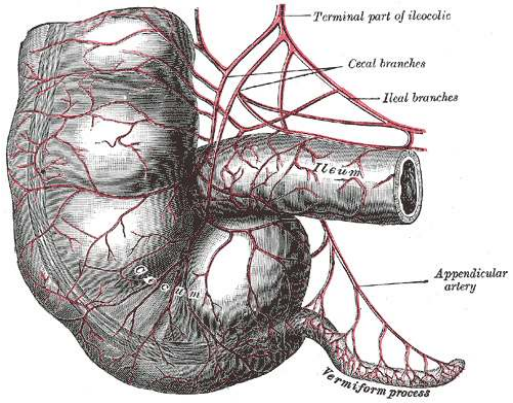


Figure **2.2.2.11**: In humans, the appendix is a vestigial structure; it has lost much of its ancestral function.

There are also several reflexes and behaviors that are considered to be vestigial. The formation of goosebumps in humans under stress is a vestigial reflex its function in human ancestors was to raise the body's hair, making the ancestor appear larger and scaring off predators. The arrector pili muscle, which is a band of smooth muscle that connects the hair follicle to connective tissue. When it contracts it creates goosebumps on the skin.

Vestigial Structures in Evolution

Vestigial structures are often homologous to structures that function normally in other species. Therefore, vestigial structures can be considered evidence for evolution, the process by which beneficial heritable traits arise in populations over an extended period of time. The existence of vestigial traits can be attributed to changes in the environment and behavior patterns of the organism in question. As the function of the trait is no longer beneficial for survival, the likelihood that future offspring will inherit the "normal" form of it decreases. If there are no selection pressures actively lowering the fitness of the individual, the trait will persist in future generations unless the trait is eliminated through genetic drift or other random events.

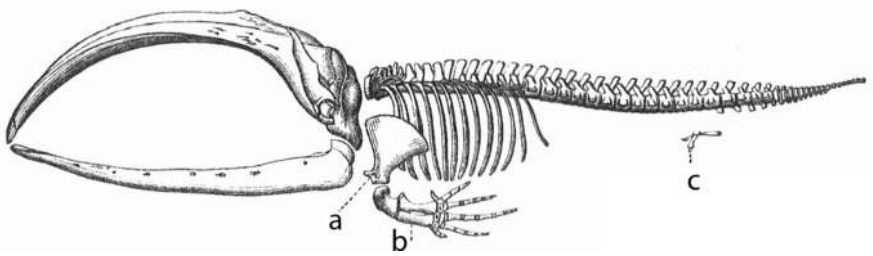
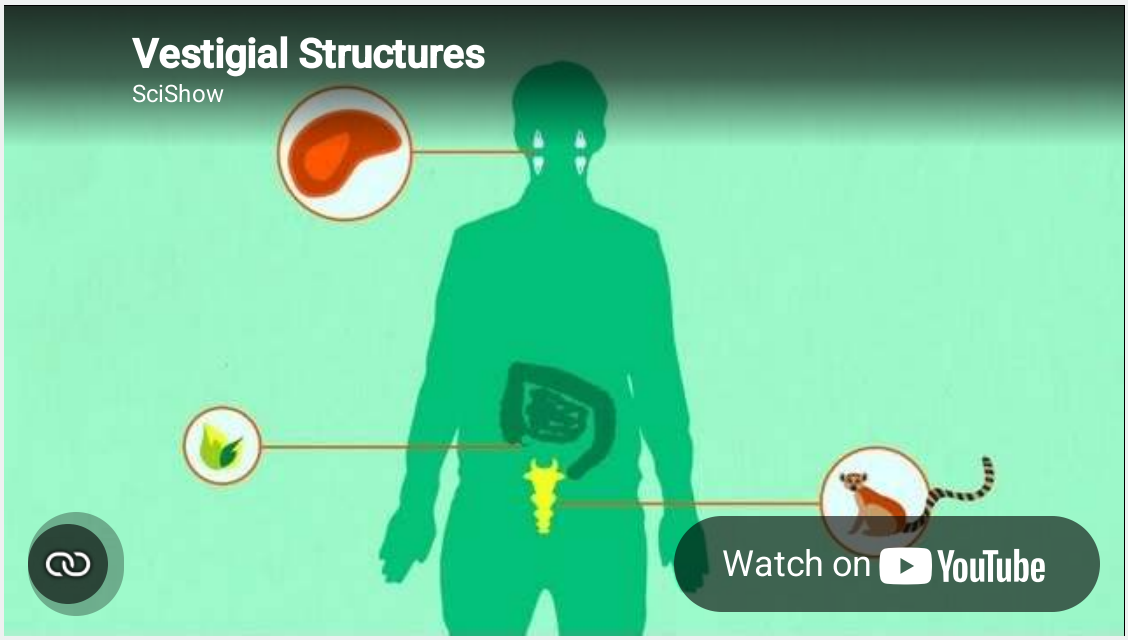


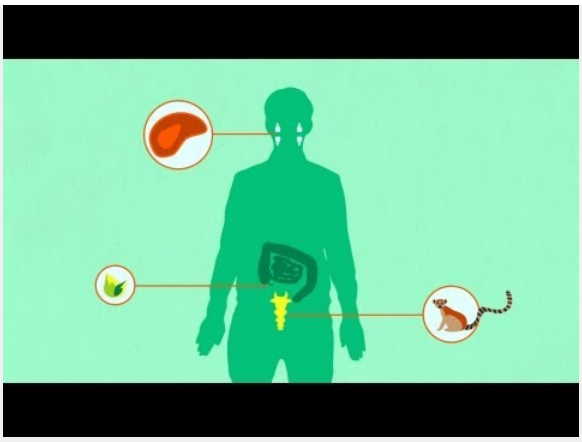
Figure **2.2.2.12**: The pelvic bones in whales are also a good example of vestigial evolution (whales evolved from four-legged land mammals and secondarily lost their hind legs). Letter c in the picture indicates the undeveloped hind legs of a baleen whale.

In some cases, the structure becomes detrimental to the organism. Although in many cases the vestigial structure is of no direct harm, all structures require extra energy in terms of development, maintenance, and weight and are also a risk in terms of disease (e.g., infection, cancer). This provides some selective pressure for the removal of parts that do not contribute to an organism's fitness, but a structure that is not directly harmful will take longer to be 'phased out' than one that is. Some vestigial structures persist due to limitations in development, such that complete loss of the structure could not occur without major alterations of the organism's developmental pattern, and such alterations would likely produce numerous negative side effects.

The vestigial versions of a structure can be compared to the original version of the structure in other species in order to determine the homology of the structure. Homologous structures indicate common ancestry with those organisms that have a functional version of the structure. Vestigial traits can still be considered adaptations because an adaptation is often defined as a trait that has been favored by natural selection. Adaptations, therefore, need not be adaptive, as long as they were at some point.

Video





This 4-minute video takes you on a tour of vestigial structures in the human body.
Question after watching: We say that vestigial structures are evidence for evolution. Why is that? What could account for these structures if evolution was not the reason?

Convergent Evolution

Sometimes, similar phenotypes evolve independently in distantly related species. For example, flight has evolved in both bats and insects, and they both have wings, which are adaptations to flight. However, the wings of bats and insects have evolved from very different original structures. This phenomenon is called **convergent evolution**, where similar traits evolve independently in species that do not share a recent common ancestry.

Examples of Convergent Evolution

Convergent evolution describes the independent evolution of similar features in species of different lineages. The two species came to the same function, flying, but did so separately from each other. They have "converged" on this useful trait. Both sharks and dolphins have similar body forms, yet are only distantly related: sharks are fish and dolphins are mammals. Such similarities are a result of both populations being exposed to the same selective pressures. Within both groups, changes that aid swimming have been favored. Thus, over time, they developed similar appearances (morphology), even though they are not closely related.

One of the most well-known examples of convergent evolution is the camera eye of cephalopods (e.g., octopus), vertebrates (e.g., mammals), and cnidaria (e.g., box jellies). Their last common ancestor had at most a very simple photoreceptive spot, but a range of processes led to the progressive refinement of this structure to the advanced camera eye. There is, however, one subtle difference: the cephalopod eye is "wired" in the opposite direction, with blood and nerve vessels entering from the back of the retina, rather than the front as in vertebrates.

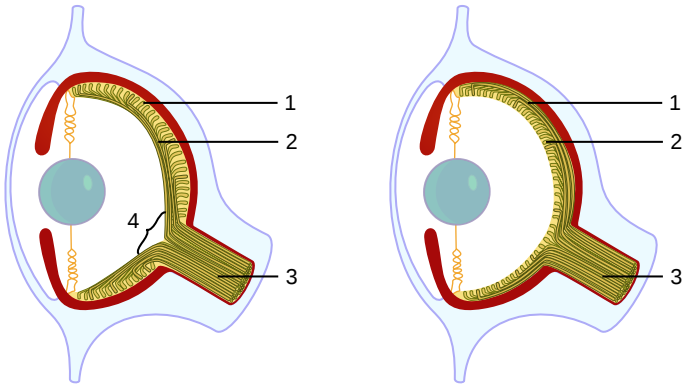


Figure **2.2.2.13**: Vertebrates and octopuses developed the camera eye independently. In the vertebrate version (left), the nerve fibers pass in front of the retina, and there is a blind spot (4) where the nerves pass through the retina. In the octopus version (right), the eye is constructed the "right way out," with the nerves attached to the rear of the retina. This means that octopuses do not have a blind spot.

The opposite of convergent evolution is **divergent evolution**, whereby related species evolve different traits. On a molecular level, this can happen due to random mutation unrelated to adaptive changes. More will be discussed on divergent evolution in Unit 2.3.

Biogeography and the Modern Distribution of Species

Biogeography is the study of the geographic distribution of living things and the abiotic factors that affect their distribution. Abiotic factors, such as temperature and rainfall, vary based on latitude and elevation, primarily. As these abiotic factors change, the composition of plant and animal communities also changes.

Patterns of Species Distribution

Ecologists who study biogeography examine patterns of species distribution. No species exists everywhere; for example, the Venus flytrap is endemic to a small area in North and South Carolina. An **endemic species** is one that is naturally found only in a specific geographic area that is usually restricted in size. Other species are **cosmopolitan**: species that live in a wide variety of geographic areas. The raccoon, for example, is native to most of North and Central America.

Since species distribution patterns are based on biotic and abiotic factors and their influences during the very long periods of time required for species evolution, early studies of biogeography were closely linked to the emergence of evolutionary thinking in the eighteenth century. Some of the most distinctive assemblages of plants and animals occur in regions that have been physically separated for millions of years by geographic barriers. Biologists estimate that Australia, for example, has between 600,000 and 700,000 species of plants and animals. Approximately 3/4 of living plant and mammal species are endemic species found solely in Australia.



Figure **2.2.2.14**: Australia is home to many endemic species. The (a) wallaby (*Wallabia bicolor*), a medium-sized member of the kangaroo family, is a pouched mammal, or marsupial. The (b) echidna (*Tachyglossus aculeatus*) is an egg-laying mammal.

The geographic distribution of organisms on the planet follows patterns that are best explained by evolution in conjunction with the movement of tectonic plates over geological time. Broad groups that evolved before the breakup of the supercontinent Pangaea (about 200 million years ago) are distributed worldwide. Groups that evolved since the breakup appear uniquely in regions of the planet, such as the unique flora and fauna of northern continents that formed from the supercontinent Laurasia and of the southern continents that formed from the supercontinent Gondwana. The presence of *Glossopteris* in Australia, Antarctica, India, Africa, and South America is best explained by the plant family's presence there prior to the southern supercontinent Gondwana breaking up.

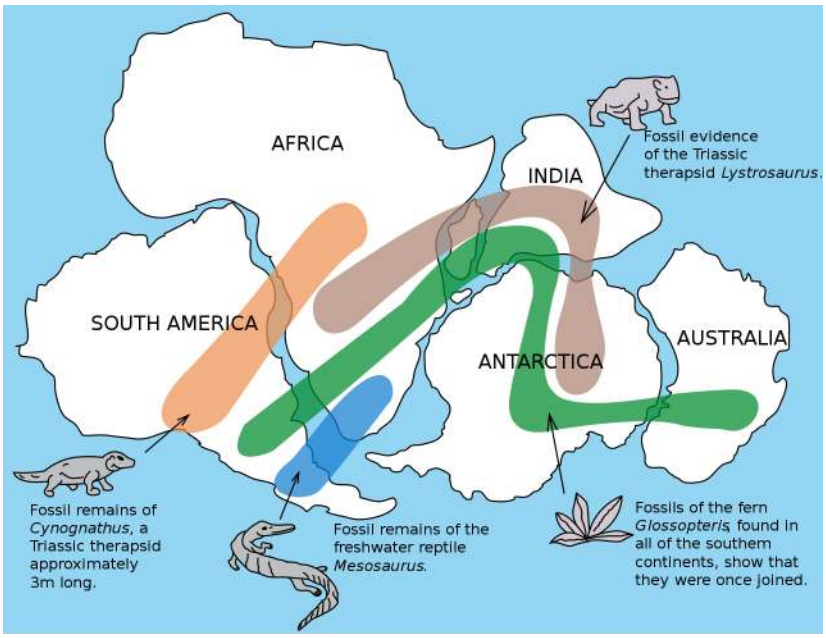


Figure **2.2.2.15**: The *Glossopteris* genus of ferns evolved before the supercontinent Gondwana broke up. Today, members of this plant family are found throughout the southern hemisphere (shown in green).

Artificial Selection: Human-Initiated Change

Most contemporary evolutionary biologists study evolution experimentally using laboratory organisms such as *Drosophila* or natural systems in the wild. However, 18th- and 19th-century evolutionary biologists, including Darwin, emphasized the similarities between natural evolution and artificial ‘ improvement’ of livestock under domestication. They believed that studying domesticated animals and plants could illuminate the mechanisms of natural evolution. Indeed, Chapter 1 of *On the Origin of Species…* is entitled ‘Variation under domestication’. Recent discoveries reveal the relationship between natural evolutionary mechanisms and the practical technologies used to breed plants, animals, yeasts, and microbes, to produce food, clothing, transport, companionship, decoration, entertainment, and medicines.

Artificial selection is any selective breeding intentionally practiced by humans leading to the evolution of domesticated organisms. Artificial selection may oppose or amplify or be neutral in relation to natural selection. Most livestock, including dogs, cats, goats, pigs, cattle, sheep, guinea pigs, horses, geese, poultry, and scores of crop plants were domesticated more than 5000 years ago. Estimates of dates of domestication based upon the archeological record differ enormously from those based on genetic analysis for almost all crops and livestock. However, experts agree that dogs were among the first mammalian species to become domesticated, followed by sheep. During the last few hundred years, people have domesticated a wide range of other animals such as guppies, hamsters, mice, and budgerigars, mostly for use as pets, together with thousands of culinary, medicinal, and ornamental plants.

Domesticated animals are usually held in small, isolated populations with limited opportunities for interbreeding. For centuries, drovers herded large numbers of non-breeding pigs, cattle, sheep, geese, and poultry to market for slaughter, often over hundreds of kilometers. However, the breeding stocks were usually kept within a small area because moving sexually active bulls and large boars over long distances was much less practical. It is important to note that true domestication is different from the taming of wild animals. Certain individuals of many species, especially juveniles and females, can be tamed and live in captivity where they are protected from predators and provided with food and shelter. Domesticated livestock are also fed and protected, but many generations breed and spend their entire lives in close association with humans.

For centuries, livestock breeders have nurtured strains of animals that thrive on various diets or in particular climates or that excel in certain roles. Sometimes, domestication was simply due to the whims of the breeder. The variety of such animals seems bewildering but certain changes consistently emerge in a surprisingly wide range of domesticated species and among humans, suggesting that similar mechanisms are operating.

Videos



This 5-minute video explains the current hypothesis for the origins of the modern dog.
Question after watching: Human-initiated selection is a large influence on the evolution of modern dogs. What role did natural selection also play?



This 6-minute video describes how broccoli, cabbage, and kohlrabi are all varieties of the same species.
Question after watching: You go to the garden centre and obtain a few strawberry plants. You want to breed the sweetest berries. How would you go about obtaining such a berry? Link each step to a similar step in the process of natural selection.

Parts adapted from ("Evolution: artificial selection and domestication"; CC BY-NC-SA 2.0 UK)

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Unit 2.2.3 - Natural Selection and Adaptive Evolution

- Please read and watch the following Learning Resources.
- Reading the material for understanding, and taking notes during videos, will take approximately 1.5 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 2.2.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Explain how natural selection leads to adaptive evolution
- Contrast stabilizing selection, directional selection, and diversifying selection.
- Describe frequency-dependent selection
- Explain the effects of sexual dimorphism on the reproductive potential of an organism

Introduction to Natural Selection

Natural selection drives adaptive evolution by selecting for and increasing the occurrence of beneficial traits in a population. Natural selection only acts on the population's heritable traits: selecting for beneficial alleles and, thus, increasing their frequency in the population, while selecting against deleterious alleles and, thereby, decreasing their frequency. This process is known as **adaptive evolution** (Figure **2.2.3.1**). Natural selection does not act on individual alleles, however, but on entire organisms. An individual may carry a very beneficial genotype with a resulting phenotype that, for example, increases the ability to reproduce. If that same individual also carries an allele that results in a fatal childhood disease, however, the fecundity phenotype will not be passed on to the next generation because the individual will not live to reach reproductive age. Natural selection acts at the level of the individual. It selects for individuals with greater contributions to the gene pool of the next generation, known as an organism's **evolutionary fitness**.

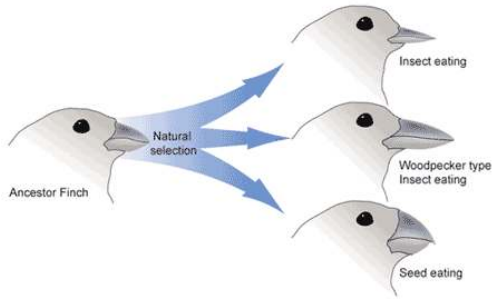


Figure **2.2.3.1**: Through natural selection, a population of finches evolved into three separate species by adapting to several different selection pressures. Each of the three modern finches has a beak adapted to its life history and diet.

Evolutionary fitness is often quantifiable as the contribution of genetic information by an individual to subsequent generations. However, it is not the absolute fitness of an individual that counts, but rather how it compares to the other organisms in the population. This concept, called **relative fitness**, allows researchers to determine which individuals are contributing additional offspring to the next generation and, thus, how the population might evolve.

Genetic Variation and Natural Selection

Natural selection and some of the other evolutionary forces can only act on heritable traits, namely an organism's genetic code. Because alleles are passed from parent to offspring, those that confer beneficial traits or behaviors may be selected for, while deleterious alleles may be selected against. Acquired traits, for the most part, are not heritable. For example, if an athlete works out

in the gym every day, building up muscle strength, the athlete's offspring will not necessarily grow up to be a bodybuilder. If there is a genetic basis for the ability to run fast, on the other hand, this may be passed to a child.

Genetic variation is a measure of the genetic differences (diversity of alleles and genotypes) that exist within a population. The genetic variation of an entire species is often called genetic diversity. Genetic variations are the differences in DNA segments or genes between individuals and each variation of a gene is called an allele. For example, a population with many different alleles at a single chromosome locus has a high amount of genetic variation. Genetic variation is essential for natural selection because natural selection can only increase or decrease the frequency of alleles that already exist in the population.

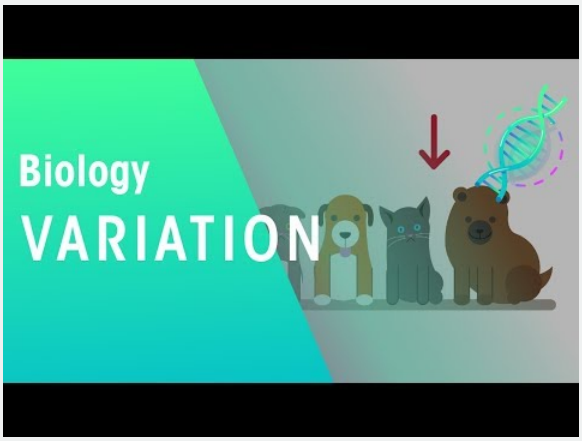
Genetic variation is caused by:

- mutation (discussed further in Section 2.2.4)
- random mating between organisms (discussed further in Section 2.2.4)
- random fertilization
- genetic recombination during meiosis

Mutations are the only method of creating new alleles; mutations are ultimately the engine that drives evolution. Sexual reproduction (including random mating, random fertilization, and crossing over) are ways to reshuffle and recombine those genes in new ways, giving offspring combinations that differ from their parents and from others.

Video





This 4-minute video provides a brief introduction to variation in humans and a method for identifying traits that are encoded by genetics and those determined by the environment.

Question after watching: In most cases, when a person who has an identical two develops a disease like cancer, their identical twin does not. What does this tell you about the causes of cancer?

Evolution and Adaptation to the Environment

Variation allows some individuals within a population to adapt to the changing environment. Because natural selection acts directly only on phenotypes, more genetic variation within a population usually enables more phenotypic variation. Some new alleles increase an organism's ability to survive and reproduce, which then ensures the survival of the allele in the population. Other new alleles may be immediately detrimental (such as a malformed oxygen-carrying protein) and organisms carrying these new mutations will die out. Neutral alleles are neither selected for nor against and usually remain in the population. Genetic variation is advantageous because it enables some individuals and, therefore, a population, to survive despite a changing environment (Figure **2.2.3.2**).

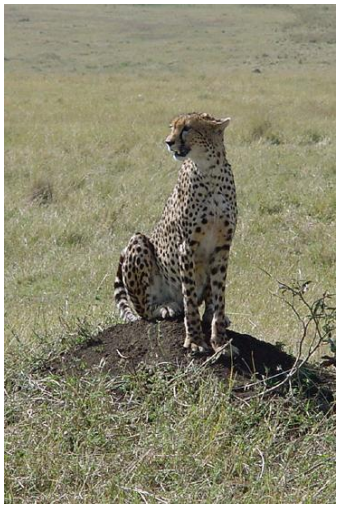


Figure **2.2.3.2**: Populations of wild cheetahs have very low genetic variation. Because wild cheetahs are threatened, their species has a very low genetic diversity. This low genetic diversity means they are often susceptible to disease and often pass on lethal recessive mutations; only about 5% of cheetahs survive to adulthood.

Geographic Variation

Some species display geographic variation as well as variation within a population. Geographic variation, or the distinctions in the genetic makeup of different populations, often occurs when populations are geographically separated by environmental barriers or when they are under selection pressures from a different environment. One example of geographic variation are **clines**, gradual changes in a trait across an organism's geographic distribution.

Species of warm-blooded animals, for example, tend to have larger bodies in the cooler climates closer to the earth's poles, allowing them to better conserve heat. This is considered a *latitudinal cline* (Figure **2.2.3.3**). Alternatively, flowering plants tend to bloom at different times depending on where they are along the slope of a mountain, known as an *altitudinal cline*.

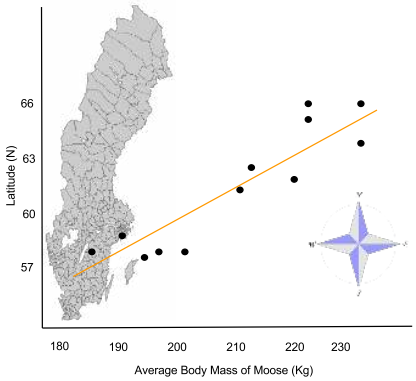


Figure **2.2.3.3**: This graph shows geographical variation in moose; body mass increase positively with latitude. Bergmann's Rule is an ecologic principle that states that as latitude increases the body mass of a particular species increases. The data are taken from a Swedish study investigating the size of moose as latitude increases as shows the positive relationship between the two, supporting Bergmann's Rule.

Environmental Variance

Genes are not the only players involved in determining population variation. Phenotypes are also influenced by other factors, such as the environment (Figure **2.2.3.4**). Some major characteristics, such as gender, are determined by the environment for some species. For example, some turtles and other reptiles have temperature-dependent sex determination (TSD). TSD means that individuals develop into males if their eggs are incubated within a certain temperature range or females at a different temperature range.



Figure **2.2.3.4**: The sex of the American alligator (*Alligator mississippiensis*) is determined by the temperature at which the eggs are incubated. Eggs incubated at 30°C produce females, and eggs incubated at 33°C produce males. (credit: Steve Hillebrand, USFWS)

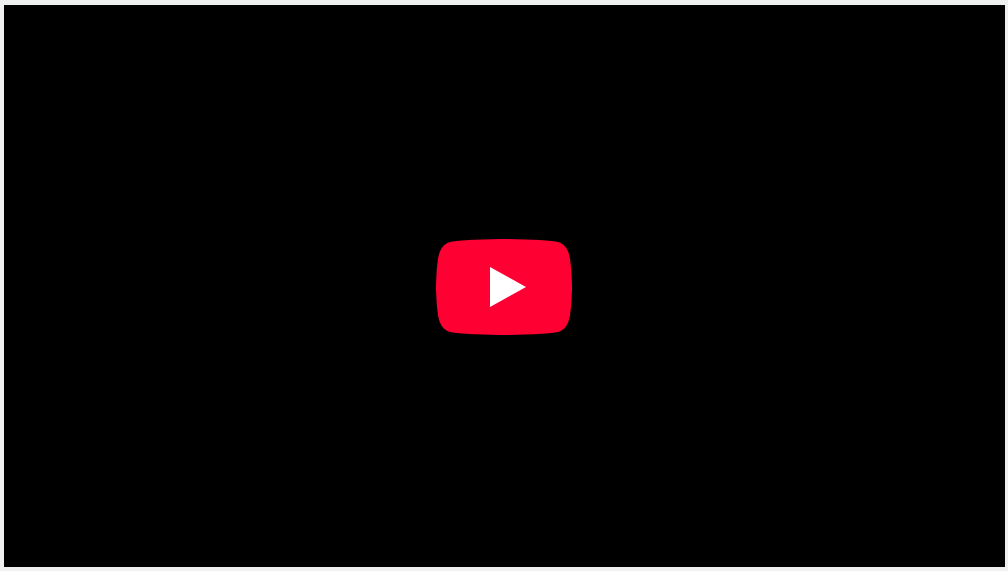
Types of Natural Selection

There are several ways selection can affect population variation (each is described in detail below) (Figure **2.2.3.9**):

- stabilizing selection
- directional selection
- diversifying selection
- frequency-dependent selection
- sexual selection

As natural selection influences the traits in a population, individuals can either become more or less genetically similar to one another and the phenotypes displayed can become more similar or more disparate. In the end, natural selection cannot produce perfect organisms from scratch, it can only generate populations that are better adapted to survive and successfully reproduce in their environments through the aforementioned selections.

Video





In this 3-minute video, David Attenborough explains how iguana evolved to swim on the Galpagos islands. Question after watching: Propose a series of steps that could have led to this evolution in the iguana population in the Galpagos. Specifically, explain how they evolved to live for short periods underwater from their land ancestor.

Stabilizing, Directional, and Diversifying Selection

Stabilizing Selection

If natural selection favors an average phenotype by selecting against extreme variation, the population will undergo **stabilizing selection** (Figure **2.2.3.5**).

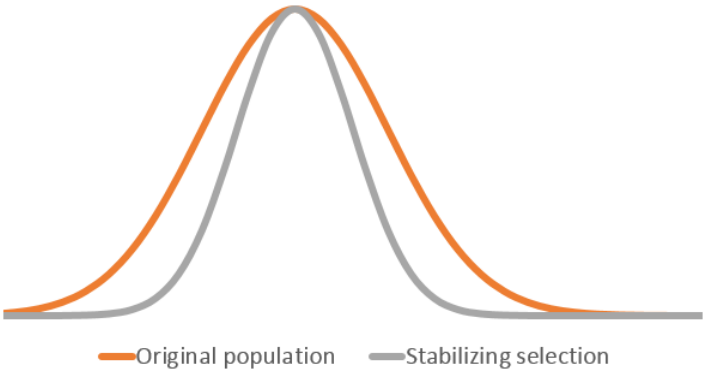


Figure **2.2.3.5**: Stabilizing selection occurs when the population stabilizes on a particular trait value and genetic diversity decreases. In the graph above, the x-axis indicates the variation in a trait. The y-axis indicates the percentage of individuals in a population that have a particular trait. In stabilizing selection, the average becomes more common over time, with less variation in the population.

For example, in a population of mice that live in the woods, natural selection will tend to favor individuals that best blend in with the forest floor and are less likely to be spotted by predators. Assuming the ground is a fairly consistent shade of brown, those mice whose fur most closely matches that color will most probably survive and reproduce, passing on their genes for their brown coat. Mice that carry alleles that make them slightly lighter or slightly darker will stand out against the ground and will more probably die from predation. As a result of this stabilizing selection, the population's genetic variance will decrease.

Directional Selection

When the environment changes, populations will often undergo **directional selection**, which selects for phenotypes at one end of the spectrum of existing variation (Figure **2.2.3.6**).

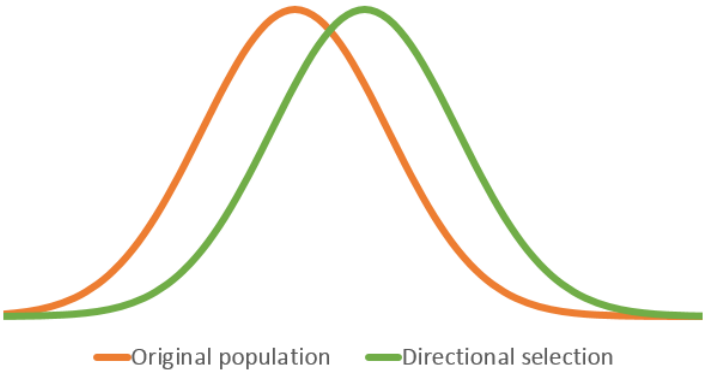


Figure **2.2.3.6**: Directional selection occurs when a single phenotype is favored, causing the population to shift towards one end of the trait variation. In the graph above, the x-axis indicates the variation in a trait. The y-axis indicates the percentage of individuals in a population that have a particular trait. In directional selection, the average shifts in one direction or another but the total variation in the population remains.

A classic example of this type of selection is the evolution of the peppered moth (*Biston betularia*) in eighteenth- and nineteenth-century England. Prior to the Industrial Revolution, the moths were predominately light in color, which allowed them to blend in with the light-colored trees and lichens in their environment. As soot began spewing from factories, the trees darkened and the light-colored moths became easier for predatory birds to spot.

Over time, the frequency of the melanic (dark) form of the moth increased because their darker coloration provided camouflage against the sooty tree; they had a higher survival rate in habitats affected by air pollution (Figure **2.2.3.7**). Similarly, a hypothetical mouse population may evolve to take on a different coloration if their forest floor habitat changed. The result of this type of selection is a shift in the population's genetic variance toward the new, fit phenotype.



Figure **2.2.3.7**: Two morphs of the peppered moth (*Biston betularia*) resting on the same tree. The light-colored typical moroph (below the bark's scar) is nearly invisible on this pollution-free tree, camouflaging it from predators while the carbonaria morph stands out clearly.

Diversifying (or Disruptive) Selection

Sometimes natural selection can select for two or more distinct phenotypes that each have their advantages in **diversifying (disruptive) selection**. In these cases, the intermediate phenotypes are often less fit than their extreme counterparts (Figure **2.2.3.8**).

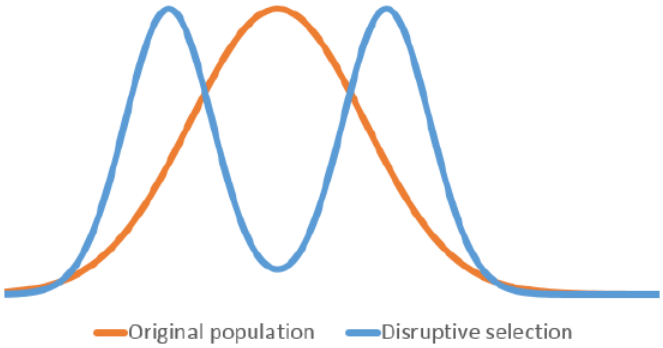


Figure **2.2.3.8**: Diversifying selection occurs when extreme values for a trait are favored over intermediate values. This type of selection often drives speciation. In the graph above the x-axis indicates the variation in a trait. The y-axis indicates the percentage of individuals in a population that have a particular trait. In directional selection, the average is selected against, leading to selection for the rarer variations of a trait.

This is seen in many populations of animals that have multiple male mating strategies, such as lobsters. Large, dominant alpha males obtain mates by brute force, while small males can sneak in for furtive copulations with the females in an alpha male's territory. In this case, both the alpha males and the "sneaking" males will be selected for, but medium-sized males, which cannot overtake the alpha males and are too big to sneak copulations, are selected against.

Diversifying selection can also occur when environmental changes favor individuals on either end of the phenotypic spectrum. Imagine a population of mice living at the beach where there is light-colored sand interspersed with patches of tall grass. In this scenario, light-colored mice that blend in with the sand would be favored, as well as dark-colored mice that can hide in the grass. Medium-colored mice, on the other hand, would not blend in with either the grass or the sand and, thus, would more probably be eaten by predators. The result of this type of selection is increased genetic variance as the population becomes more diverse.

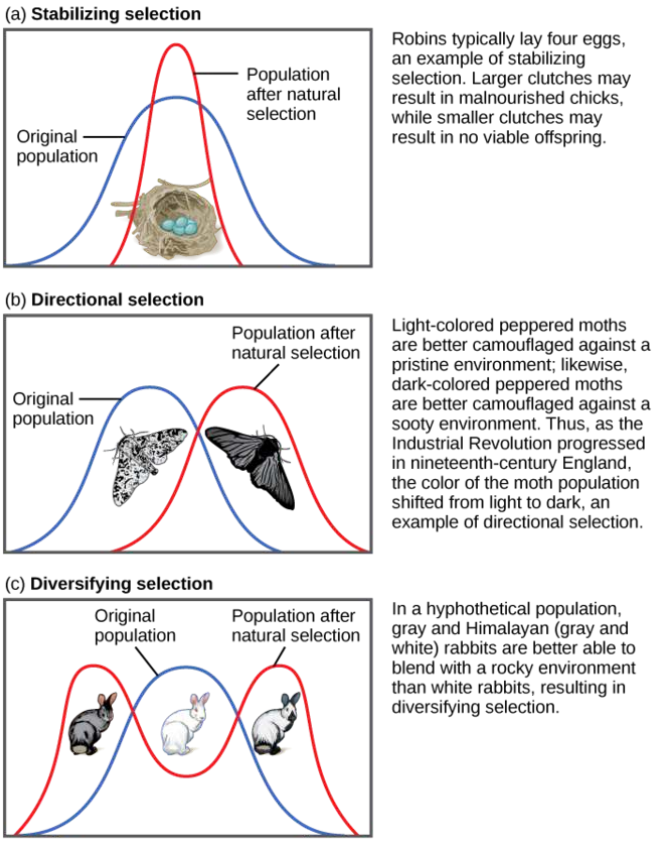
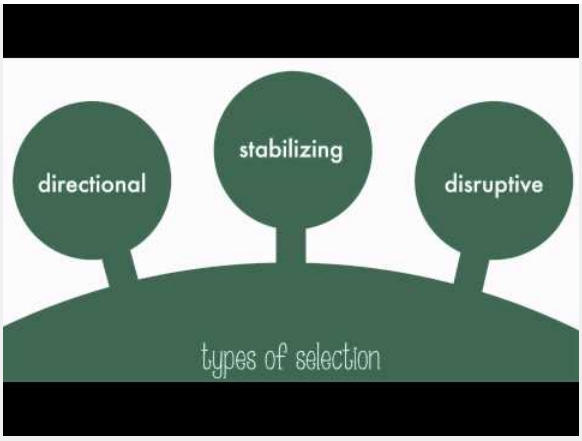


Figure **2.2.3.9**: Different types of natural selection can impact the distribution of phenotypes within a population. In (a) stabilizing selection, an average phenotype is favored. In (b) directional selection, a change in the environment shifts the spectrum of phenotypes observed. In (c) diversifying selection, two or more extreme phenotypes are selected for, while the average phenotype is selected against.

Video





This 2.5-minute video highlights directional, stabilizing, and disruptive selection.
Question after watching: In the video, the narrator speaks of disruptive selection (this textbook called it diversifying selection). What is being disrupted?

Frequency-Dependent Selection

Another type of selection, called **frequency-dependent selection**, favors phenotypes that are either common (positive frequency-dependent selection) or rare (negative frequency-dependent selection).

Negative Frequency-Dependent Selection

Negative frequency-dependent selection increases the population's genetic variance by selecting for rare phenotypes. An interesting example of this type of selection is seen in a unique group of lizards in the deserts of the United States. Male common side-blotched lizards come in three throat-color patterns: orange, blue, and yellow. Each of these forms has a different reproductive strategy: orange males are the strongest and can fight other males for access to their females; blue males are medium-sized and form strong pair bonds with their mates; and yellow males are the smallest and look a bit like female, allowing them to sneak copulations.

Like a game of rock-paper-scissors, orange beats blue, blue beats yellow, and yellow beats orange in the competition for females. The big, strong orange males can fight off the blue males to mate with the blue's pair-bonded females; the blue males are successful at guarding their mates against yellow sneaker males; and the yellow males can sneak copulations from the potential mates of the large, polygynous orange males (Figure **2.2.3.10**).

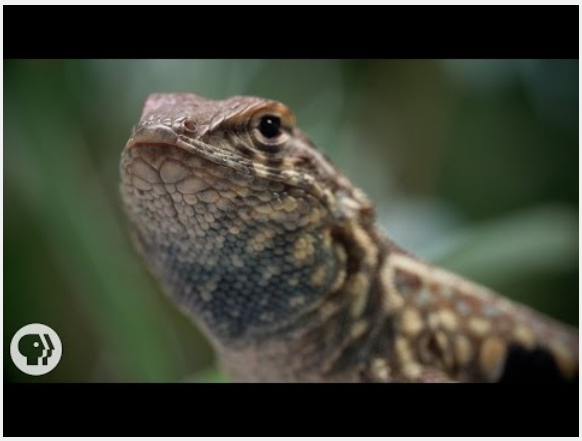
In this scenario, orange males will be favored by natural selection when the population is dominated by blue males, blue males will thrive when the population is mostly yellow males, and yellow males will be selected for when orange males are the most populous. As a result, populations of side-blotched lizards cycle in the distribution of these phenotypes. In one generation, orange might be predominant and then yellow males will begin to rise in frequency. Once yellow males make up a majority of the population, blue males will be selected for. Finally, when blue males become common, orange males will once again be favored. So, orange (strong) > blue (cooperation) > yellow (sneaky) > orange (strong)...etc.



Figure **2.2.3.10**: A yellow-throated side-blotched lizard (seen here) is smaller than either the blue-throated or orange-throated males and appears a bit like the females of the species, allowing it to sneak copulations. Frequency-dependent selection allows for both common and rare phenotypes of the population to appear in a frequency-aided cycle.

Video





This 3.5-minute video illustrates the side-blotched lizard case study of negative frequency-dependent selection. Question after watching: The video mentions that the blues can be altruistic, which is to say exhibit behavior that would benefit not themselves but another animal. Propose a hypothesis about the evolutionary advantage of altruism in this case.

Positive Frequency-dependent Selection

Positive frequency-dependent selection usually decreases genetic variance by selecting for common phenotypes. An example of positive frequency-dependent selection is the mimicry of the warning coloration of dangerous species of animals by other species that are harmless.

The scarlet kingsnake (*Lampropeltis elapsoides*), a harmless species, mimics the coloration of the eastern coral snake *(Micrurus fulvius)*, a venomous species typically found in the same geographical region (Figure **2.2.3.11**). Predators learn to avoid both species of snake due to the similar coloration. As a result, the scarlet kingsnake becomes more common and its coloration phenotype becomes more variable due to relaxed selection. This phenotype is, therefore, more "fit" as the population of species that possess it (both dangerous and harmless) becomes more numerous. In geographic areas where the coral snake is less common, the pattern becomes less advantageous to the kingsnake, and much less variable in its expression, presumably because predators in these regions are not "educated" to avoid the pattern.



Figure **2.2.3.11**: The scarlet kingsnake (*Lampropeltis elapsoides*), left, mimics the coloration of the poisonous eastern coral snake (Micrurus fulvius), right. Positive frequency-dependent selection reinforces the common phenotype because predators avoid the distinct coloration. The eastern coral snake (Micrurus fulvius)is venomous and advertises this through its coloring.

Video



In this short 1-minute narrated by David Attenborough, you will see several examples of biomimicry, where animals evolved shapes and colors that make them look like something else. This is a type of positive frequency-dependent selection. Question after watching: What appears to be the purpose of biomimicry in most organisms? At which step in a process of natural selection would mimicry provide an advantage?

Sexual Selection

Sexual selection, the selection pressure on males and females in mating, can result in traits designed to maximize sexual success. In species with sexual selection, typically one sex is less-limited due to their ability to produce an overabundance of gametes and the other is more-limited due to their higher parental investment (e.g. produce eggs, gestate a fetus, raise young, etc.). The more-limited sex typically reproduces fewer times and has higher parental investment than the less-limited sex; they are typically more discerning about who they mate with in order to optimize those reproductive events.

Sexual selection in animals takes two major forms: **intersexual selection** in which, the less-limited sex (typically males) are chosen by the more-limited sex (typically females) based on certain characteristics and **intrasexual selection** in which members of the less-limited sex compete aggressively among themselves for access to the more-limited sex (Figure **2.2.3.12**).



Figure **2.2.3.12**: This male elk has large antlers to compete with rival males for available females (intrasexual competition). In addition, the many points on his antlers represent health and longevity, and therefore he may be more desirable to females (intersexual selection).

Video





This 3-minute video highlights extreme behaviors that arise from intense sexual selection pressure.
Question after watching: What can you surmise about which of the sexes are 'choosier' in most mammals, based on morphological and behavioural dimorphism?

Sexual Dimorphism in Animals

Males and females of certain animal species are often quite different from one another in ways beyond the reproductive organs. Male vertebrates are often larger, for example, and display many elaborate colors, adornments, and behaviors such as seen in the

figure below, while females of the same species tend to be smaller and less attention-seeking. These differences are called **sexual dimorphisms** and arise from the variation in reproductive success (Figure **2.2.3.13**).

Animal females do not have trouble finding mates for reproduction, while reproduction is not guaranteed for males. The bigger, stronger, or more decorated males usually obtain the vast majority of the total reproductive events, while other males receive none. This can occur because the males are better at fighting off other males (intrasexual selection), or because females will choose to mate with the bigger, brasher, or more decorated males (intersexual selection). In either case, this variation in reproductive success generates a strong selection pressure among males to compete for mates, resulting in the evolution of bigger body sizes or elaborate ornaments in order to increase their chances of mating. Females, on the other hand, tend to get a handful of selected matings; therefore, they are more likely to be selective in their mates.



Figure **2.2.3.13**: Morphological differences between males and females of the same species is known as sexual dimorphism. These differences can be observed in (a) peacocks and peahens, (b) *Argiope appensa* spiders (the female spider is the large one), and (c) wood ducks.

Sexual dimorphism varies widely among species; some species are even sex-role reversed. In such cases, females tend to have a greater variation in their reproductive success than males and are, correspondingly, selected for the bigger body size and elaborate traits usually characteristic of males.

The Handicap Principle

Sexual selection can be so strong that it selects for traits that are actually detrimental to the individual's survival because they maximize its reproductive success. For example, while the male peacock's tail is beautiful, and the male with the largest, most colorful tail will more probably win a female's attention, it is not practical or advantageous (Figure **2.2.3.14**). In addition to making the males more visible to predators, it slows down any needed escapes. There is some evidence that this risk is why females like the big, bright tails. Because large tails carry risk, only the best males can survive that risk, and therefore the bigger the tail the more fit the male must be. This idea is known as the **handicap principle**.



Figure **2.2.3.14**: This male ribbon-tailed astrapia, *Astrapia mayeri*, a bird of paradise, carries an extremely long tail as the result of sexual selection. The tail is flamboyant and detrimental to the bird's own survival, but it increases his reproductive success. This may be an example of the handicap principle.

The Good Genes Hypothesis

The **good genes hypothesis** states that males develop these impressive ornaments to show off their efficient metabolism or their ability to fight disease. Females then choose males with the most impressive traits because it signals their genetic superiority, which they will then pass on to their offspring. Though it might be argued that females should not be so selective because it will likely reduce their number of offspring, if better males father more fit offspring, it may be beneficial. Fewer, healthier offspring may increase the chances of survival more than many, weaker offspring.

Video





This 8.5-minute video is an overview of natural and sexual selection.
Questions after watching: How is sexual selection an example or type of natural selection? Explain the following statement: "evolution is just a numbers game"

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Unit 2.2.4 - Additional Mechanisms of Evolution

- Please read and watch the following Learning Resources.
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
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Learning Objectives

- Identify the four agents of evolutionary change other than natural selection
- Explain genetic drift, including the bottleneck and founder effects
- Describe gene flow and how it maintains genetic variance in a population
- Explain how each evolutionary force can influence the allele frequencies of a population

In addition to natural selection, there are four other agents of evolutionary change: mutation, genetic drift, gene flow, and non-random mating. These serve to either increase or decrease genetic variation in the population. Mutations are changes to an organism's DNA and are an important driver of diversity in populations. Genetic drift is the impact on a population's genetic variance due to random chance events, such as natural disasters. Gene flow is the exchange of genetic information between populations and serves to keep disparate populations more similar to one another. Nonrandom mating describes the process of "choice" within reproduction based on perceived evolutionary fitness. Each of these additional agents is discussed below in concert with natural selection as none of these forces acts in isolation.

Four Additional Agents of Evolutionary Change

1. Mutation

Species ultimately evolve because of the accumulation of mutations that occur over time. The appearance of new mutations is the most common way to introduce novel genotypic and phenotypic variance (Figure **2.2.4.1**). Without new mutations, genetic variance in a population would lessen over time in stable environmental conditions (stabilizing selection) leading populations to be less able to survive future changes. Mutations can only influence evolution if they are heritable (e.g. carried within the gametes).

Some mutations are unfavorable or harmful and are quickly eliminated from the population by natural selection as seen in Figure **2.2.4.2**. Others are beneficial and will spread through the population. Whether or not a mutation is beneficial or harmful is determined by whether it helps an organism survive to sexual maturity and reproduce. Some mutations do not do anything and can linger, unaffected by natural selection, in the genome (e.g. in the somatic cells). Some can have a dramatic effect on a gene and the resulting phenotype.



Figure **2.2.4.1**: A mutation has caused this garden moss rose to produce flowers of different colors. This mutation has introduced a new allele into the population that increases genetic variation and may be passed on to the next generation.

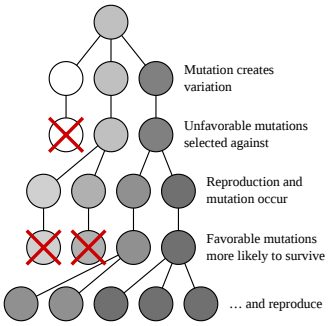


Figure **2.2.4.2**: As mutations create variation, natural selection affects the frequency of that trait in a population. Mutations that confer a benefit (such as running faster or digesting food more efficiently) can help that organism survive and reproduce, carrying the mutation to the next generation.

Video



This 7-minute video provides an overview of DNA mutations and their impact on the proteins they encode and the phenotype of an organism.

Question after watching: If a mutation does not impact an organism's phenotype, and this mutation is found over time to increase in a population, does this constitute evolution? If so, what is the likely cause of this evolution?

2. Genetic Drift

Another way a population's allele and genotype frequencies can change is **genetic drift**, which is simply the effect of chance on the population's genetic variation. For example, some individuals will have more offspring than others—not due to an advantage conferred by some genetically-encoded trait, but just because one male happened to be in the right place at the right time (when the receptive female walked by) or because the other one happened to be in the wrong place at the wrong time (when a fox was hunting).

Genetic Drift vs. Natural Selection

Genetic drift is the opposite of natural selection. The theory of natural selection maintains that some individuals in a population have traits that enable them to survive and produce more offspring, while other individuals have traits that are detrimental and may cause them to die before reproducing. Over successive generations, these selection pressures can change the gene pool and the traits within the population. For example, a big, powerful male gorilla will mate with more females than a small, weak male and therefore more of his genes will be passed on to the next generation. His offspring may continue to dominate the troop and pass on their genes as well. Over time, the selection pressure will cause the allele frequencies in the gorilla population to shift toward large, strong males.

Unlike natural selection, genetic drift describes the effect of chance on populations in the absence of positive or negative selection pressure. Through random sampling or the survival or reproduction of a random sample of individuals within a population, allele frequencies within a population may change. Rather than a male gorilla producing more offspring because he is stronger, he may be the only male available when a female is ready to mate. His genes are passed on to future generations because of chance, not because he was the biggest or the strongest. Genetic drift is the shift of alleles within a population due to chance events that cause random samples of the population to reproduce or not.

Small populations are more susceptible to the forces of genetic drift. Large populations, on the other hand, are buffered against the effects of chance. If one individual of a population of 10 individuals happens to die at a young age before leaving any offspring to the next generation, all of its genes (1/10 of the population's gene pool) will be suddenly lost. In a population of 100, that individual represents only 1 percent of the overall gene pool; therefore, genetic drift has much less impact on the larger population's genetic structure.

The Bottleneck Effect

Genetic drift can be magnified by natural events, such as a natural disaster that kills a large portion of the population at random. This **bottleneck effect** occurs when only a few individuals survive and reduce variation in the gene pool of a population (Figure **2.2.4.3**). The genetic structure of the survivors becomes the genetic structure of the entire population, which may be very different from the pre-disaster population.

Captive breeding programs can fall victim to the bottleneck effect when species are at endangered or threatened levels. When scientists are involved in the breeding of a species, such as with animals in zoos and nature preserves, they try to increase a population's genetic variance to preserve as much of the phenotypic diversity as they can. This also helps reduce the risks associated with inbreeding, the mating of closely related individuals, which can have the undesirable effect of bringing together deleterious recessive mutations that can cause abnormalities and susceptibility to disease.

For example, a disease that is caused by a rare, recessive allele might exist in a population, but it will only manifest itself when an individual carries two copies of the allele. Because the allele is rare in a normal, healthy population with unrestricted habitat, the chance that two carriers will mate is low, and even then, only 25 percent of their offspring will inherit the disease allele from both parents. While it is likely to happen at some point, it will not happen frequently enough for natural selection to be able to swiftly eliminate the allele from the population, and as a result, the allele will be maintained at low levels in the gene pool. However, if a family of carriers begins to interbreed with each other, this will dramatically increase the likelihood of two carriers mating and eventually producing diseased offspring, a phenomenon known as inbreeding depression.

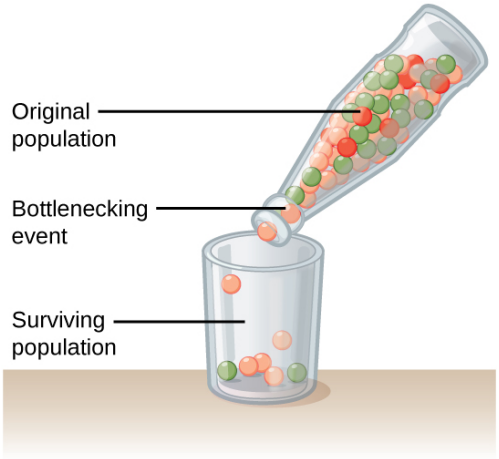


Figure 2.2.4.3: A chance event or catastrophe can reduce the genetic variability within a population.

Video



This 4.5-minute video describes how genetic drift occurs by chance.
Question after watching: Describe a situation in which a population would undergo the bottleneck effect and explain what impact that would have on the population's genetic variance.

The Founder Effect

Another scenario in which populations might experience a strong influence of genetic drift is if some portion of the population leaves to start a new population in a new location or if a population gets divided by a physical barrier of some kind (Figure 2.2.4.4). In this situation, it is improbable that those individuals are representative of the entire population, which results in the **founder effect**. The founder effect occurs when the genetic structure changes to match that of the new population's founding fathers and mothers.

The founder effect is believed to have been a key factor in the genetic history of the Afrikaner population of Dutch settlers in South Africa, as evidenced by mutations that are common in Afrikaners, but rare in most other populations. This was probably due to the fact that a higher-than-normal proportion of the founding colonists carried these mutations. As a result, the population expresses unusually high incidences of Huntington's disease (HD) and Fanconi anemia (FA), a genetic disorder known to cause blood marrow and congenital abnormalities, even cancer.

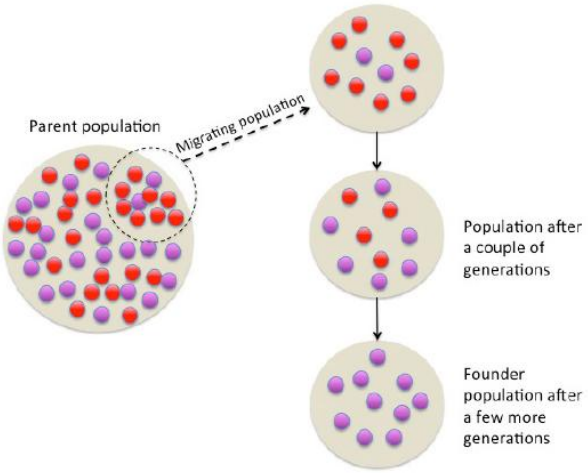
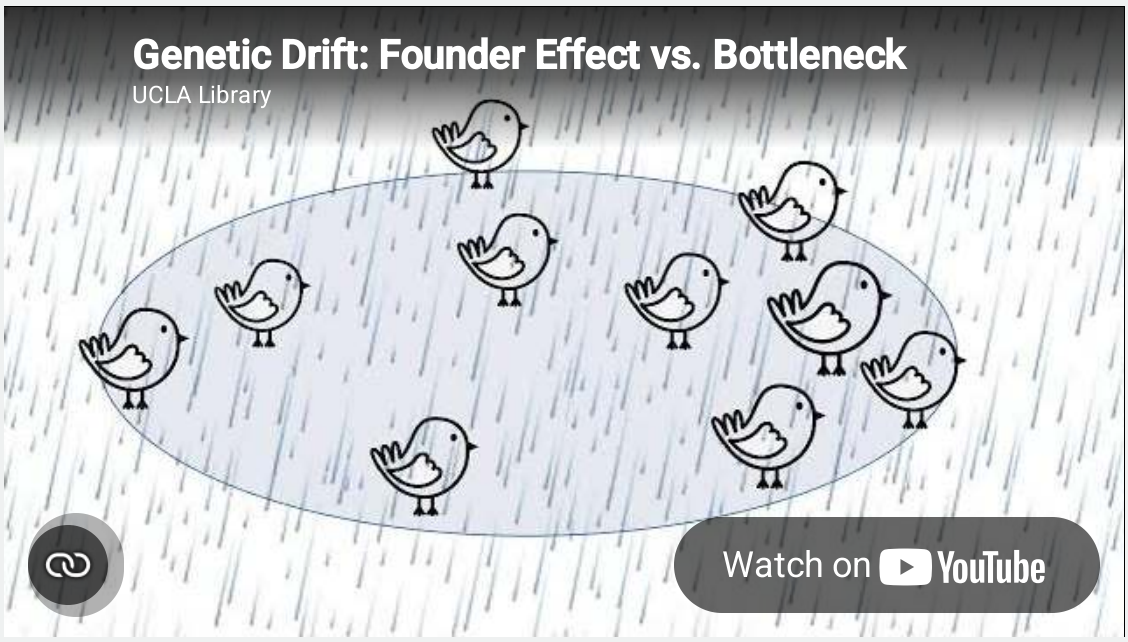
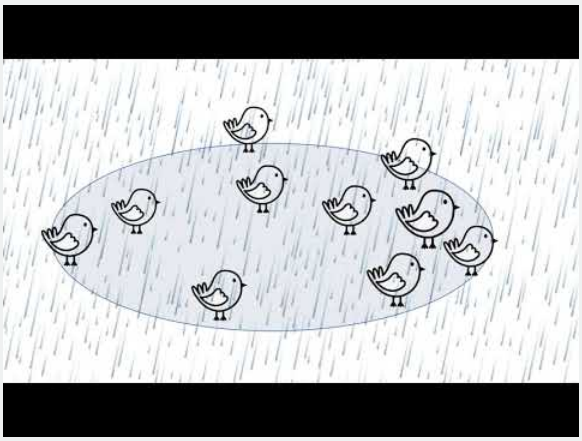


Figure **2.2.4.4**: The founder effect occurs when a portion of the population (i.e. “founders”) separates from the old population to start a new population with different allele frequencies. (Tsaneda; CC-BY-SA 4.0)

Video





This 1-minute video differentiates the founder effect from a bottleneck event, which are similar but different. Question after watching: 50,000 years ago, a small group of people migrated out of Africa. Their descendants populated Asia, Europe, and the Americas. Which type of event is this: founder or bottleneck?

[Optional Activity] Scientific Method Connection: Testing the Bottleneck Effect

Question: How do natural disasters affect the genetic structure of a population?

Background: When much of a population is suddenly wiped out by an earthquake or hurricane, the individuals that survive the event are usually a random sampling of the original group. As a result, the genetic makeup of the population can change dramatically. This phenomenon is known as the bottleneck effect.

Hypothesis: Repeated natural disasters will yield different population genetic structures; therefore, each time this experiment is run, the results will vary.

Test the hypothesis: Count out an original parent population of 100 individuals using different colored beads. For example, red, blue, and yellow beads might represent red, blue, and yellow individuals. After recording the number of each individual in the original population, place them all in a bottle with a narrow neck that will only allow a few beads out at a time. Then, pour approximately 33 beads into a bowl. This represents the surviving individuals after a natural disaster kills a majority (67%) of the population. Count the number of the different colored beads in the bowl, and record it. Then, place all of the beads back in the bottle and repeat the experiment four more times.

Analyze the data: Compare the five populations that resulted from the experiment. Do the surviving populations all contain the same number of different colored beads or do they vary? Remember, these populations all came from the same exact parent population.

Form a conclusion: Most likely, the five resulting surviving populations will differ quite dramatically. This is because natural disasters are not selective—they kill and spare individuals at random. Now think about how this might affect a real population. What happens when a hurricane hits the Gulf Coast of the United States? How do the seabirds that live on the beach fare?

Optional Activity 2.2.4.1

Do you think genetic drift would happen more quickly on an island or on the mainland? Why?

Answer

Genetic drift is likely to occur more rapidly on an island where smaller populations are expected to occur.

3. Gene Flow

Another important evolutionary force is **gene flow**: the flow of alleles in and out of a population due to the migration of individuals or gametes (Figure 2.2.4.5). While some populations are fairly stable, others experience more flux. Many plants, for example, send their pollen far and wide, by wind or by bird, to pollinate other populations of the same species some distance away. Even a population that may initially appear to be stable, such as a pride of lions, can experience its fair share of immigration and emigration as developing males leave their mothers to seek out a new pride with genetically unrelated females. This variable flow of individuals in and out of the group not only changes the gene structure of the population but can also introduce new genetic variation to populations in different geological locations and habitats.

Maintained gene flow between two populations can also lead to a combination of the two gene pools, reducing the genetic variation between the two groups. Gene flow strongly acts against speciation, by recombining the gene pools of the groups, thus repairing the developing differences in genetic variation that would have led to full speciation and creation of daughter species.

For example, if a species of grass grows on both sides of a highway, pollen is likely to be transported from one side to the other and vice versa. If this pollen is able to fertilize the plant where it ends up and produce viable offspring, then the alleles in the pollen have effectively linked the population on one side of the highway with the other.

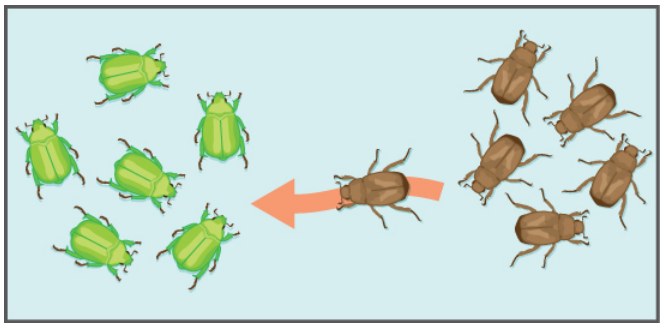
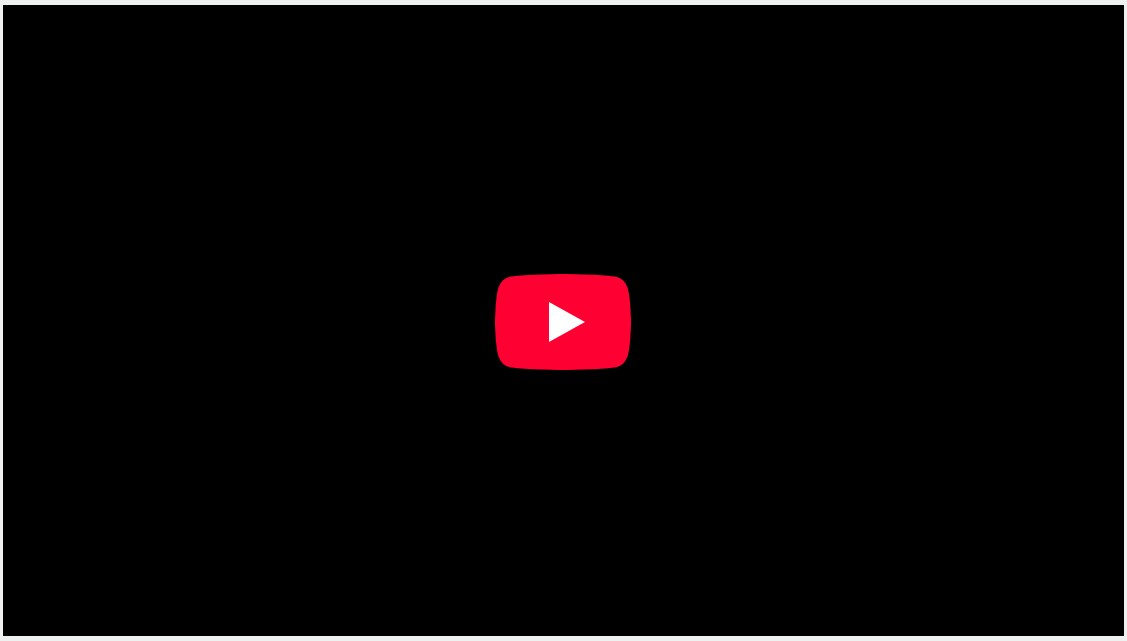


Figure 2.2.4.5: Gene flow can occur when an individual travels from one geographic location to another.

Video





This video takes the examples of the finches in the Galapagos islands and explains how the different sized beaks on each island resulted from the lack of gene flow between the population on each island.
Question after watching: Why does the narrator say that in time the different populations that stop having gene flow can become different species. What step needs to happen for this to occur?

4. Nonrandom Mating

If individuals nonrandomly mate with their peers, the result can be a changing population. There are many reasons nonrandom mating occurs. One reason is simple mate choice; for example, female robins may prefer males with brighter, more orange breast feathers Figure 2.2.4.6. Traits that lead to more matings for an individual become selected for by natural selection.

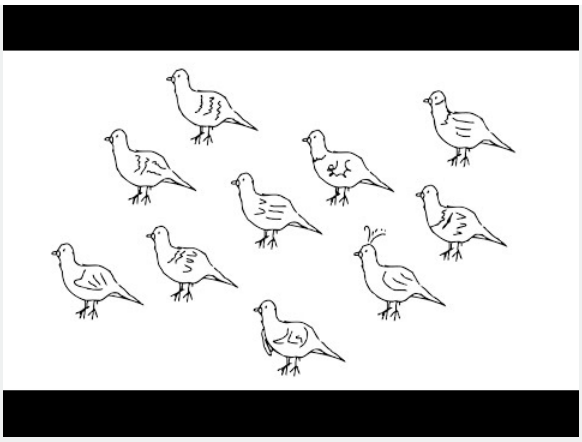
One common form of mate choice, called **assortative mating**, is an individual's preference to mate with partners who are phenotypically similar to themselves. Another cause of nonrandom mating is physical location. This is especially true in large populations spread over large geographic distances where not all individuals will have equal access to one another. Some might be miles apart through woods or over rough terrain, while others might live immediately nearby.



Figure 2.2.4.6: The American robin (*Turdus migratorius*) may practice assortative mating on plumage color, a melanin-based trait, and mate with other robins who have the most similar shade of color. However, there may also be some sexual selection for more vibrant plumage which indicates health and reproductive performance.

Video





This 12-minute video makes the connection between DNA, mutations, genetic reshuffling through sexual reproduction, and phenotypes/variability between individuals.

Question after watching: Imagine that the creation of the Panama canal re-opens a route between the two populations of fish presented in the video that had been separated by the landmass. What sort of evolutionary changes would need to happen in either population to lead to specialization?

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SECTION OVERVIEW

2.3: The Origin of Species

Learning Objectives

- Define species and describe how scientists identify species as different
- Describe genetic variables that lead to speciation
- Identify prezygotic and postzygotic reproductive barriers
- Explain allopatric and sympatric speciation
- Describe adaptive radiation
- Explain the two major theories on rates of speciation

2.3.1: Species Defined

2.3.2: Speciation

2.3.3: Rates of Speciation and Extinction

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Unit 2.3.1 - Species Defined

- Please read and watch the following Learning Resources.
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Learning Objectives

- Confirm whether two organisms belong to the same species using the biological definition of species as a guide
- Explain how reproductive isolation can result in speciation

Introduction - What is a Species?

A ***biological* species** is defined as a group of individuals that, in nature, are able to mate and produce viable, fertile offspring. There are other definitions of species but, according to the biological definition, one species is distinguished from another when, in nature, it is not possible for matings between individuals from each species to produce fertile, living offspring.

Members of the same species share both external and internal characteristics which develop from their DNA. The closer relationship two organisms share, the more DNA they have in common, just like people and their families. People's DNA is likely to be more like their father or mother's DNA than their cousin's or grandparent's DNA. Organisms of the same species have the highest level of DNA alignment and, therefore, share characteristics and behaviors that lead to successful reproduction.

Species' appearance can be misleading in suggesting an ability or inability to mate. For example, even though domestic dogs (*Canis lupus familiaris*) display phenotypic differences, such as size, build, and coat, most dogs can interbreed and produce viable puppies that can mature and sexually reproduce.



Figure **2.3.1.1**: Dogs of different breeds still have the ability to reproduce. The (a) poodle and (b) cocker spaniel can reproduce to produce a breed known as (c) the cockapoo.

In other cases, individuals may appear similar although they are not members of the same species. For example, even though bald eagles (*Haliaeetus leucocephalus*) and African fish eagles (*Haliaeetus vocifer*) are both birds and eagles, each belongs to a separate species group. If humans were to artificially intervene and fertilize the egg of a bald eagle with the sperm of an African fish eagle and a chick did hatch, that offspring, called a hybrid (a cross between two species), would probably be infertile: unable to successfully reproduce after it reached maturity. Different species may have different genes that are active in development; therefore, it may not be possible to develop a viable offspring with two different sets of directions. Thus, even though hybridization may take place, the two species still remain separate.



(a) (b)

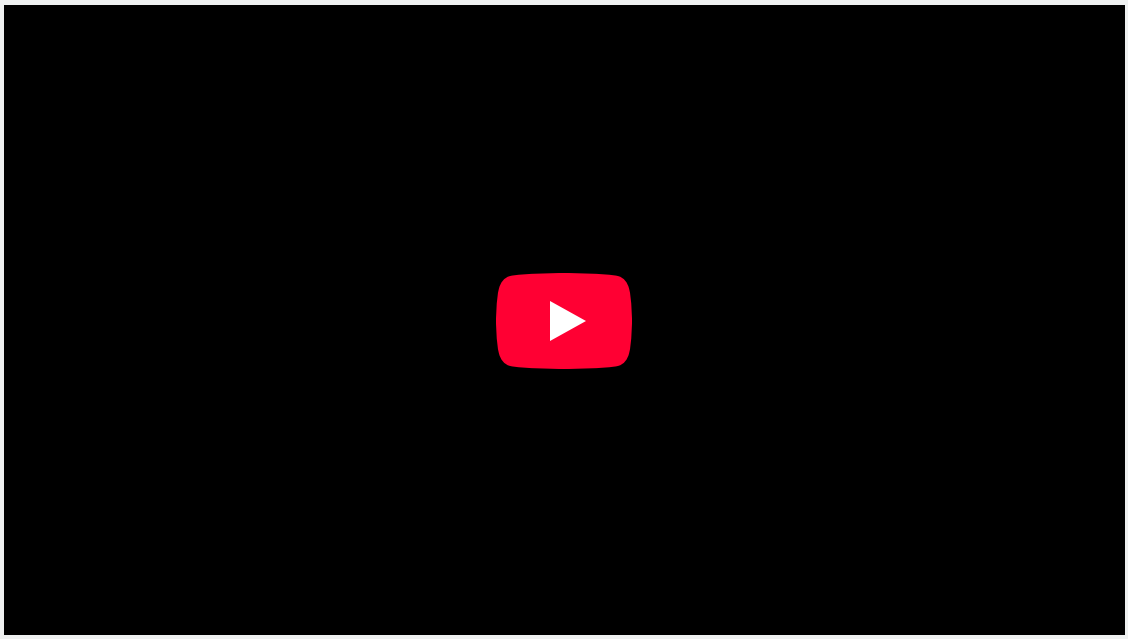
Figure **2.3.1.2**: Species that appear similar may not be able to reproduce. The (a) African fish eagle is similar in appearance to the (b) bald eagle, but the two birds are members of different species.

Gene Pools

Populations of species share a **gene pool**: a collection of all the variants of genes in the species. The basis of any change in a group or population of organisms must be genetic; it is the only way to share and pass on traits. Variations within a species can only be passed to the next generation via asexual reproduction or sexual reproduction. Changes will be passed on asexually if the reproducing cell already possesses the changed trait and the offspring will be a genetic copy of the parent.

In sexual reproduction, unlike sexual reproduction, only the changed traits in gametes can be passed down to offspring. In other words, sexually-reproducing organisms can experience genetic changes in their body, or somatic, cells but if these changes do not also occur in a gamete, the changed trait will not appear in the next generation from the parents. Only heritable traits can evolve. Therefore, reproduction plays a large role for genetic changes to take root in a population or species. In summary, organisms must be able to reproduce with each other to pass new traits to offspring.

Video





In this 10.5-minute video explains the concepts of species and speciation.
Questions after watching: There is a colony of green aphids on a tomato plant. On the tomato plant that is next to the first one, there are red aphids. The two colonies started from a third one, that was green, on another nearby plant. The green and the red aphids are distinct species because the green aphids are attracted to green counterparts; and red ones only have interest in other red ones. Which does this example represent: Allopatric or sympatric speciation? Pre-zygotic and post-zygotic speciation?

Reproductive Isolation

Reproductive isolation, through mechanical, behavioral, and physiological barriers, is an important component of speciation. Given enough time, the genetic and phenotypic divergence between populations will affect characters that influence reproduction. In other words, if individuals of the two populations were to be brought together, mating would be improbable, but if mating did occur, offspring would be non-viable or infertile. Many factors may influence this process known as **reproductive isolation**. Reproductive isolation is the inability of two populations to interbreed with one another.

There are two different types of barriers that prevent the members of two different species from mating, to producing offspring, or having fertile offspring: prezygotic barriers and postzygotic barriers. Recall that a **zygote** is a fertilized egg: the first cell of the development of an organism that reproduces sexually. Therefore, a **prezygotic barrier** is a mechanism that blocks reproduction from taking place; this includes barriers that prevent fertilization when organisms attempt reproduction. A **postzygotic barrier** occurs after zygote formation; this includes organisms that do not survive the embryonic stage and those that are born sterile.

? Optional Activity 2.3.1.1

Which condition is the basis for a species to be reproductively isolated from others?

a. It does not share its habitat with related species.
b. It does not exist outside of a single habitat.
c. It does not exchange genetic information with other species.
d. It does not undergo evolutionary changes for a significant amount of time.

Answer

c. It does not exchange genetic information with other species.

Prezygotic Barriers

There are several different types of prezygotic barriers, including temporal, habitat, behavioral, gametic, and mechanical. Some of these prezygotic barriers prevent reproduction entirely. Many organisms only reproduce at certain times of the year, often just annually.

Temporal isolation

Differences in breeding schedules, called **temporal isolation**, can act as a form of reproductive isolation. For example, two species of frogs inhabit the same area, but one reproduces from January to March, whereas the other reproduces from March to May.



(a) (b)

Figure **2.3.1.3**: These two related frog species exhibit temporal reproductive isolation. (a) Rana aurora breeds earlier in the year than (b) Rana boylii.

Habitat Isolation

In some cases, populations of a species move to a new habitat and take up residence in a place that no longer overlaps with other populations of the same species; this is called **habitat isolation**. Reproduction with the parent species ceases and a new group exists that is now reproductively and genetically independent. For example, a cricket population that was divided after a flood could no longer interact with each other. Over time, the forces of natural selection, mutation, and genetic drift will likely result in the divergence of the two groups.

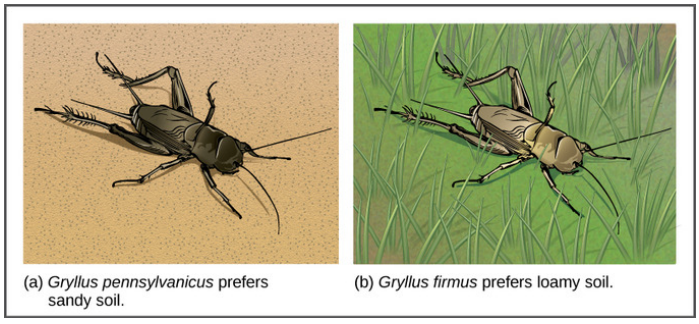


Figure **2.3.1.4**: Speciation can occur when two populations occupy different habitats. The habitats need not be far apart. The cricket (a) *Gryllus pennsylvanicus* prefers sandy soil, while the cricket (b) *Gryllus firmus* prefers loamy soil. The two species can live in close proximity, but because of their different soil preferences, they became genetically isolated.

Behavioral Isolation

Behavioral isolation occurs when the presence or absence of a specific behavior prevents reproduction from taking place. For example, male fireflies use specific light patterns to attract females. Various species display their lights differently; if a male of one species tried to attract the female of another, she would not recognize the light pattern and would not mate with the male.

Gametic and Mechanical Barriers

Other prezygotic barriers work when differences in their gamete cells prevent fertilization from taking place; this is called a **gametic barrier**. Similarly, in some cases, closely-related organisms try to mate, but their reproductive structures simply do not fit together (**mechanical barrier**). For example, damselfly males of different species have differently-shaped reproductive organs.



Figure **2.3.1.5**: The shape of the male reproductive organ varies among male damselfly species and is only compatible with the female of that species. Reproductive organ incompatibility keeps the species reproductively isolated.

In plants, certain structures aimed to attract one type of pollinator simultaneously prevent a different pollinator from accessing the pollen. The tunnel through which an animal must access nectar can vary in length and diameter, which prevents the plant from

being cross-pollinated with a different species.



(a) Honeybee drinking nectar from a foxglove flower

(b) Ruby-throated hummingbird drinking nectar from a trumpet creeper flower

Figure **2.3.1.6**: Some flowers have evolved to attract certain pollinators. The (a) wide foxglove flower is adapted for pollination by bees, while the (b) long, tube-shaped trumpet creeper flower is adapted for pollination by humming birds.

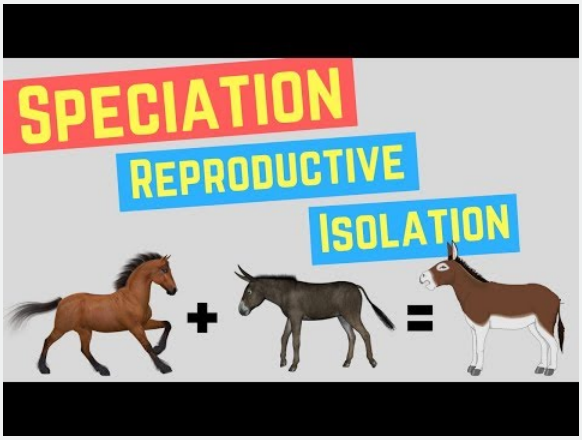
Postzygotic Barriers

There are different types of postzygotic barriers as well, including hybrid inviability and hybrid sterility. When fertilization takes place and a zygote forms, postzygotic barriers can prevent reproduction.

Hybrid individuals in many cases cannot form normally in the womb and simply do not survive past the embryonic stages; this is called **hybrid inviability**.

In another postzygotic situation, reproduction leads to the birth and growth of a hybrid that is sterile and unable to reproduce offspring of their own; this is called **hybrid sterility**.

Video



This 3-minute video provides an overview of pre-zygotic and post-zygotic barriers to reproduction, which lead to speciation. Question after watching: In most cases, which do you hypothesize arises first: pre-zygotic or post-zygotic barriers? Why?

? Optional Activity 2.3.1.2

Which situation is not an example of a prezygotic barrier?

a. Two species of turtles breed at different times of year.
b. Two species of flowers attract different pollinators.
c. Two species of birds display different mating dances.
d. Two species of insects produce infertile offspring.

Answer

d. Two species of insects produce infertile offspring.

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Unit 2.3.2 - Speciation

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Learning Objectives

- Define speciation and discuss the ways in which it may occur
- Give examples of allopatric speciation
- Give examples of sympatric speciation
- Discuss how the fitness of a hybrid will lead to changes in the hybrid zone over time

Introduction

A biological species is a group of potentially interbreeding individuals that produce viable, fertile offspring. For the majority of sexually-reproducing species, this holds true. However, there are exceptions to this rule. Some species are similar enough that hybrid offspring are possible and may occur. The presence of hybrids in nature between similar species suggests that they may have descended from a single interbreeding species and that **speciation**, a process where a single species branches to form two or more new species, may not yet be complete.

There are mechanisms for speciation. Darwin envisioned this process as a branching event. The modern diagram shows that as one species changes over time, it branches repeatedly to form more than one new species as long as the population survives or until the organism becomes extinct.

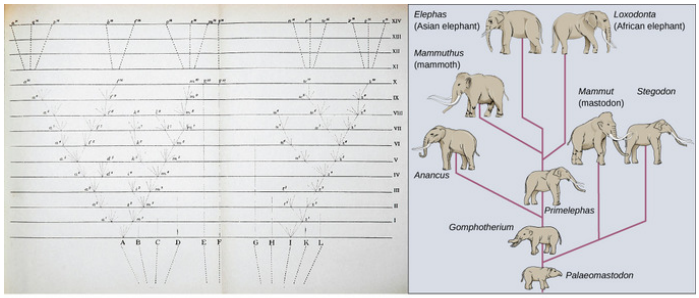


Figure **2.3.2.1**: The only illustration in Darwin's On the Origin of Species is (a) a diagram showing speciation events leading to biological diversity. The diagram shows similarities to phylogenetic charts that are drawn today to illustrate the relationships of species. (b) Modern elephants evolved from the *Palaeomastodon*, a species that lived in Egypt 35–50 million years ago.

For speciation to occur, two new populations must be formed from one original population. They must evolve in such a way that it becomes impossible for individuals from the two new populations to interbreed. Biologists have proposed mechanisms by which this could occur that fall into two broad categories: allopatric speciation and sympatric speciation. **Allopatric speciation** (allo- = "other"; -patric = "homeland") involves geographic separation of populations from a parent species and subsequent evolution. **Sympatric speciation** (sym- = "same"; -patric = "homeland") involves speciation occurring within a parent species remaining in one location.

Biologists typically think of speciation events as the splitting of one ancestral species into two descendant species. There is no reason why there might not be more than two species formed at one time except that it is less likely; multiple events can be conceptualized as single splits occurring close in time.

Allopatric Speciation

A geographically-continuous population has a gene pool that is relatively homogeneous. Gene flow, the movement of alleles across the range of the species, is relatively free because individuals can move and then mate with individuals in their new location. Thus, the frequency of an allele at one end of the range will be similar to the frequency of the allele at the other end.

Allopatric speciation occurs when a single species becomes geographically separated from a natural or human barrier, into two or more populations. Each population evolves new and distinctive traits since gene flow is prevented. If the populations are separated for a long enough period of time, the two populations evolve along different trajectories. New alleles arise by mutation and allele frequencies gradually become different in the two populations. Typically, environmental pressures, such as climate, resources, predators, and competitors for each population will differ causing natural selection to select for different adaptations in each group.

Geographic separation of populations can occur in a variety of ways: a river forming a new branch, erosion forming a new valley, a landslide cutting off a mountain pass, or seeds floating over the ocean to an island. The nature of the geographic separation necessary to isolate populations depends on the biology of the organism and its potential for dispersal. If two flying insect populations took up residence in separate nearby valleys, chances are individuals from each population would fly back and forth, continuing gene flow. However, if two rodent populations became divided by the formation of a new lake, continued gene flow would be improbable and speciation would occur.

Scientists have documented numerous cases of allopatric speciation. For example, along the west coast of the United States and Canada, two separate subspecies of spotted owls exist. The northern spotted owl has genetic and phenotypic differences from its close relative, the Mexican spotted owl, which lives in the south. They have been separated by the emergence of mountain ranges and deserts. Additionally, scientists have found that the further the spatial distance between two groups that once were the same species, the more probable it is that speciation will occur. This seems logical because as the distance increases, the various environmental factors would generally have less in common than locations in close proximity. Consider the two owls: in the north, the climate is cooler than in the south causing the types of prey organisms in each ecosystem to differ. Also, the hunting habits and locations of each would vary. These variances can lead to evolved differences in the owls, resulting in speciation.



Figure **2.3.2.2**: The northern spotted owl and the Mexican spotted owl inhabit geographically separate locations with different climates and ecosystems. The owl is an example of allopatric speciation.

Isolated Evolutionary Change

In isolation, changes in the gene pool can occur through some combination of natural selection and genetic drift (the bottleneck or founder effects). These factors may produce distinct subpopulations on the different islands. So long as they remain separate (allopatric) we consider them **subspecies**. In fact, they might not be able to interbreed with other subspecies but so long as we do not have evidence, we assume that they can.

How much genetic change is needed to create a new species? Perhaps not as much as you might think. Changes at one or just a few gene loci might cause speciation. For example, a single mutation altering flower color or petal shape could immediately prevent cross-pollination between the new and the parental types.

Adaptive Radiation

In some cases, a population of one species disperses throughout an area with each finding a distinct niche or isolated habitat. Over time, the varied demands of their new lifestyles lead to multiple speciation events originating from a single species. This is called **adaptive radiation** because many adaptations evolve from a single point of origin, causing the species to radiate into several new ones. Island archipelagos like the Hawaiian Islands provide an ideal context for adaptive radiation events because water surrounds each island which leads to geographical isolation for many organisms.

The Hawaiian honeycreeper illustrates one example of adaptive radiation. From a single species, called the founder species, numerous species have evolved. The response to natural selection based on specific food sources in each new habitat led to the evolution of a different beak suited to the specific food source. The seed-eating birds have a thicker, stronger beak which is suited to break hard nuts. The nectar-eating birds have long beaks to dip into flowers to reach the nectar. The insect-eating birds have beaks like swords, appropriate for stabbing and impaling insects.

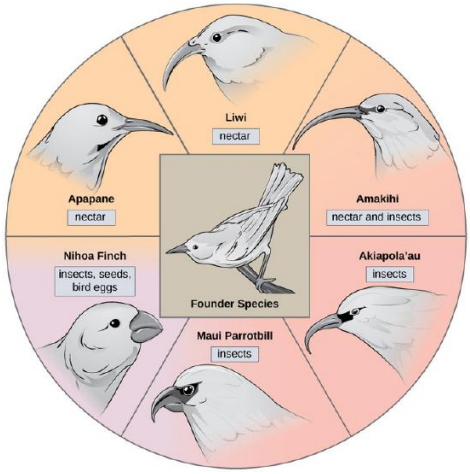


Figure **2.3.2.3**: The honeycreeper birds illustrate adaptive radiation. From one original species of bird, multiple others evolved, each with its own distinctive characteristics.

? Optional Activity 2.3.2.1

Which situation would most likely lead to allopatric speciation?

a. A flood causes the formation of a new lake.
b. A storm causes several large trees to fall down.
c. A mutation causes a new trait to develop.
d. An injury causes an organism to seek out a new food source.

Answer

a. A flood causes the formation of a new lake.

Sympatric Speciation

Can divergence occur if no physical barriers are in place to separate individuals who continue to live and reproduce in the same habitat? The answer is yes. The process of speciation within the same space is called sympatric speciation. Sympatric speciation occurs when two individual populations diverge from an ancestral species without being separated geographically.

One form of sympatric speciation can begin with a large chromosomal aberration during cell division. In a normal cell division event, chromosomes replicate, pair up, and then separate so that each new cell has the same number of chromosomes. However, sometimes the pairs separate and the end cell product has too many or too few individual chromosomes in a condition called **aneuploidy**.

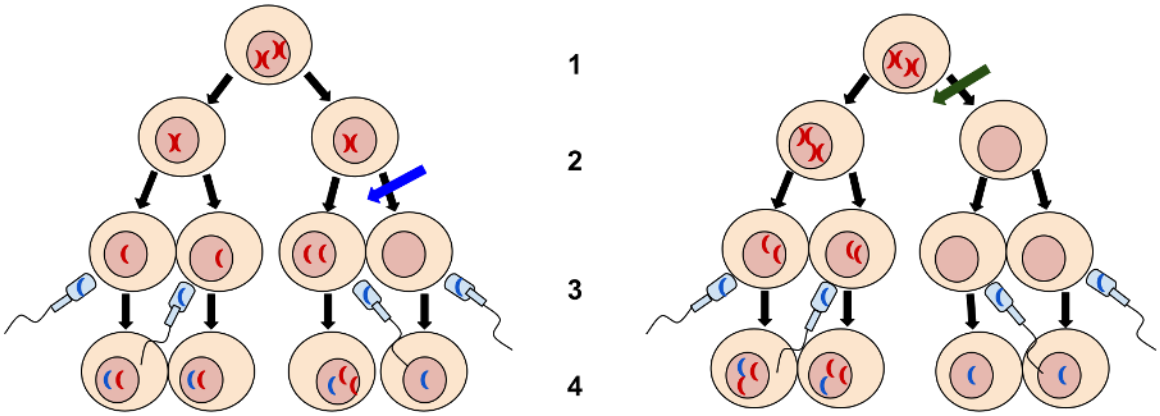


Figure **2.3.2.4**: Aneuploidy results when the gametes have too many or too few chromosomes due to nondisjunction during meiosis. In the example shown here, the resulting offspring will have 2n+1 or 2n-1 chromosomes (Tweety207; CC-BY-SA 3.0)

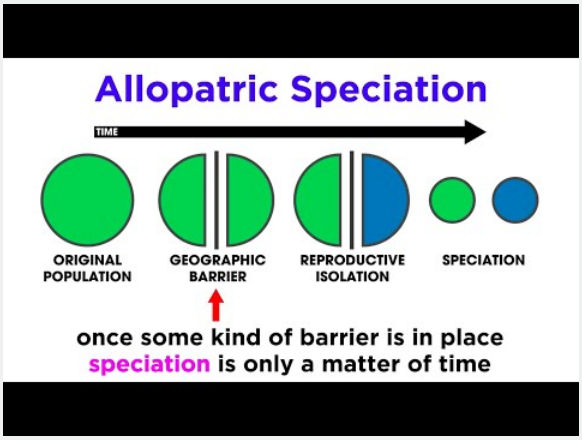
Most organisms without enough chromosomes (2n-1) will not develop. However, **polyploidy** is a condition in which a cell or organism has an extra set, or sets, of chromosomes (2n+1) and some of these organisms can develop and survive. Although polyploidy occurs occasionally in animals, it takes place most commonly in plants. The cultivated forms of wheat, cotton, and tobacco plants are all polyploids. Animals with any of the types of chromosomal aberrations described above are unlikely to survive and produce normal offspring. Scientists have discovered more than half of all plant species studied relate back to an ancestral species evolved through polyploidy. With such a high rate of polyploidy in plants, some scientists hypothesize that this mechanism takes place more as an adaptation than as an error.

Reunion

The question of two populations' status - subspecies or true new species - is resolved if the two ever come to occupy the same territory again (become sympatric). If successful interbreeding occurs, the differences will gradually disappear, and a single population will be formed again. Speciation will not have occurred. If, on the other hand, two subspecies reunite but fail to resume breeding, speciation has occurred and they have become separate species.

The medium tree finch *Camarhynchus pauper* is found only on Floreana Island in the Galápagos. Its close relative, the large tree finch, *Camarhynchus psittacula*, is found on all the central islands of the Galápagos, including Floreana. Were it not for its presence on Floreana, both forms would be considered subspecies of the same species. Because they do coexist and maintain their separate identity on Floreana, we know that speciation has occurred.

Video



Allopatric, sympatric, and parapatric speciation are all summarized in this 7-minute video.
Question after watching: Why do island chains provide ideal conditions for adaptive radiation to occur?

Continued Isolating Mechanisms

What might keep two subpopulations from interbreeding when reunited geographically? There are several mechanisms.

Prezygotic isolating mechanisms act before fertilization occurs. On Floreana, *Camarhynchus psittacula* has a longer beak than *Camarhynchus pauper*, and the research teams led by Peter and Rosemary Grant have demonstrated that beak size is an important criterion by which Darwin's finches choose their mates. Two subpopulations may occupy different habitats in the same area and thus fail to meet at breeding time. In plants, a shift in the time of flowering can prevent pollination between the two subpopulations. Structural differences in the sex organs may become an isolating mechanism. The sperm may fail to reach or fuse with the egg.

Postzygotic isolating mechanisms act even if fertilization does occur. Even if a zygote is formed, genetic differences may have become so great that the resulting hybrids are less viable or less fertile than the parental types. The sterile mule produced by mating a horse with a donkey is an example. Sterility in males produced by hybridization is more common than in females. In fact, it is the most common postzygotic isolating mechanism. When *Drosophila melanogaster* attempts to mate with its relative *Drosophila simulans*, no viable males are even produced. Mutations in a single gene are responsible.

Speciation by Hybridization

Speciation occurs over a span of evolutionary time. Over time, two species may further diverge or reconnect, depending on the fitness strength and the reproductive barriers of the hybrids. When a new species arises, there is a transition period during which the closely-related species continue to interact.

After speciation, two species may recombine or even continue interacting indefinitely. Individual organisms will mate with any nearby individual with which they are capable of breeding. An area where two closely-related species continue to interact and reproduce, forming hybrids, is called a **hybrid zone**. Over time, the hybrid zone may change depending on the fitness strength and the reproductive barriers of the hybrids.

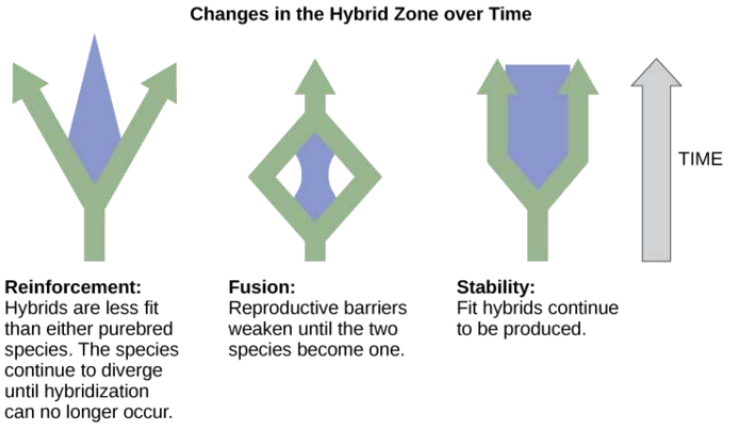


Figure **2.3.2.7**: After speciation has occurred, the two separate-but-closely-related species (green lines) may continue to produce offspring in an area called the hybrid zone (blue area). The thicker the blue line, the more hybridization occurs between the two species.

Reinforcement

When two species that have separated in allopatry become reunited, their prezygotic and postzygotic isolating mechanisms may become more stringent than those between the same species existing apart from each other. This phenomenon is called **reinforcement**. It arises from natural selection working to favor individuals that avoid interspecific matings, which would produce less-fit hybrids, when the two species are first reunited.

Hybrids can have less fitness, more fitness, or about the same fitness level as their purebred parents. Usually, hybrids tend to be less fit; therefore, reproduction to produce hybrids will diminish over time, which nudges the two species to diverge further. This term is used because the low success of the hybrids reinforces the original speciation. If the hybrids are less fit than the parents, reinforcement of speciation occurs, and the species will continue to diverge until they can no longer mate and produce viable offspring.

If the hybrids are as fit or more fit than the parents, or the reproductive barriers weaken, the two species may fuse back into one species. For a hybrid form to persist, it will generally have to be able to exploit the available resources better than either parent species, with which, in most cases, it will have to compete.

Over time, the hybrids themselves can become separate species. Reproductive isolation between hybrids and their parents was once thought to be particularly difficult to achieve; thus, hybrid species were thought to be extremely rare. With DNA analysis becoming more accessible in the 1990s, hybrid speciation has been shown to be a fairly common phenomenon, particularly in plants.

Video





This 8.5-minute animated video explains how species are created using a fictional bird species that lands on a volcanic island (which mirrors what happened on the Galápagos Islands).
Question after watching: Given what you have learned about the process of speciation, why do humans not have any sister species? Propose a hypothesis…

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Unit 2.3.3 - Rates of Speciation and Extinction

- Please read and watch the following Mandatory Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 30 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 2.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Explain how the interaction of an organism's population size in association with environmental changes can lead to different rates of speciation

Introduction - Varying Rates of Speciation

Scientists around the world study speciation, documenting observations both of living organisms and those found in the fossil record. As their ideas take shape and as research reveals new details about how life evolves, they develop models to help explain rates of speciation. In terms of how quickly speciation occurs, two patterns are currently observed: the gradual speciation model and the punctuated equilibrium model.

In the **gradual speciation** model, species diverge gradually over time in small steps (Figure **2.3.3.1**). In the **punctuated equilibrium** model, a new species changes quickly from the parent species and then remains largely unchanged for long periods of time afterward. This early change model is called punctuated equilibrium, because it begins with a punctuated or periodic change and then remains in balance afterward. While punctuated equilibrium suggests a faster tempo, it does not necessarily exclude gradualism.

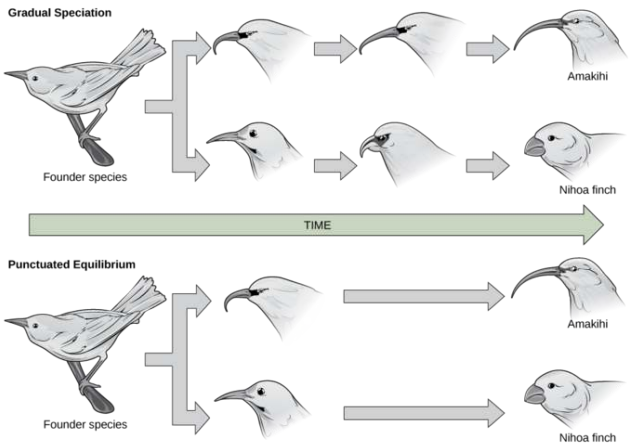


Figure **2.3.3.1**: In (a) gradual speciation, species diverge at a slow, steady pace as traits change incrementally. In (b) punctuated equilibrium, species diverge quickly and then remain unchanged for long periods of time.

The primary influencing factor on changes in speciation rate is environmental conditions. Under some conditions, selection occurs quickly or radically. Consider a species of snails that had been living with the same basic form for many thousands of years. Their fossils would appear similar for a long time. When a change in the environment takes place, such as a drop in the water level, a small number of organisms are separated from the rest in a brief period of time, essentially forming one large and one tiny population. The tiny population faces new environmental conditions. Because its gene pool quickly became so small, any variation that aids in surviving the new conditions becomes the predominant form. More on speciation (and extinction) is discussed in Unit 3.3.1.

Optional Activity 2.3.3.1

Which of the following statements is false?

a. Punctuated equilibrium is most likely to occur in a small population that experiences a rapid change in its environment.
b. Punctuated equilibrium is most likely to occur in a large population that lives in a stable climate.
c. Gradual speciation is most likely to occur in species that live in a stable climate.
d. Gradual speciation and punctuated equilibrium both result in the divergence of species.

Answer

B. Punctuated equilibrium is most likely to occur in a large population that lives in a stable climate.

British Columbia Connections 2.3.3.1

Evolutionary biologist Stephen J. Gould used the formations of the Burgess Shales, between Golden, British Columbia and Banff, Alberta, to support his hypothesis of the punctuated equilibrium model. The Burgess Shales are one of the foremost places in the world to study the fossils of the Cambrian Explosion of life from 550 million years ago.

The Burgess Shales foundation website: https://www.burgess-shale.bc.ca/the-cambrian-explosion-and-the-burgess-shale/

American Museum of Natural History website on Burgess Shales: https://www.amnh.org/research/paleontology/collections/fossil-invertebrate-collection/trilobite-website/niles-eldredge-trilobites-punctuated-equilibria

Canadian Encyclopedia entry on Burgess Shales: https://www.thecanadianencyclopedia.ca/en/article/burgess-shale-fossils

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SECTION OVERVIEW

2.4: Genes Within Populations

Learning Objectives

- Explain how population genetics and evolution are related.
- Describe how different selection forces can change the genetic structure of a population, leading to evolution.
- Use the Hardy-Weinberg principle to provide evidence that evolution is either occurring or not occurring.

2.4.1: Evolution of Genomes

2.4.2: Evolution in Populations

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Unit 2.4.1 - Evolution of Genomes

- Please read and watch the following Learning Resources.
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 2.4.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
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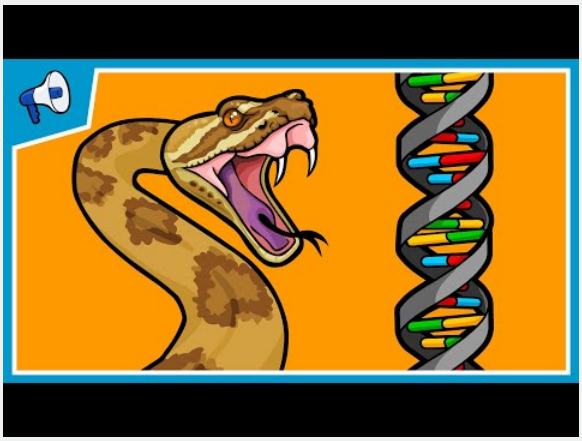
Learning Objectives

- Identify how variations in the size and number of genes in different species can impact evolution;
- Explain the importance of genomic changes in an evolutionary context;
- Recognize the evolutionary implications of observed genome similarities between distant species.

Introduction

Video





This 9-minute video provides an overview of how the genes and genome of a species can change over time to lead to different species.

Questions after watching: How can a gene duplication event fuel evolution? Can you think of another example where something was duplicated and then repurposed by evolution?

Genetic Diversity

Genetic variation is essential for a species to evolve in response to environmental change, including any variation in nucleotides, genes, chromosomes, or genomes of organisms. Each of these levels of genetic diversity adds to the capacity of a population to evolve.

Variations in Number of Genes

DNA is contained in the chromosomes present within the cell; some chromosomes are contained within specific organelles in the cell (for example, the chromosomes of mitochondria and chloroplast). A gene is a discrete section of a chromosome that codes for one or more proteins. Each gene is a hereditary section of DNA that occupies a specific place on the chromosome and controls a particular characteristic of an organism. Genetic diversity at its most elementary level is represented by differences in the sequence of nucleotides (with one of the following bases: adenine, cytosine, guanine) that form DNA (deoxyribonucleic acid) within the cells of the organism. During sexual reproduction, offspring inherit alleles from both parents. These inherited alleles might be slightly different, especially if there has been migration or hybridization of organisms. Also, when the offspring's chromosomes are copied after fertilization, genes can be exchanged in a process called sexual recombination. Helpful or silent mutations and sexual recombination may allow the evolution of new characteristics.

Sometimes whole genes are duplicated, or deleted. This results in an organism having more or fewer copies of that gene than others. The effect on the phenotype may be to increase or decrease the gene product's function (e.g., if the gene encoded a protein that makes pigment, and now the organism has two genes encoding pigment, the organism may now be twice as pigmented as its parents with only one copy of the gene). Natural selection may then select for or against organisms with this altered number of gene copies.

Sometimes there is no immediate effect of the gene duplication on phenotype. The additional copy of the gene may accumulate mutations without deleterious effects on the organism. These mutations will likely modify the gene product's function if it is transcribed. In doing this, the gene may acquire slightly different abilities, such as the factor X blood clotting example the video above.

Variations in Number of Chromosomes

Many organisms are diploid, having two sets of chromosomes, and therefore two copies (called alleles) of each gene. However, some organisms can be haploid, triploid, or tetraploid (having one, three, or four sets of chromosomes respectively). Within any single organism, there may be variation between the two (or more) alleles for each gene. This variation is introduced either through mutation of one of the alleles or as a result of recombination during sexual reproduction.

During replication events, there can be mutations that involve whole chromosomes or whole chunks of chromosomes. Some mutations duplicate a whole chromosome (a whole stretch of DNA with many genes); some may delete a large portion. Some rearrange chromosomes, keeping all of the DNA information but putting it in different places in the genome. It turns out that in some instances, the location matters because it contains sites that initiate and control transcription. In bacteria, this can matter because one transcription factor can control the transcription of many genes in a row.

Changes in chromosome number or structure can affect many genes at the same time. Like changes in individual genes, this can result in some immediate effects because of the change in the number of genes producing the gene products (proteins). Or there can be little to no immediate effect, but the extra copy gives rise to "spare copies" that are free to mutate and acquire new abilities and functions.

Variation in Genome Size

A **genome** is the total genetic information of a cell or organism. The evolution of the genome is characterized by the accumulation of changes. Analysis of genomes and their changes in sequence or size over time involves various fields.

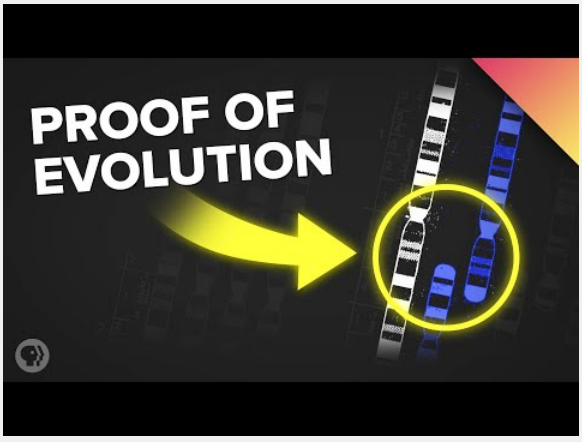
Genome size is usually measured in base pairs (or bases in single-stranded DNA or RNA). Different species can have different numbers of genes within the entire DNA or genome of the organism. Gene number is the main factor influencing the size of the prokaryotic genome. However, a greater total number of genes might not correspond with greater complexity in the phenotype (behavior, structure, or function) of eukaryotes.

For example, the predicted size of the human genome is not much larger than the genomes of some invertebrates and is far smaller than some species of ferns. However, in humans, more proteins are encoded *per gene* than in other species. In eukaryotic organisms, this is an observed paradox: the number of genes that make up the genome does not correlate with genome size. In other words, the genome size is much larger than would be expected given the total number of protein-coding genes.

Larger amounts of genetic information may allow for more variation in the overall genome, conferring additional adaptability to environmental change. It may also play a role in speciation. On the other hand, longer genomes take more energy and time to duplicate, so there is an evolutionary trade-off.

Video





In this 8-minute video, evidence of human evolution in the human genome is demonstrated.
Question after watching: What are three lines of evidence from the human genome of our evolutionary past?

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Unit 2.4.2 - Evolution in Populations

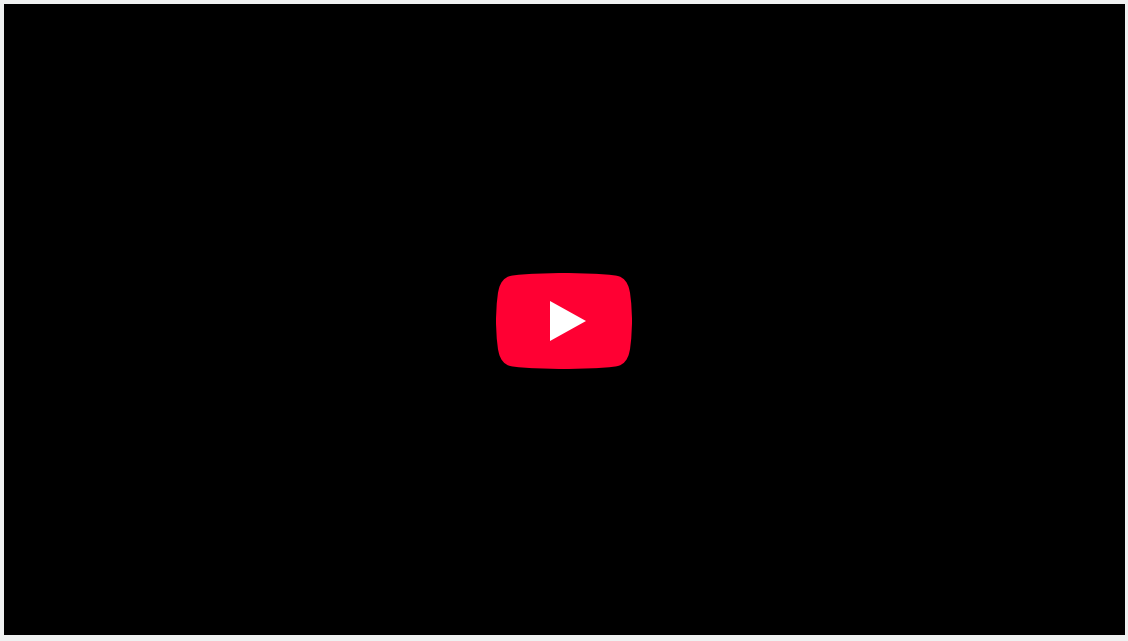
- Please read and watch the following Learning Resources.
- Reading the material for understanding, and taking notes during videos, will take approximately 1.5 hours.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to the Unit 2 Glossary, use the Contents menu at the top of the page OR the right arrow on the side of the page.
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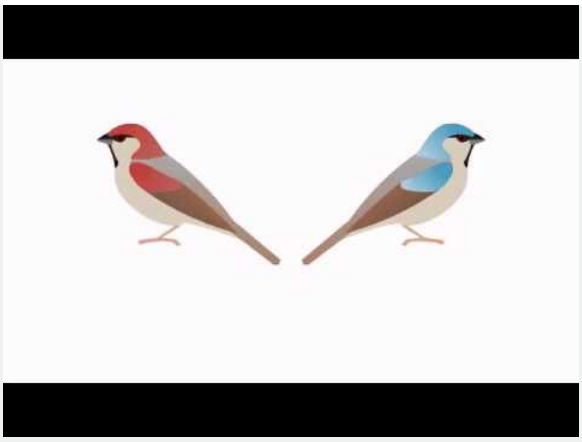
Learning Objectives

- Describe how mutations, natural selection, genetic drift, and gene flow can modify the genes in a population.
- Define a population gene pool.
- Explain how the size of the gene pool can affect the evolutionary success of a population.
- Use the Hardy-Weinberg equation to calculate allelic and genotypic frequencies in a population.
- Use the results of a Hardy-Weinberg analysis to determine whether evolution is taking place in a population.

Introduction

Video





This short 3-minute video provides a good introduction to population genetics and its relationship to evolution. Question after watching: At 2:13, the slide shows four elements that the narrator says are the elements that make up the gene pool. She is incorrect on one count. Which one? And why? Integrate some of the concepts you have learned previously with the ones introduced in this video. Describe how something like a genetic bottleneck might create changes in a population's gene pool.

The Evolution of Populations

According to evolutionary theory, every organism from humans to beetles to plants to bacteria shares a common ancestor (Figure 2.4.2.1). Millions of years of evolutionary pressure caused some species to go extinct while others survived. Earth is filled with more diversity now than at any other point in its history. All life is still connected, however. For example, all organisms are composed of cells and use DNA. The theory of evolution gives us a unifying theory to explain what caused the diversity of species that now exist.



Figure 2.4.2.1: Evolution has resulted in living things that may be single-celled or complex, multicellular organisms. They may be plants, animals, fungi, bacteria, or Archaea. This diversity results from evolution.

Genetic Variation in Populations

A **population** is a group of individuals that can all interbreed, often distinguished as a species. These individuals can share genes and pass on combinations of genes to the next generation, containing all of the variation in its gene pool. The process of evolution occurs *only* in populations and not in individuals. A single individual cannot evolve alone; evolution is the process of changing the gene frequencies within a gene pool. Five forces can cause genetic variation and evolution in a population: mutations, genetic recombination, natural selection, genetic drift, and gene flow. Refresh your understanding of these concepts in Unit 2.2.

Allele Frequencies

A gene for a particular characteristic may have several variations called **alleles**. These variations code for different traits associated with that characteristic. The **allele frequency** (or gene frequency) is the rate at which a specific allele exists within a population. Allele frequencies can be expressed as a decimal or as a percent and always add up to 1, or 100 percent, of the total population. The

gene pool is the sum of all the alleles of all genes in a population. When calculating the frequency of an allele in a population, remember that for diploid organisms like humans and animals, there are two alleles of each gene in the population.

For example, in the ABO blood type system in humans, three alleles (I^A, I^B, or i) determine the particular blood-type of red blood cells (Figure **2.4.2.2**). Individuals who are phenotypically blood group "A" have the ability to attach certain sugars to the surface of red blood cells. The genotype that confers that ability are I^AI^A or I^Ai. Individuals who are blood group "B" have a different allele of that gene that codes for a protein that adds a different type of sugar on the surface of blood cells. The alleles is labeled I^B, so homozygous I^BI^B or heterozygous I^Bi have that blood type. Individuals who have one allele of each, I^A and I^B can add both sugars on the surface of their blood cells. Finally, people who lack either of these alleles encode an enzyme that cannot add either sugar types and so are blood type "O" and have homozygous alleles ii.

A diploid organism can only carry two alleles for a particular gene. In human blood type, the combinations are composed of two alleles such as I^AI^A or I^AI^B. Although each organism can only carry two alleles, more than those two alleles may be present in the larger population. In a population of fifty people where all the blood types are represented, there may be more I^A alleles than i alleles.

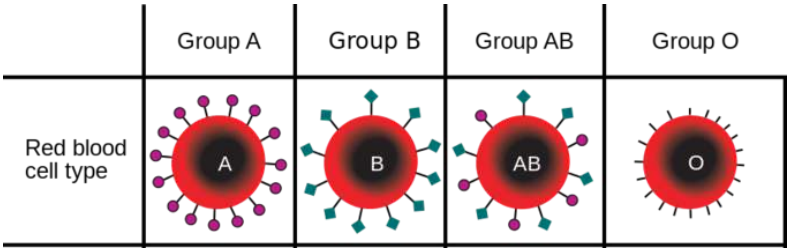
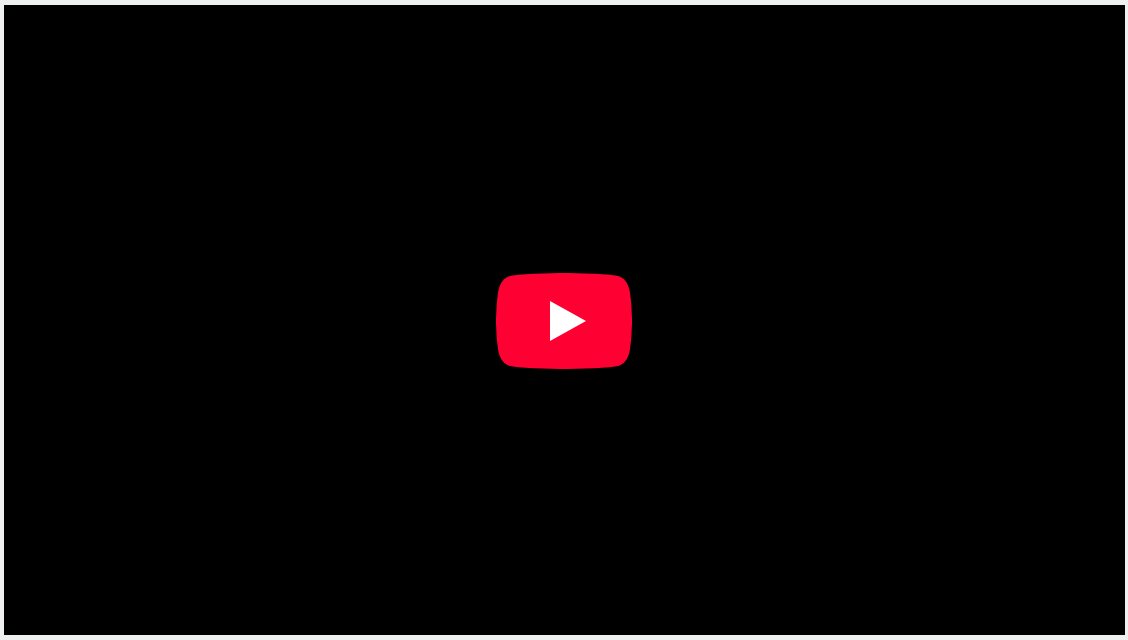


Figure **2.4.2.2**: In humans, each blood type corresponds to a combination of two alleles. Human blood types are A, B, AB, and O.

Using the ABO blood type system as an example, the frequency of one of the alleles, for example I^A, is the number of copies of that allele divided by all the copies of the ABO gene in the population, i.e. all the alleles. In a sample population of humans, the frequency of the I^A allele might be 0.26, which would mean that 26% of the chromosomes in that population carry the I^A allele. If we also know that the frequency of the I^B allele in this population is 0.14, then the frequency of the i allele is 0.6, which we obtain by subtracting all the known allele frequencies from 1 (thus: 1 – 0.26 – 0.14 = 0.6). A change in any of these allele frequencies over time would constitute evolution in the population.

Video





This 4.5-minute video explains how to calculate allelic frequencies in a population. It will also introduce the concept of Hardy-Weinberg equilibrium, which we will explore later in this chapter.
Question after watching: How would you explain the concept of allele frequencies to someone not in your course?

Case of the Hamsters (Part I) - Establishing Alleles

Our case begins with hypothetical species of hamster that carries two alleles for coat color in the population: black which is dominant (**B**) and grey, which is recessive (**b**).

Using a Punnett square, if two black hamsters mate that are heterozygous (e.g., **Bb**) (Table **2.4.2.1**), we find that

- 25% of their offspring are homozygous for the dominant allele (**BB**)
- 50% are heterozygous like their parents (**Bb**)
- 25% are homozygous for the recessive allele (**bb**) and thus, unlike their parents, express the recessive phenotype.

> **Note**
>
> Find a refresher on Punnett squares here: Punnett Squares

This is what Mendel found when he crossed monohybrids. It occurs because meiosis separates the two alleles of each heterozygous parent so that 50% of the gametes will carry one allele and 50% the other and when the gametes are brought together at random, each **B** (or **b**)-carrying egg will have a 1 in 2 probability of being fertilized by a sperm carrying **B** (or **b**).

Table **2.4.2.1**. Results of the random union of the two gametes produced by two individuals, each heterozygous for a given trait. As a result of meiosis, half the gametes produced by each parent will carry allele **B**; the other half allele **b**.

	0.5 **B**	0.5 **b**
0.5 **B**	0.25 **BB**	0.25 **Bb**
0.5 **b**	0.25 **Bb**	0.25 **bb**

However, the frequency of two alleles in an *entire population* of organisms is unlikely to be exactly the same. We will return to this case in a moment.

The Hardy-Weinberg Principle: A Theory of Population Evolution

Theoretical Background

In the early twentieth century, English mathematician Godfrey Hardy and German physician Wilhelm Weinberg stated the principle of equilibrium to describe the population's genetic makeup. The theory, which later became known as the Hardy-Weinberg principle of equilibrium, states that a population's allele and genotype frequencies are inherently stable— unless some kind of evolutionary force is acting upon the population, neither the allele nor the genotypic frequencies would change.

Ultimately, the Hardy-Weinberg principle models a population without evolution under the following conditions:

1. no mutations
2. no immigration/emigration
3. no natural selection
4. only random matings
5. a large population

In theory, if a population is at equilibrium—that is, there are no evolutionary forces such as natural selection, mutation, etc. acting upon it—generation after generation would have the same gene pool and genetic structure, and the allele frequencies would stay the same over time. This is because all of the alleles would have an equal chance of being passed to the next generation and the ratios would remain constant.

Of course, even Hardy and Weinberg recognized that no natural population is immune to evolution. Evolution involves changes in the gene pool. Populations in nature are constantly changing in genetic makeup due to drift, mutation, possibly migration, and selection.

Note: The Hardy-Weinberg Principle

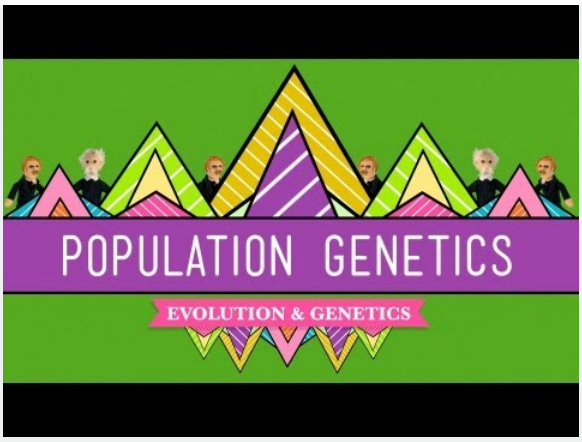
So long as certain conditions are met (discussed below), allele frequencies and genotype ratios in a randomly-breeding population remain constant from generation to generation. This is known as the Hardy-Weinberg Principle.

As a result, the only way to determine the exact distribution of phenotypes in a population is to go out and count them. A population in Hardy-Weinberg equilibrium shows no change. What the law tells us is that populations are able to maintain a reservoir of variability so that if future conditions require it, the gene pool can change. If the frequencies of alleles or genotypes deviate from the value expected from the Hardy-Weinberg equation, then the population is evolving.

When populations are in the Hardy-Weinberg equilibrium, the allelic frequency is stable from generation to generation and the distribution of alleles can be determined. If the allelic frequency measured in the field differs from the predicted value, scientists can make inferences about what evolutionary forces are at play. However, what ultimately interests most biologists is not the frequencies of different alleles, but the frequencies of the resulting genotypes, from which scientists can surmise phenotype distribution.

Video





This 11-minute Crash Course video provides an overview of population genetics in a humorous manner. Questions after watching: In this video, the narrator says there are five ways to alter the gene pool of a population. Explain how this could be. What's another way to say that a population is in Hardy-Weinberg equilibrium?

Applying Hardy-Weinberg

While no population can satisfy those conditions, the principle offers a useful model against which to compare real population changes. The genetic variation of natural populations is constantly changing from genetic drift, gene flow, mutation, migration, and natural selection. **Population genetics** is the study of the distributions and changes of allele frequency in a population. In population genetics, evolution is defined as a change in the frequency of an allele in a population.

The Hardy-Weinberg principle gives scientists a mathematical baseline of a non-evolving population to which they can compare observable populations in the field or laboratory to determine whether they are evolving. If scientists record allele frequencies over time and then calculate the expected frequencies based on Hardy-Weinberg values, then scientists can detect when a population deviates from HW expectations and therefore confirm that the population is evolving. The Hardy-Weinberg principle states that a population's allele and genotype frequencies will remain constant in the absence of evolutionary mechanisms. Note that this conclusion does not inform the researcher as to which mechanism of allelic frequency change is at play, only that allelic frequencies are changing (i.e. that evolution is occurring).

Working under this theory, population geneticists represent different alleles as different variables in their mathematical models (Figure **2.4.2.3**). The variable p, for example, represents the frequency of a particular allele, say A for the trait of tall plants in Mendel's peas, while the variable q represents the frequency of alleles that confer the short plant trait, a. If these are the only two possible alleles for a given locus in the population, then $p + q = 1$. In other words, all the p alleles and all the q alleles comprise all of the alleles for that locus in the population.

If we observe the phenotype, we can know only the homozygous recessive allele's genotype. The Hardy-Weinberg calculations provide an estimate of the remaining genotypes. Since each individual carries two alleles per gene, if we know the allele frequencies (p and q), predicting the genotypes' frequencies is a simple mathematical calculation to determine the probability of obtaining these genotypes if we draw two alleles at random from the gene pool, as we will see below.

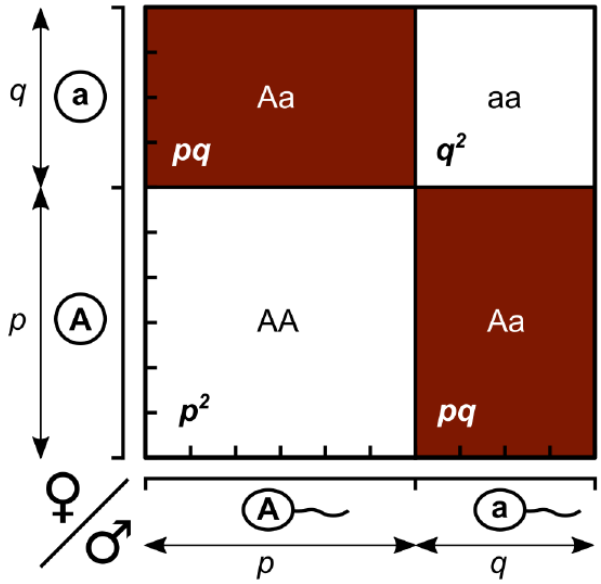


Figure **2.4.2.3**: Hardy-Weinberg and the Punnett Square. (CC0 1.0)

Calculating Gene Pools and Genotype Frequencies

Gene pools

The total number of genes in a population is its gene pool.

- Let p represent the frequency of the dominant allele in the gene pool and q the frequency of the recessive allele in the gene pool.
- Because p and q together equal all of the alleles in the gene pool, $p + q = 1$

Genotype frequencies

- Homozygous dominant individuals have two p alleles. Their genotype frequency can be determined by p x p or p^2.
- Similarly, homozygous recessive individuals have two q alleles. Their genotype frequency can be determined by q x q or q^2
- Heterozygous individuals are $2pq$. Their genotype frequency can be determined by 2 x p x q or $2pq$. [There are two possible types of heterozygous unions: pq and qp. Therefore, we calculate 2 x p x q]
- Because p^2, q^2, and $2pq$ together equal all of the genotypes in a population, $p^2 + 2pq + q^2 = 1$

If any one of the variables above is known, the allele frequency or genotype frequencies can be calculated. We will revisit our case study below to see how these equations are put into practice by scientists to understand whether evolution is occurring in a population.

Video



This 11-minute video describes how to calculate allele and gene pool frequencies with the Hardy-Weinberg equations. Examples and practice equations are given below.

Case of the Hamsters (Part II) - Calculating Allele and Genotype Frequency

The frequency of two alleles in an *entire population* of organisms is unlikely to be exactly the same as we saw in the Punnett square of Part 1. However, from a given genotype (or recessive phenotypes since that genotype is known), we can infer the frequencies of the alleles in a population.

Since each diploid individual carries two alleles per gene, we can predict the frequencies of these genotypes using a probability matrix Table **2.4.2.2**. If two alleles are drawn at random from the gene pool, we can determine the probability of each genotype. We are now calculating percentages based on overall populations (not individual pairings like a Punnett square). In this type of probability matrix, *all* of the alleles that can mix in a population to produce the next generation are represented.

1. Revisiting our hypothetical case of a population of hamsters, for the purposes of example, we will establish that 80% of all the gametes in the population carry a dominant allele for black coat (B) and 20% carry the recessive allele for gray coat (b). So, p = 0.8 and q = 0.2.
2. We can now use those two values to calculate the genotype frequencies where p^2 = 0.64 and q^2 = 0.04
3. The equation above states $p^2 + 2pq + q^2 = 1$. We have calculated p^2 and q^2 but need to now solve for $2pq$.
4. We can determine from our calculations that 0.64 + $2pq$ + 0.04 = 1
5. From there 0.64 + 0.04 + $2pq$ = 1
6. And 0.68 + $2pq$ = 1
7. So, $2pq$ = 1 - 0.68 = 0.32 or 32%

Therefore, in this case, the random union of these allele frequencies will produce a generation:

- 64% homozygous for BB
- 32% Bb heterozygotes
- 4% homozygous (bb) for gray coat

So 96% of the next generation will have black coats; only 4% gray coats. If you notice, this is the same phenotype ratio as the initial population. No change has occurred, which is explained in more detail below.

Table **2.4.2.2**. Results of random union of the gametes produced by an entire population with a gene pool containing 80% **B** and 20% **b**.

	0.8 **B**	0.2 **b**
0.8 **B**	0.64 **BB**	0.16 **Bb**
0.2 **b**	0.16 **Bb**	0.04 **bb**

Hardy-Weinberg and Selection Pressures

Natural selection affects allele and genotype frequency. If an allele confers a phenotype that enables an individual to better survive or have more offspring, the frequency of that allele will increase because the individual carrying these alleles will be effective at transferring them into the next generation. Because many of those offspring will also carry the beneficial allele and, therefore, the phenotype, they will have more offspring of their own that also carry the allele. Over time, the allele will spread throughout the population and may become fixed: every individual in the population carries the allele. If an allele is dominant but detrimental, it may be swiftly eliminated from the gene pool when the individual with the allele does not reproduce. However, a detrimental recessive allele can linger for generations in a population, hidden by the dominant allele in heterozygotes. In such cases, the only individuals to be eliminated from the population are those unlucky enough to inherit two copies of such an allele.

So, will deleterious alleles eventually disappear? No. Let's see why using our case study.

Imagine that the grey coat color carries with it some sore of negative selection pressure. If we calculate the allele frequencies, using our genotype frequencies from Table **2.4.2.2** above, we can recalculate how much of the population carries the dominant allele and what percentage carries the recessive allele.

- All the gametes formed by BB hamsters will contain allele B (0.64) as will one-half the gametes formed by heterozygous (Bb) hamsters (0.32/2).
  - So, 80% (0.64 + (0.32*1/2)) of the pool of gametes formed by this generation will contain B.
- All the gametes of the gray (bb) hamsters (4%) will contain b (0.04) but one-half of the gametes of the heterozygous hamsters will as well (0.32/2).
  - So 20% (0.04 + (0.32*1/2)) of the gametes will contain b.

What we find from this analysis is that in the parental generation, 80% of the alleles were B and 20% of the alleles were b. The organisms of that population mated and produced generation 2. This was a random sampling event of the alleles in the parental gene pool. In the generation 2 alleles, we find that 80% of the alleles are B and 20% are b. This is identical to the parental allelic frequency.

The proportion of allele b in the population has remained the same from the parent generation. The heterozygous hamsters ensure that each generation will contain 4% gray hamsters. Recessive genes do not tend to be lost from a population no matter how small their representation. If recessive alleles were continually tending to disappear, the population would soon become homozygous. Under Hardy-Weinberg conditions, genes that have no present selective value will nonetheless be retained.

If an allele confers a phenotype that enables an individual to better survive or have more offspring, the frequency of that allele will increase because the individual carrying these alleles will be effective at transferring them into the next generation. Because many of those offspring will also carry the beneficial allele and, therefore, the phenotype, they will have more offspring of their own that also carry the allele. Over time, the allele will spread throughout the population and may become fixed: every individual in the population carries the allele. If an allele is dominant but detrimental, it may be swiftly eliminated from the gene pool when the individual with the allele does not reproduce. However, a detrimental recessive allele can linger for generations in a population, hidden by the dominant allele in heterozygotes. In such cases, the only individuals to be eliminated from the population are those unlucky enough to inherit two copies of such an allele.

? Optional Activity 2.4.2.1

In the Punnett square in Figure **2.4.2.4**, an individual pea plant could be pp (YY), and thus produce yellow peas; pq (Yy), also yellow; or qq (yy), and thus produce green peas. If 9% of the overall plants in a population produce green peas, what percentage of pea plants are heterozygous for pea color?

Answer (Click here)

According to the Hardy-Weinberg principle, the variable *p* represents the frequency of a particular allele, usually a dominant one. For example, assume that *p* represents the frequency of the dominant allele, Y, for yellow pea pods. The variable *q* represents the frequency of the recessive allele, y, for green pea pods. If p and q are the only two possible alleles for this characteristic, then the sum of the frequencies must add up to 1, or 100 percent. We can also write this as p + q = 1. If the frequency of the Y allele in the population is 0.6, then we know that the frequency of the y allele is 0.4.

In the example, our three genotype possibilities are: pp (YY), producing yellow peas; pq (Yy), also yellow; or qq (yy), producing green peas. The frequency of homozygous dominant individuals is p^2; the frequency of heterozygous individuals is 2pq; and the frequency of homozygous recessive individuals is q^2. If p and q are the only two possible alleles for a given trait in the population, these genotype frequencies will sum to one: $p^2 + 2pq + q^2 = 1$.

In our example, the possible genotypes are homozygous dominant (YY), heterozygous (Yy), and homozygous recessive (yy). If we can only observe the phenotypes in the population, then we know only the recessive phenotype (yy). For example, in a garden of 100 pea plants, 86 might have yellow peas and 16 have green peas. We do not know how many are homozygous dominant (Yy) or heterozygous (Yy), but we do know that 16 of them are homozygous recessive (yy).

Therefore, by knowing the recessive phenotype and, thereby, the frequency of that genotype (16 out of 100 individuals or 0.16), we can calculate the number of other genotypes.

1. If q^2 represents the frequency of homozygous recessive plants, then $q^2 = 0.16$.

2. Therefore, q = 0.4 (the square root of 0.16 is 0.4...we cannot have a negative number when working with allele frequencies).
3. Because p + q = 1 and q = 0.4, then 1 – 0.4 = p.
4. p = 0.6.
5. The frequency of homozygous dominant plants (p^2) is $(0.6)^2 = 0.36$. So, out of 100 individuals, there are 36 homozygous dominant (YY) plants.
6. The frequency of heterozygous plants (2pq) is 2(0.6)(0.4) = 0.48. Therefore, 48 out of 100 plants are heterozygous yellow (Yy).

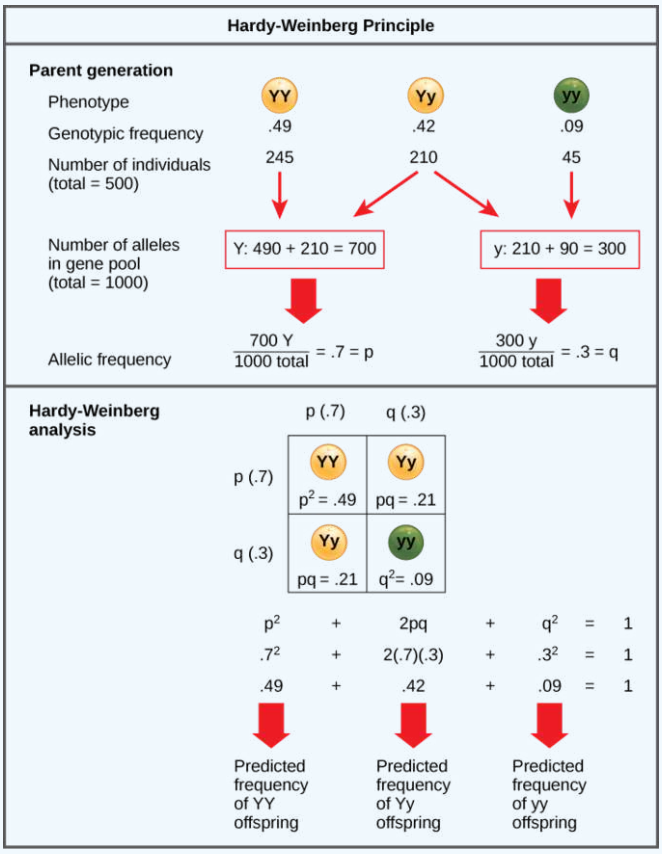


Figure **2.4.2.4**: Predicted frequencies of alleles and genotypes of a population with 9% green peas.

? Optional Activity 2.4.2.2

In plants, violet flower color (V) is dominant over white (v). If q = 0.2 in a population of 500 plants, how many individuals would you expect to be homozygous dominant (VV), heterozygous (Vv), and homozygous recessive (vv)? How many plants would you expect to have violet flowers, and how many would have white flowers?

Answer

Remember that p indicates the frequency of the dominant allele (V) and q indicates the frequency of the recessive allele (v). It is easier to begin with the recessive allele.

In this population, if q = 0.2, then $q^2 = 0.04$. We know that q^2 is the frequency of homozygous recessive individuals, so 0.04 x 500 total plants (the overall population) = 20. Therefore, 20 plants would be expected to be homozygous recessive (white).

For the dominant allele, p, we need to use the formula p + q = 1. Since q = 0.2, we can calculate p + 0.2 = 1. From there, we get p = 1 - 0.2 so p = 0.8.

If p = 0.8, then p2 = 0.64. We know that p2 is the frequency of homozygous dominant individuals, so 0.64 x 500 total plants (the overall population) = 320. Therefore, 320 plants are expected to be homozygous dominant (violet).

To complete the problem, we calculate 2pq, or the frequency of heterozygous individuals. So, 2 x 0.8 x 0.2 = 0.32. We will then take and calculate 0.32 x 500 to get 160. Therefore, 160 plants are expected to be heterozygous (violet).

Optional Resource

Find an additional Hardy-Weinberg problem to solve, with a solution and walk-through, here.

When the Hardy-Weinberg Law Fails

To see what forces lead to evolutionary change, we must examine the circumstances in which the Hardy-Weinberg law may fail to apply. In any of these cases (which is the reality of the natural world), evolution is occurring. There are five:

1. Mutation

The frequency of gene B and its allele b will not remain in Hardy-Weinberg equilibrium if the rate of mutation of B -> b (or vice versa) changes, or if a new allele B^o comes to be. By itself, this type of mutation probably plays only a minor role in evolution; the rates are simply too low. However, gene (and whole genome) duplication - a form of mutation - probably has played a major role in evolution. In any case, evolution depends on mutations because this is the only way that new alleles are created. After being shuffled in various combinations with the rest of the gene pool, these provide the raw material on which natural selection can act.

2. Gene Flow

Many species are made up of local populations whose members tend to breed within the group. Each local population can develop a gene pool distinct from that of other local populations. However, members of one population may breed with occasional immigrants from an adjacent population of the same species. This can introduce new genes or alter existing gene frequencies in the residents. Whether within a species or between species, gene flow increases the variability of the gene pool.

3. Genetic Drift

Genetic drift is the evolution that happens when there is no selective advantage for the alleles that grow in frequency. That growth is due to chance events. For example, if a rock falls on a population of beetles that have green and red alleles and kills more of those individuals with the red allele, the gene frequency for this gene will change, but it was not adaptive. It just happened due to chance events. The smaller a population, the more susceptible it is to mechanisms such as genetic drift. Random events that alter allele frequencies will have a much larger effect when the gene pool is small.

If the population is small, Hardy-Weinberg may be violated. Chance, including abiotic impacts, alone may eliminate certain members out of proportion to their numbers in the population. In such cases, the frequency of an allele may begin to drift toward higher or lower values. Ultimately, the allele may represent 100% of the gene pool or, just as likely, disappear from it. Drift produces evolutionary change, but there is no guarantee that the new population will be more fit than the original one. Evolution by drift is aimless, not adaptive.

4. Nonrandom Mating

One of the cornerstones of the Hardy-Weinberg equilibrium is that mating in the population must be random. If individuals (usually females) are choosy in their selection of mates, the gene frequencies may become altered.

Nonrandom mating seems to be quite common. Breeding territories, courtship displays, "pecking orders" can all lead to it. In each case, certain individuals do not get to make their proportionate contribution to the next generation. If some males reproduce more than others, then more of their genes are represented in the next generation.

5. Natural Selection

If individuals having certain genes are better able to produce mature offspring than those without them, the frequency of those genes will increase in the next generation. This is simply expressing Darwin's natural selection in terms of alterations in the gene pool. Natural selection results from *differential mortality* (some individuals survive longer than others) and/or *differential fecundity (some individuals have more offspring than others)*. Ultimately, this causes the sampling of one generation's gene pool to be

skewed; the next generation's gene pool is different from the first. Not every allele has an equal chance of being passed on to the next generation.

Video





This 4-minute video explains what the Hardy-Weinberg equilibrium is and why finding a population that does not conform to HW expectations tells you that the population is in the process of evolving with regard to one trait.
Question after watching: The HW principle is defined using mathematical terms. Based on what you now know about the HW principle, what is being quantified and monitored in the HW principle to assess whether a population is evolving?

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2.G: Unit 2 Glossary

Unit 2.2

adaptation
a heritable trait that aids the survival and reproduction of an organism in its present environment

adaptive evolution
see: natural selection

anagenesis
a gradual change in an entire population's gene frequency

analogous structures
similar traits between two different species that evolved separately (see: convergent evolution)

artificial selection/human-initiated change
any selective breeding intentionally practiced by humans leading to the evolution of domesticated organisms

assortive mating
an individual’s preference to mate with partners who are phenotypically similar to themselves

biogeography
study of the geographic distribution of living things and the abiotic factors that affect their distribution

biostratigraphy
aligning isolated rocks to fossils of organisms that lived for a short period of time

bottleneck effect
a type of genetic drift where a population's size is drastically diminished, reducing variation in the gene pool

cladeogenesis
a population splitting into two distinct evolutionary branches

cline
gradual changes in a trait across an organism's geographic distribution

convergent evolution
where similar traits evolve independently in species that do not share a common ancestry

cosmopolitan species
species that live in a wide variety of geographic areas

directional selection
when, in natural selection, a single phenotype is favored, causing the population to shift towards one end of the trait variation

divergent evolution
species that evolve in diverse directions from a common point (often leading to speciation)

diversifying selection
when, in natural selection, the average is selected against, leading to selection for the rarer variations of a trait

endemic species

species naturally found only in a specific geographic area that is usually restricted in size

evolution
a change in the gene pool of a species over time

evolutionary fitness
the genetic contribution of an individual to future generations

fossil
preserved remains or traces of animals, plants, and other organisms from the past

fossil record
totality of fossils, both discovered and undiscovered, and their placement in rock layers

founder effect
a type of genetic drift where some portion of the population leaves to start a new population in a new location or if a population gets divided by a physical barrier of some kind

gene flow
the flow of alleles in and out of a population due to the migration of individuals or gametes

genetic diversity
variation within a population arising from two main mechanisms: mutation and sexual reproduction

genetic drift
the effect of chance on a population's genetic variation

genetic variation
measure of the genetic differences (diversity of alleles and genotypes) that exist within a population

genetics
study of the mechanisms of inheritance

genotype
genetic makeup of an individual

good genes hypothesis
the selection for harmful traits in sexual selection signals other abilities such as predator avoidance or superior feeding abilities

handicap principle
a type of sexual selection for that selects for harmful traits to maximize reproductive success

homologous structures
traits in two different species derived from a common ancestor

homology
relationship between structures or DNA derived from the most recent common ancestor

hypothesis
a tentative explanation for something that is proposed to either be supported or disproved

intersexual selection
when the more-limited sex chooses their mates from the less-limited sex

intrasexual selection
when those of the less-limited sex compete amongst each other for opportunities to mate with the more-limited sex

macroevolution
processes that gave rise to new species and higher taxonomic groups with widely divergent characters

microevolution
gradual change of a population over time

modern synthesis
the current, coherent understanding of the relationship between natural selection and genetics

molecular clock
the assumed constant rate of DNA mutations over time

mutation
a change in a DNA sequence

natural selection
the more prolific reproduction of individuals with favorable traits that survive environmental change because of those traits

negative frequency-dependent selection
in natural selection, increases the population's genetic variance by selecting for rare phenotypes

perimineralization
a process of fossilization that occurs when an organism is buried

phenotype
physical, metabolic, or behavioral expression of a genotype

polymorphic
populations with two or more variations of a particular phenotype

population variation
distribution of phenotypes among individuals within a population

positive frequency-dependent selection
in natural selection, decreases the population's genetic variance by selecting for common phenotypes

radiocarbon dating
method for identifying the age of rocks or fossils less than 60,000 years old, usually based on a comparison between the observed abundance of carbon-14 and its decay products

relative fitness
the proportional genetic contribution of an individual to future generations as compared to others in the population

sexual dimophism
the variation between sexes in a given species due to sexual selection pressures

sexual selection
the selection pressure on males and females to maximize mating success

stabilizing selection

when, in natural selection, the average of a trait is selected for and becomes more common over time, with less variation in the population

stratigraphy
science of understanding the strata, or layers, that form the sedimentary record

theory
a concept that has been extensively tested and supported over time

trace fossil
marks left behind by an organism while it was alive, such as footprints or feces

vestigial structures
structures with no apparent function which appear to be residual parts from a past ancestor

Unit 2.3

adaptive radiation
multiple speciation events originating from a single species

allopatric speciation
geographic separation of populations from a parent species and subsequent evolution into new species

aneuploidy
gametes with too few or two many chromosomes after meiosis

behavioral isolation
prezygotic barrier based on presence or absence of appropriate reproductive behaviors

gametic barrier
prezygotic barrier where gametes are unable to fuse

gene pool
a collection of all the variants of genes in the species

gradual speciation
a model of speciation where species diverge gradually over time in small steps

habitat isolation
prezygotic barrier based on geographic difference in population locations

hybrid inviability
postzygotic barrier where hybrid offspring of two populations do not form normally and/or do not survive past the embryonic stage

hybrid sterility
postzygotic barrier where hybrid offspring are born sterile and unable to reproduce

hybrid zone
an area where two closely-related species continue to interact and reproduce

mechanical barrier
prezygotic barrier where populations are not physically able to mate with one another due to anatomical differences

polyploidy
gametes with extra set, or sets, of chromosomes

postzygotic barrier
type of reproductive isolation that occurs after zygote formation

prezygotic barrier
type of reproductive isolation that blocks reproduction from taking place

punctuated equilibrium
a model of speciation where new species evolve quickly from parent species and then remain largely unchanged for long periods of time

reinforcement
a process of natural selection working to favor individuals that avoid interspecific matings

reproductive isolation
the inability of two populations to interbreed with one another

speciation
a process where a single species branches to form two or more new species

species (biological)
a group of individuals that, in nature, are able to mate and produce viable, fertile offspring

subspecies
geographically separate populations of organisms in the process of allopatric speciation but still able to interbreed

sympatric speciation
speciation due to mutation occurring within a parent species remaining in one location

temporal islation
prezygotic barrier based on differences in timing of mating

zygote
a fertilized egg

Unit 2.4

allele
variations of a gene for a given trait

allele frequency
the rate at which a specific allele exists within a population

genome
the total genetic information of a cell or organism

Hardy-Weinberg Principle
the concept that allele frequencies and genotype ratios in a randomly-breeding population remain constant from generation to generation, given certain criteria

population
a group of individuals that can all interbreed, often distinguished as a species.

population genetics

study of the distributions and changes of allele frequency in a population

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2.S: Unit 2 Summary

In Unit 2, we learned about macroevolution, speciation, and microevolution.

Unit 2.2

Evolution is the biological theory that populations change over time. In addition to natural selection, evolution may take place as a result of random mutation, genetic drift, gene flow, and/or non-random mating events. The theory of evolution is a cornerstone in understanding nearly all biological processes and the adaptations of organisms to their environmental conditions.

Fossils, along with the comparative anatomy of present-day organisms, constitute the morphological, or anatomical, record. Fossils provide solid evidence that organisms from the past are not the same as those found today; fossils show a progression of evolution. By comparing the anatomies of both modern and extinct species, paleontologists can infer the lineages of those species.

Because natural selection acts to increase the frequency of beneficial alleles and traits while decreasing the frequency of deleterious qualities, it is adaptive evolution. Natural selection acts at the individual level, selecting for those that have a higher overall fitness compared to the rest of the population. If the fit phenotypes are those that are similar, natural selection will result in stabilizing selection, and an overall decrease in the population's variation. Directional selection works to shift a population's variance toward a new, fit phenotype, as environmental conditions change. In contrast, diversifying selection results in increased genetic variance by selecting for two or more distinct phenotypes. Other types of selection include frequency-dependent selection, in which individuals with either common (positive frequency-dependent selection) or rare (negative frequency-dependent selection) are selected. Finally, sexual selection results from one sex having more variability in reproductive success than the other.

Evolution is a challenging concept and there are, therefore, some misconceptions among those that have not studied it. The theory of evolution is often challenged by incorrectly conflating the scientific meaning of a theory with the vernacular meaning. Evolution is sometimes mistakenly interpreted to mean that individuals evolve, when in fact only populations can evolve as their gene frequencies change over time. It is often spoken in goal-directed terms by which organisms change through intention, and selection operates on mutations present in a population that have not arisen in response to a particular environmental stress. Evolution is often characterized as being controversial among scientists; however, it is accepted by the vast majority of working scientists.

Unit 2.3

Speciation occurs along two main pathways: geographic separation (allopatric speciation) and through mechanisms that occur within a shared habitat (sympatric speciation). Both pathways isolate a population reproductively in some form. Mechanisms of reproductive isolation act as barriers between closely related species, enabling them to diverge and exist as genetically independent species. Prezygotic barriers block reproduction prior to formation of a zygote; whereas, postzygotic barriers block reproduction after fertilization occurs. For a new species to develop, something must introduce a reproductive barrier. Sympatric speciation can occur through errors in meiosis that form gametes with extra chromosomes (polyploidy). Autopolyploidy occurs within a single species; whereas, allopolyploidy occurs between closely related species.

Speciation is not a precise division: overlap between closely related species can occur in areas called hybrid zones. Organisms reproduce with other similar organisms. The fitness of these hybrid offspring can affect the two species' evolutionary path. Scientists propose two models for the rate of speciation: one model illustrates how a species can change slowly over time. The other model demonstrates how change can occur quickly from a parent generation to a new species. Both models continue to follow natural selection patterns.

Unit 2.4

The modern synthesis of evolutionary theory grew out of the cohesion of Darwin's, Wallace's, and Mendel's thoughts on evolution and heredity, along with the more modern study of population genetics. It describes the evolution of populations and species, from small-scale changes among individuals to large-scale changes over paleontological time periods. To understand how organisms evolve, scientists can track populations' allele frequencies over time. If they differ from generation to generation, scientists can conclude that the population is not in Hardy-Weinberg equilibrium, and is thus evolving.

Both genetic and environmental factors can cause phenotypic variation in a population. Different alleles can confer different phenotypes, and different environments can also cause individuals to look or act differently. Only those differences encoded in an individual's genes, however, can pass to its offspring and, thus, be a target of natural selection. Natural selection works by selecting for alleles that confer beneficial traits or behaviors, while selecting against those for deleterious qualities. Genetic drift stems from the chance occurrence that some individuals in the gene line have more offspring than others. When individuals leave or join the population, allele frequencies can change as a result of gene flow. Mutations to an individual's DNA may introduce new variation into a population. Allele frequencies can also alter when individuals do not randomly mate with others in the group.

In Unit 3, we will be expanding on the ideas above and considering the diversity of life, how science classifies and differentiates organisms, as well as the history of life on Earth.

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CHAPTER OVERVIEW

Unit 3: Systematics, Phylogeny, and Biological Diversity

In Unit 3, the diversity of life is explored through systematics and classification with a detailed study of select organisms and discussion of emerging phylogenetic relationships. This unit moves from viruses to the prokaryotes, discusses the organisms formerly grouped as protists, identifies the major characteristics of fungi, and devotes two chapters each to plant and animal life.

- 3.1: Unit 3 Introduction
- 3.2: Systematics, Phylogeny, and Cladistics
  - 3.2.1: Systematics and Classification
  - 3.2.2: Phylogeny and Cladistics
- 3.3: History of Life on Earth
  - 3.3.1: Deep Time
  - 3.3.2: Origins of Life
  - 3.3.3: Evidence for Early Life
  - 3.3.4: Eukaryotic Origins
- 3.4: Biological Diversity
  - 3.4.1: Acellular Entities - Viruses, Prions, and Viroids
  - 3.4.2: Kingdoms Bacteria and Archaea
  - 3.4.3: Protists
  - 3.4.4: Kingdom Fungi
  - 3.4.5: Kingdom Animalia - Evolution and Phylogeny
  - 3.4.6: Kingdom Animalia - Adaptations
  - 3.4.7: Kingdom Plantae - Evolution and Phylogeny
  - 3.4.8: Kingdom Plantae - Adaptations
- 3.G: Unit 3 Glossary
- 3.S: Unit 3 Summary

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3.1: Unit 3 Introduction

Unit 3 Introduction

This unit introduces learners to systematics and classification as well as the history and diversity of life on Earth. The core concepts of phylogeny, the history of life, and the defining features of the domains and kingdoms of organisms are discussed through examples. The diversity and importance of life are reinforced through media and special call-out features on sweetgrass and salmon to make connections between Western Science and Indigenous ways of knowing.

Unit 3 Course Learning Outcomes

By the end of this Unit, you will be able to:

- Explain our changing view of the evolutionary history of biological diversity;
- Classify living organisms;
- Understand and articulate the principles and processes of scientific inquiry; and
- Think critically about the principles of biology studied and communicate your thinking clearly and concisely in speaking and in writing.

Unit 3 Table of Contents

3.1 Introduction

3.2 Systematics, Cladistics, and Phylogeny

- 3.2.1 Systematics and Classification
- 3.2.2 Phylogeny and Cladistics

3.3 History of Life on Earth

- 3.3.1 Deep Time
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3.4 Biological Diversity

- 3.4.1 Viruses, Prions, and Viroids
- 3.4.2 Prokaryotes: Eubacteria and Archaebacteria
- 3.4.3 Protists
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- 3.4.6 Kingdom Animalia - Evolution and Phylogeny
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3.G Glossary

3.S Summary

Unit 3 Assessments

If you are a TRU student using this resource, all of your assessed learning activities and assignments are in your course Moodle site.

Please click on the blue arrow on the right to start Unit 3: Chapter 3.2. If you are on a mobile device, use the navigation links at the bottom of this page.

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- **Unit I: The Chemistry of Life** by OpenStax is licensed CC BY 4.0.

SECTION OVERVIEW

3.2: Systematics, Phylogeny, and Cladistics

Learning Objectives

- State the theoretical basis for modern classification systems
- Recognize and write scientific names using the binomial classification system
- Explain the purpose of cladistics
- Design a cladogram
- Recognize and interpret a phylogenetic tree
- Explain a phylogenetic tree's components and purpose

3.2.1: Systematics and Classification

3.2.2: Phylogeny and Cladistics

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Unit 3.2.1 - Systematics and Classification

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 45 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.2.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- State the theoretical basis for modern classification systems
- Recognize and write scientific names using the binomial classification system

The Levels of Classification

Taxonomy (which means “arrangement law” in Latin) is the science of classifying organisms to construct internationally-shared classification systems with each organism placed into increasingly more inclusive groupings. Taxonomic classification divides species into a hierarchical system beginning with a **domain** (Bacteria, Archaea, and Eukarya) and ending with a single species. Within each domain is a second level called a **kingdom** (Archaea, Bacteria, Protista, Fungi, Plantae, and Animalia). Each domain contains several kingdoms. Within kingdoms, the subsequent categories of increasing specificity are phylum, class, order, family, genus, and species.

Think about how a grocery store is organized. One large space is divided into departments, such as produce, dairy, and meats. Then each department is further divided into aisles, then each aisle into categories and brands, and then, finally, a single product. This organization from larger to smaller, more-specific categories is called a hierarchical system.

As an example, the classification levels for the domestic dog are shown in Figure 3.2.1.1. The group at each level is called a **taxon** (plural: taxa). In other words, for the dog, Carnivora is the taxon at the order level, Canidae is the taxon at the family level, and so forth. Organisms also have a common name that people typically use, such as domestic dog, or wolf.

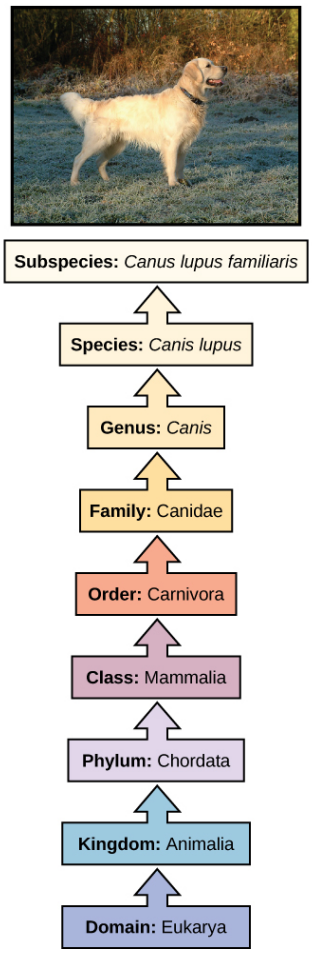


Figure **3.2.1.1**: The taxonomic classification system uses a hierarchical model to organize living organisms into increasingly specific categories. The common dog, *Canis lupus familiaris*, is a subspecies of *Canis lupus*, which also includes the wolf and dingo.

Scientists refer to an organism by its genus and species names together, commonly called a **scientific name**, or Latin name. This two-name system is called **binomial nomenclature**. The full name of an organism technically has eight terms. Dogs, for example, are technically: Eukarya, Animalia, Chordata, Mammalia, Carnivora, Canidae, *Canis*, and *lupus*. Notice that each name is capitalized except for species and that genus and species names are italicized. Dogs share a domain (Eukarya) with the widest diversity of organisms, including plants and butterflies.

A recent study of the DNA of domestic dogs and wolves suggests that the domestic dog is a subspecies of the wolf, not its own species, thus it is given an extra name to indicate its subspecies status, *Canis lupus familiaris*. The scientific name of the wolf is therefore *Canis lupus*. Subspecies are members of the same species that are capable of mating and producing viable offspring, but they are considered separate subspecies due to geographic isolation, behavioral isolation, or other factors.

Video



This 7-minute video explores how life is organized using binomial nomenclature and some examples.
Question after watching: Can you come up with a mnemonic device to remember the categories of classification?

Figure **3.2.1.2** also shows how taxonomic levels move toward specificity. Notice how within the domain we find the dog grouped with the widest diversity of organisms. These include plants and other organisms not pictured, such as fungi and protists. The organisms become more similar at each sublevel because they are more closely related. Before Darwin's theory of evolution was developed, naturalists sometimes classified organisms using arbitrary similarities, but since the theory of evolution was proposed in the 19th-century, biologists work to make the classification system reflect evolutionary relationships. This means all members of a taxon should have a common ancestor and be more closely related to each other than to members of other taxa. Historically, scientists classified organisms using physical characteristics, but as DNA technology developed, more precise relationships have been determined.

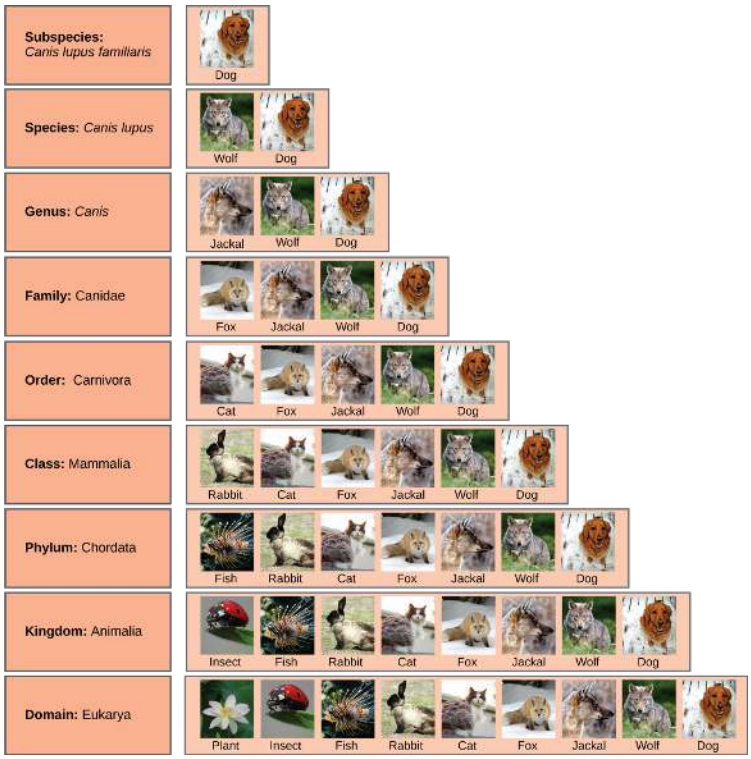


Figure **3.2.1.2**: At each sublevel in the taxonomic classification system, organisms become more similar. Dogs and wolves are the same species because they can breed and produce viable offspring, but they are different enough to be classified as different subspecies. (credit “plant”: modification of work by "berduchwal"/Flickr; credit “insect”: modification of work by Jon Sullivan; credit “fish”: modification of work by Christian Mehlführer; credit “rabbit”: modification of work by Aidan Wojtas; credit “cat”: modification of work by Jonathan Lidbeck; credit “fox”: modification of work by Kevin Bacher, NPS; credit “jackal”: modification of work by Thomas A. Hermann, NBII, USGS; credit “wolf” modification of work by Robert Dewar; credit “dog”: modification of work by "digital_image_fan"/Flickr)

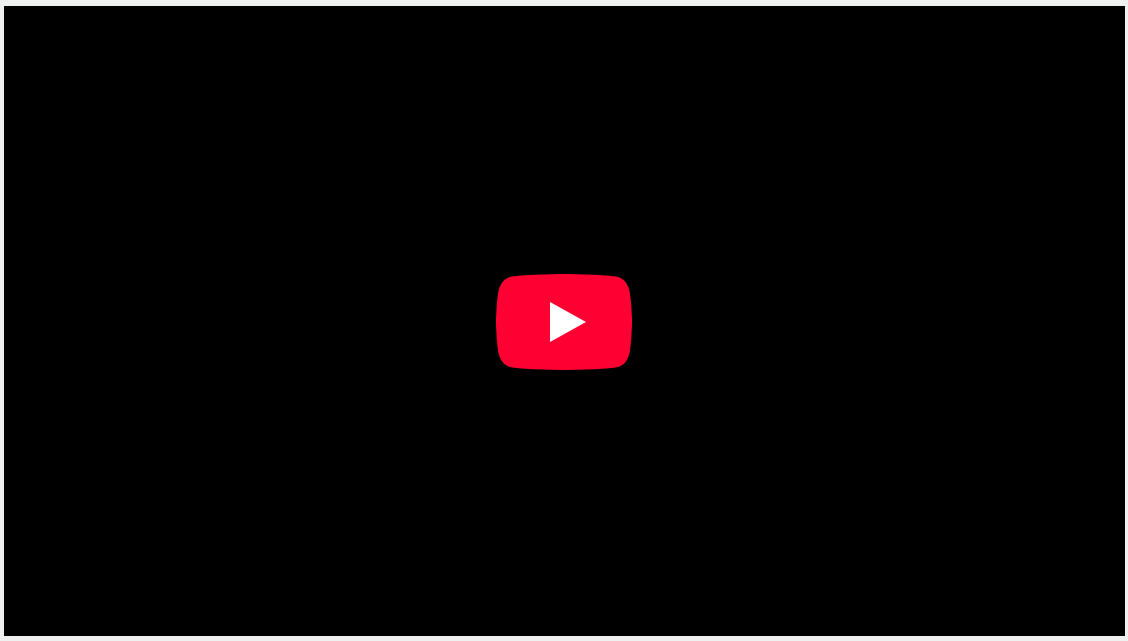
? Optional Activity

Question: Refer to Figure **3.2.1.2**. At what levels are cats and dogs considered to be part of the same group?

Answer

Cats and dogs are part of the same group at five levels: both are in the domain Eukarya, the kingdom Animalia, the phylum Chordata, the class Mammalia, and the order Carnivora.

Video





In this 12-minute video, the science of taxonomy is explained, including an overview of the major kingdoms of life. Question after watching: Using your favorite organism, find its scientific name and try placing it into its appropriate classifications.

Optional Activity

List the different levels of the taxonomic classification system.

Answer

From most inclusive to least inclusive: domain, kingdom, phylum, class, order, family, genus, species.

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- **20.1C: The Levels of Classification** by Boundless is licensed CC BY-SA 4.0.

Unit 3.2.2 - Phylogeny and Cladistics

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 3 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Explain the purpose of cladistics
- Design a cladogram
- Recognize and interpret a phylogenetic tree
- Explain a phylogenetic tree's components and purpose

Introduction to Phylogeny

All life on Earth evolved from a common ancestor. Biologists map how organisms are related by constructing **phylogenetic trees**. Phylogenetic trees are diagrams used to reflect evolutionary relationships among organisms or groups of organisms. In other words, a “tree of life” can be constructed to illustrate when different organisms evolved and to show the relationships among different organisms, as shown in Figure **3.2.2.1**. Notice that from a single point, the three domains of Archaea, Bacteria, and Eukarya diverge and then branch repeatedly. The small branch that plants and animals (including humans) occupy in this diagram shows how recently these groups had their origin compared with other groups. A **phylogeny** is the evolutionary history and the relationships among a species or group of species. The study of organisms with the purpose of deriving their relationships is called **systematics**.

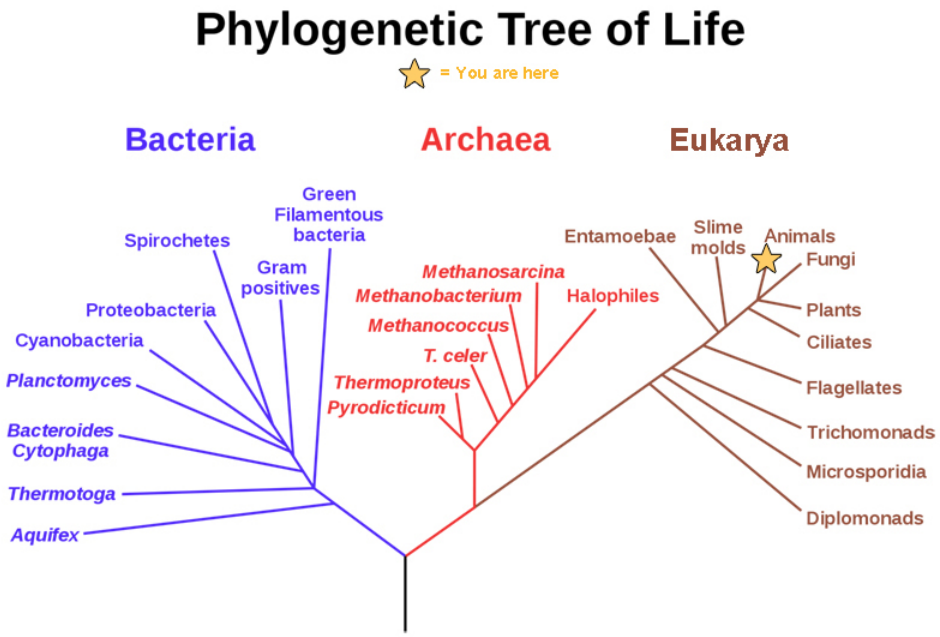


Figure **3.2.2.1**: In the evolution of life on Earth, the three domains of life—Archaea, Bacteria, and Eukarya—branch from a single point. (credit: modification of work by Eric Gaba)

Understanding Phylogeny

Two Measures of Similarity

Organisms that share similar physical features *and* genetic sequences tend to be more closely related than those that do not. Features that overlap both morphologically and genetically are referred to as homologous structures; the similarities stem from common evolutionary paths. For example, as shown in Figure **3.2.2.2**, the bones in the wings of bats and birds, the arms of humans, and the foreleg of a horse are homologous structures. Notice the structure is not simply a single bone, but rather a grouping of several bones arranged in a similar way in each organism even though the elements of the structure may have changed shape and size.

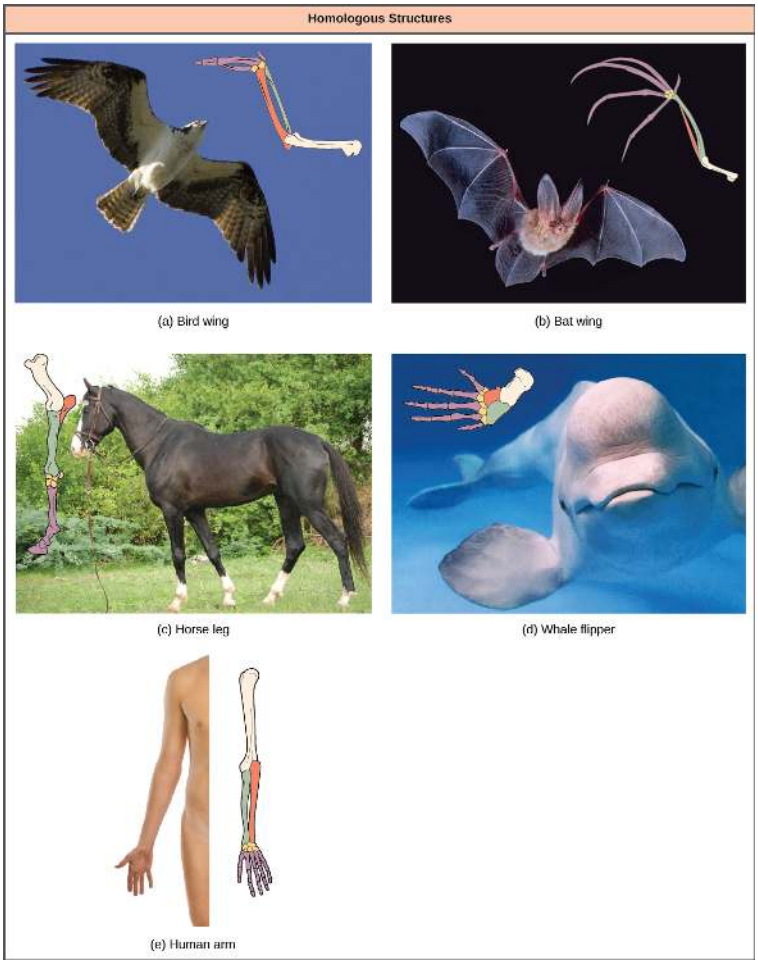


Figure **3.2.2.2**: Bat and bird wings, the foreleg of a horse, the flipper of a whale, and the arm of a human are homologous structures, with similar bones indicated by the same color. This indicates that bats, birds, horses, whales, and humans share a common evolutionary past. (credit a photo: modification of work by Steve Hillebrand, USFWS; credit b photo: modification of work by U.S. BLM; credit c photo: modification of work by Virendra Kankariya; credit d photo: modification of work by Russian Gov./Wikimedia Commons)

Misleading Appearances

Some organisms may be very closely related, even though a minor genetic change caused a major morphological difference to make them look quite different. For example, chimpanzees and humans, the skulls of which are shown in Figure **3.2.2.3** are very similar genetically, sharing 99 percent[1] of their genes. However, chimpanzees and humans show considerable anatomical differences, including the degree to which the jaw protrudes in the adult and the relative lengths of our arms and legs.



Figure **3.2.2.3**: (a) The chimpanzee jaw protrudes to a much greater degree than (b) the human jaw. (credit a: modification of work by "Pastorius"/Wikimedia Commons)

However, unrelated organisms may be distantly related yet appear very much alike, usually because common adaptations to similar environmental conditions evolved in both independently. An example is the streamlined body shapes, the shapes of fins and appendages, and the shape of the tails in fishes (which are from the fish taxon) and whales (which are from the mammal taxon). These structures bear superficial similarity because they are adaptations to moving and maneuvering in the same environment—water. When a characteristic that is similar occurs by adaptive convergence (convergent evolution), and not because of a close evolutionary relationship, it is called an analogous structure.

In another example, insects use wings to fly like bats and birds. We call them all wings because they perform the same function and have a superficially similar form, but the embryonic origin of the three wings is different. The difference in the development, or embryogenesis, of the wings in each case is a signal that insects versus bats or birds do not share a common ancestor that had a wing. The wing structures, shown in Figure **3.2.2.4** evolved independently in the two lineages (insects versus vertebrates).

Similar traits can be either homologous or analogous. Homologous traits share an evolutionary path that led to the development of that trait. Analogous traits may look similar but they do not share a common evolutionary origin. Scientists must determine which type of similarity a feature exhibits to decipher the phylogeny of the organisms being studied.

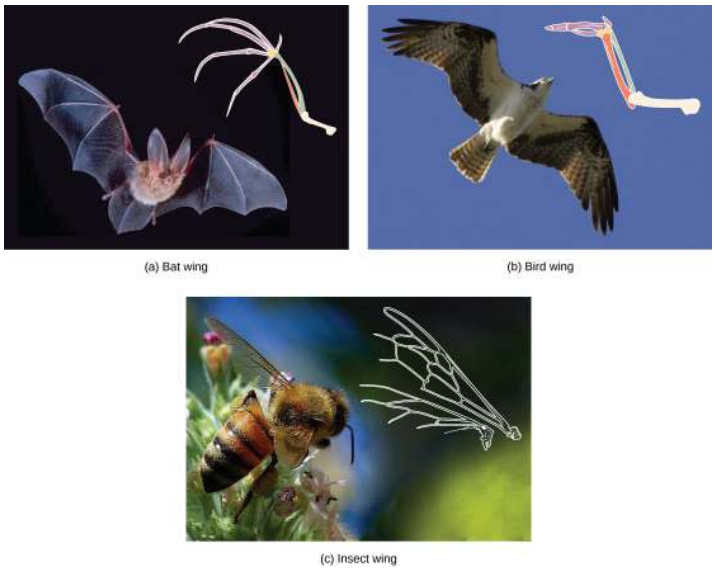


Figure **3.2.2.4**: The wing of a honeybee is similar in shape to a bird wing and a bat wing and it serves the same function (flight). The bird and bat wings are homologous structures. However, the honeybee wing has a different structure (it is made of a chitinous exoskeleton, not a boney endoskeleton) and embryonic origin. The bee versus bird or bat wing types illustrate an analogy—similar structures that do not share an evolutionary history. (credit a photo: modification of work by U.S. BLM; credit b: modification of work by Steve Hillebrand, USFWS; credit c: modification of work by Jon Sullivan)

Optional Activity 3.2.2.1

Which statement about analogies is correct?

a. They occur only as errors.
b. They are synonymous with homologous traits.
c. They are derived due to similar environmental constraints.
d. They are a form of mutation.

Answer

c. They are derived due to similar environmental constraints.

Molecular Comparisons

With the advancement of DNA technology, the area of **molecular systematics**, which describes the use of information on the molecular level including DNA sequencing, has blossomed. New analysis of molecular characters not only confirms many earlier classifications, but also uncovers previously made errors based on morphology alone. **Molecular characters** can include differences in the amino-acid sequence of a protein, shapes of a protein, RNA, location of a gene, differences in the individual nucleotide sequence of a gene, or differences in the arrangements of genes. Phylogenies based on molecular characters assume that the more similar the sequences are in two organisms, the more closely related they are. Different genes change evolutionarily at different rates and this affects the level at which they are useful at identifying relationships. Rapidly evolving sequences are useful for determining the relationships among closely related species. More slowly evolving sequences are useful for determining the relationships between distantly related species. To determine the relationships between very different species such as Eukarya and Archaea, the genes used must be very ancient, slowly evolving genes that are present in both groups, such as the genes for ribosomal RNA. Comparing phylogenetic trees using different sequences and finding them similar helps to build confidence in the inferred relationships.

Sometimes two segments of DNA in distantly related organisms randomly share a high percentage of bases in the same locations, causing these organisms to appear closely related when they are not. For example, the fruit fly shares 60 percent of its DNA with humans.[2] These similar sections are those that make fruit flies and humans both eukaryotes and animals. This 60 percent is important but does not tell us as much about why we are different. In this situation, computer-based statistical algorithms have been developed to help identify how far back our common ancestor was, which is difficult, if not impossible with morphology alone. Ultimately, the coupled use of both morphologic and molecular information is most effective in determining phylogeny.

Optional Resource

This Click and Learn describes the process of aligning DNA sequences from different organisms so that they can be compared to one another: https://media.hhmi.org/biointeractive/click/Phylogenetic_Trees/01.html

To navigate this resource, use the forward and back arrows at the top right of the webpage. There will be short videos on most pages. Click on the Play symbol (arrow in a rectangle) to play the video.

Video



This 12.5-minute video discusses some interesting phylogenetic mysteries.
Question after watching: Of the three cases featured, which one helped you understand phylogeny better?

Classification and Phylogeny

Scientists use phylogenetic trees to show the evolutionary pathways and relationships between organisms. The hierarchical classification of groups nested within more inclusive groups is reflected in diagrams. Scientists consider phylogenetic trees to be a hypothesis of the evolutionary past because one cannot go back through time to confirm the proposed relationships. Unlike taxonomy, a phylogenetic tree can be read like a map of evolutionary history.

Scientists apply the concept of **maximum parsimony**, which states that the likeliest order of events is the simplest shortest path. For evolutionary events, this would be the path with the least number of major divergences that correlate with the evidence.

Recent genetic analysis and other advancements have found that some earlier taxonomic classifications do not reflect actual evolutionary relationships, and therefore, changes and updates must be made as new discoveries take place. Recall that phylogenetic trees are hypotheses and are modified as data becomes available. In addition, classification historically has focused on grouping organisms mainly by shared characteristics and does not necessarily illustrate how the various groups relate to each other from an evolutionary perspective. For example, despite the fact that a hippopotamus resembles a pig more than a whale, the hippopotamus may be the closest living relative to the whale. One dramatic and recent example was the breaking apart of

prokaryotic species which, until the 1970s, were all classified as 'bacteria'. Their division into Archaea and Bacteria came about after the recognition that their large genetic differences warranted their separation into two of three fundamental Domains of life.

Phylogenetic Trees

The phylogenetic tree in Figure 3.2.2.1 illustrates the pathway of evolutionary history. The pathway can be traced from the origin of life to any individual species by navigating through the evolutionary branches between the two points. Also, by starting with a single species and tracing backward to any branch point, the organisms related to it by various degrees of relatedness can be identified.

Many phylogenetic trees have a single branch point at the base representing a **common ancestor** of all the branches in the tree. This is known as a **rooted tree.** The branching from that root indicates evolutionary relationships as in Figure 3.2.2.6. The point where a split occurs, called a branch point or "**node**", represents where a single lineage evolved into distinct new ones.

A lineage that evolved early from the root and remains unbranched is called **basal taxon**. When two lineages stem from the same node, they are called **sister taxa**. A node with more than two lineages is called a **polytomy** and serves to illustrate where scientists have not definitively determined all relationships. It is important to note that while sister taxa or polytomy share an ancestor, this does not mean that one taxon evolved from the other. The branch point, or split, represents a common ancestor that existed in the past, but that no longer exists. Organisms in two taxa may have split apart at a specific node, but neither taxon gave rise to the other.

Rooted phylogenetic trees can serve as a pathway to understanding evolutionary history. The pathway can be traced from the origin of life to any individual species by navigating through the evolutionary branches between the two points. Also, by starting with a single species and tracing back towards the “trunk” of the tree, one can discover that species’ ancestors, as well as where lineages share a common ancestry. In addition, the tree can be used to study entire groups of organisms.

Another point to mention on phylogenetic tree structure is that *rotation at nodes does not change the information* Figure \(\PageIndex{7}\). For example, if a node was rotated and the taxon order changed, this would not alter the information because the evolution of each taxon from the node was independent of the other.

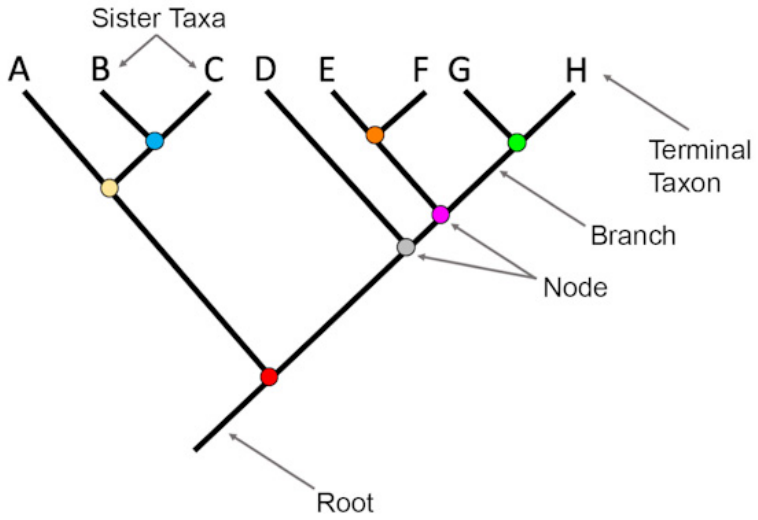


Figure 3.2.2.6: Parts of a phylogenetic tree, including terminal taxa, sister taxa, root, branch, and node. Image by Jonathan R. Hendricks (CC-BY-SA 4.0).

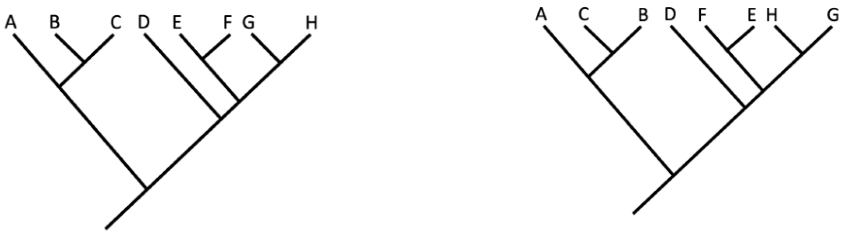
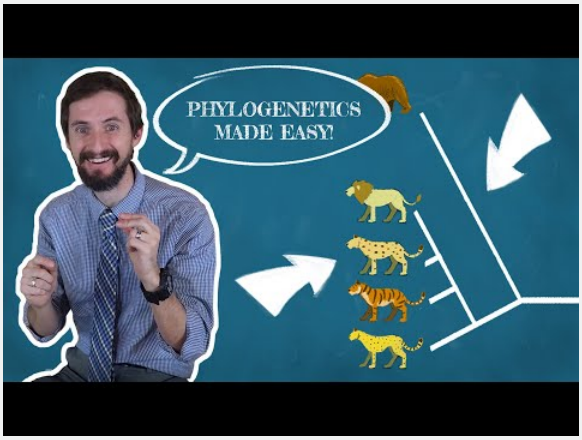


Figure **3.2.2.7:** Branches may be rotated about nodes without any change in the hypothesized relationships depicted on a tree diagram. There is no difference in the evolutionary relationships being depicted between these two trees. Images by Jonathan R. Hendricks (CC-BY-SA 4.0).

Video



This 8-minute video explains phylogenetics.
Question after watching: Which big cat is most closely related to the cheetah?

Figure 3.2.2.8 is a rooted tree for the modern great apes. The two species of orangutans are sister taxa. The three branches leading to the gorilla subspecies are a polytomy. The names of the species that are at the tip of the branches are co-existing species at the current time. The common ancestor that gave rise to two currently existing species was neither of these current species, but rather an ancestral species to both that no longer exists. For example, humans did not evolve from bonobos or chimpanzees (nor did chimpanzees evolve from humans) although they are our closest living relatives. Humans, bonobos, and chimpanzees all evolved from a common ancestor that lived, scientists believe, six million years ago and looked different from modern chimpanzees, bonobos, AND humans.

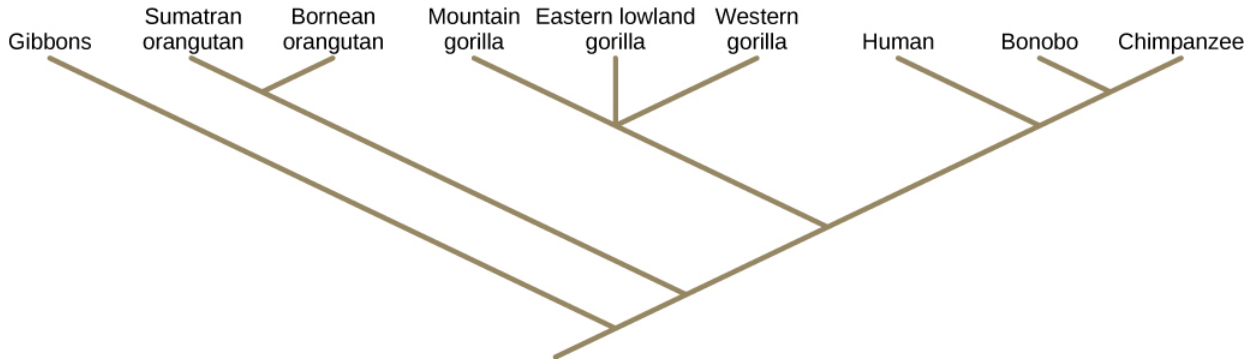


Figure 3.2.2.8: This phylogenetic tree is rooted and shows how different organisms, in this case the species and subspecies of living apes, evolved from a common ancestor.

The nodes and the branches in phylogenetic tree structure imply evolutionary change. Sometimes significant adaptive changes are identified on a branch or node. For example, in Figure 3.2.2.9, the node that gives rise to the mammal and reptile lineage from the frog lineage shows the origin of the amniotic egg character. Also, the node that gives rise to organisms with legs is indicated as the common ancestor of mammals, reptiles, amphibians, and jawed fishes.

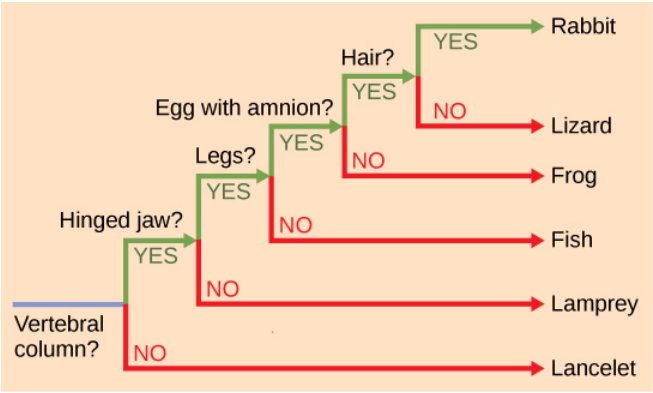


Figure 3.2.2.9: This phylogenetic tree is rooted by an organism that lacked a vertebral column. At each branch point, organisms with different characters are placed in different groups.

Understanding Phylogenetic Trees

One of the most common forms of a phylogenetic tree is a **cladogram**, seen in Figures 3.2.2.10 and 3.2.2.11. To begin this diagram, scientists often organize the homologous and analogous traits of various organisms using a system called **cladistics**. This system sorts organisms into **clades**: groups of organisms that descended from a single ancestor. For example, all organisms in the orange region in Figure 3.2.2.10 evolved from a single ancestor that had amniotic eggs. Consequently, all these organisms also have amniotic eggs and make a single clade, also called a **monophyletic group**. Clades must include all descendants from a branch point.

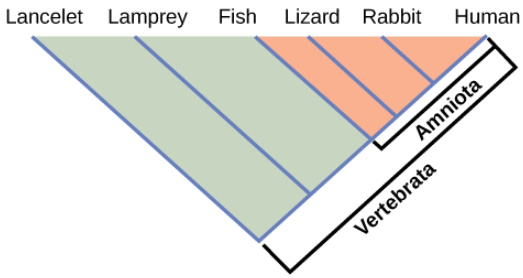


Figure **3.2.2.10**: Lizards, rabbits, and humans all descend from a common ancestor that had an amniotic egg. Thus, lizards, rabbits, and humans all belong to the clade Amniota. Vertebrata is a larger clade that also includes fish and lamprey.

Clades can vary in size depending on which branch point is being referenced. The important factor is that all organisms in the clade or monophyletic group stem from a single point on the tree. This can be remembered because monophyletic breaks down into "mono," meaning one, and "phyletic," meaning evolutionary relationship. Notice in the examples of clades how each clade comes from a single point, whereas the non-clade groups show branches that do not share a single point.

? Optional Activity 3.2.2.2

On a phylogenetic tree, which term refers to lineages that diverged from the same place?

a. sister taxa
b. basal taxa
c. rooted taxa
d. dichotomous taxa

Answer

a. sister taxa

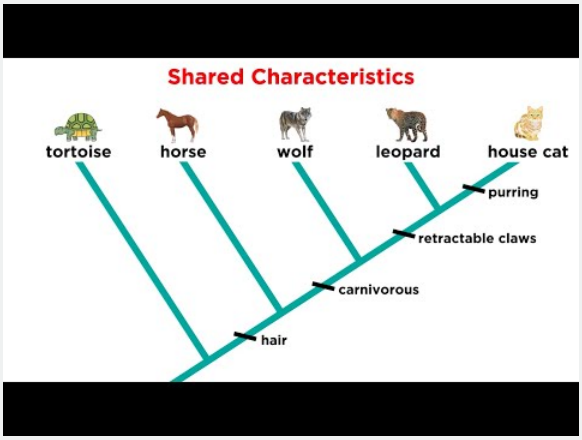
? Optional Activity 3.2.2.3

Which animals in the phylogenetic tree in Figure **3.2.2.10** belong to a clade that includes animals with hair? Which evolved first: hair or the amniotic egg?

Answer

Rabbits and humans belong in the clade that includes animals with hair. The amniotic egg evolved before hair, because the Amniota clade branches off earlier than the clade that encompasses animals with hair.

Video



This 10-minute video is the first part of a sequence that describes how cladograms are created.
Question after watching: How does science represent the relationships between organisms?

Cladistics and Shared Characteristics

Organisms evolve from common ancestors and then diversify. Scientists use the phrase “descent with modification” because even though related organisms have many of the same characteristics and genetic codes, changes occur.

This pattern repeats as one goes through the phylogenetic tree of life:

1. A change in the genetic makeup of an organism leads to a new trait that becomes prevalent in the group.
2. Many organisms descend from this point and have this trait.
3. New variations continue to arise: some are adaptive and persist, leading to new traits.
4. With new traits, a new branch point is determined (go back to step 1 and repeat).

Cladistics rests on three assumptions.

1. Living things are related by descent from a common ancestor, which is a general assumption of evolution.
2. Speciation occurs by splits of one species into two, never more than two at a time, and at one point in time. This is a simplification but is accepted by most biologists.
3. Traits change enough over time to be considered to be in a different state.

It is also assumed that one can identify the direction of change for an adaptation. In other words, we assume that an amniotic egg is a later character state than non-amniotic eggs. We know this by reference to a group outside the clade: for example, insects have non-amniotic eggs; therefore, this is the older or ancestral character state.

Cladistics compares **ingroups** and **outgroups**. An ingroup (lizard, rabbit and human in our example) is the group of taxa being analyzed in Figure **3.2.2.10**. An outgroup (lancelet, lamprey and fish in our example) is a species or group of species that diverged before the lineage containing the group(s) of interest. By comparing ingroup members to each other and to the outgroup members, we can determine which characteristics are evolutionary adaptations determining the branch points of the ingroup's phylogeny.

If a characteristic is found in all members of a group, it is a **shared ancestral character**: there has been no change in the adaptation during the descent of each member of the clade. Although these traits appear interesting because they unify the clade, in cladistics they are considered not helpful when we are trying to determine the relationships of the members of the clade because every member is the same. In contrast, consider the amniotic egg characteristic of Figure **3.2.2.10**. Only some of the organisms have this trait; to those that do, it is called a **shared-derived character** because this trait derived at some point but does not include all of the ancestors in the tree. This character tells us about the relationships among the members of the clade; it tells us that lizards, rabbits, and humans group more closely together than any of these organisms do with fish, lampreys, and lancelets.

The tricky aspect to shared-ancestral and shared-derived characters is the fact that these terms are relative. The same trait could be either ancestral or derived depending on the diagram being used and the organisms being compared. Scientists find these terms useful when distinguishing between clades during the building of phylogenetic trees, but it is important to remember that their meaning depends on context.

Video



In this 13-minute video, learn how biologists use genetic data to determine relationships among organisms.
Question after watching: Are fungi closest to plants or animals, in evolutionary terms? What is the evidence for this?

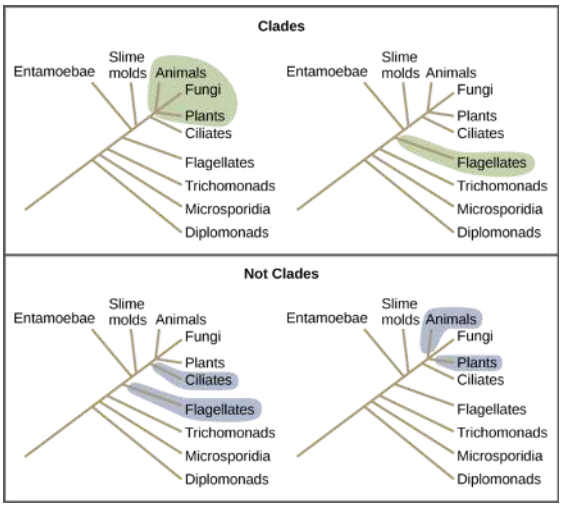


Figure **3.2.2.11**: All the organisms within a clade stem from a single point on the tree. A clade may contain multiple groups, as in the case of animals, fungi, and plants, or a single group, as in the case of flagellates. Groups that diverge at a different branch point, or that do not include all groups in a single branch point, are not considered clades.

? Optional Activity 3.2.2.4

What is true about organisms that are a part of the same clade?

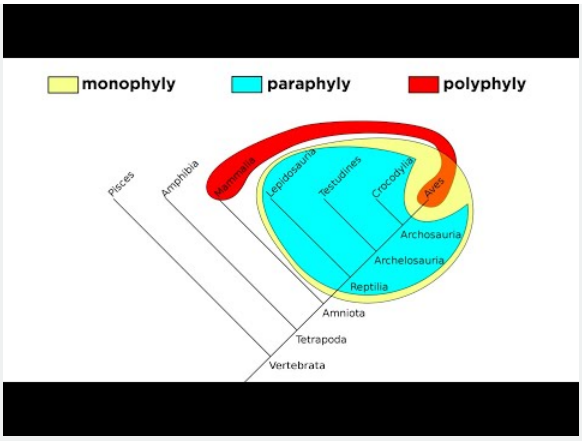
a. They all share the same basic characteristics.
b. They evolved from a shared ancestor.
c. They usually fall into the same classification taxa.
d. They have identical phylogenies.

Answer

b. They evolved from a shared ancestor.

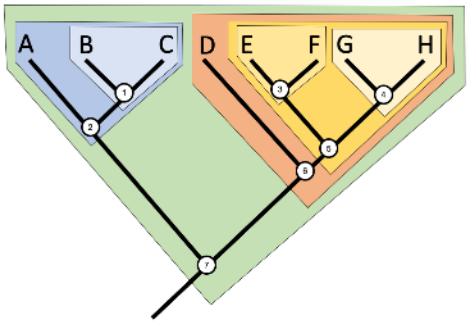
Video





This 6.5-minute video describes clades and their representation on phylogenetic trees.
Question after watching: How can you distinguish between a taxon and a clade?

? Optional Activity 3.2.2.5



Clades are not mutually exclusive, but rather form nested sets on a tree. Thus, any given taxon can belong to many clades. For example, in the tree above, Taxon B belongs to three clades, a clade defined by Node 1, a more inclusive clade defined by Node 2, and an even more inclusive clade defined by Node 7. Taxon E belongs to four clades defined by Nodes 3, 5, 6, and 7, respectively.

Try to figure out how many clades Taxon A and Taxon H belong to, and determine which nodes define each clade. (Jonathan R. Hendricks; CC-BY-SA 4.0)

Answer

Taxon A belongs to two clades and is defined by Node 2 and, more inclusively, Node 7. Taxon H belongs to four clades and is defined by Nodes (from least to most inclusive) 4, 5, 6, and 7.

Limitations of Phylogenetic Trees

It is easy to assume that more closely related organisms look more alike, and while this is often the case, it is not always true. If two closely related lineages evolved under significantly different surroundings or after the evolution of a major new adaptation, they may look quite different from each other, even more so than other groups that are not as closely related. For example, the phylogenetic tree in Figure **3.2.2.10** shows that lizards and rabbits both have amniotic eggs, whereas salamanders (within the frog lineage) do not. This means that evolutionarily, lizards and rabbits last shared a common ancestor more recently than lizards and salamanders. Superficially, however, lizards and salamanders appear more similar than lizards and rabbits.

Another aspect of phylogenetic trees is that, unless otherwise indicated, *branches do not show length of time*, they show only the order in time of evolutionary events. In other words, a long branch does not necessarily mean more time passed, nor does a short

branch mean less time passed— unless specified on the diagram. For example, in Figure **3.2.2.9**, the tree does not indicate how much time passed between the evolution of amniotic eggs and hair. What the tree does show is the *order* in which things took place. Again using Figure **3.2.2.9**, the tree shows that the oldest trait is the vertebral column, followed by hinged jaws, and so forth. Remember that any phylogenetic tree is a part of the greater whole, and similar to a real tree, it does not grow in only one direction after a new branch develops. So, for the organisms in Figure **3.2.2.9**, just because a vertebral column evolved does not mean that invertebrate evolution ceased, it only means that a new branch formed. Also, groups that are not closely related, but evolve under similar conditions, may appear more similar to each other than to a close relative.

Why Does Phylogeny Matter?

In addition to enhancing our understanding of the evolutionary history of species, our own included, phylogenetic analysis has numerous practical applications. Two of those applications include understanding the evolution and transmission of disease and making decisions about conservation efforts. A 2010 study[3] of MRSA (methicillin-resistant *Staphylococcus aureus*), an antibiotic-resistant pathogenic bacterium, traced the origin and spread of the strain in the past 40 years. The study uncovered the timing and patterns in which the resistant strain moved from its point of origin in Europe to centers of infection and evolution in South America, Asia, North America, and Australasia. The study suggested that introductions of the bacteria to new populations occurred very few times, perhaps only once, and then spread from that limited number of individuals. This contrasts with the possibility that many individuals carried the bacteria from one place to another. This result suggests that public health officials should concentrate on quickly identifying the contacts of individuals infected with a new strain of bacteria to control its spread.

A second area of usefulness for phylogenetic analysis is in conservation. Biologists argue that it is important to protect species throughout a phylogenetic tree rather than just those from one branch of the tree. Doing this preserves more of the variation produced by evolution. This is important because genetic variation makes a species more robust to disruption by being more likely to have some individuals with the traits necessary to survive a change in the environment. For example, conservation efforts should focus on a single species without sister species rather than other species that have a cluster of close sister species that recently evolved. If a single evolutionarily distinct species goes extinct, a disproportionate amount of genetic variation from the tree will be lost compared to one species in a cluster of closely related species. Closely related species share more genetic information and, therefore, some of this genetic information will be retained in living organisms versus those who have no sister species.

A study published in 2007[4] made recommendations for the conservation of mammal species worldwide based on how evolutionarily distinct and at risk of extinction they are. The study found that their recommendations differed from priorities based on simply the level of extinction threat to the species. The study recommended protecting some threatened and valued large mammals such as the orangutans, the giant and lesser pandas, and the African and Asian elephants. But they also found that some much lesser-known species should be protected based on how evolutionary distinct they are. These include several rodents, bats, shrews, and hedgehogs. In addition, there are some critically endangered species that did not rate as very important in evolutionary distinctiveness including species of deer mice and gerbils. While many criteria affect conservation decisions, preserving phylogenetic diversity provides an objective way to protect the full range of diversity generated by evolution.

Choosing the Right Relationships

Constructing a phylogenetic tree, or cladogram, from the character data is a monumental task that is usually left up to a computer. The computer draws a tree such that all clades share the same list of derived characters. However, there are decisions to be made. For example, what if a species present in a clade is supported by all of the shared derived characters for that clade except one? One conclusion is that the trait evolved in the ancestor, but then changed back in that one species. Also, a character state that appears in two clades must be assumed to have evolved independently in those clades. These inconsistencies are common in trees drawn from character data and complicate the decision-making process about which tree most closely represents the real relationships among the taxa.

To aid in the tremendous task of choosing the best tree, scientists use maximum parsimony, which means they assume that events occurred in the simplest, most obvious way. This means that the “best” tree is the one with the fewest number of character reversals, the fewest number of independent character changes, and the fewest number of character changes throughout the tree. Computer programs search through all of the possible trees to find the small number of trees with the simplest evolutionary pathways.

Optional Activity 3.2.2.6

Why do scientists apply the concept of maximum parsimony?

a. to decipher accurate phylogenies
b. to eliminate analogous traits
c. to identify mutations in DNA codes
d. to locate homoplasies

Answer

a. to decipher accurate phylogenies

Footnotes

1. 1 Gibbons, A. (2012, June 13). *Science Now*. Retrieved from news.sciencemag.org/scienceno...sequenced.html
2. 2 *Background on comparative genomic analysis*. (2002, December). Retrieved from http://www.genome.gov/10005835
3. 3 Harris, S.R. et al. 2010. Evolution of MRSA during hospital transmission and intercontinental spread. *Science* 327:469–474.
4. 4 Isaac NJ, Turvey ST, Collen B, Waterman C, Baillie JE (2007) Mammals on the EDGE: Conservation Priorities Based on Threat and Phylogeny. PLoS ONE 2(3): e296. doi:10.1371/journal.pone.0000296

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SECTION OVERVIEW

3.3: History of Life on Earth

Learning Objectives

- Identify the major evolutionary leaps at given points in the geologic timeline
- Identify the origins of given taxonomic groupings on the geologic timeline
- Explain possible causes of mass extinction in Earth's history
- Utilize phylogeny and biogeography to identify reasons for the present distribution of various organisms
- Describe the current hypotheses on the origin of life
- Describe the evidence for the evolution of prokaryotes and eukaryotes

3.3.1: Deep Time

3.3.2: Origins of Life

3.3.3: Evidence for Early Life

3.3.4: Eukaryotic Origins

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Unit 3.3.1 - Deep Time

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1.5 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.3.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Identify the major time frames on the geologic timeline
- Explain the evidence scientists use to explain the age of the Earth and mass extinctions

Geologic Time

The **geological time scale** in Figure 3.3.1.1 is one of the crowning achievements of science in general and geology in particular. It is a reference and communication system for comparing rocks and fossils found throughout the world and is geology's equivalent of the periodic table of the elements. It is also an important way to help organize when important milestones in the history of life on Earth occurred. For example, a paleontologist can call her colleague and say, "I just found an amazing new trilobite from the Devonian of British Columbia" and her colleague will immediately understand when in geological time that trilobite lived.

Most of the boundaries on the geological time scale correspond to the origination or extinction of particular fossils. Knowing when major groups of fossils first appeared or went extinct is therefore useful for determining the ages of rocks in the field. For example, if someone finds a rock with a trilobite fossil upon it, they will immediately know that the rock is Paleozoic in age, from 541 million years ago (Ma) to 252 Ma, and not older or younger; knowing the species of trilobite allows even greater precision.

The geological time scale provides a global summary of countless small-scale temporal correlations of rock layers made at local and regional scales. It is based almost entirely upon careful observations of the distributions of fossils in time and space.

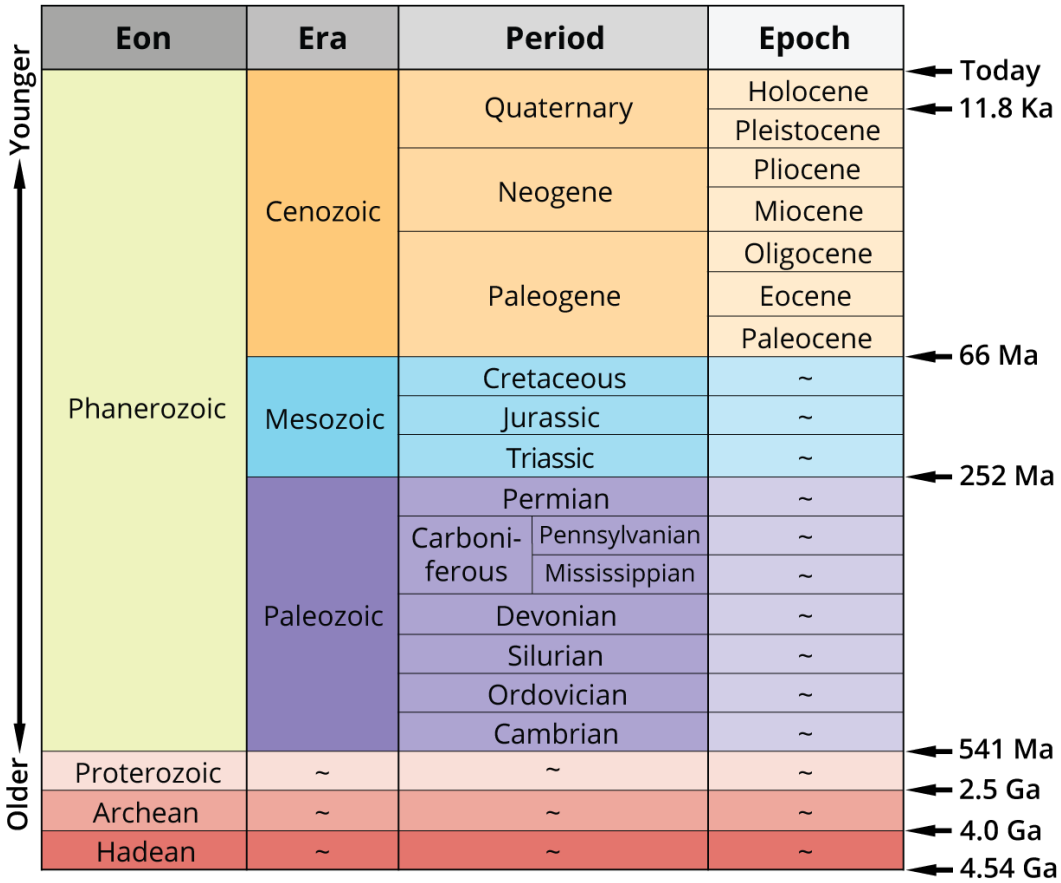


Figure **3.3.1.1**: The geological time scale. Ka = thousands of years, Ma = millions of years, and Ga = billions of years. (Jonathan R. Hendricks CC-BY-SA 4.0)

Eons

The **Eon** is the broadest category of geological time. All geologic time is measured in years before the present and are indicated in abbreviated terms: "Ga" indicates billions of years, "Ma" indicates millions of years and, "Ka" indicates thousands of years. The Earth is 4.54 billion years old (4.54 Ga). Earth's history is characterized by four eons; in order from oldest to youngest, these are the Hadeon, Archean, Proterozoic, and Phanerozoic. Collectively, the Hadean, Archean, and Proterozoic are sometimes informally referred to as the **Precambrian**. The Cambrian Period defines the beginning of the Phanerozoic Eon; so, all rocks older than the Cambrian are *Pre*cambrian in age. The Hadean is the oldest Eon on Earth and accounts for the formation of the planet and the origins of life. The Archaean, 4.0 Ga, includes the first prokaryotes and the oldest rocks still in existence. During the Proterozoic, the first multicellular life evolved.

Most of Earth's history is represented by the three Precambrian eons. These older eons tell the story of Earth's beginning, life's origin, and the rise of complex life. The Hadean and Archean are difficult eons to study, however, because they are exposed in very limited places on Earth's surface. Since they are the oldest eons, rocks that are Hadean and Archean in age are often buried far below younger rocks at the Earth's surface. Proterozoic rocks, which span nearly 2 billion years or 42% of Earth's history, are much more accessible. But, until recently, these have received significantly less attention from paleontologists than rocks from the younger, fossil-rich Phanerozoic eon. That is slowly beginning to change, however, as more clues about the origins of complex life begin to be revealed from Proterozoic-aged rocks.

Humans live during the **Phanerozoic**, which means "visible life". This is the interval of geological time characterized by abundant, complex fossilized remains. Being the youngest eon of time, it is also well represented by rocks at Earth's surface. Because of these two factors, most paleontologists and geologists study fossils and rocks from the Phanerozoic eon. The Phanerozoic Eon began 541 Ma (or, 0.541 Ga) and represents only 12% of Earth's history.

Eras

Eons of geological time are subdivided into **Eras**, which are the second-longest units of geological time. The Phanerozoic eon is divided into three eras: the Paleozoic, Mesozoic, and Cenozoic.

Most of our knowledge of the fossil record comes from the three eras of the Phanerozoic eon. The Paleozoic ("old life") Era is characterized by trilobites, the first four-limbed vertebrates, and the origin of land plants. The Mesozoic ("middle life") Era represents the "age of dinosaurs," though is also noteworthy for the first appearances of mammals and flowering plants. Finally, the Cenozoic ("new life") Era is sometimes called the "age of mammals" and is the era we live in today.

As temporal points of reference, it is worth memorizing the ages of the boundaries that separate the three eras of the Phanerozoic Eon. Long before geologists knew these absolute age dates, they realized that the boundaries represent important events in the history of life: **mass extinctions**. For example, many fossils that are commonly found in the youngest Paleozoic rocks are not found in overlying Mesozoic rocks. Similarly, dinosaur fossils found in the youngest Mesozoic rocks are never again found in the overlying Cenozoic rocks. Mass extinctions are when large numbers of species go extinct within a very short period of geologic time. Paleontologists and geologists used these mass extinction events to define these (and other) boundaries within the Phanerozoic portion of the geological time scale. It is therefore no coincidence that some of the major boundaries coincide with mass extinction events.

The older Archean and Proterozoic Eons are similarly divided into several Eras. For example, the youngest Era of the Proterozoic Eon is called the Neoproterozoic. For the sake of simplicity, these older Eras are not included on the time scale shown at the top of this page; they do, however, exist.

Periods

Just as eons are subdivided into eras, Eras are subdivided into units of time called **Periods**. The most well-known of all geological periods is the Jurassic Period of the Mesozoic era. The Paleozoic Era is divided into six Periods. From oldest to youngest, these are the Cambrian (a time of rapid evolution and rise in biodiversity), Ordovician (primitive fish evolve), Silurian (first land plants), Devonian (first amphibians and forests), Carboniferous (massive forests and first reptiles), and Permian (first known mass extinction event). Note that in North America, the Carboniferous is divided into two separate Periods: the Mississippian and the Pennsylvanian. The Mesozoic era is divided into the Triassic (first dinosaurs and mammals), Jurassic (height of dinosaur diversity), and Cretaceous (early flowering plants and extinction of most dinosaurs) Periods. Finally, the Cenozoic Era is divided into three Periods: the Paleogene (evolution of early primates), Neogene (grassy ecosystems dominate plains), and Quaternary (evolution of modern humans).

Epochs and Ages

Periods of geological time are subdivided into **Epochs**. In turn, epochs are divided into even narrower units of time called **Ages**. For the sake of simplicity, only the epochs of the Paleogene, Neogene, and Quaternary Periods are shown on the time scale at the top of this page. It is important to note, however, that all of the periods of the Phanerozoic era are subdivided into epochs and ages.

The Paleogene Period is divided into--from oldest to youngest--the Paleocene, Eocene, and Oligocene Epochs. The Neogene is divided into the Miocene and Pliocene Epochs. Finally, the Quaternary is divided into the Pleistocene and Holocene Epochs.

Some geologists think now that humans are having such a notable impact on the Earth and its life, a new, youngest epoch should be added to the Quaternary: the **Anthropocene**. These impacts include the destruction of large swaths of habitat, overexploitation of species, and planetary climate change, among others. These are discussed more in Unit 5. There is still considerable discussion in the geological community about whether this epoch should be added, as well as debate about what characteristics should define its beginning.

Video



This 12-minute video details the geologic record and important events through Earth's history that have shaped life.
Question after watching: For each of the eras, eons, epochs, and periods in Figure **3.3.1.1**, *what is a main characteristic of this time period? Create a concept map, flow chart, table, or annotation of Figure* **3.3.1.1**.

Video



The first era of the current eon, the Paleozoic Era, is probably the most deceptively fascinating time in Earth's history. This 11-minute video describes it and the conditions of the Permian Extinction.
Question after watching:
Why do scientists say that mass extinctions provide opportunities? Continue to work on the notes that you started with the video above that outlines the major characteristics of each time period.

The Geologic and Evolutionary Record

A remarkable feature of Earth's history is how often evolutionary changes coincided with geologic and climatologic changes. In addition, consider that changes in geology (e.g., mountain formation or lowering of the sea level) can cause changes in climate. Changes in climate, in turn, can cause changes in geology through things like global loss/gain of ice. Geology and climate alter the habitats available for life. Past and present climate change will be covered in depth in Unit 5.

Here, we look at two types of geologic change that have had dramatic effects on life: **continental drift** and the impact of meteors**.**

Theory of Continental Drift

A body of evidence, both geological and biological, supports the conclusion that 200 million years ago, at the start of the Mesozoic era, all the continents were attached to one another in a single landmass, named **Pangaea**, seen in Figure **3.3.1.2**. This drawing of Pangaea is based on a computer-generated fit of the continents as they would look if the sea level were lowered by 1800 meters.

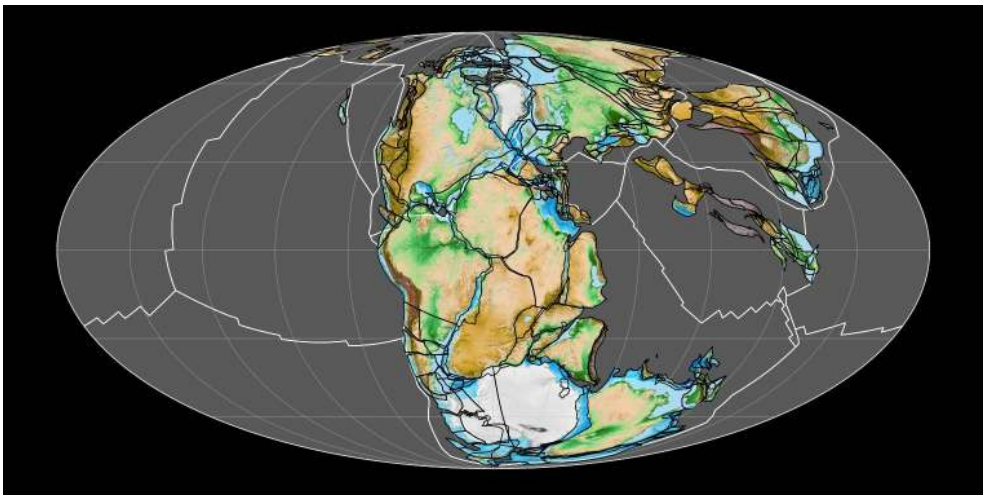


Figure **3.3.1.2**: The supercontinent Pangaea in the early Mesozoic (at 200 Ma). The modern continents are highlighted for reference with North America in the upper left-hand corner, South America directly to the south, and Africa to the east. Antarctica is at the bottom with Australia to its right. (Fama Clamosa; CC-BY-SA 4.0)

During the Triassic Period, Pangaea began breaking up, first into two major landmasses:

- **Laurasia** in the Northern Hemisphere
- **Gondwana** in the Southern Hemisphere.

The present continents separated at intervals throughout the Mesozoic and Cenozoic Eras, eventually reaching the positions they have today. Evidence for this theory includes the shape of the continents, the geologic record, and fossils.

Shape of the Continents

The shape of the east coast of South America and the west coast of Africa and are strikingly complementary like puzzle pieces that fit together (Figure **3.3.1.2**). This is even more dramatic when one fits the continents together using the boundaries of the continental slopes, (e.g., 1800 meters down), rather than the present-day shorelines.

Geology

- In both mineral content and age, the rocks in a region on the east coast of Brazil match precisely those found in Ghana on the west coast of Africa.
- The low mountain ranges and rock types in eastern Canada and the New England region of the United States appear to be continued in parts of Great Britain, France, and Scandinavia.
- India and the southern part of Africa both show evidence of periodic glaciation during Paleozoic times (even though both are now close to the equator). The pattern of glacial deposits in the two regions match each other and glacial deposits found in South America, Australia, and Antarctica.

Fossils

- Fossil reptile species found in South Africa are also found in Brazil and Argentina.
- Fossil amphibians and reptiles found in Antarctica are also found in South Africa, India, and China.
- Most of the marsupials alive today are confined to South America and Australia. If these two continents were connected by Antarctica in the Mesozoic, as the theory suggests, one might expect to find fossil marsupials there. In March 1982, this prediction was fulfilled with the discovery in Antarctica of the remains of *Polydolops*, a 2.7 meter marsupial.

Video



This 9-minute video discusses supercontinents and how their formation and breakup shaped life.
Question after watching: What type of fossils might you expect to find in Kenorland? Why (what is the rationale?) What about Rodinia? What kinds of fossils might be found in Labrador?

Meteors: The Impact Hypotheses

The Cretaceous period, the last period of the Mesozoic, marked the end of the Age of Reptiles. It was followed by the Cenozoic era, the Age of Mammals. Although extinctions have occurred throughout the history of life, many of them occurred in a relatively brief period at the end of the Cretaceous. Why?

The Alvarez Hypothesis

In the 1980s, Louis Alvarez, his son Walter, and their colleagues proposed that a giant asteroid or comet striking the Earth some 66 million years ago caused the massive die-off at the end of the Cretaceous Period. The impact is hypothesized to have generated so much dust and gases that skies were darkened all over the Earth, photosynthesis declined, and global temperatures dropped. As many as 75% of all species, including most dinosaurs, became extinct.

The key piece of evidence for the **Alvarez Hypothesis** was the finding of thin deposits of clay containing the element iridium at the interface between the rocks of the Cretaceous and those of the Paleogene Epoch (called the K-Pg boundary after the German word for Cretaceous). Iridium is a rare element on Earth but occurs in certain meteorites at concentrations thousands of times greater than in the Earth's crust.

In the 1990s, the Alvarez Hypothesis gained strong support from the discovery of the remains of a huge (180 km in diameter) crater in the Yucatan Peninsula of Mexico that dated to 65 million years ago.

The abundance of sulfate-containing rock in the region suggests that the impact generated enormous amounts of sulfur dioxide (SO_2), which later returned to Earth as long-lasting showers of acid rain. A smaller crater in Iowa, formed at the same time, indicates another impact may have contributed to the devastation. Perhaps during this period, the Earth passed through the tail of a comet, or a swarm of asteroids. These repeated impacts would have made the Earth uninhabitable for many creatures of the Mesozoic Era.

Video



This entertaining video provides an overview of the evidence that led researchers to conclude that an asteroid impact caused the demise of the dinosaurs.

Question after watching:

One researcher, in tongue-in-cheek fashion, claims that we still live in the age of the dinosaurs. How do you think that the ages are named (i.e., why is this called the age of the mammals)? Dinosaurs are often thought to be ectotherms ("cold-blooded") like reptiles. However, birds are endothermic ("warm-blooded"). Based on this observation, do you think that dinosaurs were ectothermic or endothermic? Explain your reasoning.

Other Impacts

Mass extinctions have occurred at other times in Earth's history. There was another large extinction of non-dinosaur reptiles that occurred earlier, at the end of the Triassic. It was followed by a great expansion in the diversity of dinosaurs. The recent discovery of a layer enriched in iridium in rocks formed at the boundary between the Triassic and Jurassic suggests that impact from an asteroid or comet may have been responsible then, just as it was at the K-Pg boundary.

Attributions

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Unit 3.3.2 - Origins of Life

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.3.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Explain the different problems to solve, and scientific hypotheses, on the origins of life

Introduction

The Origins of Life - A Mystery to Solve

To account for the origin of life on our Earth requires solving several problems:

1. How did the organic molecules that define life, e.g., amino acids, nucleotides, originate?
2. How were macromolecules assembled, e.g., proteins and nucleic acids, - a process requiring catalysts?
3. How were macromolecules able to reproduce themselves?
4. How were these macromolecules assembled into a system separate from their surroundings (i.e., a cell)?

Several hypotheses address each of these problems.

Video



This 13-minute video provides an overview of the origins of life, exploring along the way "what is life"?
Question after watching: "Life is what living things do" (in contrast to what living things have). What does this mean? Do you agree with this statement based on what you know so far from this course?

Problem 1: How did the organic molecules that define life, e.g., amino acids, nucleotides, originate?

For the first problem, four hypotheses have been proposed:

- Hypothesis 1: Organic molecules were synthesized from inorganic compounds in the atmosphere,
- Hypothesis 2: Organic molecules rained down on the Earth from outer space,
- Hypothesis 3: Organic molecules were synthesized at hydrothermal vents on the ocean floor, and/or
- Hypothesis 4: Organic molecules were synthesized when comets or asteroids struck the early Earth.

Hypothesis 1: Organic molecules were synthesized from inorganic compounds in the atmosphere

In the fall of 1951, **Stanley Miller** was a graduate student looking for a research project. He attended a lecture by Nobel Laureate Harold C. Urey. Urey described how the Earth's atmosphere was thought to be in its early formation and how it might have led, through chemical reactions, to the formation of the first organic molecules. Miller decided to test this idea. He created an apparatus that mimicked the Earth's early conditions and atmosphere (or at least, what was thought, in 1951, to be the Earth's early

conditions). The apparatus is shown in Figure **3.3.2.1**. He filled it with water (H2O), methane (CH4), ammonia (NH3), and hydrogen (H2) but no oxygen since before life existed no oxygen had been released in the atmosphere by photosynthesis. The mixture circulated in the system by continuously boiling and then condensing/cooling the water. The gases passed through a chamber containing two electrodes with a spark passing between them, simulating lightening.

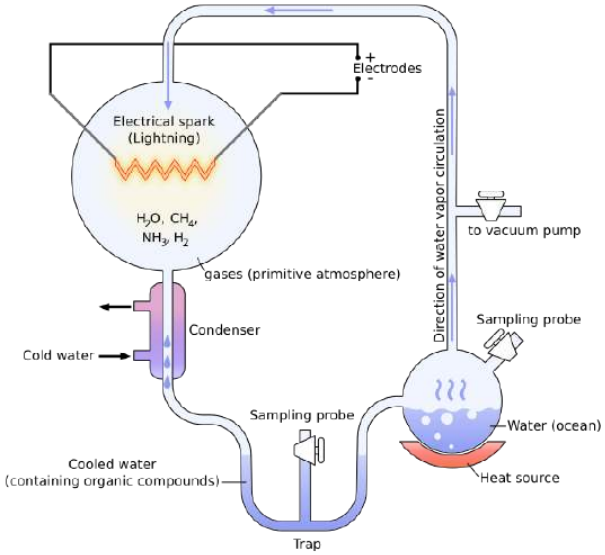


Figure **3.3.2.1**: Miller experiment. (CC BY-SA; Yassine Mrabet).

At the end of the week-long experiment, Miller used paper chromatography to analyze the chemicals found in the flask. He discovered it now contained several amino acids (glycine, alanine, and aspartic acid) as well as other organic molecules, such as gamma-amino butyric acid or GABA (a chemical now used by many animals as a neurotransmitter).

It is now thought that the atmosphere of the early Earth was different than Miller supposed. However, in the years since Miller's work, many variants of his procedure have been tried with different mixtures of gases as our understanding of the early Earth's composition has changed. In nearly all versions of the experiment, organic molecules have almost always been formed, including the following results:

- 17 of the 20 amino acids used in protein synthesis, and all the purines and pyrimidines used in nucleic acid synthesis can be created in experiments similar to Miller's. They are easy to create by chemical reactions outside of living organisms.
- The synthesis of ribose, and thus of nucleotides, has been much more difficult outside of living organisms. However, success in synthesizing pyrimidine ribonucleotides under conditions that might have existed in the early Earth was reported in the 14 May 2009 issue of the scientific journal Nature. Thus, the synthesis of these molecules outside of a living organism is possible.
- In 2015, chemists in Cambridge, England led by John Sutherland reported that they had synthesized precursors for 12 of the 20 amino acids used in protein synthesis, two (of the four) ribonucleotides used to make RNA, and a precursor of lipids - all from a non-living system. In fact, they created these molecules using only hydrogen cyanide (HCN) and hydrogen sulfide (H_2S) irradiated with ultraviolet light in the presence of mineral catalysts.

Hypothesis 2: Organic molecules rained down on the Earth from outer space

Video



This 4 min video provides an overview of the hypothesis that the molecules of life may have been brought to Earth from outer space.

Question after watching: What is the evidence for the hypothesis of Panspermia?

Astronomers, using infrared spectroscopy, have identified a variety of organic molecules in interstellar gas clouds, including methane (CH_4), methanol (CH_3OH), formaldehyde (HCHO), cyanoacetylene (HC_3N) (which in Miller-type experiments is a precursor to the pyrimidine cytosine), polycyclic aromatic hydrocarbons (PAHs), as well as other important molecules such as carbon dioxide (CO_2), carbon monoxide (CO), ammonia (NH_3), hydrogen sulfide (H_2S), and hydrogen cyanide (HCN). There are organic molecules in space. These could have found their way to Earth and provided the building blocks of life.

Several laboratories have reported producing amino acids and other organic molecules by taking a mixture of molecules known to be present in interstellar space such as ammonia (NH_3), carbon monoxide (CO), methanol (CH_3OH), water (H_2O), and hydrogen cyanide (HCN) and exposing it to temperatures close to that of space (near absolute zero) and intense ultraviolet (UV) radiation. In other words, there is nothing special about creating organic molecules – they arise in the universe through the conditions found in space. They do not require living systems to create them. Whether or not the molecules that formed terrestrial life arrived here from space, there is little doubt that organic matter continuously rains down on the Earth (estimated at 30 tons per day). These could have served as the building blocks for the first living organism.

Alternatively, organic molecules can be transported to Earth via meteorites as demonstrated by the Murchison Meteorite that fell near Murchison, Australia on 28 September 1969 (Figure **3.3.2.2**). This meteorite contains many organic molecules including purines and pyrimidines and 12 different amino acids. The relative proportion of each amino acid in the meteorite mirrored those found as a result of Miller's experiments. This suggests that abiotic chemical reactions produce these organic molecules easily and reliably, and whether they were formed on the early Earth or in space, they could have served to construct the first living organism.

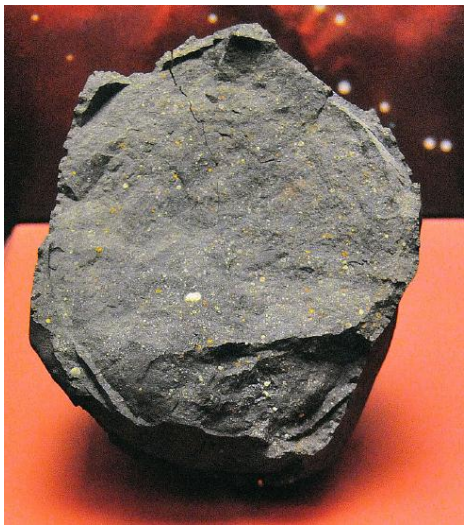


Figure **3.3.2.2**: Murchison meteorite at The National Museum of Natural History (Washington). (CC SA-BY 3.0; Basilicofresco)

Hypothesis 3: Organic molecules were synthesized at hydrothermal vents on the ocean floor

Another location suspected of serving as a cradle for life are deep-sea hydrothermal vents. These vents would have provided a relatively stable environment for life to begin while the early planet was bombarded by meteorites. Some deep-sea hydrothermal vents discharge copious amounts of hydrogen, hydrogen sulfide, and carbon dioxide at temperatures around 100°C. The gases bubble up through chambers rich in iron sulfides (FeS, FeS_2). The iron sulfide surfaces can facilitate chemical reactions (i.e., serve as catalysts) that lead to the formation of simple organic molecules like acetate. Note also that life today depends on enzymes that have Fe and S atoms in their active (catalytic) site, so these iron sulfide minerals could have been a precursor for today's living system enzymes.

Video



This 5-minute video provides an overview of the hypothesis that life began at hydrothermal vents.
Question after watching: What are some characteristics of LUCA? How do we know that this organism had these characteristics?

Hypothesis 4: Organic molecules were synthesized when comets or asteroids struck the early Earth

The ingredients for the creation of organic molecules include basic inorganic chemicals like carbon dioxide (CO_2) or hydrogen cyanide (HCN), but the rearrangement of their atoms into organic molecules also requires an infusion of energy. In the hypotheses we have investigated thus far, the energy came from lighting, chemical gradients, or UV light. In this hypothesis, the energy comes from the impact of meteorites with the early Earth.

Researchers in the Czech Republic reported in 2014 that they had succeeded in the abiotic synthesis of adenine (A), guanine (G), cytosine (C), and uracil (U) — the four bases found in RNA and three of the four found in DNA. They achieved this by bombarding a mixture of formamide and clay with powerful laser pulses that mimicked the temperature and pressure expected when a large meteorite strikes the Earth. Formamide is a simple substance, CH_3NO, thought to have been abundant on the early Earth and containing the four elements fundamental to all life. It could serve as a basis for the creation of many of the organic molecules used by living systems today. Thus, the meteorite impact may have sparked life on Earth.

Problem 2: How were macromolecules assembled?

Once the organic molecules of life are created (monomers), the next step in the creation of life is to assemble them into large macromolecules (polymers). For example, nucleotides need to be assembled into RNA or DNA; and amino acids need to assemble into proteins.

Researchers who study this problem think that early polymers were assembled on solid, mineral surfaces These surfaces worked like catalysts, holding the monomers in the right orientation to facilitate their assembly into larger polymers, and once formed the mineral surface held on to the polymer and in so doing, protected them from degradation. In the laboratory, polypeptides and polynucleotides (RNA molecules) containing about ~50 monomers linked together have been synthesized on mineral (e.g., clay) surfaces.

Today, all living organisms have metabolism to create more of themselves from simpler building blocks and this activity depends on enzymes. Until recently, every enzyme science knew off was a protein. But proteins are synthesized from information encoded in DNA and translated into mRNA. So here is a chicken-and-egg dilemma. The synthesis of DNA and RNA requires proteins. So proteins cannot be made without nucleic acids and nucleic acids cannot be made without proteins.

The discovery that certain RNA molecules have enzymatic activity on their own provides a possible solution. These RNA molecules, called **ribozymes**, incorporate both the features required of life: storage of information and the ability to act as catalysts. This leads to what is known as the **RNA World Hypothesis**.

Video



This 3-minute video describes the RNA World Hypothesis.

Question after watching: In your notes, write a short description of the RNA world hypothesis and the argument for it. How could natural selection operate on the molecular level (as demonstrated in the RNA World Hypothesis)?

While no ribozyme in nature has yet been found that can replicate itself, ribozymes have been synthesized in the laboratory (using artificial selection) that can catalyze the assembly of short oligonucleotides into exact complements of themselves. The ribozyme serves as both the *template* on which short lengths of RNA ("oligonucleotides" are assembled following the rules of base pairing and the *catalyst* for covalently linking these oligonucleotides.

In principle, life might have begun as a self-replicating RNA. Only later did proteins take over the catalytic machinery of metabolism and DNA take over as the repository of the genetic code. Several other bits of evidence support the RNA World Hypothesis:

- Many of the enzyme cofactors important for life today are based on a ribose nucleotide; for example:
  - ATP
  - NAD
  - FAD
  - coenzyme A
  - cyclic AMP

- GTP
- In the cell, all deoxyribonucleotides are synthesized from ribonucleotide precursors.
- Many organisms control the transcription and/or translation of certain genes with RNA molecules, not protein molecules.

Problem 3: How were macromolecules able to reproduce themselves?

Once macromolecules were created, the next problem we must try to understand is how they were able to generate more of themselves, identical in composition and structure. Without this reproductive ability, life would change each generation and there would be no continuity.

The advantage of the RNA World Hypothesis is that it proposes a way in which the creation of the first macromolecule (an RNA with the ability to encode information and replicate itself) and of creating progeny with similar properties. It would explain this step, and provide a mechanism for natural selection to work on this population of "organisms" (RNA ribozymes) to change, with the best replicators emerging from the pool in greater numbers at each succeeding generation.

For the other hypotheses about the creation of life, the mechanism for the reproduction of macromolecules is less understood.

Problem 4: How were these macromolecules assembled into a system separate from their surroundings (i.e., a cell)?

To function, the machinery of life must be separated from its surroundings so that the building blocks are held in greater concentration to facilitate chemical reactions and so that the products do not float away. The chemicals of life need to be separated from the extracellular fluid (ECF). Today, this function is provided by the plasma membrane.

The plasma membranes of all currently living organisms are made of a double layer of phospholipids. They are only permeable to small, uncharged molecules like H_2O, CO_2, and O_2. Specialized transmembrane transporters are needed for ions, hydrophilic, and charged organic molecules (e.g., amino acids and nucleotides) to pass into and out of the cell.

Researchers in this field, including Jack Szostak and colleagues from Harvard University, have confirmed that fatty acids, fatty alcohols, and monoglycerides, all molecules that can be synthesized under prebiotic conditions, can also form lipid bilayers and these can spontaneously assemble into enclosed vesicles.

Unlike phospholipid vesicles, these

- admit charged molecules like nucleotides
- admit hydrophilic molecules like ribose
- grow by self-assembly
- are impermeable to, and thus retain, polymers like oligonucleotides.

Here, then, is a simple system that is a plausible model for the creation of the first cells from the primeval "soup" of organic molecules.

Other hypotheses have been proposed, like the formation of an iron sulfide cell as a precursor of cells in deep-sea hydrothermal vents. The advantage of these enclosures is that they would have served as catalysts as well as to keep the chemicals created by the early life from floating away. In time, lipids may have come to coat the surface of these metal cells and bud away, seeding life in the ocean.

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Unit 3.3.3 - Evidence for Early Life

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.3.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Discuss the origins of prokaryotic organisms in terms of the geologic timeline
- Distinguish Bacteria from Archaea in terms of their origins
- Discuss the distinguishing features of extremophiles and the environments that produce biofilms

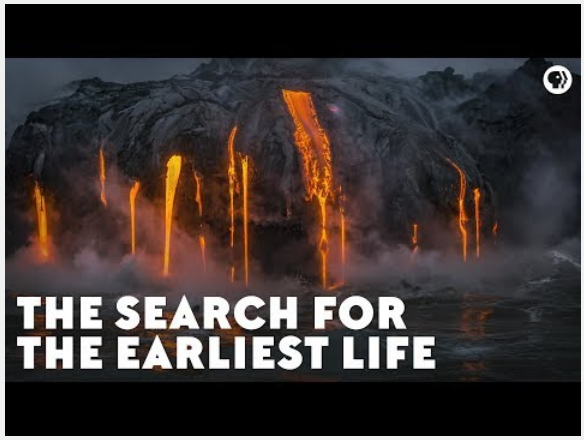
Introduction

When and where did life begin? What were the conditions on Earth when life began? Prokaryotes were the first forms of life on Earth, existing for billions of years before plants and animals appeared. The Earth and its moon are about 4.54 Ga. This estimate is based on evidence from radiometric dating of meteorite material together with other substrate material from the Earth and the moon.

Early Earth had a very different atmosphere than it does today, for example, it contained less molecular oxygen since photosynthesis had not yet evolved to produce it as a by-product. It was also subjected to strong radiation from outer space since the composition of the early atmosphere did not protect the surface as it does today. Thus, the first organisms would have flourished where they were more protected, such as in ocean depths or beneath the surface of the Earth. Also at this time, strong volcanic activity was common on Earth. It is probable that these first organisms, the first prokaryotes, were adapted to very high temperatures. The early Earth was prone to geological upheaval, volcanic eruptions, and bombardment by mutagenic radiation from the sun. The first organisms were prokaryotes that could withstand these harsh conditions. **Prokaryotes** are single-celled organisms without a nucleus or membrane-bound organelles.

Although prokaryotic cell fossils date to almost 3.5 billion years ago, most prokaryotes do not have distinctive morphologies; fossil shapes cannot be used to distinguish them between Archaea and Bacteria. Instead, chemical fossils of unique lipids are more informative because such compounds do not occur in other organisms. Some publications suggest that archaean or eukaryotic lipid remains are present in rock formations dating from 2.7 billion years ago in Precambrian formations. The oldest such traces come from Greenland, in Earth's oldest sediments, which formed 3.8 billion years ago.

Video



This 5.5-minute video describes the search for the earliest evidence of life on Earth.
Question after watching: Evidence for life on Earth is that it happened relatively quickly after the formation of the planet. What are the implications of this hypothesis?

Optional Activity 3.3.3.1

Why do scientists believe that the first organisms on Earth were extremophiles?

Answer

Because the environmental conditions on early Earth were extreme by current standards: high temperatures, lack of oxygen, high radiation, etc.

Current Model: Prokaryotes, the First Inhabitants of Earth

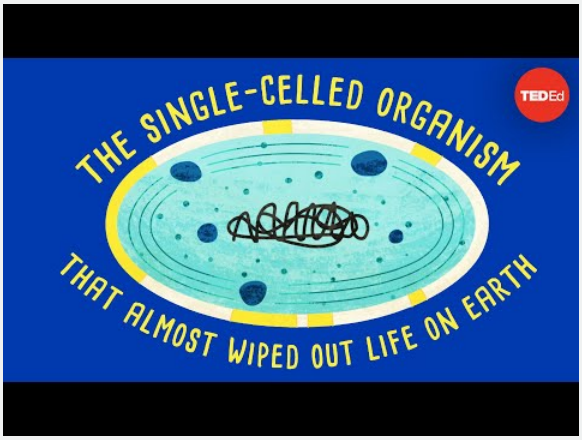
The first, living organisms were likely prokaryotes, which may have evolved from one or more of the circumstances in Unit 3.3.2. The evidence strongly suggests that eukaryotes evolved much later in the history of life. They are discussed in Unit 3.3.4.

Evolution of Prokaryotes

In the recent past, scientists grouped living things into five kingdoms (animals, plants, fungi, protists, and prokaryotes) based on several criteria such as: the absence or presence of a nucleus and other membrane-bound organelles, the absence or presence of cell walls, multicellularity, etc. In the late 20th century, the pioneering work of Carl Woese and others compared sequences of the small-subunit ribosomal RNA (SSU rRNA), which are found in every living organism. This resulted in insights into the evolution of living organisms, their relationships, and a more fundamental way to group organisms on Earth. Based on differences in the structure of cell membranes and in the sequences of their rRNA, Woese and his colleagues proposed that all life on Earth evolved along three domains. The **Domain Bacteria** comprises all eubacteria (a type of prokaryote), the **Domain Archaea** comprises the archaeans (also a type of prokaryote), and the **Domain Eukarya** comprises all eukaryotes, including organisms in the kingdoms Animalia, Plantae, Fungi, and Protista.

Two of the three domains, Bacteria and Archaea, are prokaryotic. Based on fossil and molecular evidence, prokaryotes were the first inhabitants on Earth, appearing 3.5-3.8 billion years ago during the Precambrian Period. These organisms are abundant and ubiquitous; that is, they are present everywhere on Earth today. In addition to inhabiting moderate environments, they are found in extreme conditions: from boiling hot springs to permanently frozen environments such as tundra and sea ice; from salty environments like the Dead Sea to environments under tremendous pressure, such as the depths of the ocean; and from areas without oxygen, such as a waste management plant, to radioactively-contaminated regions, such as Chernobyl in Ukraine. Prokaryotes reside in the human digestive system and on human skin, are responsible for some illnesses, and serve an important role in the preparation of many foods.

Video



This 4-minute video explains how bacteria almost extinguished life on Earth early in life's history.
Question after watching: Why was the creation of oxygen by photosynthesis problematic?

Prokaryotic Life

Microbial Mats

Microbial mats**,** or large **biofilms**, may represent the earliest forms of life on Earth; there is fossil evidence of their presence starting about 3.5 billion years ago. A microbial mat is a multi-layered sheet of prokaryotes that includes mostly bacteria, but also archaea (Figure **3.3.3.1**). Microbial mats are a few centimeters thick, typically growing where different types of materials interface, mostly on moist surfaces. The different species of prokaryotes that comprise the mats use different metabolic pathways, which is the reason for their varied colors. Prokaryotes in a microbial mat are held together by a glue-like sticky substance that they secrete called **extracellular matrix**.

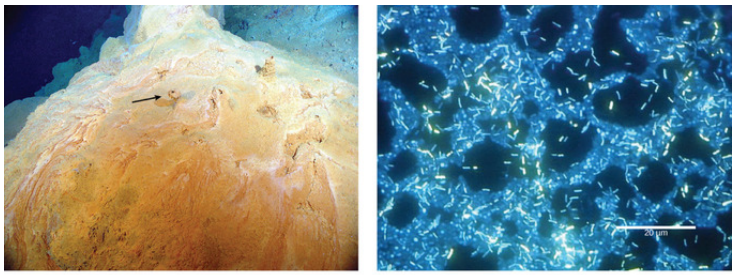


Figure **3.3.3.1**: (a) This microbial mat, about one meter in diameter, grows over a hydrothermal vent in the Pacific Ocean in a region known as the "Pacific Ring of Fire." The mat helps retain microbial nutrients. Chimneys, such as the one indicated by the arrow, allow gases to escape. (b) In this micrograph, individual bacteria in a microbial mat are visualized using fluorescence microscopy.

The organisms in the first biofilms likely obtained their energy from chemicals found near **hydrothermal vents**. A hydrothermal vent is a fissure in the Earth's surface that releases geothermally-heated water and chemicals leached from rocks in the Earth's interior. With the evolution of photosynthesis about 3 billion years ago, some prokaryotes in microbial mats came to use a more widely available energy source, sunlight, whereas others were still dependent on chemicals from hydrothermal vents for energy and food.

? Optional Activity 3.3.3.2

Microbial mats _____.

A. are the earliest forms of life on Earth
B. obtain their energy and food from hydrothermal vents
C. are multi-layered sheets of prokaryotes including mostly Bacteria but also Archaea
D. all of the above

Answer

D. All of the above

The Ecology of Biofilms

Until a couple of decades ago, microbiologists used to think of prokaryotes as isolated entities living apart. This model, however, does not reflect the now better-understood ecology of prokaryotes, most of which prefer to live in communities where they can interact. A biofilm is a microbial community held together in a gummy-textured matrix that consists primarily of polysaccharides secreted by the organisms, together with some proteins and nucleic acids (Figure **3.3.3.2**). Biofilms grow attached to surfaces to secure them in place. Some of the best-studied biofilms are composed of prokaryotes, although fungal biofilms have also been described, as well as some composed of a mixture of fungi and bacteria.

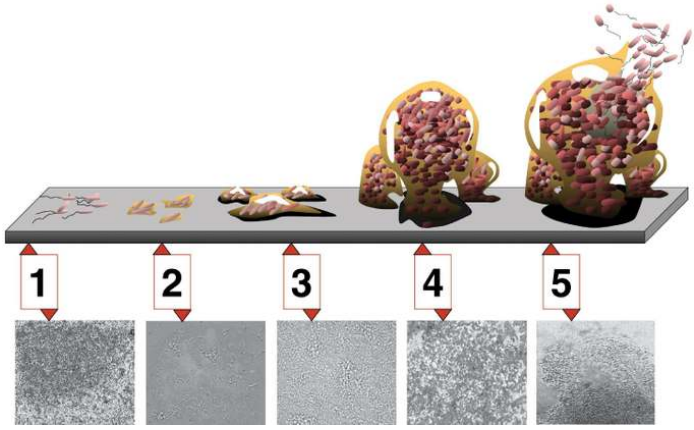


Figure **3.3.3.2**: Micrographs of a *Pseudomonas aeruginosa* biofilm in each of the stages of development. Biofilm development occurs in five stages as shown. During stage 1, initial attachment, prokaryotes adhere to a solid surface. During stage 2, irreversible attachment, hairlike appendages called pili permanently anchor the prokaryotes to the surface. During stage 3, maturation I, the biofilm grows through cell division and recruitment of other prokaryotes. An extracellular matrix composed primarily of polysaccharides holds the biofilm together. During stage 4, maturation II, the biofilm continues to grow and takes on a more complex shape. During stage 5, dispersal, the biofilm matrix is partly broken down, allowing some prokaryotes to escape and colonize another surface.

Biofilms are present almost everywhere: they are visible on the surface of some lakes and can cause the clogging of pipes. They also colonize household surfaces, such as kitchen counters, cutting boards, sinks, and toilets, as well as places on the human body, such as the surfaces of our teeth (plaque). They also play a major role in food contamination.

Interactions among the organisms that populate a biofilm, together with their protective extracellular matrix, make these communities more robust than free-living prokaryotes. The sticky substance that holds bacteria together also excludes most antibiotics and disinfectants, making biofilm bacteria hardier than their free-living counterparts. Overall, biofilms are very difficult to destroy because they are resistant to many common forms of sterilization.

Stromatolites

Fossilized microbial mats represent the earliest record of life on Earth. A **stromatolite** is a sedimentary structure formed when minerals are precipitated out of water by prokaryotes in a microbial mat (Figure **3.3.3.3**). Stromatolites form layered rocks made of carbonate or silicate. Although most stromatolites are artifacts from the past, there are places on Earth where stromatolites are still forming. For example, growing stromatolites have been found in the Anza-Borrego Desert State Park in San Diego County, California.



Figure **3.3.3.3**: Stromatolites: (a) These living stromatolites are located in Shark Bay, Australia. (b) These fossilized stromatolites, found in Glacier National Park, Montana, are nearly 1.5 billion years old.

In addition, the US's National Aeronautic and Space Administration (NASA) is studying Pavilion Lake, north of Whistler BC, for its microbialite populations (Figure **3.3.3.4**). These bacteria colonies live at the bottom of the lake and precipitate minerals that form coral-like structures. These structures formed 10,000 years ago when the glaciers retreated from the area.

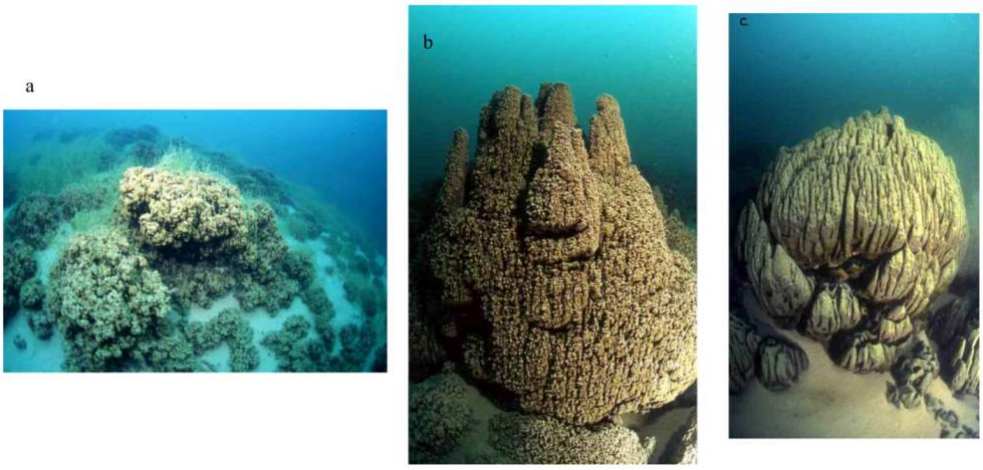


Figure **3.3.3.4**: Examples of microbialite morphologies in Pavillion Lake (CC-BY-SA; Schulze-Makuch, D. et al. https://www.mdpi.com/2075-1729/3/1/21#)

Video





This 2-minute video describes what stromatolites are.
Question after watching: Why are stromatolites relevant to the study of the origin and early evolution of life?

Microbes Are Adaptable: Life in Moderate and Extreme Environments

Some organisms have developed strategies that allow them to survive harsh conditions. Prokaryotes thrive in a vast array of environments; some grow in conditions that would seem very normal to us, whereas others are able to thrive and grow under conditions that would kill a plant or animal. Almost all prokaryotes have a cell wall: a protective structure that allows them to survive in both hyper- and hypo-osmotic conditions. Some soil bacteria can form endospores that resist heat and drought, thereby allowing the organism to survive until favorable conditions recur. These adaptations, along with others, have made bacteria the most abundant life form in all terrestrial and aquatic ecosystems today.

Other bacteria and archaea are adapted to grow under extreme conditions and are called **extremophiles**, meaning "lovers of extremes". Extremophiles have been found in all kinds of environments: the depth of the oceans, hot springs, the Arctic and the Antarctic, in very dry places, deep inside the Earth, in harsh chemical environments, and in high radiation environments, just to mention a few (Figure **3.3.3.5**).



Figure **3.3.3.5**: Certain prokaryotes can live in extreme environments such as the Morning Glory pool, a hot spring in Yellowstone National Park, Wyoming, USA. The spring's vivid blue color is from prokaryotes that thrive in its hot waters.

These organisms give us a better understanding of prokaryotic diversity and help us understand the range of environmental conditions that life can tolerate. This allows us to understand where life may have originated, and where we may find it in the future (including on other planets and moons in the solar system). In addition, the unique enzymes and chemical pathways that extremophiles develop to adapt to their environment raise the possibility of finding new therapeutic drugs or industrial applications.

Because they have specialized adaptations that allow them to live in extreme conditions, many extremophiles cannot survive in moderate environments. There are many different groups of extremophiles. They are identified based on the conditions in which they grow best. For example, organisms that live in acidic (low pH) conditions are called **acidophiles**. Those that live in hot environments are called **thermophiles**. Some habitats are extreme in multiple ways. For example, a soda lake is both salty and alkaline, so organisms that live in a soda lake must be both **alkaliphiles** and **halophiles**.

Other extremophiles, like radioresistant organisms, do not prefer an extreme environment (in this case, one with high levels of radiation), but have adapted to survive in it (Figure **3.3.3.6**).

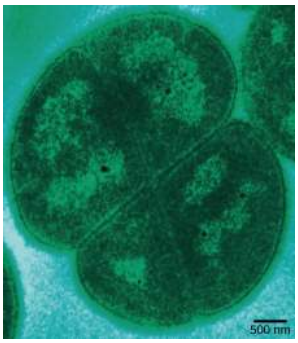


Figure **3.3.3.6**: Deinococcus radiodurans, visualized in this false-color transmission electron micrograph, is a prokaryote that can tolerate very high doses of ionizing radiation. It has evolved DNA repair mechanisms, refined from existing ones found in other organisms, but specialized for its environment, that allow it to reconstruct its chromosome even if it has been broken into hundreds of pieces by radiation or heat.

Prokaryotes in the Dead Sea

One example of a harsh environment is the Dead Sea, a hypersaline basin that is located between Jordan and Israel. **Hypersaline** environments are concentrated seawater. In the Dead Sea, the sodium concentration is 10 times higher than in seawater. The water also contains high levels of magnesium (about 40 times higher than seawater) that are toxic to most living things. Iron, calcium, and magnesium, elements that form divalent ions (Fe^{2+}, Ca^{2+}, and Mg^{2+}), produce what is commonly referred to as “hard” water. Taken together, the high concentration of divalent cations, the acidic pH (6.0), and the intense solar radiation flux make the Dead Sea a unique, and hostile, ecosystem.



Figure **3.3.3.6**: (a) The Dead Sea is hypersaline. Nevertheless, salt-tolerant bacteria thrive in this sea. (b) These halobacteria cells can form salt-tolerant bacterial mats.

Career Connection: Paleontologist

Natural history museums display the fossil casts of extinct animals and information about how these animals evolved, lived, and died. Paleontologists are scientists who study past life. They use fossils to observe and explain how life evolved on Earth and how species interacted with each other and the environment. A paleontologist must be knowledgeable in biology, ecology, chemistry, geology, and other scientific disciplines. A paleontologist’s work may involve field studies: searching for and studying fossils. In addition to digging for and finding fossils, paleontologists also prepare fossils for further study and analysis. Although dinosaurs are probably the first animals that come to mind when thinking about paleontology, paleontologists study everything from plant life, fungi, and fish to sea animals and birds.

An undergraduate degree in Earth science or biology is a good place to start toward the career path of becoming a paleontologist. Most often, a graduate degree is necessary. Additionally, work experience in a museum or in a paleontology lab is useful.

Optional Resource

Paleontology in Western Canada

In Western Canada, there are several sites rich in fossils that are active sites of research. The Burgess Shales, located in Yoho National Park in BC (near Golden) is a designated World Heritage Site. Fossils from this location date to 508 Ma, in the middle of the Cambrian Explosion, when many animal body plans first evolved. Although the site is now at the top of the Rockies, 508

Ma it was at the bottom of a shallow sea where a mudslide likely buried many animals, preserving the structure of even soft-bodied creatures.

In Alberta, Dinosaur Provincial Park is also a UNESCO World Heritage site. Located 48 km east of Calgary, it is not just a recreational area but also an active research site for dinosaurs that lived roughly 75 Ma in the late Cretaceous. Tyrannosaurus, one of the most well-known large dinosaurs, are found here. Dinosaur bones are so plentiful that they are regularly seen sticking out of the ground. Other active dig sites exist in Edmonton, Alberta's river valley and around Grande Prairie.

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Unit 3.3.4 - Eukaryotic Origins

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- List the unifying characteristics of eukaryotes
- Describe what scientists know about the origins of eukaryotes based on the last common ancestor
- Explain endosymbiotic theory

Introduction

Living things fall into three large Domains: Archaea, Bacteria, and Eukarya. The first two have prokaryotic cells, and the third contains all eukaryotes. A relatively sparse fossil record is available to help discern what the first members of each of these lineages looked like, so it is possible that all the events that led to the last common ancestor of extant eukaryotes will remain unknown. However, the comparative biology of extant organisms and the limited fossil record provide some insight into the history of Eukarya.

The earliest fossils of living organisms appear to be Bacteria, most likely cyanobacteria. They are about 3.5 billion years old and are recognizable because of their relatively complex structure and, for prokaryotes, relatively large cells. Most other prokaryotes have small cells, 1 or 2 µm in size, and would be difficult to pick out as fossils. Most living eukaryotes have cells measuring 10 µm or greater. Structures this size, which might be fossils, appear in the geological record about 2.1 billion years ago.

Characteristics of Eukaryotes

Data from these fossils have led comparative biologists to the conclusion that living eukaryotes are all descendants of a single common ancestor. Mapping the characteristics found in all major groups of eukaryotes reveals that the following characteristics must have been present in the last common ancestor.

These characteristics that are common to nearly all eukaryotes include:

1. Cells with nuclei that are surrounded by a nuclear envelope with nuclear pores. This is the single characteristic that is both necessary and sufficient to define an organism as a eukaryote. All currently living eukaryotes have cells with nuclei.
2. Mitochondria. An organelle that processes glucose using oxygen to produce ATP. Some extant eukaryotes have very reduced remnants of mitochondria in their cells, whereas other members of their lineages have “typical” mitochondria.
3. A cytoskeleton containing the structural and motility components called actin microfilaments and microtubules. All extant eukaryotes have these cytoskeletal elements.
4. Flagella and cilia, organelles associated with cell motility. Some extant eukaryotes lack flagella and/or cilia, but there is molecular evidence that they are descended from ancestors that possessed them.
5. Chromosomes, each consisting of a linear DNA molecule coiled around basic (alkaline) proteins called histones. The few eukaryotes with chromosomes lacking histones clearly evolved from ancestors that had them based on information contained in their DNA.
6. Mitosis, which is a process of cellular division wherein replicated chromosomes are divided and separated into two new cells using elements of the cytoskeleton. Mitosis is universally present in eukaryotes.
7. Sexual reproduction and meiosis, a process of cell division and genetic recombination unique to eukaryotes.

Endosymbiosis and the Evolution of Eukaryotes

To understand eukaryotic organisms, it is necessary to understand that all **extant** (currently living) eukaryotes are descendants of an organism that was a composite of a host cell and the cell(s) of an alpha-proteobacterium that "took up residence" inside it. This major theme in the origin of eukaryotes is known as endosymbiosis, one cell engulfing another such that the engulfed cell survives and both cells benefit. Endosymbiotic events likely contributed to the origin of the last common ancestor of today's eukaryotes and to later diversification in certain lineages of eukaryotes such as plants. Before explaining this further, it is necessary to consider metabolism in prokaryotes.

Prokaryotic Metabolism

Prokaryotes are much more metabolically diverse than eukaryotes. This makes sense when considering that the evolution of eukaryotes represents only one branch of the tree of life, and a relatively recent one at that.

Many important metabolic processes such as nitrogen fixation (see Unit 3.4.2), are never found in eukaryotes. One that is not unique to eukaryotes (i.e., some prokaryotes can do it), but that is present in all eukaryotes is the process of **aerobic respiration** (cellular respiration in the presence of oxygen) and it happens in the mitochondria. This suggests that the ability to respire came from a type of prokaryote that could do aerobic respiration; they eventually became the eukaryotic cell's mitochondria. This is discussed in more detail below.

The Problem with Oxygen

While today's atmosphere is about one-fifth molecular oxygen (O_2), geological evidence shows that the atmosphere originally lacked O_2. Without oxygen, aerobic respiration would not be possible, and prokaryotes would have relied on fermentation as a means of transforming the energy in their food into something that they use for their cells. At some point around 3.5 billion years ago, some prokaryotes began using energy from sunlight to power the formation of organic compounds. That is, they evolved the ability to do **photosynthesis**. The group of Gram-negative bacteria that gave rise to cyanobacteria used water as the hydrogen source and released O_2 as a waste product. They used chemical gradients across their cell membrane to do it.

Eventually, the amount of photosynthetic oxygen built up in some environments to levels that were toxic to the organisms living at that time. Oxygen is reactive (it is a strong electron acceptor) and can damage many organic compounds. Metabolic processes evolved to protect organisms from oxygen. Aerobic respiration, one of these processes, utilized the newly available chemical, and its properties as an electron acceptor, to extract energy out of reduced chemicals (a reduced chemical is one that contains many electrons). As energy was extracted from these reduced chemicals, the cell captured the energy to make ATP, a chemical it could readily use to power its processes. This ability to use oxygen to process reduced chemicals (i.e., aerobic respiration) became widely present among prokaryotes, including in a group we now call alpha-proteobacteria (described below).

Organisms that did not evolve aerobic respiration continued to exist, but the were restricted to living in oxygen-free environments. Originally, oxygen-rich environments were likely localized around places where cyanobacteria were active. By about 2 billion years ago, however, geological evidence shows that oxygen built up to higher concentrations in the atmosphere. This is known as the **Great Oxygenation Event (GOE)** (Figure 3.3.4.1). Even though levels were rising, oxygen amounts similar to today's only arose within the last 600 Ma just before the beginning of the Cambrian Period.

Recall that the first fossils that we believe to be eukaryotes date to about 2 Ga, so they appeared during the GOE. Also, recall that all extant eukaryotes descended from an ancestor with mitochondria. These organelles were first observed by scientists in the late 1800s, where they were described as somewhat worm-shaped structures that moved around in the cell. Some early observers suggested that they might be bacteria living inside host cells, but these hypotheses remained unknown or rejected in most scientific communities.

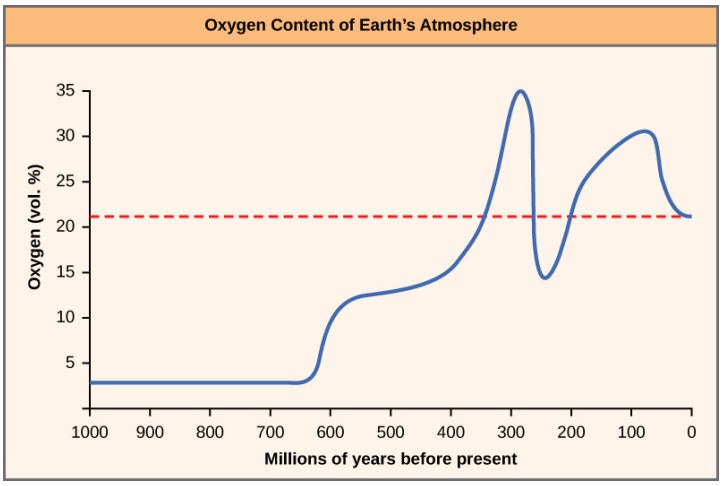


Figure **3.3.4.1**: The oxygen concentration in Earth's atmosphere rose sharply around 300 million years ago. The red dotted line indicates current levels of oxygen in the atmosphere for reference.

Endosymbiotic Theory

As cell biology developed in the twentieth century, it became clear that mitochondria were the organelles responsible for producing ATP using aerobic respiration. In the 1960s, biologist Lynn Margulis proposed the **endosymbiotic theory**, suggesting that eukaryotes were the product of one cell engulfing another. In the proposed model, once engulfed, the two cells continued to live together and evolved co-dependence so that they could no longer live independently of one another. Although Margulis' work initially was met with resistance, this once-revolutionary hypothesis is now widely accepted, with work progressing on uncovering the steps involved in this evolutionary process and the key players involved.

Broadly, it has become clear that many of the nuclear genes and the molecular machinery responsible for replication and the expression of those genes appear closely related to those in Archaea. On the other hand, the metabolic organelles and genes responsible for many energy-harvesting processes had their origins in bacteria.

Much remains to be clarified about how this relationship occurred; this continues to be an exciting field of discovery in biology. For instance, it is not known whether the endosymbiotic event that led to mitochondria occurred before or after the host cell had a nucleus. Such organisms would be among the extinct precursors of the last common ancestor of all eukaryotes. Over many generations, a symbiotic relationship can result if the two organisms depend on each other so completely that neither could survive on its own.

Video



This 8-minute video provides an overview of the steps in the evolution of eukaryotes from prokaryotes.
Question after watching: Which organelle do you think evolved first: chloroplasts that photosynthesize or mitochondria that extract energy from reduced chemicals using oxygen? What is your rationale?

Evidence for Endosymbiosis: Mitochondria

One of the major features distinguishing prokaryotes from eukaryotes is the presence of **mitochondria**. Eukaryotic cells may contain anywhere from one to several thousand mitochondria, depending on the cell's level of energy consumption. Each mitochondrion measures 1 to 10 or greater micrometers (µm) in length and exists in the cell as an organelle that can be ovoid, worm-shaped, or intricately branched (Figure **3.3.4.2**).

Mitochondria arise from the division of existing mitochondria; they may fuse together; and they may be moved around inside the cell by interactions with the cytoskeleton. However, mitochondria cannot survive outside the cell. As the atmosphere was oxygenated by photosynthesis, and as successful aerobic prokaryotes evolved, evidence suggests that an ancestral cell with some membrane compartmentalization engulfed a free-living aerobic prokaryote, specifically an alpha-proteobacterium, thereby giving the host cell the ability to use oxygen to release energy stored in nutrients.

Alpha-proteobacteria are a large group of bacteria that includes species symbiotic with plants, disease organisms that can infect humans via ticks, and many free-living species that use light for energy. Several lines of evidence support that mitochondria are derived from this endosymbiotic event. Most mitochondria are shaped like alpha-proteobacteria and are surrounded by two

membranes, which would result when one membrane-bound organism was engulfed into a vacuole by another membrane-bound organism. The mitochondrial inner membrane is extensive and involves substantial infoldings called cristae that resemble the textured, outer surface of alpha-proteobacteria. The matrix and inner membrane are rich with the enzymes necessary for aerobic respiration.

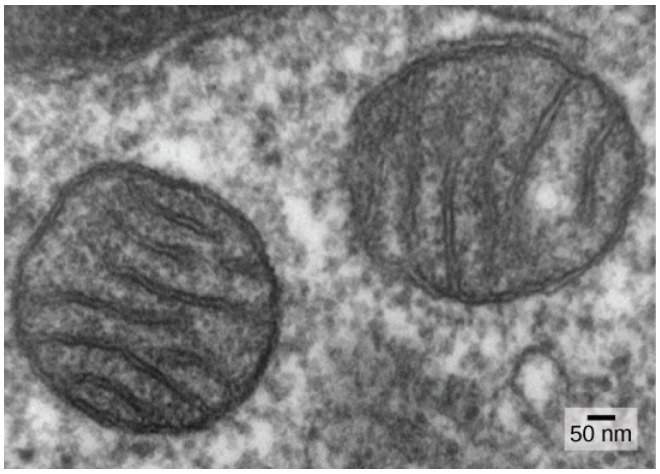


Figure **3.3.4.2**: In this transmission electron micrograph of mitochondria in a mammalian lung cell, the cristae, infoldings of the mitochondrial inner membrane, can be seen in cross-section. (credit: Louise Howard)

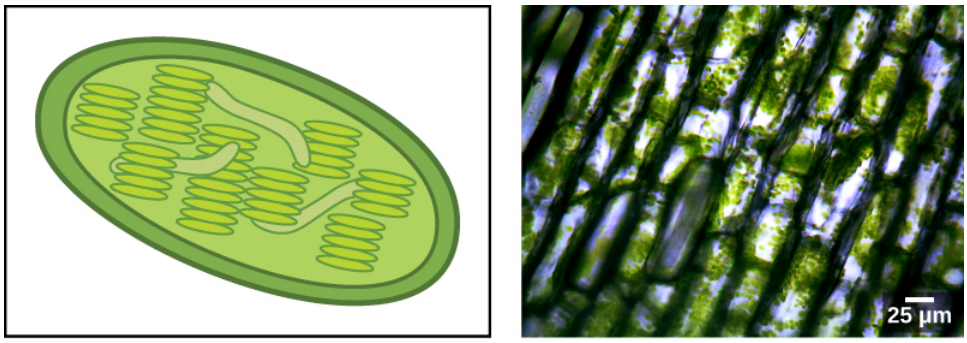
Mitochondria divide independently by a process that resembles binary fission in prokaryotes. Specifically, mitochondria are not formed from scratch (de novo) by the eukaryotic cell; they reproduce within it and are distributed with the cytoplasm when a cell divides or two cells fuse. Therefore, although these organelles are highly integrated into the eukaryotic cell, they still reproduce as if they are independent organisms within the cell. However, their reproduction is synchronized with the activity and division of the cell. Mitochondria have their own (usually) circular DNA chromosome that is stabilized by attachments to the inner membrane and carries genes like genes expressed by alpha-proteobacteria. Mitochondria also have special ribosomes and transfer RNAs that resemble these components in prokaryotes. These features all support that mitochondria were once free-living prokaryotes.

Mitochondria that carry out aerobic respiration have their own genomes, with genes similar to those in alpha-proteobacteria. However, many of the genes for respiratory proteins are located in the nucleus. When these genes are compared to those of other organisms, they appear to be of alpha-proteobacterial origin. Additionally, in some eukaryotic groups, such genes are found in the mitochondria, whereas in other groups, they are found in the nucleus. This has been interpreted as evidence that genes have been transferred from the endosymbiont chromosome to the host genome. This loss of genes by the endosymbiont is probably one explanation why mitochondria cannot live without a host.

Some living eukaryotes are anaerobic and cannot survive in the presence of oxygen. Some appear to lack organelles that could be recognized as mitochondria. In the 1970s to the early 1990s, many biologists suggested that some of these eukaryotes were descended from ancestors whose lineages had diverged from the lineage of mitochondrion-containing eukaryotes before endosymbiosis occurred. However, later findings suggest that reduced organelles are found in most, if not all, anaerobic eukaryotes, and that all eukaryotes appear to carry some genes in their nuclei that are of mitochondrial origin. In addition to the aerobic generation of ATP, mitochondria have several other metabolic functions. One of these functions is to generate clusters of iron and sulfur that are important cofactors of many enzymes. Such functions are often associated with the reduced mitochondrion-derived organelles of anaerobic eukaryotes. Therefore, most biologists now accept that the LCA of eukaryotes had mitochondria.

Evidence of Endosymbiosis: Plastids

Some groups of eukaryotes are photosynthetic. Their cells contain, in addition to the standard eukaryotic organelles, another kind of organelle called a plastid. When such cells are carrying out photosynthesis, their plastids are rich in the pigment chlorophyll *a* and a range of other pigments, called **accessory pigments**, which are involved in harvesting energy from light. Photosynthetic plastids are called **chloroplasts** (Figure **3.3.4.3**).



(a) (b)

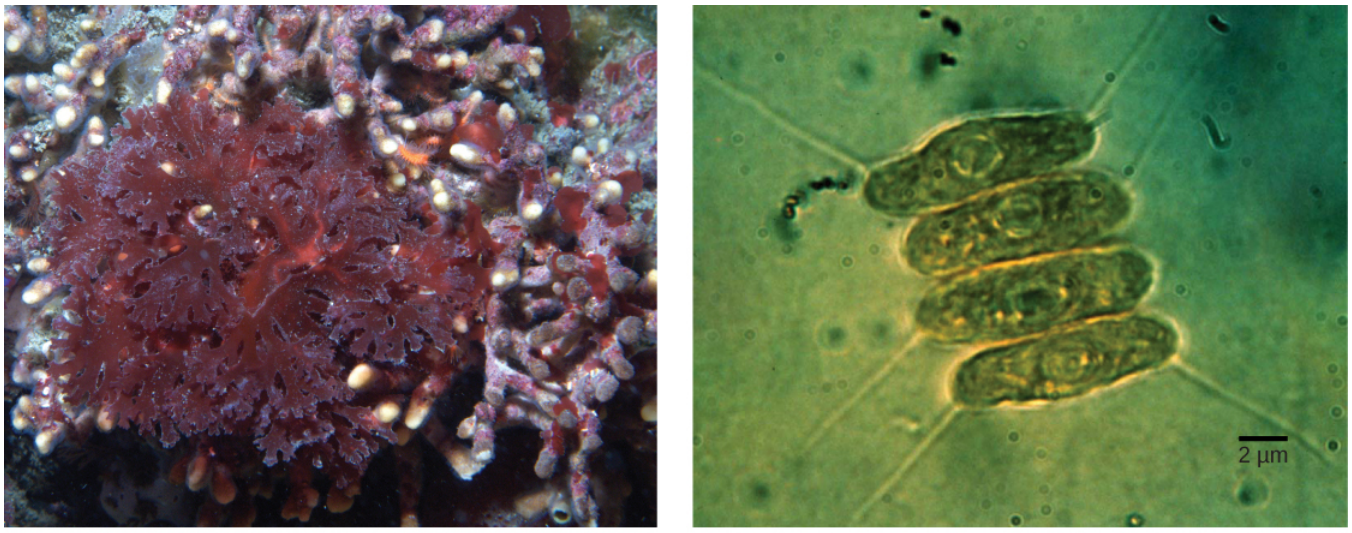
Figure **3.3.4.3**: (a) This chloroplast cross-section illustrates its elaborate inner membrane organization. Stacks of thylakoid membranes compartmentalize photosynthetic enzymes and provide scaffolding for chloroplast DNA. (b) In this micrograph of *Elodea* sp., the chloroplasts can be seen as small green spheres. (credit b: modification of work by Brandon Zierer; scale-bar data from Matt Russell)

Like mitochondria, plastids appear to have an endosymbiotic origin. This hypothesis was also championed by Lynn Margulis. Plastids are derived from cyanobacteria that lived inside the cells of an ancestral, aerobic, heterotrophic eukaryote. This is called primary endosymbiosis, and plastids of primary origin are surrounded by two membranes. This likely happened twice in the history of eukaryotes.

Cyanobacteria are a group of Gram-negative bacteria with all the conventional structures of the group. However, unlike most prokaryotes, they have extensive, internal membrane-bound sacs called thylakoids. Chlorophyll is a component of these membranes, as are many of the proteins of the light reactions of photosynthesis (Figure **3.3.4.4**). Cyanobacteria also have the peptidoglycan wall and lipopolysaccharide layer associated with Gram-negative bacteria.

Chloroplasts of primary origin have thylakoids, a circular DNA chromosome, and ribosomes like those of cyanobacteria. Each chloroplast is surrounded by two membranes. The outer membrane surrounding the plastid is thought to be derived from the vacuole in the host, and the inner membrane is thought to be derived from the plasma membrane of the symbiont.

There is also, as with the case of mitochondria, strong evidence that many of the genes of the endosymbiont were transferred to the nucleus. Plastids, like mitochondria, cannot live independently outside the host. In addition, like mitochondria, plastids are derived from the division of other plastids and are never built from scratch. Researchers have suggested that the endosymbiotic event that led to the engulfing of the chloroplast ancestor occurred 1 to 1.5 billion years ago, at least 500 million years after the fossil record suggests that eukaryotes were present.



(a) (b)

Figure **3.3.4.4**: (a) Red algae and (b) green algae (visualized by light microscopy) share similar DNA sequences with photosynthetic cyanobacteria. Scientists speculate that, in a process called endosymbiosis, an ancestral prokaryote engulfed a photosynthetic cyanobacterium that evolved into modern-day chloroplasts. (credit a: modification of work by Ed Bierman; credit b: modification of work by G. Fahnenstiel, NOAA; scale-bar data from Matt Russell)

? Optional Activity 3.3.4.1

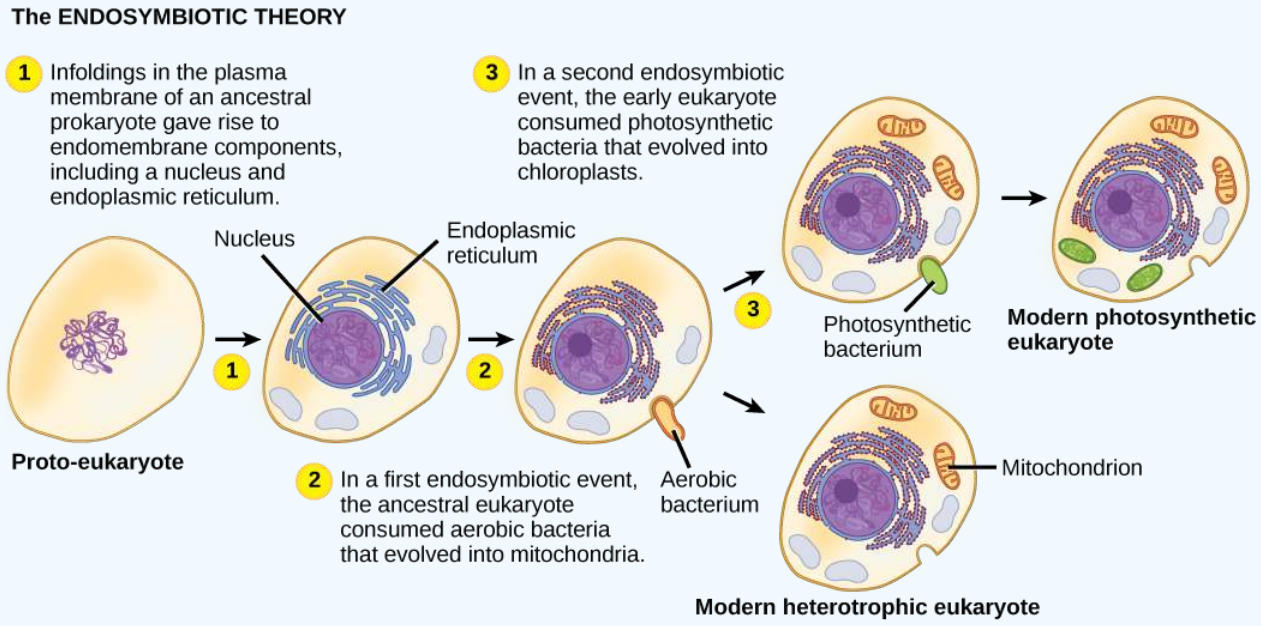


Figure **3.3.4.5**: The first eukaryote may have originated from an ancestral prokaryote that had undergone membrane proliferation, compartmentalization of cellular function (into a nucleus, lysosomes, and an endoplasmic reticulum), and the establishment of endosymbiotic relationships with an aerobic prokaryote, and, in some cases, a photosynthetic prokaryote, to form mitochondria and chloroplasts, respectively.

What evidence is there that mitochondria were incorporated into the ancestral eukaryotic cell before chloroplasts?

Answer

All eukaryotic cells have mitochondria, but not all eukaryotic cells have chloroplasts.

Video



This 4.5-minute video provides a quick overview of the differences between prokaryotes and eukaryotes.
Question after watching: What do the characteristics contained in both prokaryotes and eukaryotes tell you about the evolution of life on Earth?

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SECTION OVERVIEW

3.4: Biological Diversity

Learning Objectives

- Recognize the characteristics of life
- Discuss the difference between a virus, viroid, prion, and a living cell.
- Describe the mechanisms of viral infection.
- Describe the distinguishing characteristics of organisms within Bacteria, Archaea, and Eukaryota
- Compare and contrast the variety of organisms within Protista
- Describe the characteristics of the Fungi, Plantae, and Animalia

In this section, the diversity of life is explored with a detailed study of various organisms and a discussion of emerging phylogenetic relationships. This unit moves from viruses to living organisms like bacteria, discusses the organisms formerly grouped as protists, and devotes multiple chapters to plant and animal life.

3.4.1: Acellular Entities - Viruses, Prions, and Viroids

3.4.2: Kingdoms Bacteria and Archaea

3.4.3: Protists

3.4.4: Kingdom Fungi

3.4.5: Kingdom Animalia - Evolution and Phylogeny

3.4.6: Kingdom Animalia - Adaptations

3.4.7: Kingdom Plantae - Evolution and Phylogeny

3.4.8: Kingdom Plantae - Adaptations

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Unit 3.4.1 - Acellular Entities: Viruses, Prions, and Viroids

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.4.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe how viruses were first discovered and how they are detected
- Identify three hypotheses about how viruses evolved
- Explain the Baltimore classification systems for viruses
- Describe prions and their basic properties
- Define viroids and their targets of infection

Viruses

No one knows exactly when viruses emerged or from where they came, since viruses do not leave physical footprints such as fossils. Modern viruses are thought to be a mosaic of bits and pieces of nucleic acids picked up from past hosts along their evolutionary paths.

Viruses exist in a netherworld between a living organism and a nonliving entity. Living things grow, metabolize, reproduce, and evolve. Viruses exhibit some of these abilities but cannot do any of them on their own. They must infect a host cell and hijack the host's replication machinery to produce (nearly) identical progeny virus particles. Since their reproduction is not perfect, they can evolve through natural selection. They do not have their own metabolism and are entirely dependent on their host cells to replicate. They do not metabolize or grow but rather are assembled into their mature form by the host cell.

Viruses are acellular parasitic entities that are not classified within any domain or kingdom. Viruses are diverse entities. They vary in their structure, their replication methods, and in their target hosts. Nearly all forms of life—from bacteria and archaea to eukaryotes such as plants, animals, and fungi—have viruses that infect them. While most biological diversity can be understood through evolutionary history such as how species have adapted to conditions and environments, much about virus origins and evolution remains unknown.

Video





In this 4-minute video, viruses are described as the most common biological unit on Earth, outnumbering all all other types combined.

Question after watching: Why do scientists talk about "types" of viruses rather than "species" of viruses?

Video





This 11-minute video points out, viruses are all around us, they evolve, grow, and can be killed.
Question after watching: What hypotheses are offered to reconsider viruses as being alive? Are you convinced? Why or why not?

Virus Discovery and Detection

Viruses were first discovered after the development of a porcelain filter, called the Chamberland-Pasteur filter, which could remove all bacteria visible in the microscope from any liquid sample. In 1886, Adolph Meyer demonstrated that a disease of tobacco plants, tobacco mosaic disease, could be transferred from a diseased plant to a healthy one via liquid plant extracts. In 1892, Dmitri Ivanowski showed that this disease could be transmitted in this way even after the Chamberland-Pasteur filter had removed all viable bacteria from the extract. Still, it was many years before it was proven that these "filterable" infectious agents were not simply very small bacteria but were a new type of very small, disease-causing particle.

Virions, single virus particles outside of the cell, are very small, about 20–250 nanometers in diameter. These individual virus particles are the infectious form of a virus outside the host cell. Unlike bacteria (which are about 100x larger), we cannot see viruses with a light microscope (except for some large virions of the poxvirus family). It was not until the development of the electron microscope in the late 1930s that scientists got their first look of the structure of the tobacco mosaic virus (TMV) (Figure **3.4.1.1**) and other viruses (Figure **3.4.1.2**). The surface structure of virions can be observed by both scanning and transmission electron microscopy, whereas the internal structures of the virus can only be observed in images from a transmission electron microscope. The use of these technologies has allowed for the discovery of many viruses from all types of living organisms. They were initially grouped by shared morphology. Later, groups of viruses were classified by the type of nucleic acid they contained, DNA or RNA, and whether their nucleic acid was single- or double-stranded. More recently, molecular analysis of viral replicative cycles has further refined their classification.

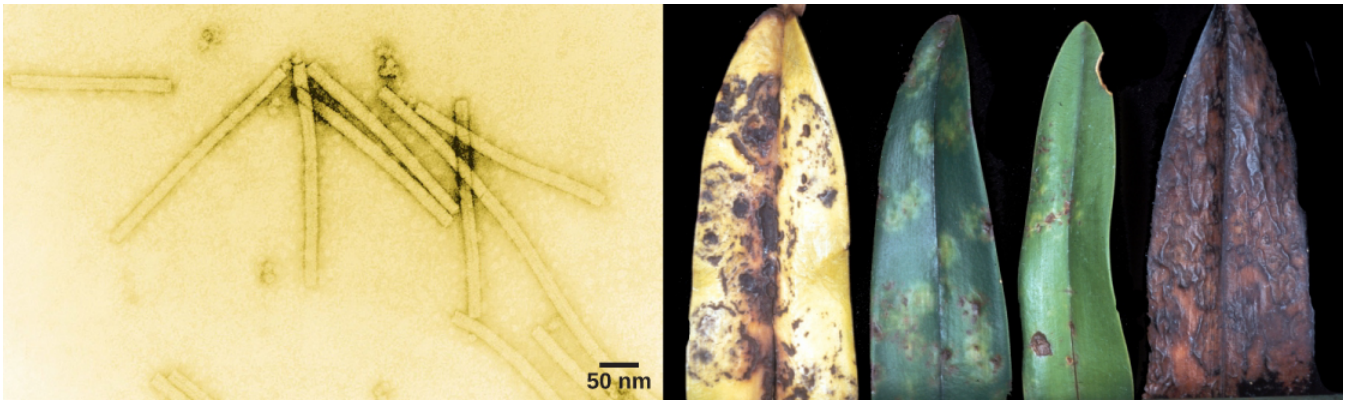
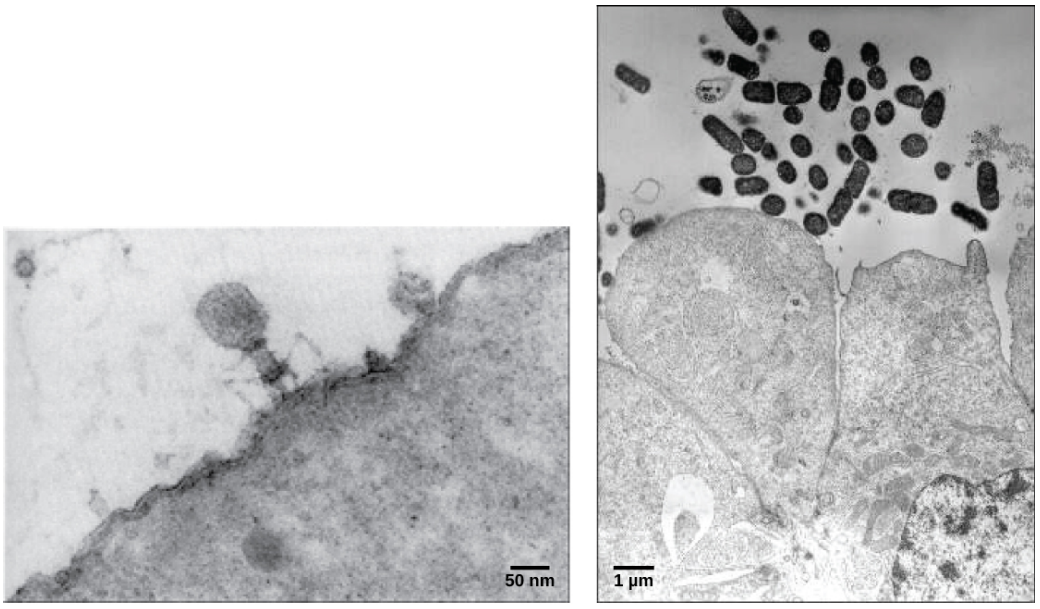


Figure **3.4.1.1**: The tobacco mosaic virus (left), seen here by transmission electron microscopy, was the first virus to be discovered. The virus causes disease in tobacco and other plants, such as the orchid (right). (credit a: USDA ARS; credit b: modification of work by USDA Forest Service, Department of Plant Pathology Archive North Carolina State University; scale-bar data from Matt Russell)



(a) (b)

Figure **3.4.1.2**: In these transmission electron micrographs, (a) a virus (which looks like a moon lander) is dwarfed by the bacterial cell it infects (only a portion of which fills the bottom right of the image). For size comparison, (b) bacterial *E. coli* cells (dark oval shapes) are dwarfed by cultured colon cells (the light grey larger blobs in the middle and bottom of the image). (credit a: modification of work by U.S. Dept. of Energy, Office of Science, LBL, PBD; credit b: modification of work by J.P. Nataro and S. Sears, unpub. data, CDC; scale-bar data from Matt Russell)

Evolution of Viruses

Although biologists have accumulated a significant amount of knowledge about how present-day viruses evolve, much less is known about how viruses originated in the first place. When exploring the evolutionary history of most organisms, scientists can look at fossil records and similar physical evidence. However, viruses do not fossilize, so researchers must conjecture by investigating how today's viruses evolve and by using biochemical and genetic information to create speculative virus histories.

While most findings agree that viruses do not have a single common ancestor, scholars have yet to agree on a hypothesis about the origins of viruses. One such hypothesis, called devolution or the **regressive hypothesis**, proposes that viruses evolved from free-living cells that progressively lost the ability to reproduce and metabolize on their own. A second hypothesis (called escapist or the **progressive hypothesis**) suggests that viruses originated from RNA and DNA molecules that escaped from a host cell. This theory accounts for viruses having either an RNA or a DNA genome. A third hypothesis posits a system of self-replication similar to that of other self-replicating molecules, likely evolving alongside the cells they rely on as hosts. Studies of some plant pathogens support this hypothesis.

As technology advances, scientists may develop and refine further hypotheses to explain the origin of viruses. The emerging field called **virus molecular systematics** attempts to do that through comparisons of sequenced genetic material. Researchers in this field hope their work could someday lead to advances in the treatments for the ailments of viral diseases.

Video



This 2-minute video describes the speed at which viruses evolve through mutations.
Questions after watching: Why do some evolutionary scientists focus on viruses? Why is it important to humans?

Video

The SARS-CoV-2 (Covid-19) pandemic has altered life throughout the world. This 1.5-minute video describes how SARS-CoV-2 infects humans and reproduces.

Question after watching: What are three things you learned from this video that you did not know prior to watching?

Viral Structure and Function

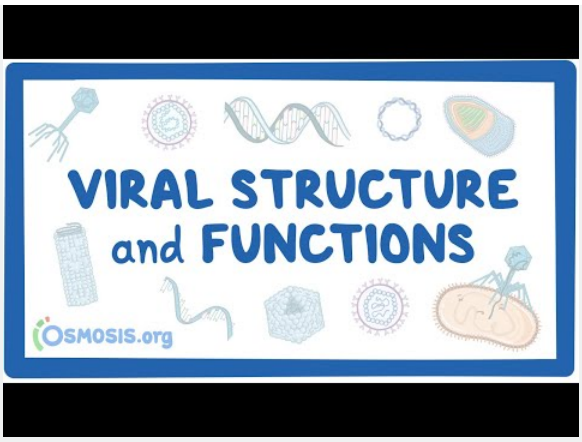
Viruses are **acellular**, meaning they are biological entities that do not have a cellular structure. Therefore, they lack most of the components of cells, such as organelles, ribosomes, and the plasma membrane. A virion consists of a nucleic acid core, an outer protein coating or capsid, and sometimes (notably among viruses that infect animal cells) an outer envelope made of protein and phospholipid membranes derived from the host cell. Viruses may also contain additional proteins, such as enzymes. The most obvious difference between members of viral families is their morphology, which is quite diverse. An interesting feature of viral complexity is that the complexity of the host does not correlate with the complexity of the virion. Some of the most complex virion structures are observed in **bacteriophages**, viruses that infect the simplest living organisms, bacteria.

Viruses come in many shapes and sizes, but these are consistent and distinct for each viral family. All virions have a nucleic acid genome covered by a protective layer of proteins, called a **capsid**. The capsid is made up of protein subunits called capsomeres. Some viral capsids are simple polyhedral “spheres,” whereas others are quite complex in structure.

Unlike nearly all living organisms that use DNA as their genetic material, viruses may use either DNA or RNA to encode their information. Some viruses are composed of single-stranded RNA, double-stranded RNA, single-stranded DNA, or double-stranded DNA. It may be linear or circular. While most viruses contain a single nucleic acid, others have genomes that have several, which are called **segments** (analogous to chromosomes). The **virus core** contains the genome or total genetic content of the virus. Viral genomes tend to be small, containing only those genes that encode proteins that the virus cannot get from the host cell.

Video





In this 7-minute video, discover the wide variety of viral shapes and types.
Question after watching: Why are viruses dependent on other organisms for their reproduction?

Virus Classification

To understand the features shared among different groups of viruses, a classification scheme is necessary. Biologists have used several classification systems in the past, based on the morphology and genetics of different viruses. However, these earlier classification methods grouped viruses differently, based on which features of the virus they were using to classify them. The most commonly used classification method today is called the Baltimore classification scheme and is based on how messenger RNA (mRNA) is generated in each type of virus.

Baltimore Classification

The most commonly used system of virus classification was developed by Nobel Prize-winning biologist David Baltimore in the early 1970s. In addition to the differences in morphology and genetics mentioned above, the **Baltimore classification** scheme groups viruses according to how the mRNA is produced during the replicative cycle of the virus. The characteristics of each group in the Baltimore classification are summarized in Table **3.4.1.1** with examples of each group.

Table **3.4.1.1**: Baltimore Classification

Group	Characteristics	Mode of mRNA Production	Example
I	Double-stranded DNA	mRNA is transcribed directly from the DNA template	Herpes simplex (herpesvirus)
II	Single-stranded DNA	DNA is converted to double-stranded form before RNA is transcribed	Canine parvovirus (parvovirus)
III	Double-stranded RNA	mRNA is transcribed from the RNA genome	Childhood gastroenteritis (rotavirus)
IV	Single stranded RNA (+)	Genome functions as mRNA	Common cold (pircornavirus)
V	Single stranded RNA (-)	mRNA is transcribed from the RNA genome	Rabies (rhabdovirus)
VI	Single stranded RNA viruses with reverse transcriptase	Reverse transcriptase makes DNA from the RNA genome; DNA is then incorporated in the host genome; mRNA is transcribed from the incorporated DNA	Human immunodeficiency virus (HIV)
VII	Double stranded DNA viruses with reverse transcriptase	The viral genome is double-stranded DNA, but viral DNA is replicated through an RNA intermediate; the RNA may serve directly as mRNA or as a template to make mRNA	Hepatitis B virus (hepadnavirus)

Virus Replication

Viruses can be seen as obligate, intracellular parasites. A virus must attach to a living cell's surface, be taken inside, manufacture its proteins and copy its genome, and find a way to escape the cell so that the virus can infect other cells. Viruses can infect only certain species and only certain cells within that host. Cells that a virus may use to replicate are called **permissive**. For most viruses, the molecular basis for this specificity is that a particular surface molecule known as the **viral receptor** must be found on the host cell surface for the virus to attach. Also, metabolic and host cell immune response differences seen in different cell types based on differential gene expression are a likely factor in the type of cells a virus may target. The permissive cell must make the substances that the virus needs or the virus will not be able to replicate there.

A virus must use cell processes to replicate. The viral replication cycle can produce dramatic biochemical and structural changes in the host cell, which may cause cell damage. These changes, called **cytopathic** (causing cell damage) effects, can change cell functions or even destroy the cell. Some infected cells, such as those infected by the common cold virus known as rhinovirus, die through **lysis** (bursting) or **apoptosis** (programmed cell death or “cell suicide”), releasing all progeny virions at once. The symptoms of viral diseases result from the immune response to the virus, which attempts to control and eliminate the virus from the body, and from cell damage caused by the virus. Many animal viruses, such as HIV (human immunodeficiency virus), leave the infected cells of the immune system by a process known as **budding**, where virions leave the cell individually. During the budding process, the cell does not undergo lysis and is not immediately killed. However, the damage to the cells that the virus infects may make it impossible for the cells to function normally, even though the cells remain alive for a period of time.

? Optional Activity 3.4.1.1

Influenza virus is packaged in a viral envelope that fuses with the plasma membrane. This way, the virus can exit the host cell without killing it. What advantage does the virus gain by keeping the host cell alive?

Answer

The host cell can continue to make new virus particles.

Career Connection: Virologist

Virology is the study of viruses, and a virologist is an individual trained in this discipline. Training in virology can lead to many different career paths. Virologists are actively involved in academic research and teaching in colleges and medical schools. Some virologists treat patients or are involved in the development and/or production of vaccines. They might participate in epidemiologic studies (Figure **3.4.1.3**) or become science writers, to name just a few possible careers.

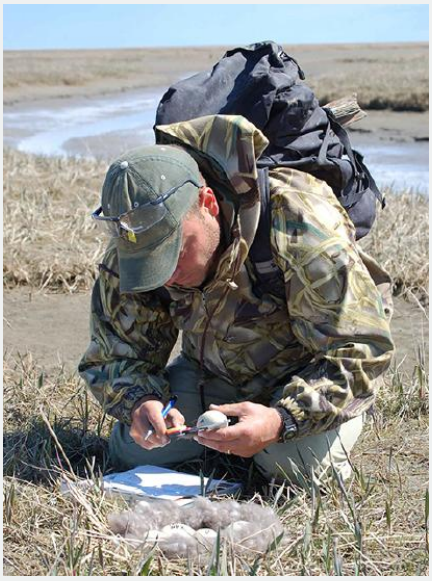


Figure **3.4.1.3**: This virologist is engaged in fieldwork, sampling eggs from this nest for avian influenza. (credit: Don Becker, USGS EROS, U.S. Fish and Wildlife Service)

If you think you may be interested in a career in virology, find a mentor in the field. Many large medical centers have departments of virology, and smaller hospitals usually have virology labs within their microbiology departments. Volunteer in a virology lab for a semester or work in one over the summer. Discussing the profession and getting a first-hand look at the work will help you decide whether a career in virology is right for you.

Other Acellular Entities: Prions and Viroids

Prions and viroids are **pathogens** (agents with the ability to cause disease) that have simpler structures than viruses but, in the case of prions, still can produce deadly diseases.

Prions

Prions, so-called because they are made of a protein, are infectious particles—smaller than viruses—that contain no nucleic acids (neither DNA nor RNA). Historically, the idea of an infectious agent that did not use nucleic acids was considered impossible, but pioneering work by Nobel Prize-winning biologist Stanley Prusiner has convinced most biologists that such agents exist.

Fatal neurodegenerative diseases, such as kuru in humans and bovine spongiform encephalopathy (BSE) in cattle (commonly called “mad cow disease”) were shown to be transmitted by prions. The disease was spread by the consumption of meat, nervous tissue, or internal organs. Individuals with kuru and BSE show symptoms of loss of motor control and unusual behaviors, such as uncontrolled bursts of laughter with kuru, followed by death.

BSE was initially thought to only affect cattle. Cattle dying of the disease were shown to have developed lesions or “holes” in the brain, causing the brain tissue to resemble a sponge. Later, however, it was shown that a similar encephalopathy in humans known as Creutzfeldt-Jakob disease (CJD) could be acquired from eating meet from animals with BSE (Figure **3.4.1.4**). This led to bans by several countries on the importation of British beef and causing considerable economic damage to the British cattle industry. BSE

still exists in some areas of the world, and although a rare disease, CJD is difficult to detect and to treat. The disease can be spread from human to human by blood, so many countries have banned blood donation from regions associated with BSE.

The cause of spongiform encephalopathies, such as kuru and BSE, is an infectious structural variant of a normal cellular protein called PrP (prion protein). It is this variant that constitutes the prion particle. PrP exists in two forms, PrP^{c}, the normal form of the protein, and PrP^{sc}, the infectious form. Once introduced into the body, the PrP^{sc} prion binds to normal PrP^{c} protein and converts it to PrP^{sc}. This leads to an exponential increase of PrP^{sc} proteins, which aggregate. PrP^{sc} is folded abnormally, and the resulting conformation (shape) is directly responsible for the lesions seen in the brains of infected cattle with BSE and humans with CJD. Thus, the prion seems to be an entirely new form of infectious agent, the first one found whose transmission is not reliant upon genes made of DNA or RNA.

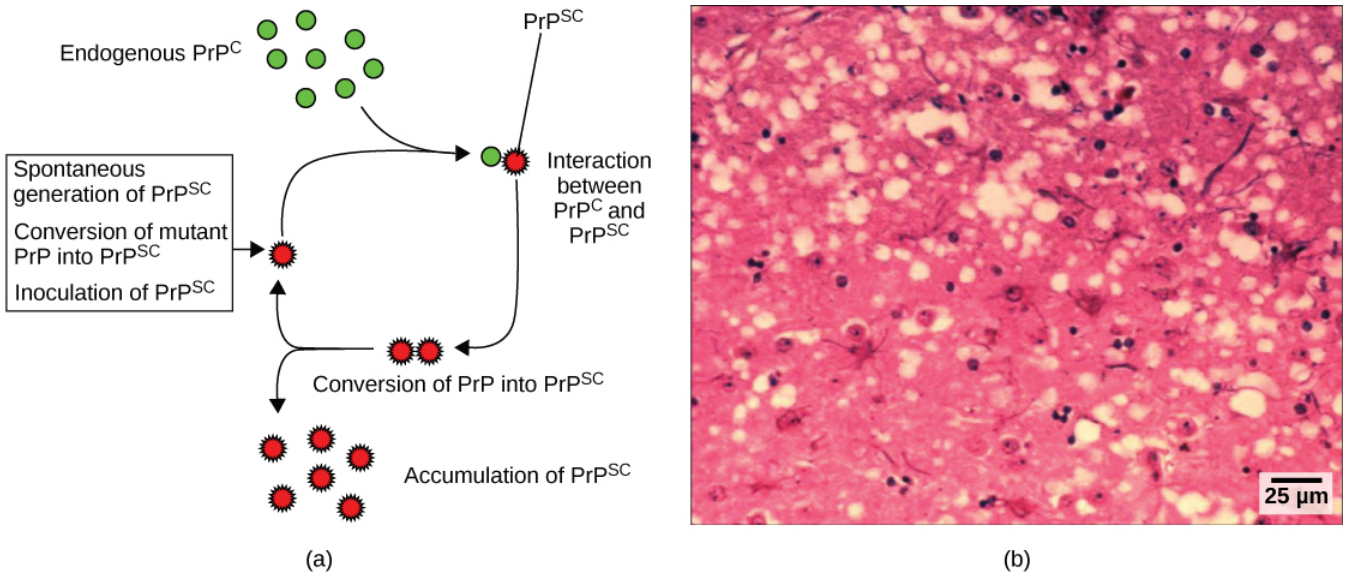
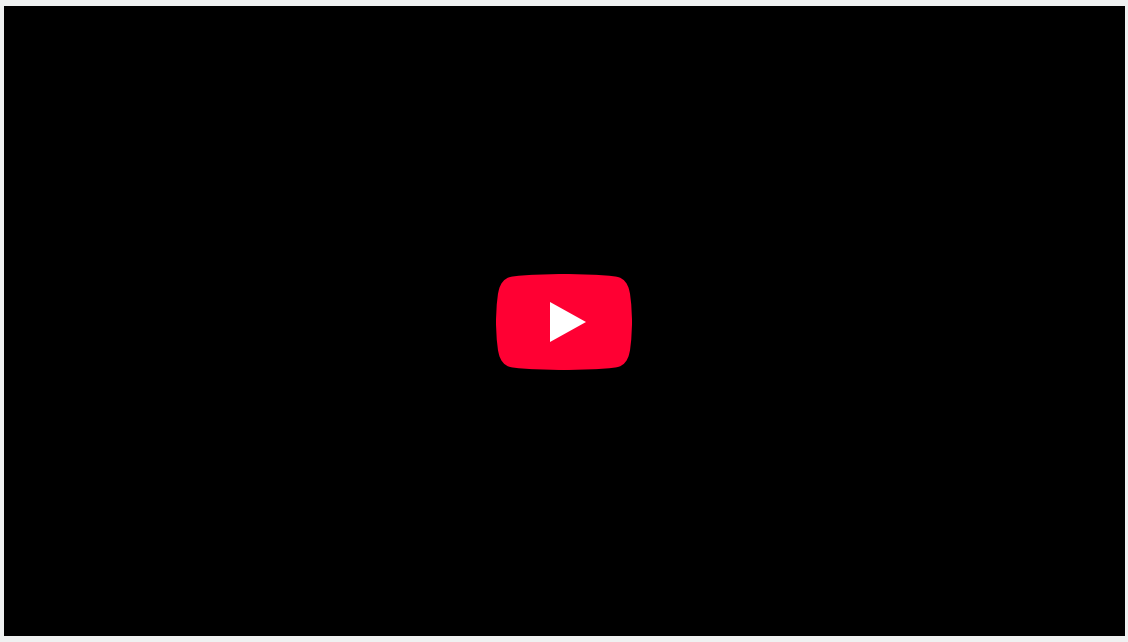


Figure **3.4.1.4**: (a) Endogenous normal prion protein (PrP^{c}) is converted into the disease-causing form (PrP^{sc}) when it encounters this variant form of the protein. PrP^{sc} may arise spontaneously in brain tissue, especially if a mutant form of the protein is present, or it may occur via the spread of misfolded prions consumed in food. (b) This prion-infected brain tissue, visualized using light microscopy, shows the vacuoles that give it a spongy texture (the light-colored holes), typical of transmissible spongiform encephalopathies. (credit b: modification of work by Dr. Al Jenny, USDA APHIS; scale-bar data from Matt Russell)

Video





In this 5-minute video, Hank describes prions - misfolded proteins that are responsible for destroying brain cells and infect new hosts by eating an abnormal prion protein.
Question after watching: Why were some women and children more at risk to Kuru than men? Why were some resistant to Kuru?

? Optional Activity 3.4.1.1

Which of the following is not associated with prions?

A. replicating shapes
B. mad cow disease
C. DNA
D. mutations in the gene for a protein

Answer

C

Viroids

Viroids are plant pathogens: small, single-stranded, circular RNA particles that are much simpler than a virus. They do not have a capsid or outer envelope, but like viruses can reproduce only within a host cell. Viroids do not, however, manufacture any proteins, and they only produce a single, specific RNA molecule. Human diseases caused by viroids have yet to be identified.

Viroids are known to infect plants (Figure **3.4.1.5**) and are responsible for crop failures and the loss of millions of dollars in agricultural revenue each year. Some of the plants they infect include potatoes, cucumbers, tomatoes, chrysanthemums, avocados, and coconut palms.



Figure **3.4.1.5**: These potatoes have been infected by the potato spindle tuber viroid (PSTV), which is typically spread when infected knives are used to cut healthy potatoes, which are then planted. (credit: Pamela Roberts, University of Florida Institute of Food and Agricultural Sciences, USDA ARS)

Video





This 4-minute video describes the discovery of viroids: infectious, replicating bits of RNA.

Question after watching:

How are viroids helping biologists investigate the origin of life?

? Optional Activity 3.4.1.2

Which statement is true of viroids?

A. They are single-stranded RNA particles.
B. They reproduce only outside of the cell.
C. They produce proteins.
D. They affect both plants and animals.

Answer

A. They are single-stranded RNA particles.

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Unit 3.4.2 - Kingdoms Bacteria and Archaea

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1.5 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.4.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe the basic structure of a typical prokaryote
- Describe important differences in structure between Archaea and Bacteria
- Identify the macronutrients needed by prokaryotes, and explain their importance
- Describe the ways in which prokaryotes get energy and carbon for life processes
- Describe the roles of prokaryotes in the carbon and nitrogen cycles

Introduction

The domain Bacteria comprises all organisms in the kingdom Bacteria, the domain Archaea comprises the rest of the prokaryotes, and the domain Eukarya comprises all eukaryotes—including organisms in the kingdoms Animalia, Plantae, Fungi, and Protista (Figure **3.4.2.1**).

Unit 3.3 explored the diversity of prokaryotes, their formation, and the role they played in the early Earth. Two of the three domains—Bacteria and Archaea—are prokaryotic. Prokaryotes were the first inhabitants on Earth, appearing 3.5 to 3.8 billion years ago. These organisms are abundant and ubiquitous; that is, they are found everywhere on the planet. In addition to inhabiting moderate environments, they are found in extreme conditions: from boiling springs to permanently frozen environments in Antarctica; from salty environments like the Dead Sea to environments under tremendous pressure, such as the depths of the ocean; and from areas without oxygen, such as a waste management plant, to radioactively contaminated regions (Figure **3.4.2.2**). In addition, the evolution from prokaryotic to eukaryotic life was explored.

In this section, the focus will be on prokaryotes beginning with the definition of what they are. There are many differences between prokaryotic and eukaryotic cells. However, all cells have four common structures: the plasma membrane, which functions as a barrier for the cell and separates the cell from its environment; the cytoplasm, a jelly-like substance inside the cell; nucleic acids, the genetic material of the cell; and ribosomes, where protein synthesis takes place. Prokaryotes come in many shapes, but most fall into three categories: **cocci** (spherical), **bacilli** (rod-shaped), and **spirilli** (spiral-shaped) (Figure **3.4.2.3**).

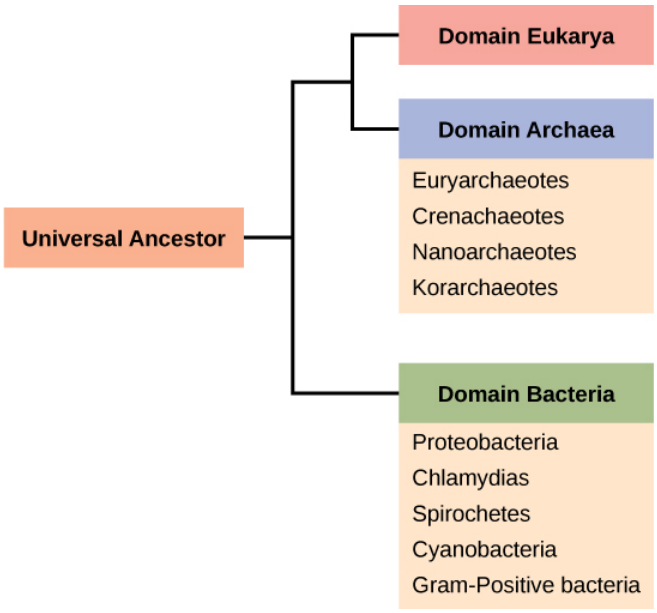


Figure **3.4.2.1**: Bacteria and Archaea are both prokaryotes but differ enough to be placed in separate domains. An ancestor of modern Archaea is believed to have given rise to Eukarya, the third domain of life. Archaeal and bacterial phyla are shown; the evolutionary relationship between these phyla is still open to debate.



Figure **3.4.2.2**: Certain prokaryotes can live in extreme environments such as the Morning Glory pool, a hot spring in Yellowstone National Park, Wyoming, USA. The spring's vivid blue color is from the prokaryotes that thrive in its very hot waters. (credit: modification of work by Jon Sullivan)

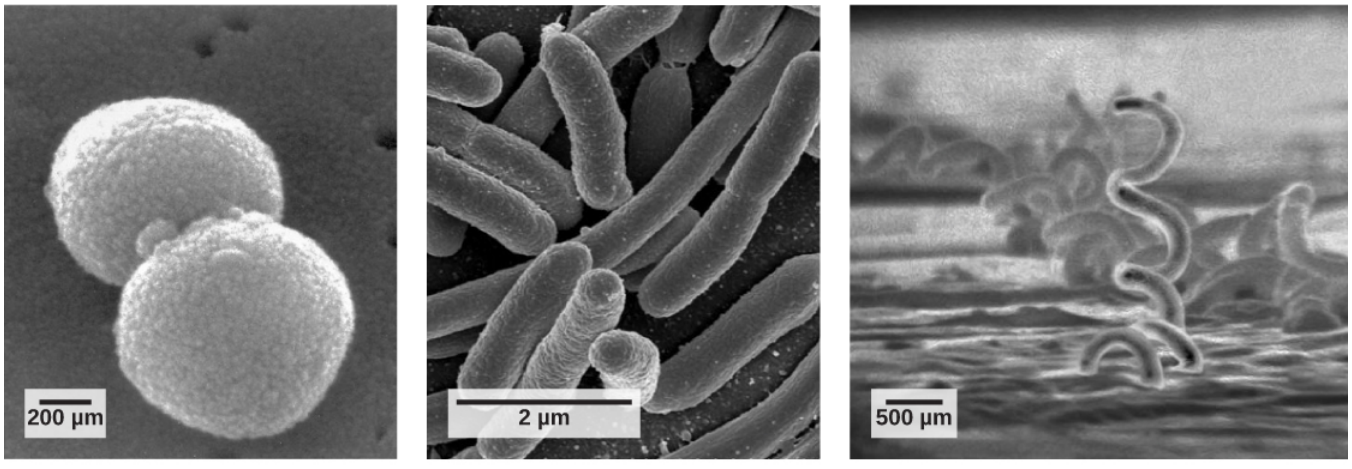
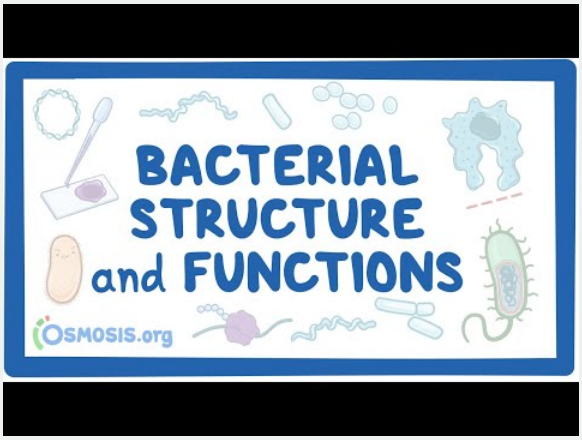


Figure **3.4.2.3**: Prokaryotes fall into three basic categories based on their shape, visualized here using scanning electron microscopy: (a) cocci or spherical (a pair is shown); (b) bacilli or rod-shaped; and (c) spirilli or spiral-shaped. (credit a: modification of work by Janice Haney Carr, Dr. Richard Facklam, CDC; credit c: modification of work by Dr. David Cox; scale-bar data from Matt Russell)

Video



This 7-minute video describes the prokaryotic cells that play an important role in human disease and health. They can cause disease but are also part of the human microbiota and live on our skin, body and on everyday objects in our environment. Question after watching: In Section 3.3.3, you were asked, in the section called "Current Model", to draw a Venn Diagram showing the similarities and differences between prokaryotes and eukaryotes. While watching this video, add to this Venn Diagram with new information.

Evolution Connection: The Evolution of Prokaryotes

How do scientists answer questions about the evolution of prokaryotes? Unlike animals, prokaryotes have few fossils to offer clues. Fossils of ancient prokaryotes look like tiny bubbles in rock. Scientists turn to genetics and to the principle of the molecular clock to piece together the evolution of prokaryotes. The principle of the molecular clock holds that the more recently two species have diverged, the more similar their genes (and thus proteins) will be. Conversely, species that diverged long ago will have independently accumulated more mutations and will have more dissimilar genes.

Scientists at the NASA Astrobiology Institute and at the European Molecular Biology Laboratory collaborated to analyze the molecular evolution of 32 specific proteins common to 72 species of prokaryotes.[1] The model they derived from their data indicates that three important groups of bacteria—Actinobacteria, *Deinococcus*, and Cyanobacteria (which the authors call *Terrabacteria*)—were the first to colonize land. (*Deinococcus* is a genus of prokaryote that is highly resistant to ionizing

radiation.) Cyanobacteria are photosynthesizers, while Actinobacteria are a group of common bacteria that include species important in the decomposition of organic wastes.

The timelines of divergence suggest that Bacteria diverged from common ancestral species between 2.5 and 3.2 billion years ago, whereas Archaea diverged earlier: between 3.1 and 4.1 billion years ago. Eukarya later diverged off the Archaean line. The work further suggests that stromatolites that formed prior to the advent of cyanobacteria (about 2.6 billion years ago) photosynthesized in an anoxic environment and that because of the modifications of the Terrabacteria for land (which includes resistance to drying and the possession of compounds that protect the organism from excess light), photosynthesis producing oxygen may be closely linked to adaptations to survive on land.

? Optional Activity 3.4.2.1

Which of the following consist of prokaryotic cells?

A. Bacteria and Fungi
B. Archaea and Fungi
C. Protista and Animalia
D. Bacteria and Archaea

Answer

D. Bacteria and Archaea.

The Prokaryotic Cell

Recall that prokaryotes (Figure **3.4.2.4**) are unicellular organisms that lack organelles or internal membrane-bound structures. Therefore, they do not have a nucleus. They generally have a single chromosome—a piece of circular, double-stranded DNA located in an area of the cell called the nucleoid. Most prokaryotes have a cell wall outside the plasma membrane.

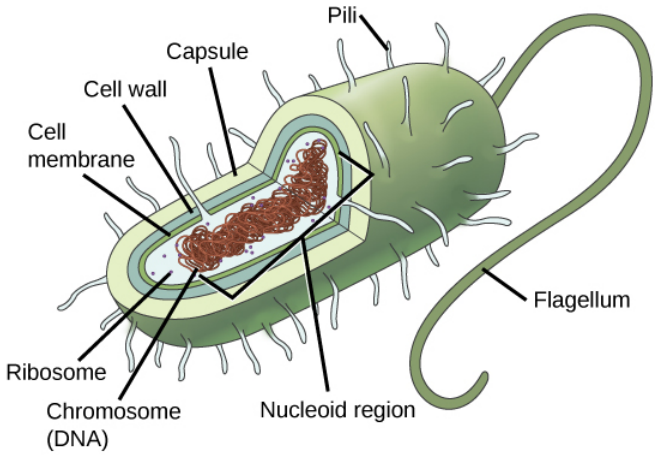
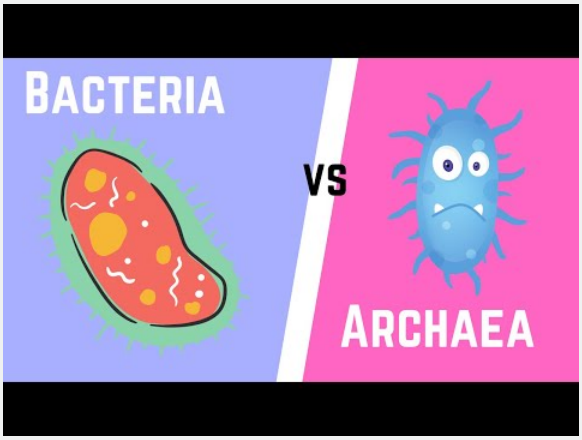


Figure **3.4.2.4**: The features of a typical prokaryotic cell are shown. Note the absence of compartmentalization inside of the cell (which is a feature of eukaryotes)

Video



This quick 2-minute video describes the similarities and differences between the two types of prokaryotes: Bacteria and Archaea.

Question after watching: What are three similarities and three differences between Bacteria and Archaea?

The Cell Wall

The cytoplasm of prokaryotic cells has a high concentration of dissolved solutes that the cell needs to function. Therefore, the osmotic pressure within the cell is relatively high. The prokaryotic **cell wall** is a protective layer that surrounds some cells and gives them shape and rigidity. It is located outside the cell membrane and prevents osmotic lysis (bursting due to increasing volume). The chemical composition of the cell walls varies between Archaea and Bacteria and between bacterial species. The composition of their cell walls is also different from the eukaryotic cell walls found in plants (cellulose) or fungi and insects (chitin).

Bacterial cell walls contain **peptidoglycan**, composed of polysaccharide chains that are cross-linked by unusual peptides. Many of our antibiotics work by mimicking portions of these chains and therefore have specific effects on bacterial cell wall synthesis. There are more than 100 different forms of peptidoglycan. Surface layer proteins are also present on the outside of cell walls of both Archaea and Bacteria.

Some bacteria have a **capsule** outside the cell wall. Other structures are present in some prokaryotic species, but not in others (Table 3.4.2.1). Up to 90 percent of the cell wall in bacteria without a capsule is composed of peptidoglycan. Most of the rest is

composed of acidic substances called **teichoic acids**. Teichoic acids may be covalently linked to lipids in the plasma membrane to form lipoteichoic acids. Lipoteichoic acids anchor the cell wall to the cell membrane.

Bacterial cells with a capsule have a relatively thin cell wall composed of a few layers of peptidoglycan (only 10 percent of the total cell wall), surrounded by an outer envelope containing lipopolysaccharides (LPS) and lipoproteins. This outer envelope is sometimes referred to as a second lipid bilayer. The chemistry of this outer envelope is very different, however, from that of the typical lipid bilayer that forms plasma membranes.

Researchers and clinicians like to categorize bacteria as belonging to either **Gram-positive** or **Gram-negative**. This grouping is based on the result of a quick and easy-to-administer laboratory test that can help researchers and clinicians identify a bacterial species known as Gram staining. Under the Domain Bacteria and the Kingdom Eubacteria, Gram-positive bacteria belong to one phylum; bacteria that are Gram-negative are spread over several phyla.

The different bacterial responses to the staining procedure are ultimately due to cell wall structure. The different bacterial responses to the staining procedure are ultimately due to cell wall structure. Gram-positive organisms typically lack a capsule. Gram-negative organisms have a capsule outside of their cell wall (Figure **3.4.2.8**).

The Plasma Membrane

As with all living organisms, Bacteria and Archaea have a thin lipid bilayer, the plasma membrane, that surrounds the cell and separates the inside from the outside. Its selectively permeable nature keeps ions, proteins, and other molecules within the cell and prevents them from diffusing into the extracellular environment, while other molecules (usually small, non-polar ones) may move through the membrane. Recall that the general structure of a cell membrane is a phospholipid bilayer composed of two layers of lipid molecules. In archaeal cell membranes, glycerol is linked to isoprene (phytanyl) chains instead of fatty acids chains as in cell membranes of Bacteria and Eukarya. Some archaeal membranes are lipid monolayers instead of bilayers (Figure **3.4.2.5** and Table **3.4.2.1**).

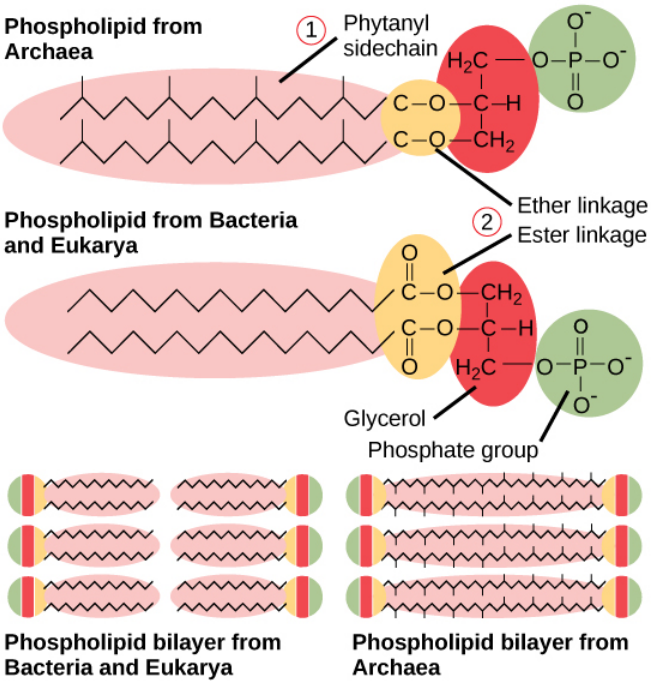
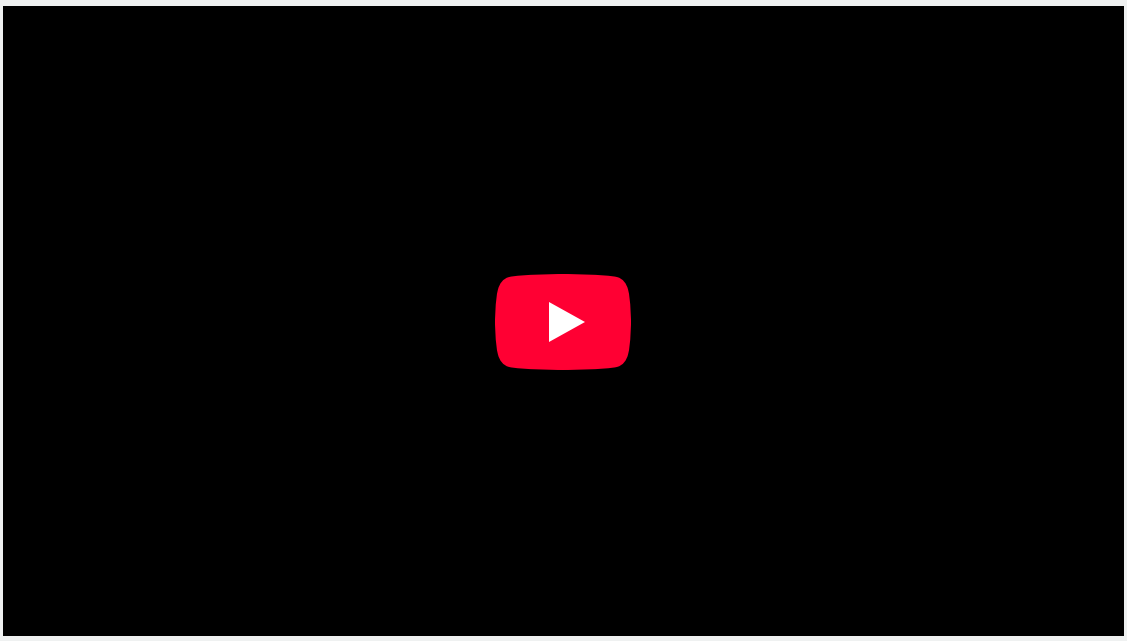
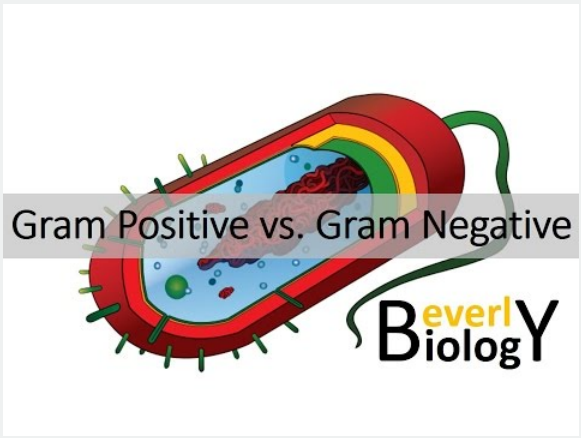


Figure **3.4.2.5**: Archaeal phospholipids differ from those found in Bacteria and Eukarya in two ways. First, they have branched phytanyl sidechains instead of linear ones. Second, an ether bond instead of an ester bond connects the lipid to the glycerol.

Video





This 9-minute video highlights the similarities and differences between Gram-positive and Gram-negative bacteria. Question after watching: How does the process of Gram staining differentiate between the two types of bacteria?

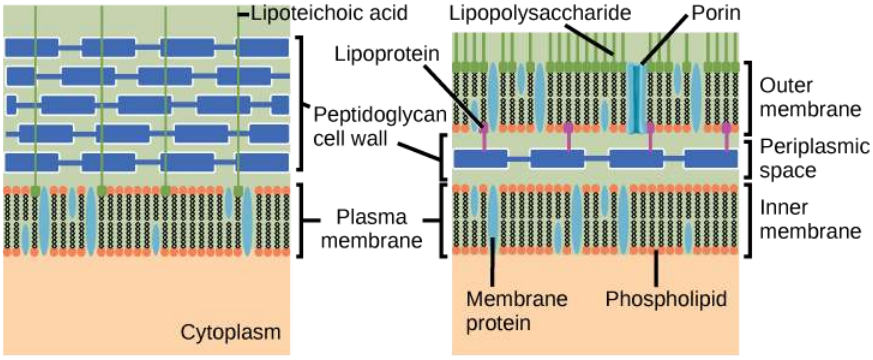


Figure 3.4.2.6: Bacteria are divided into two major groups: Gram-positive and Gram-negative. Both groups have a cell wall composed of peptidoglycan: in Gram-positive bacteria, the wall is thick, whereas in Gram-negative bacteria, the wall is thin. In Gram-negative bacteria, the cell wall is surrounded by an outer membrane that contains lipopolysaccharides and lipoproteins. Porins are proteins in this cell membrane that allow substances to pass through the outer membrane of Gram-negative bacteria. In Gram-positive bacteria, lipoteichoic acid anchors the cell wall to the cell membrane. (credit: modification of work by "Franciscosp2"/Wikimedia Commons)

Archaean cell walls do not have peptidoglycan (Table 3.4.2.1). There are four different types of Archaean cell walls. One type is composed of pseudopeptidoglycan, which is similar to peptidoglycan in morphology but contains different sugars in the polysaccharide chain. The other three types of cell walls are composed of polysaccharides, glycoproteins, or pure protein.

Table 3.4.2.1: Structural Differences and Similarities between Bacteria and Archaea

Structural Characteristic	Bacteria	Archaea
Cell type	Prokaryotic	Prokaryotic
Cell morphology	Variable	Variable
Cell wall	Contains peptidoglycan	Does not contain peptidoglycan
Cell membrane type	Lipid bilayer	Lipid bilayer or lipid monolayer
Plasma membrane lipids	Fatty acids	Phytanyl groups (contains the lipid isoprene)

? Optional Activity 3.4.2.2

Prokaryotes stain as Gram-positive or Gram-negative because of differences in the cell _____.

A. wall
B. cytoplasm
C. nucleus
D. chromosome

Answer

A. wall

? Optional Activity 3.4.2.3

Identify three differences between Bacteria and Archaea.

Answer

Responses will vary. A possible answer is: Bacteria contain peptidoglycans in the cell wall; Archaea do not. The cell membrane in Bacteria is a lipid bilayer; in Archaea, it can be a lipid bilayer or a monolayer. Bacteria contain fatty acids on the cell membrane, whereas Archaea contain phytanyl (the lipid isoprene).

Prokaryotic Reproduction

Reproduction in prokaryotes is asexual and usually takes place by **binary fission**. Recall that the DNA of a prokaryote exists as a single, circular chromosome. Prokaryotes do not undergo mitosis. Rather the chromosome is replicated and the two resulting copies separate from one another, due to the growth of the cell. The prokaryote, now enlarged, is pinched inward at its equator, and the two resulting cells, which are clones, separate. Binary fission does not provide an opportunity for genetic recombination or the generation of genetic diversity, but prokaryotes can share genes by three other mechanisms: transformation, transduction, and conjugation. All three depend on the presence of plasmids. Plasmids, which are extra-chromosomal DNA, are also present in many species of Bacteria and Archaea.

In **transformation**, the prokaryote takes in DNA found in its environment that is shed by other prokaryotes. If a nonpathogenic bacterium takes up DNA for a toxin gene from a pathogen and incorporates the new DNA into its own chromosome, it also may become pathogenic.

In **transduction**, bacteriophages, the viruses that infect bacteria, move short pieces of chromosomal DNA from one bacterium to another. Transduction results in a recombinant organism. Archaea are not affected by bacteriophages but instead have their own viruses that translocate genetic material from one individual to another.

In **conjugation**, DNA is transferred from one prokaryote to another by means of a **pilus**, which brings the organisms into contact with one another. The DNA transferred can be in the form of a plasmid or as a hybrid, containing both plasmid and chromosomal DNA. These three processes of DNA exchange are shown in Figure 3.4.2.7.

Reproduction can be very rapid: a few minutes for some species. This short generation time coupled with mechanisms of genetic recombination and high rates of mutation results in the rapid evolution of prokaryotes, allowing them to respond to environmental changes (such as the introduction of an antibiotic) very quickly.

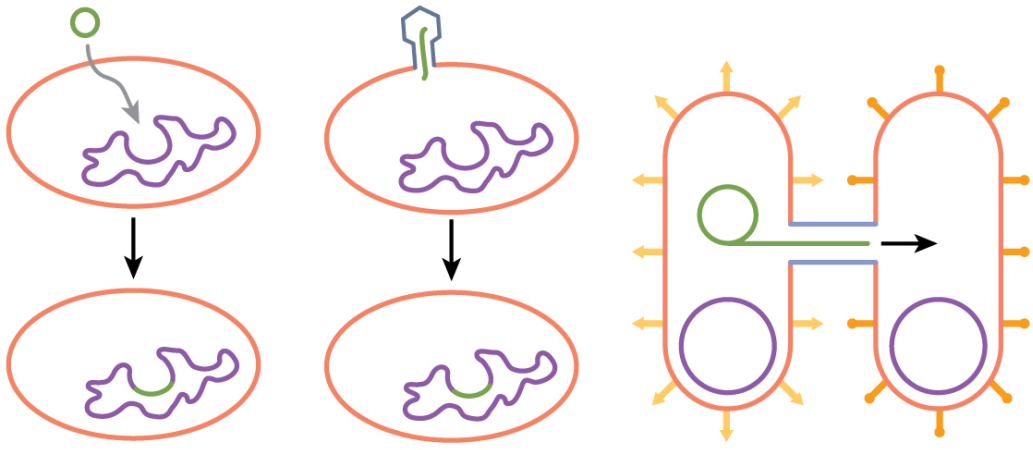
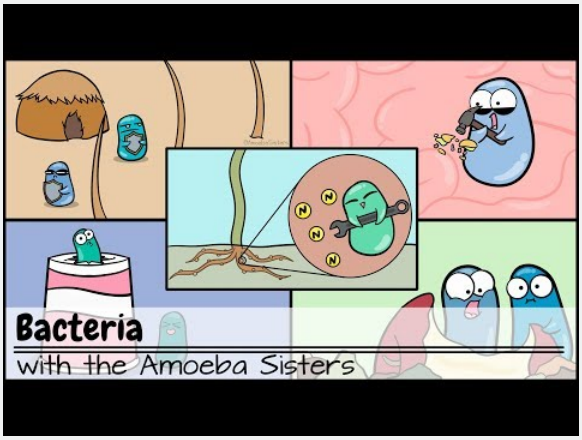
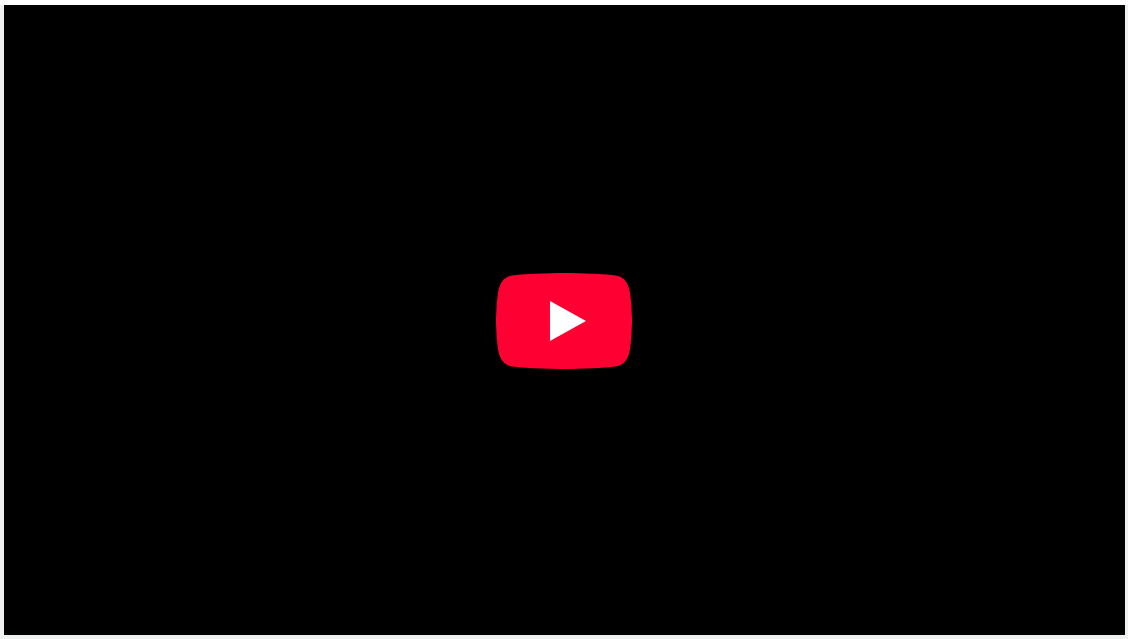
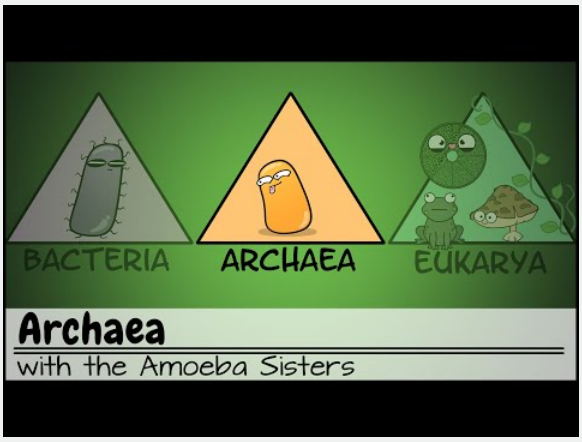


Figure 3.4.2.7: Besides binary fission, there are three other mechanisms by which prokaryotes can exchange DNA. In (a) transformation, the cell takes up prokaryotic DNA directly from the environment. The DNA may remain separate as plasmid DNA or be incorporated into the host genome. In (b) transduction, a bacteriophage injects DNA into the cell that contains a small fragment of DNA from a different prokaryote. In (c) conjugation, DNA is transferred from one cell to another via a mating bridge that connects the two cells after the sex pilus draws the two bacteria close enough to form the bridge.

Video







These two videos (7.5-minutes and 6-minutes, respectively) summarize the two Domains and Kingdoms of prokaryotes: Bacteria and Archaea

Question after watching: In what ways are prokaryotes problematic and helpful for humans?

Prokaryotic Metabolism

The diverse environments and ecosystems on Earth have a wide range of conditions in terms of temperature, available nutrients, acidity, salinity, and energy sources. Prokaryotes are very well equipped to make their living out of a vast array of nutrients and conditions. To live, prokaryotes need a source of energy, a source of carbon, and some additional nutrients.

Energy and Carbon Sources

Prokaryotes can use different sources of energy to assemble macromolecules from smaller molecules. **Photoautotrophs** (or phototrophic organisms) obtain their energy from sunlight. **Chemoautotrophs** (or chemosynthetic organisms) obtain their energy from chemical compounds. Chemoautotrophs that can use organic compounds as energy sources are called **chemoorganotrophs**. Those that can also use inorganic compounds as energy sources are called **chemolitotrophs**.

Prokaryotes not only can use different sources of energy but also different sources of carbon compounds. Organisms that can fix inorganic carbon into organic molecules are called **autotrophs**. Autotrophic prokaryotes synthesize organic molecules from carbon dioxide. In contrast, **heterotrophic** prokaryotes obtain carbon from organic compounds.

To make the picture more complex, the terms that describe how prokaryotes obtain energy and carbon can be combined. Thus, photoautotrophs use energy from sunlight, and carbon from carbon dioxide and water, whereas chemoheterotrophs obtain energy and carbon from an organic chemical source. Chemolitoautotrophs obtain their energy from inorganic compounds, and they build their complex molecules from carbon dioxide. Table **3.4.2.2** summarizes carbon and energy sources in prokaryotes.

Table **3.4.2.2**: Carbon and Energy Sources in Prokaryotes

	Energy Source	
Carbon Source	*Sunlight*	*Chemicals (such as sulfur dioxide, iron, etc.)*
Carbon Dioxide (from the atmosphere or water)	Photoautotrophs	Chemoautotrophs
Organic Compounds (from other organic matter)	Photoheterotrophs	Chemoheterotrophs

? Optional Activity 3.4.2.4

Prokaryotes that obtain their energy from chemical compounds are called _____.

A. phototrophs
B. auxotrophs
C. chemotrophs
D. lithotrophs

Answer

C. chemotrophs

Prokaryote Niches and Habitats

Prokaryotes are ubiquitous: There is no niche or ecosystem in which they are not present. Prokaryotes play many roles in the environments they occupy. The roles they play in the carbon and nitrogen cycles are vital to life on Earth.

Prokaryotes and the Carbon Cycle

Carbon is one of the most important macronutrients, and prokaryotes play an important role in the carbon cycle (Figure **3.4.2.8**). Carbon is cycled through Earth's major reservoirs: land, the atmosphere, aquatic environments, sediments and rocks, and biomass. The movement of carbon is via carbon dioxide, which is removed from the atmosphere by land plants and marine prokaryotes in photosynthesis and is returned to the atmosphere via the respiration of chemoorganotrophic organisms, including prokaryotes, fungi, and animals. Although the largest carbon reservoir in terrestrial ecosystems is in rocks and sediments, that carbon is not readily available.

A large amount of available carbon is found in land plants. Plants, which are producers, use carbon dioxide from the air to synthesize carbon compounds (i.e. organic molecules). Related to this, one very significant source of carbon compounds is humus, which is a mixture of prokaryotes and organic materials from dead plants that have resisted decomposition. Consumers such as animals use organic compounds generated by producers and release carbon dioxide into the atmosphere when they respire. Then, bacteria and fungi, collectively called decomposers, carry out the breakdown (decomposition) of plants and animals and their organic compounds. The most important contributor of carbon dioxide to the atmosphere is microbial decomposition of dead material (dead animals, plants, and humus) through respiration.

In aqueous environments and their anoxic sediments, there is another carbon cycle taking place. In this case, the cycle is based on one-carbon compounds. In anoxic sediments, prokaryotes, mostly archaea, produce methane (CH_4). This methane moves into the zone above the sediment, which is richer in oxygen and supports bacteria called methane oxidizers that oxidize methane to carbon dioxide as a way to fuel their energy needs. The carbon dioxide produced then returns to the atmosphere.

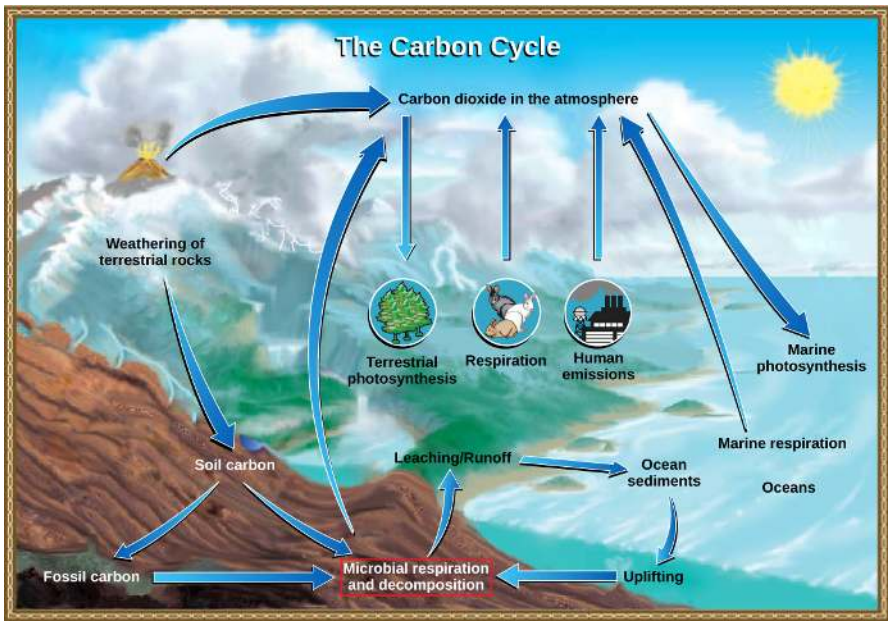


Figure **3.4.2.8**: Prokaryotes play a significant role in continuously moving carbon through the biosphere. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

Prokaryotes and the Nitrogen Cycle

Nitrogen is a very important element for life because it is part of proteins and nucleic acids. It is a macronutrient, and in nature, it is recycled from organic compounds to ammonia (NH_3), ammonium ions (NH_4^+), nitrate (NO^{-3}), nitrite (NO^{-2}), and nitrogen gas (N_2) by myriad processes, many of which are carried out only by prokaryotes. As illustrated in Figure **3.4.2.9**, prokaryotes are key to the nitrogen cycle. The largest pool of nitrogen available in the terrestrial ecosystem is gaseous nitrogen from the air, but this nitrogen is not usable by plants, which are primary producers.

Gaseous nitrogen is transformed, or "**fixed**" into more readily available forms such as ammonia through the process of nitrogen fixation. Bacteria in the soil or living on or in plant roots perform this function, making nitrogen available to plants. Ammonia can be used by plants or converted to other forms.

Another source of ammonia is **ammonification**, the process by which ammonia is released during the decomposition of nitrogen-containing organic compounds. The majority of the nitrogen produced during ammonification is N_2. The rest is as NH_4^+ and nitrous oxides (N_xO). Ammonia is catabolized anaerobically, meaning no oxygen needs to be present. This process can therefore take place deep in the soil by some prokaryotes.

Nitrification is the conversion of ammonium to nitrite and nitrate. Nitrification in soils is carried out by bacteria belonging to the genera *Nitrosomas*, *Nitrobacter*, and *Nitrospira*. The bacteria performs the reverse process, the reduction of nitrate from the soils to gaseous compounds such as N_2O, NO, and N_2, a process called **denitrification**. In this way, nitrogen is returned from the soil to the atmosphere.

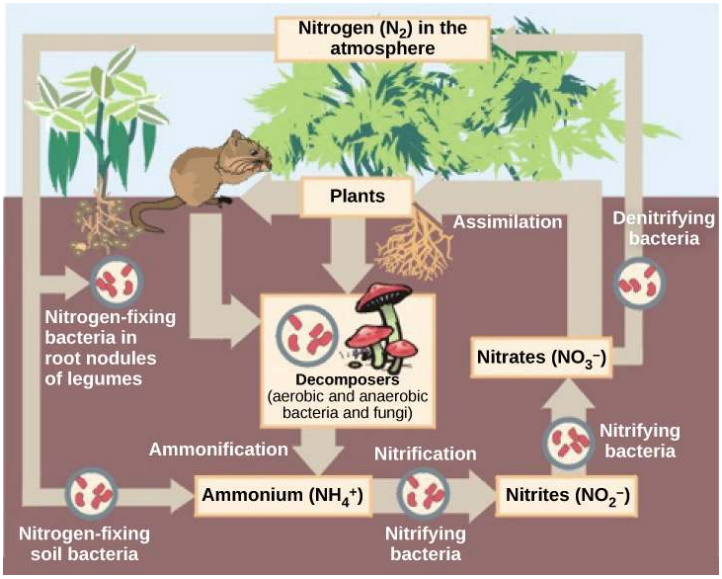


Figure **3.4.2.9**: Prokaryotes play a key role in the nitrogen cycle. (credit: Environmental Protection Agency)

? Optional Activity 3.4.2.5

Ammonification is the process by which _____.

A. ammonia is released during the decomposition of nitrogen-containing organic compounds
B. ammonium is converted to nitrite and nitrate in soils
C. nitrate from soil is transformed to gaseous nitrogen compounds such as NO, N_2O, and N_2
D. gaseous nitrogen is fixed to yield ammonia

Answer

A. ammonia is released during the decomposition of nitrogen-containing organic compounds

Footnotes

1. 1 Battistuzzi, FU, Feijao, A, and Hedges, SB. A genomic timescale of prokaryote evolution: Insights into the origin of methanogenesis, phototrophy, and the colonization of land. *BioMed Central: Evolutionary Biology* 4 (2004): 44, doi:10.1186/1471-2148-4-44.

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- **22.0: Prelude to Prokaryotes** by OpenStax is licensed CC BY 4.0.

Unit 3.4.3 - Protists

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.4.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe the cell structure characteristics of protists
- Describe the metabolic diversity of protists
- Describe the life cycle diversity of protists
- Describe representative protist organisms from each of the six presently recognized supergroups of eukaryotes
- Identify the evolutionary relationships of plants, animals, and fungi within the six presently recognized supergroups of eukaryotes

Introduction

Humans have been familiar with macroscopic organisms (organisms big enough to see with the unaided eye) since before there was written history, and it is likely that most cultures distinguished between animals and land plants, and most probably included the macroscopic fungi as plants. Therefore, it became an interesting challenge to deal with the world of microorganisms once microscopes were developed a few centuries ago. Many different naming schemes were used over the last couple of centuries, but it has become the most common practice to refer to eukaryotes that are not land plants, animals, or fungi as protists.

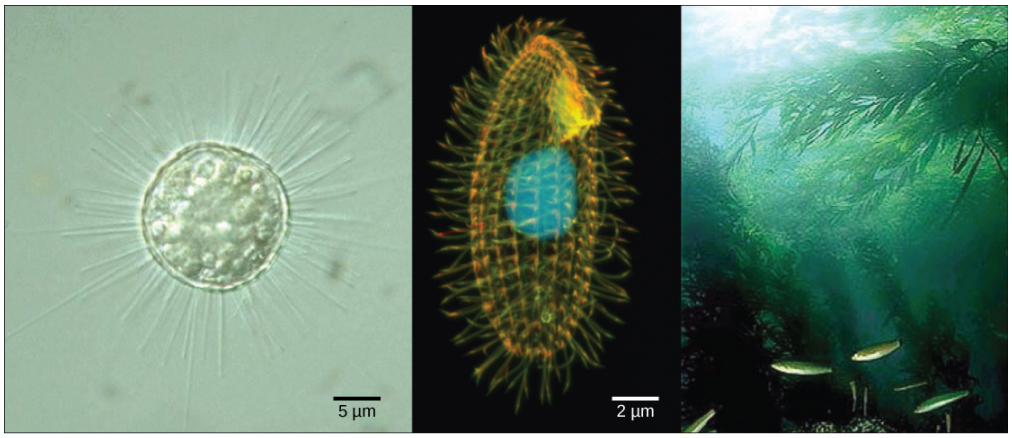


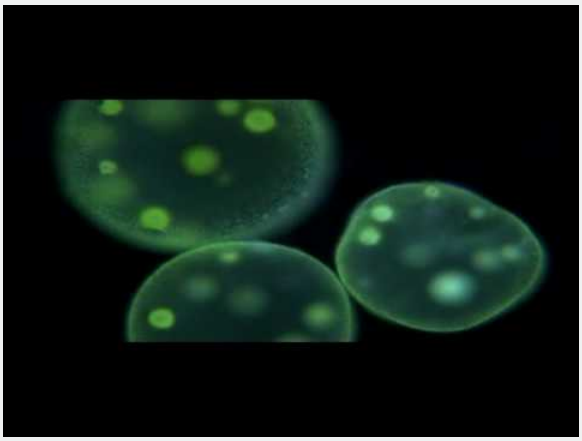
Figure **3.4.3.1**: Protists range from the (a) microscopic, single-celled *canthocystis turfacea* and the (b) ciliate *Tetrahymena thermophila*, both visualized here using light microscopy, to (c) the enormous, multicellular kelp (Chromalveolata) that extend for dozens of meters in underwater "forests" along the Pacific coast (credit a: modification of work by Yuiuji Tsukii; credit b: modification of work by Richard Robinson, Public Library of Science; credit c: modification of work by Kip Evans, NOAA; scale-bar data from Matt Russell).

The name protist was first suggested by Ernst Haeckel in the late nineteenth century. It has been applied in many contexts and has been formally used to represent a kingdom-level taxon called **Protista**. Many modern systematists (biologists who study the relationships among organisms) are naming taxa as groups of organisms thought to include all the descendants of a LCA (monophyletic group). During the past two decades, the field of molecular genetics has demonstrated that some protists are more related to animals, plants, or fungi than they are to other protists. Therefore, not including animals, plants and fungi make the kingdom Protista a **paraphyletic group**, or one that does not include all descendants of its common ancestor Figure **3.4.3.1**. For this

reason, protist lineages originally classified into the kingdom Protista continue to be examined and debated. In the meantime, the term “protist” is still used informally to describe this diverse group of eukaryotes.

Video





This 4-minute video, explore the many varied types of protists and their evolutionary history.
Question after watching: Why are all three types of algae placed in Protista rather than in Kingdom Plantae?

Classifying Protists

In the span of several decades, the Kingdom Protista has been disassembled because sequence analyses have revealed new genetic (and therefore evolutionary) relationships among these eukaryotes. Moreover, protists that exhibit similar morphological features may have evolved analogous structures because of similar selective pressures—rather than because of recent common ancestry. This convergent evolution is one reason why protist classification is so challenging. The emerging classification scheme groups the entire domain Eukaryota into six “supergroups” that contain all the protists as well as animals, plants ("land plants" in the figure), and fungi that evolved from a common ancestor (Figure **3.4.3.2**). The **supergroups** are believed to be monophyletic, meaning that all organisms within each supergroup are believed to have evolved from a single common ancestor, and thus all members are most closely related to each other than to organisms outside that group. There is still evidence lacking for the monophyly of some groups.

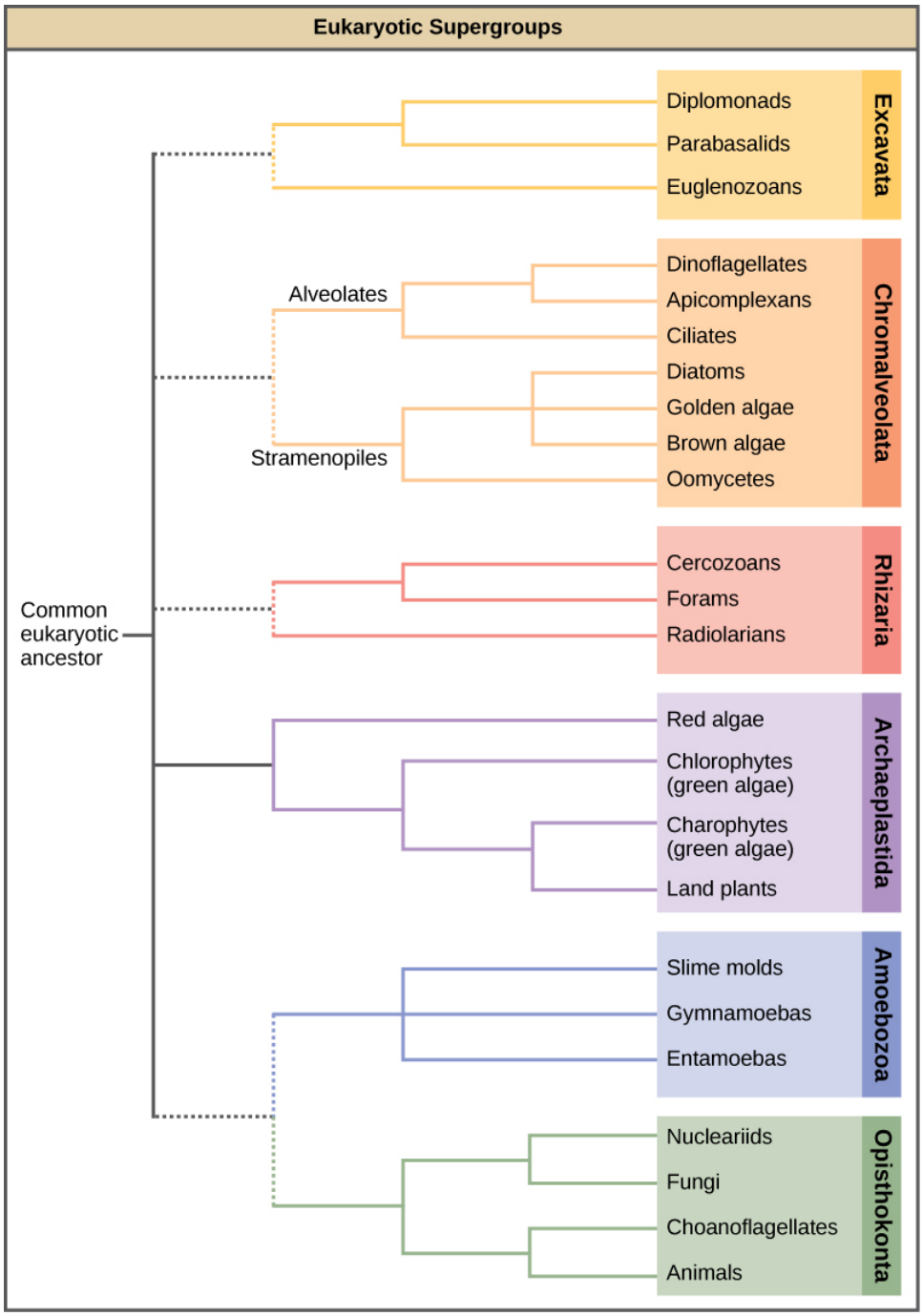


Figure **3.4.3.2**: This diagram shows a proposed classification of the domain Eukarya. Currently, the domain Eukarya is divided into six supergroups. Within each supergroup are multiple kingdoms (note the Animals - *Animalia*, *Fungi*, and Land Plants - *Plantae*; all the rest of the taxa belong to *Protista*). Dotted lines indicate suggested evolutionary relationships that remain under debate.

The classification of eukaryotes is still in flux, and the six supergroups may be modified or replaced by a more appropriate hierarchy as genetic, morphological, and ecological data accumulate. Keep in mind that the classification scheme presented here is just one of several hypotheses, and the true evolutionary relationships are still to be determined.

Cell Structure

The cells of protists are among the most elaborate of all cells. Most protists are microscopic and unicellular, but some multicellular forms exist. A few protists live as colonies that behave in some ways as a group of independent free-living cells and in other ways as a multicellular organism. Not all protists are microscopic. Some have huge, macroscopic cells, such as the plasmodia (giant amoebae) of myxomycete slime molds or the marine green alga *Caulerpa*. Some protists are multicellular, such as the red, green,

and brown seaweeds. It is among the protists that one finds the wealth of ways that organisms can grow. In fact, many protist cells are multinucleated; in some species, the nuclei are different sizes and have distinct roles in protist cell function.

Single protist cells range in size from less than a micrometer to three meters in length, to hectares in area. Protist cells may be enveloped by animal-like cell membranes or plant-like cell walls. Others are encased in glassy silica-based shells or wound with **pellicles** of interlocking protein strips. The pellicle functions like a flexible coat of armor, preventing the protist from being torn or pierced without compromising its range of motion.



Figure **3.4.3.3**: The pellicle of a euglenid can be seen here as the thread-like structures on the right side of the organism. Deuterostome CC-SA-3.0

Metabolism

Protists exhibit many forms of nutrition and may be aerobic or anaerobic. Protists that store energy by photosynthesis belong to a group of photoautotrophs and are characterized by the presence of chloroplasts. Other protists are heterotrophic and consume organic materials (such as other organisms) to obtain nutrition. Amoebas and some other heterotrophic protist species ingest particles by a process called **phagocytosis**, in which the cell membrane engulfs a food particle and brings it inward, pinching off an intracellular membranous sac, or vesicle, called a food vacuole (Figure **3.4.3.4**). The food particle is broken down into small molecules that can diffuse into the cytoplasm and be used in cellular metabolism. Undigested materials are expelled from the cell via exocytosis.

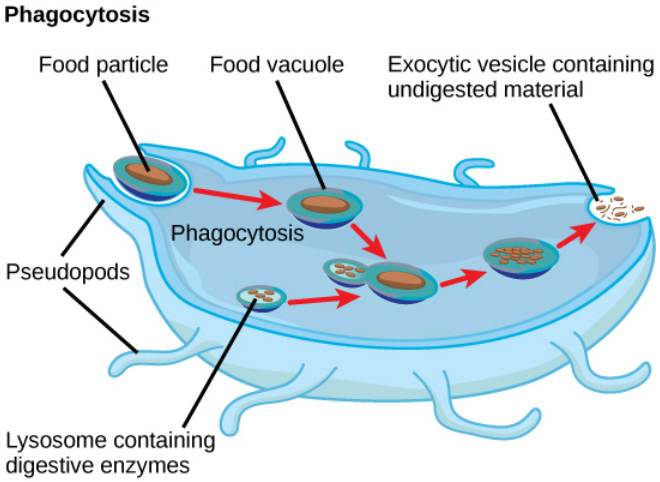


Figure **3.4.3.4**: The stages of phagocytosis include the engulfment of a food particle, the digestion of the particle using hydrolytic enzymes contained within a lysosome, and the expulsion of undigested materials from the cell.

Subtypes of heterotrophs, called **saprobes**, absorb nutrients from dead organisms or their organic wastes. Some protists can function as **mixotrophs**, obtaining nutrition by photoautotrophic or heterotrophic routes, depending on whether sunlight or organic nutrients are available.

Video

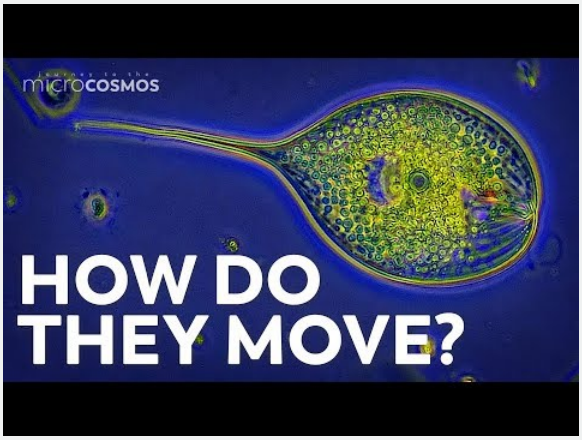


In this 11-minute video, the diverse ways that protist extract energy from their environment are explored.
Question after watching: What is the advantage of being a mixotroph in aquatic environments?

Motility

Most protists are motile, but different types of protists have evolved different modes of movement (Figure **3.4.3.5**). Some protists have one or more flagella, which they rotate or whip. Others are covered in rows or tufts of tiny cilia that they coordinately beat to swim. Still others form cytoplasmic extensions called **pseudopodia** anywhere on the cell, anchor the pseudopodia to a substrate, and pull themselves forward. Some protists can move toward or away from a stimulus, a movement referred to as taxis. Movement toward light, termed **phototaxis**, is accomplished by coupling their locomotion strategy with a light-sensing organ.

Video



In this 11-minute video, find out how these single-celled eukaryotes move through their viscous environment. Question after watching: After making a table with the three main types of possible movements, which representative organisms would you include to help you remember each one?

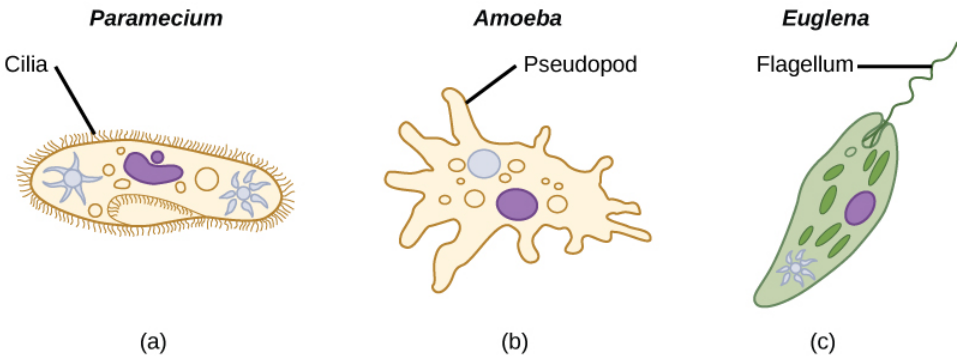


Figure 3.4.3.5: Protists use one of three methods for locomotion: (a) *Paramecium* waves hair-like appendages called cilia to propel itself. (b) *Amoeba* uses lobe-like pseudopods to anchor itself to a solid surface and pull itself forward. (c) *Euglena* uses a whip-like tail called a flagellum to propel itself.

Life Cycles

Protists reproduce by many mechanisms. Most undergo some form of asexual reproduction, such as binary fission, to produce two daughter cells. In protists, binary fission can occur along the transverse or longitudinal axis of the cell, depending on the axis of orientation. Sometimes *Paramecium* uses binary fission to reproduce. Some protists such as the true slime molds exhibit multiple fission and simultaneously divide into many daughter cells. Others produce tiny buds that go on to divide and grow to the size of the parental protist.

Sexual reproduction, involving meiosis and fertilization, is also found among protists, and many protist species can switch from asexual to sexual reproduction when necessary. Sexual reproduction is often associated with periods of stress such as when nutrients are rare or environmental changes occur. Sexual reproduction may allow the protist to recombine genes and produce new variations in its progeny that may be better suited to surviving in the new environment.

In addition, sexual reproduction is often associated with the creation of resistant **cysts** that are a protective, resting stage of the life cycle of the protist. Depending on their habitat, the cysts may be particularly resistant to temperature extremes, desiccation, or low pH. This strategy also allows certain protists to “wait out” stressors until their environment becomes more favorable for survival or until they are carried (such as by wind, water, or transport on a larger organism) to a different environment because cysts exhibit little cellular metabolism and leave the organism in a sort of suspended animation.

Protist life cycles range from simple to complex. Certain parasitic protists have complicated life cycles and must infect different host species at different developmental stages to complete their life cycle. Some protists are unicellular in the haploid form and multicellular in the diploid form, a strategy employed by animals (gametes are unicellular, but fertilized eggs rapidly develop and divide to form multicellular animals). Other protists have multicellular stages in both haploid and diploid forms, a strategy called alternation of generations that is also used by plants.

Video





In this 8.5-minute video, explore the ways that protists reproduce.
Question after watching: Explain in your own words why sexual reproduction can be useful if a protist's environment changes.

Habitats

Nearly all protists exist in aquatic environments, including freshwater and marine environments, damp soil, and even snow. They are also common in the digestive tracts of animals and in the vascular tissues of plants. Others invade the cells of other protists, animals, and plants. Protists function in diverse ecological niches. Whereas some protist species are essential components of the food chain and generators of biomass, others function in the decomposition of organic materials. Still other protists are dangerous human **pathogens** or causative agents of devastating plant diseases. Several protist species are parasites that infect animals or plants. A few protist species live on dead organisms or their wastes and contribute to their decay.

? Optional Activity 3.4.3.1

Protists with the capabilities to perform photosynthesis and to absorb nutrients from dead organisms are called _____.

A. photoautotrophs
B. mixotrophs
C. saprobes
D. heterotrophs

Answer

B. mixotrophs

? Optional Activity 3.4.3.2

Which of these locomotor organs would likely be the shortest?

A. a flagellum
B. a cilium
C. an extended pseudopod
D. a pellicle

Answer

B. a cilium

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Unit 3.4.4 - Kingdom Fungi

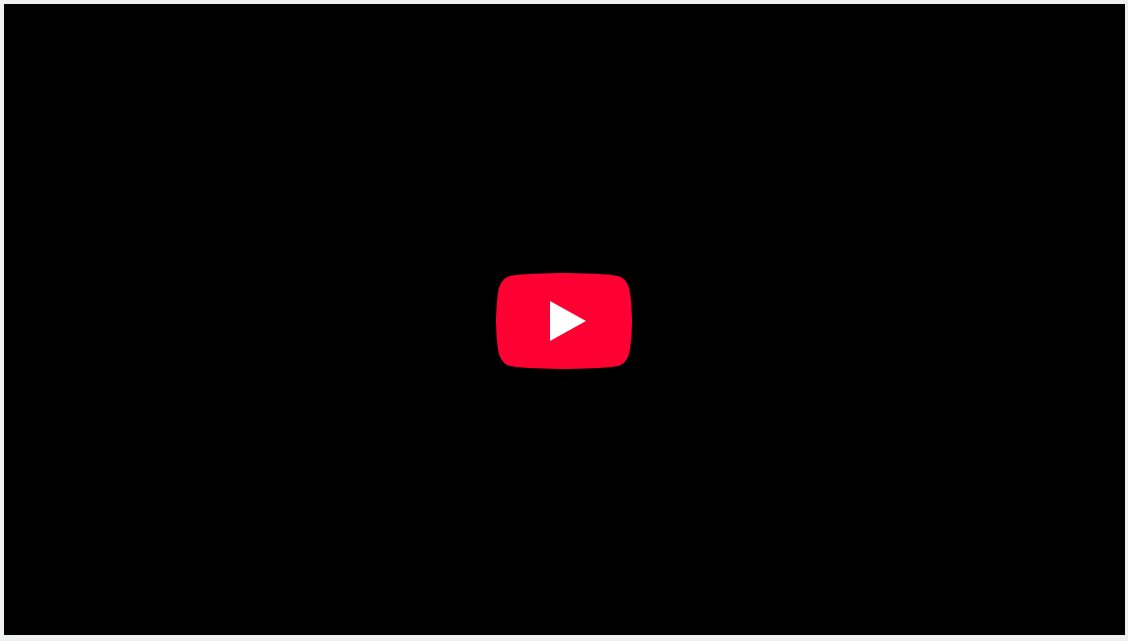
- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 90 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.4.5, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- List the characteristics of fungi
- Describe the composition of the mycelium
- Describe the mode of nutrition of fungi
- Explain sexual and asexual reproduction in fungi
- Describe the role of fungi in the ecosystem

Introduction to Fungi

Video





This 2.5-minute video introduces organisms in the kingdom Fungi.
Question after watching: Are fungi unicellular or multicellular?

The word ***fungus*** comes from the Latin word for mushrooms. Indeed, the familiar mushroom is a reproductive structure used by many types of fungi. However, there are also many fungi species that do not produce mushrooms at all (Figure **3.4.4.1**). Being eukaryotes, a typical fungal cell contains a nucleus and many membrane-bound organelles. The kingdom Fungi (pronounced either *fun-guy* or *fun-jie*) includes an wide variety of living organisms collectively referred to as Eucomycota, or true Fungi. While scientists have identified about 100,000 species of fungi, this is only a fraction of the 1.5 million species of fungus likely present on Earth. Edible mushrooms, yeasts, black mold, and the producer of the antibiotic penicillin, *Penicillium notatum*, are all members of the kingdom Fungi, which belongs to the domain Eukarya.



Figure **3.4.4.1**: Many species of fungus produce (a) the familiar mushroom (basidiocarp), which is a reproductive structure visible to the naked eye. (b) This coral fungus displays brightly colored fruiting bodies. (c) This electron micrograph shows the spore-bearing structures of *Aspergillus*, a type of toxic fungi found mostly in soil and plants. (credit "mushroom": modification of work by Chris Wee; credit "coral fungus": modification of work by Cory Zanker; credit "*Aspergillus*": modification of work by Janice Haney Carr, Robert Simmons, CDC; scale-bar data from Matt Russell)

Although humans have used yeasts and multicellular fungi since prehistoric times. Until recently, the biology of fungi was poorly understood. Up until the mid-20th century, many scientists classified fungi as plants. Fungi, like plants, are **sessile**, meaning they are seemingly rooted in place. Their mode of nutrition was poorly understood. Then came the field of **mycology**: the scientific study of fungi.

Most fungi are multicellular organisms. They display two distinct morphological stages: vegetative and reproductive. The vegetative stage consists of a tangle of slender thread-like structures called **hyphae** (singular, hypha), whereas the reproductive

stage can be more conspicuous (such as what is seen in (Figure **3.4.4.1**). The mass of hyphae is a **mycelium** (Figure **3.4.4.2**). It can grow on a surface, in soil or decaying material, in a liquid, or even on living tissue.

The vegetative body of a fungus is a unicellular or multicellular **thallus**, meaning a collection of cells or tissues not structured into organs. Dimorphic fungi can change from a unicellular to multicellular state depending on environmental conditions. Unicellular fungi are generally referred to as **yeasts**, including *Saccharomyces cerevisiae* (baker's yeast) and *Candida* species (the agents of thrush, a common fungal infection) (Figure **3.4.4.3**).

Although individual hyphae must be observed under a microscope, the mycelium of a fungus can be very large. The giant *Armillaria solidipes* (honey mushroom) is considered the largest organism on Earth, spreading across more than 2,000 acres of underground soil in eastern Oregon; it is estimated to be at least 2,400 years old.

Based on fossil evidence, fungi appeared in the pre-Cambrian era, about 450 million years ago. Molecular biology analysis of the fungal genome suggests that fungi are more closely related to animals than plants. They are a polyphyletic group of organisms that share characteristics, rather than sharing a single common ancestor.

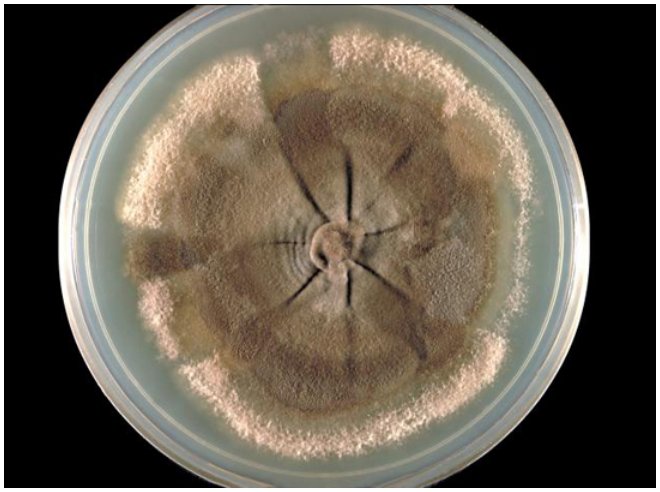


Figure **3.4.4.2**: The mycelium of the fungus *Neotestudina rosati* can be pathogenic to humans. The fungus enters through a cut or scrape and develops a mycetoma, a chronic subcutaneous infection. (credit: CDC)

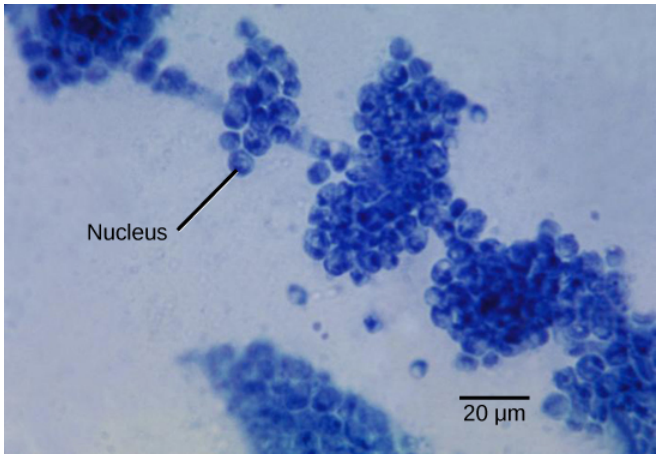


Figure **3.4.4.3**: Candida albicans is a yeast cell and the agent of candidiasis and thrush. This organism has a similar morphology to coccus bacteria; however, yeast is a eukaryotic organism (note the nucleus). (credit: modification of work by Dr. Godon Roberstad, CDC; scale-bar data from Matt Russell)

Evolutionary History of Fungi

The kingdom Fungi contains five major phyla that were established using molecular data or information about their mode of sexual reproduction. Fungi that reproduce without a sexual cycle, and that are hard to classify according to their DNA, are placed for convenience in a sixth group called a "form phylum." The form phylum is sort of like a placeholder bin where fungi that don't seem to fit anywhere else can be categorized until we learn more about them. Not all mycologists agree with this scheme.

The five true phyla of fungi are the **Chytridiomycota** (Chytrids), the **Zygomycota** (conjugated fungi), the **Ascomycota** (sac fungi), the **Basidiomycota** (club fungi) and the recently described Phylum **Glomeromycota** (Figure **3.4.4.4**). An older classification scheme grouped fungi that strictly use asexual reproduction into Deuteromycota, a group that is no longer in use.

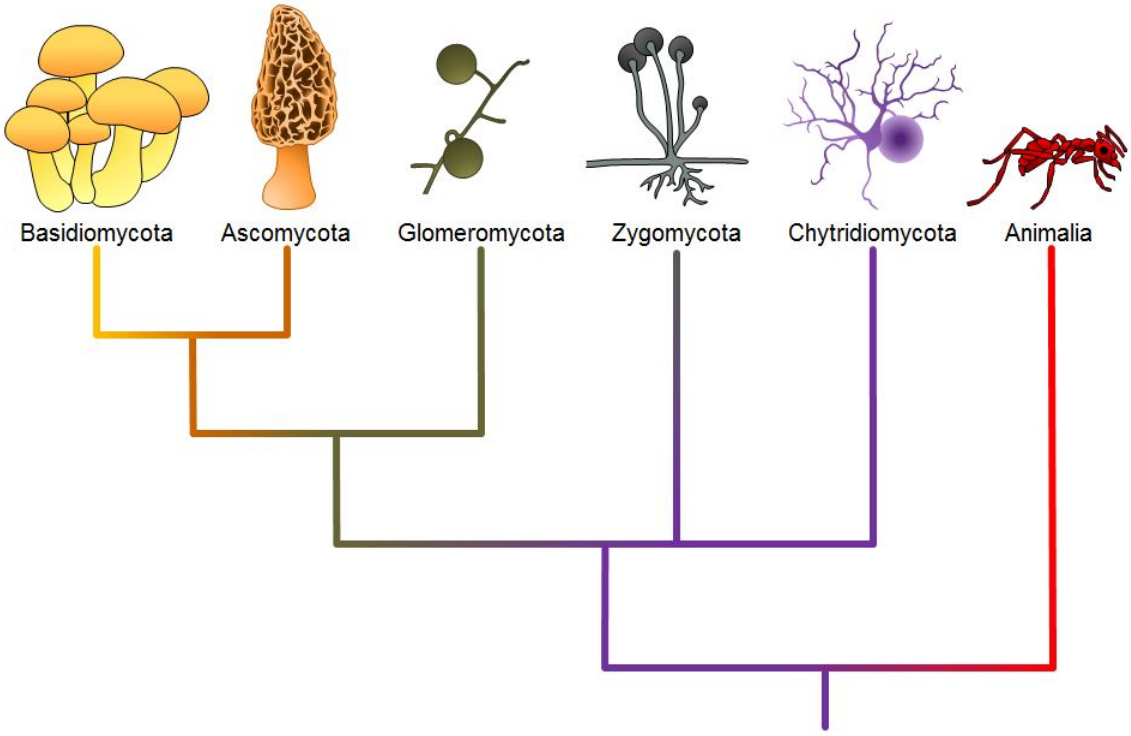


Figure **3.4.4.4**: Cladogram of the Fungi. (OpenStax Biology 2e; CC-BY 4.0)

Note

Note: “-mycota” is used to designate a phylum while “-mycetes” formally denotes a class or is used informally to refer to all members of the phylum.

Chytridiomycota (chytrids) are considered the most primitive group of fungi. They are mostly aquatic, and their gametes are the only fungal cells known to have flagella. They reproduce both sexually and asexually; the asexual spores are called **zoospores**.

Zygomycota (conjugated fungi) produce non-septated hyphae with many nuclei. Hyphae are the primary cell bodies of fungal organisms. Their hyphae fuse during sexual reproduction to produce a **zygospore** in a **zygosporangium**.

Ascomycota (sac fungi) form spores in sacs called **asci** (millions of which fuse together into **ascocarps**) during sexual reproduction. However, this name was obtained because the sexual form attracted the human eye. Asexual reproduction is their most common form of reproduction.

Basidiomycota (club fungi) produce showy fruiting bodies that contain **basidia** in the form of clubs known as **basiciocarps** (the clubs under the mushroom bell shape in what looks like gills or sheets. Magnified, these sheets have club-like protrusions). Spores are stored in the basidia. Most familiar mushrooms (including many of those sold at the supermarket, like white mushrooms) belong to this phyla.

Fungi that have no known sexual cycle were classified in the form phylum Deuteromycota. That phylum no longer exists. Present classification now puts these fungi into the phyla Ascomycota and Basidiomycota based on evolutionary relationships.

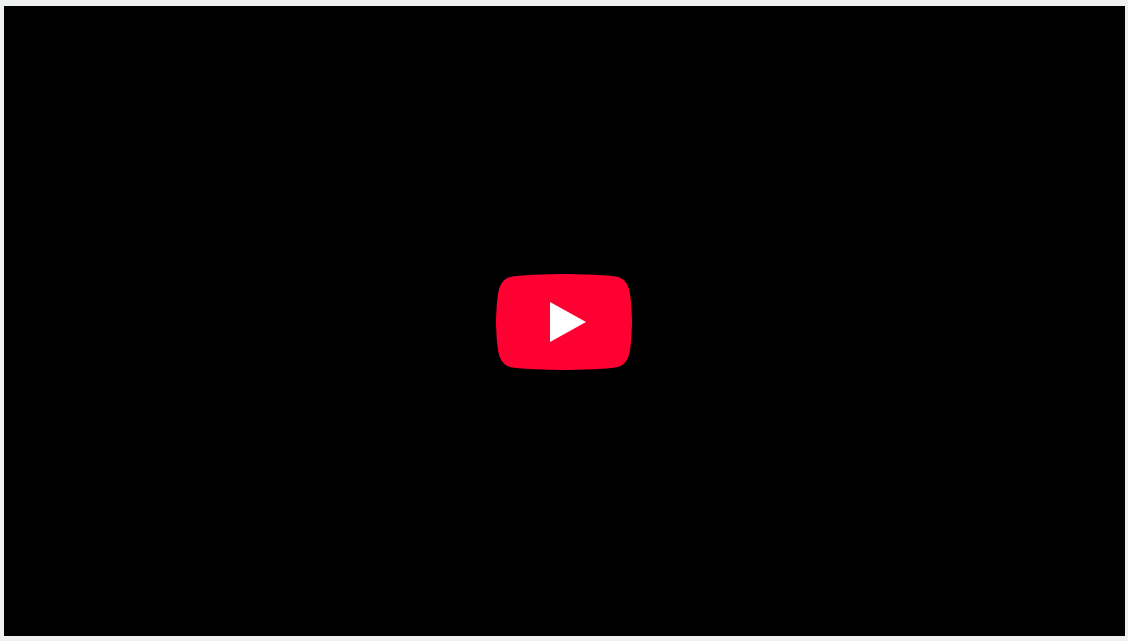
Glomeromycota form **mycorrhizal** relationships with the roots of plants.

Video



In this 9-minute lecture, the characteristics, reproduction, and categories of the kingdom Fungi are explained.
Question after watching: Mr. Anderson says that we probably have more in common in our lifestyle with fungi than with plants. What sort of evidence can you find to support this assertion?

Video





This 6.5-minute video provides an evolutionary history of fungi.
Question after watching: This video suggests that fungi were critical to the evolution of plants and animals. How?

Career Connection: Mycologist

Mycologists are biologists who study fungi. Mycology is a branch of microbiology, and many mycologists start their careers with a degree in microbiology. To become a mycologist, a bachelor's degree in a biological science (preferably majoring in microbiology) and a master's degree in mycology are minimally necessary. Mycologists can specialize in taxonomy and fungal genomics, molecular and cellular biology, plant pathology, biotechnology, or biochemistry. Some medical microbiologists concentrate on the study of infectious diseases caused by fungi (mycoses). Mycologists collaborate with zoologists and plant pathologists to identify and control difficult fungal infections, such as the devastating chestnut blight, the mysterious decline in frog populations in many areas of the world, or the deadly epidemic called white-nose syndrome, which has decimated bats in eastern North America and spreading west at a rapid rate.

Government agencies hire mycologists as research scientists and technicians to monitor the health of crops, national parks, and national forests. Mycologists are also employed in the private sector by companies that develop chemical and biological control products or new agricultural products, and by companies that provide disease control services. Because of the key role played by fungi in the fermentation of alcohol and the preparation of many important foods, scientists with a good

understanding of fungal physiology routinely work in the food technology industry. **Oenology**, the science of winemaking, relies not only on the knowledge of grape varietals and soil composition but also on an understanding of the characteristics of the wild yeasts that thrive in different winemaking regions. It is possible to purchase yeast strains isolated from specific grape-growing regions. The great French chemist and microbiologist, Louis Pasteur, made many of his essential discoveries working on the humble brewer's yeast, thus discovering the process of fermentation.

Cell Structure and Function

Fungi are eukaryotes, and as such, have a complex cellular organization. Unlike plant cells, fungal cells do not have chloroplasts or chlorophyll. Many fungi display bright colors arising from other cellular pigments, ranging from red, to green, to black. The poisonous *Amanita muscaria* (fly agaric) is recognizable by its bright red cap with white patches (Figure **3.4.4.5**). Pigments in fungi are associated with the cell wall and play a protective role against ultraviolet radiation. Some fungal pigments are toxic.



Figure **3.4.4.5**: The poisonous *Amanita muscaria* is native to temperate and boreal regions of North America, including British Columbia. (credit: Christine Majul)

Like plant cells, fungal cells have a thick cell wall. The rigid layers of fungal cell walls contain complex polysaccharides called chitin and glucans. Chitin, also found in the exoskeleton of insects, gives structural strength to the cell walls of fungi. The wall protects the cell from desiccation and predators. Fungi have plasma membranes like other eukaryotes, except that the structure is stabilized by ergosterol: a steroid molecule that replaces the cholesterol found in animal cell membranes. Most members of the kingdom Fungi are nonmotile. Flagella are produced only by the gametes in the primitive Phylum Chytridiomycota.

? Optional Activity 3.4.4.1

Which polysaccharide is usually found in the cell wall of fungi?

A. starch
B. glycogen
C. chitin
D. cellulose

Answer

C. chitin

? Optional Activity 3.4.4.2

Which of these organelles is not found in a fungal cell?

A. chloroplast
B. nucleus

C. mitochondrion
D. Golgi apparatus

Answer

A. chloroplast

Growth

Most fungal hyphae are divided into separate cells by endwalls called **septa** (singular, septum) (Figure **3.4.4.6**). In most phyla of fungi, tiny holes in the septa allow for the rapid flow of nutrients and small molecules from cell to cell along the hypha. They are described as perforated septa. The hyphae in bread molds (which belong to the Phylum Zygomycota) are not separated by septa. Instead, they are formed by large cells containing many nuclei, an arrangement described as **coenocytic hyphae** Figure **3.4.4.6**. Thus, hyphae can be formed by one unicellular (multi-nuclear) fungal cell or by a multicellular assortment of fungi cells.

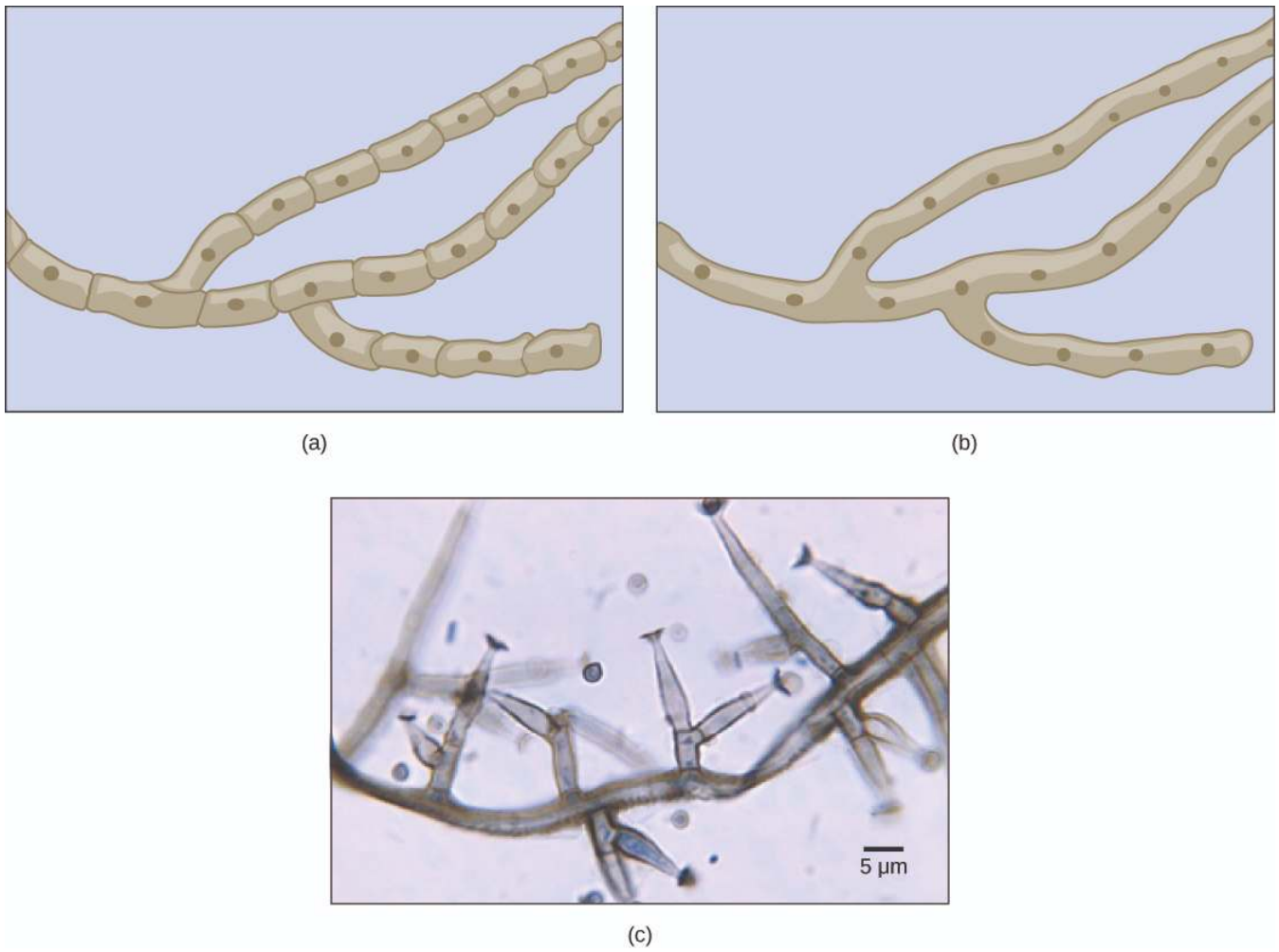


Figure **3.4.4.6**: Fungal hyphae may be (a) septated or (b) coenocytic (coeno- = "common"; -cytic = "cell") with many nuclei present in a single hypha. A bright field light micrograph of (c) *Phialophora richardsiae* shows septa that divide the hyphae. (credit c: modification of work by Dr. Lucille Georg, CDC; scale-bar data from Matt Russell)

Fungi thrive in environments that are moist and slightly acidic and can grow with or without light. They vary in their oxygen requirement. Most fungi are **obligate aerobes**, requiring oxygen to survive. Other species, such as the Chytridiomycota that reside in the rumen of cattle, are **obligate anaerobes**, in that they only use anaerobic respiration because oxygen will disrupt their metabolism or kill them. Yeasts are intermediate, being **facultative anaerobes**. This means that they grow best in the presence of oxygen using aerobic respiration but can survive using anaerobic respiration when oxygen is not available. The alcohol produced from yeast fermentation is used in wine and beer production.

? Optional Activity **3.4.4.3**

The wall dividing individual cells in a fungal filament is called a

A. thallus
B. hypha
C. mycelium
D. septum

Answer

D. septum

Nutrition

Like animals, fungi are heterotrophs; they use complex organic compounds as a source of carbon, rather than fix carbon dioxide from the atmosphere as do some bacteria and most plants. In addition, fungi do not fix nitrogen from the atmosphere. Like animals, they must obtain it from their diet. However, unlike most animals, which ingest food and then digest it internally in specialized organs, fungi perform these steps in the reverse order; digestion precedes ingestion. Fungi are **decomposers**. First, **exoenzymes** are transported out of the hyphae, where they process nutrients in the environment. Then, the smaller molecules produced by this external digestion are absorbed through the large surface area of the mycelium. As with animal cells, the polysaccharide of storage is glycogen, rather than starch, as found in plants.

Fungi are mostly saprobes: organisms that derive nutrients from decaying organic matter. They obtain their nutrients from dead or decomposing organic matter: mainly plant material. Fungal exoenzymes break down insoluble polysaccharides, such as the cellulose and lignin of dead wood, into readily absorbable glucose molecules. The carbon, nitrogen, and other elements are thus released into the environment.

Because of their varied metabolic pathways, fungi fulfill an important ecological role and are being investigated as potential tools in bioremediation. For example, some species of fungi can be used to break down diesel oil and **polycyclic aromatic hydrocarbons (PAHs)** that are often released by industrial processes as environmental pollutants. Other species take up heavy metals, such as cadmium and lead. Some fungi are parasitic, infecting either plants or animals. Smut and Dutch elm disease affect plants, whereas athlete’s foot and candidiasis (thrush) are medically important fungal infections in humans.

Reproduction

Fungi reproduce sexually and/or asexually. **Perfect fungi** reproduce both sexually and asexually, while the so-called **imperfect fungi** reproduce only asexually (by mitosis).

In both sexual and asexual reproduction, fungi produce spores that disperse from the parent organism by either floating on the wind, a liquid medium, or attaching to an animal. Fungal spores are smaller and lighter than plant seeds. The giant puffball mushroom bursts open and releases trillions of spores. The huge number of spores released increases the likelihood of landing in an environment that will support growth (Figure **3.4.4.7**).



Figure **3.4.4.7**: The (a) giant puffball mushroom (b) releases a cloud of spores when it reaches maturity. (credit a: modification of work by Roger Griffith; credit b: modification of work by Pearson Scott Foresman, donated to the Wikimedia Foundation)

Asexual Reproduction

Fungi reproduce asexually by fragmentation, budding, or producing spores. Fragments of hyphae can grow new colonies. Somatic cells in yeast form buds. During budding (a type of cytokinesis), a bulge forms on the side of the cell, the nucleus divides mitotically, and the bud ultimately detaches itself from the mother cell (Figure **3.4.4.8**).

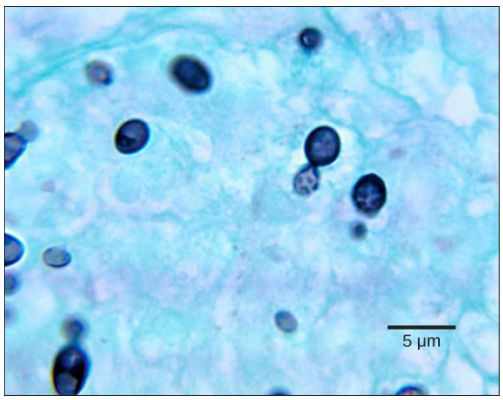


Figure **3.4.4.8**: The dark cells in this bright field light micrograph are the pathogenic yeast *Histoplasma capsulatum*, seen against a backdrop of light blue tissue. Histoplasma primarily infects lungs but can spread to other tissues, causing histoplasmosis, a potentially fatal disease. The cell in the top right quadrant is in the process of budding, with the larger bodu pinching off a smaller round daughter cell. (credit: modification of work by Dr. Libero Ajello, CDC; scale-bar data from Matt Russell)

The most common mode of asexual reproduction is through the formation of asexual **spores**, which are produced by one parent only (through mitosis) and are genetically identical to that parent (Figure **3.4.4.9**). Spores allow fungi to expand their distribution and colonize new environments. They may be released from the parent thallus either outside or within a special reproductive sac called a **sporangium**.

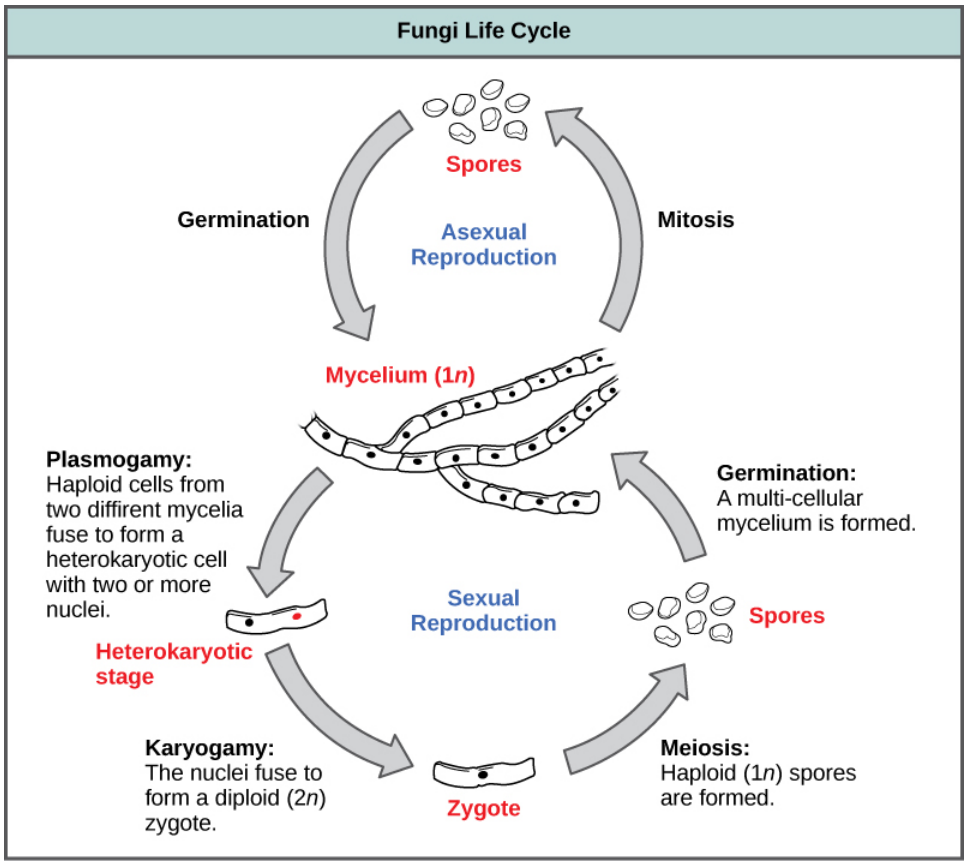


Figure **3.4.4.9**: Fungi may have both asexual and sexual stages of reproduction.

There are many types of asexual spores. **Conidiospores** are unicellular or multicellular spores that are released directly from the tip or side of the hypha. Other asexual spores originate in the fragmentation of a hypha to form single cells that are released as spores; some of these have a thick wall surrounding the fragment. Yet others bud off the vegetative parent cell. **Sporangiospores** are produced in a sporangium (Figure **3.4.4.10**).

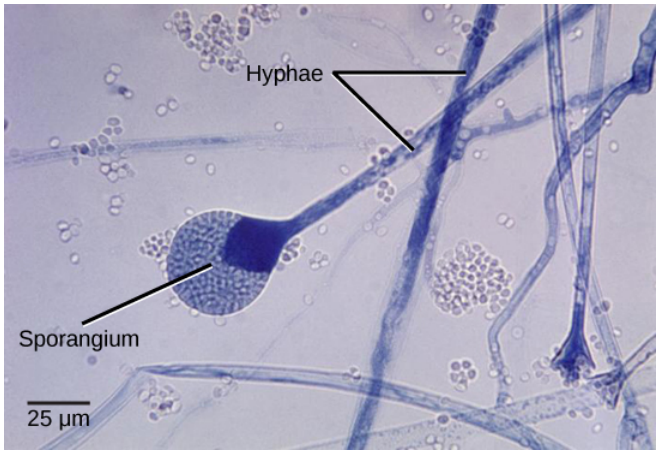


Figure **3.4.4.10**: This bright field light micrograph shows the release of spores from a sporangium at the end of a hypha called a sporangiophore. The organism is a *Mucor* sp. fungus, a mold often found indoors. (credit: modification of work by Dr. Lucille Georg, CDC; scale-bar data from Matt Russell)

Sexual Reproduction

Sexual reproduction introduces genetic variation into a population of fungi. In fungi, sexual reproduction often occurs in response to adverse environmental conditions. During sexual reproduction, two mating types are produced. When both mating types are

present in the same mycelium, it is called **homothallic**, or self-fertile. **Heterothallic** mycelia require two different, but compatible, mycelia to reproduce sexually.

Although there are many variations in fungal sexual reproduction, all include the following three stages (Figure **3.4.4.9**). First, during **plasmogamy** (literally, “marriage or union of cytoplasm”), two haploid cells fuse, leading to a dikaryotic stage where two haploid nuclei coexist in a single cell. During **karyogamy** (“nuclear marriage”), the haploid nuclei fuse to form a diploid zygote nucleus. Finally, meiosis takes place in the gametangia (singular, gametangium) organs, in which gametes of different mating types are generated. At this stage, spores are disseminated into the environment.

Niche and Habitat

Fungi have colonized nearly all environments on Earth, but are frequently found in cool, dark, moist places with a supply of decaying material. Fungi are saprobes that decompose organic matter. Many successful mutualistic relationships involve a fungus and another organism.

Decomposers and Recyclers

The food web would be incomplete without organisms that decompose organic matter (Figure **3.4.4.11**). Some elements—such as nitrogen and phosphorus—are required in large quantities by biological systems, and yet are not abundant in the environment. The action of fungi releases these elements from decaying matter, making them available to other living organisms. Trace elements present in low amounts in many habitats are essential for growth, and would remain tied up in rotting organic matter if fungi and bacteria did not return them to the environment via their metabolic activity.

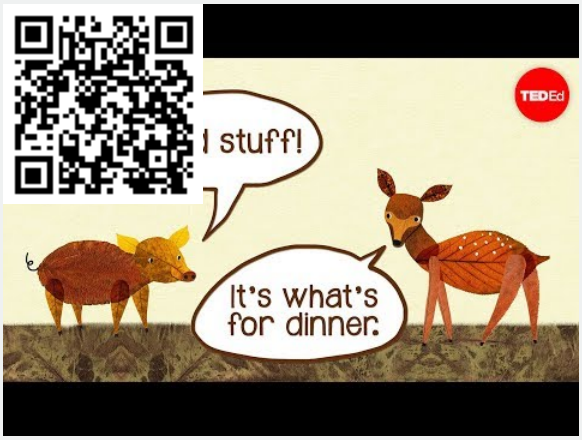


Figure **3.4.4.11**: Fungi are an important part of ecosystem nutrient cycles. These bracket fungi growing on the side of a tree are the fruiting structures of a basidiomycete. They receive their nutrients through their hyphae, which invade and decay the tree trunk. (credit: Cory Zanker)

The ability of fungi to degrade many large and insoluble molecules is due to their mode of nutrition. As seen earlier, digestion precedes ingestion. Fungi produce a variety of exoenzymes to digest nutrients. The enzymes are either released into the substrate or remain bound to the outside of the fungal cell wall. Large molecules are broken down into small molecules, which are transported into the cell by a system of protein carriers embedded in the cell membrane. Because the movement of small molecules and enzymes is dependent on the presence of water, active growth depends on a relatively high percentage of moisture in the environment.

As saprobes, fungi help maintain a sustainable ecosystem for the animals and plants that share the same habitat. In addition to replenishing the environment with nutrients, fungi interact directly with other organisms in beneficial, and sometimes damaging, ways (Figure **3.4.4.12**).

Video



This 4-minute TedEd introduces concepts of energy flow in an ecosystem, including the role of decomposers. Question after watching: Do humans sometimes eat detritus directly? Provide an example.



Figure **3.4.4.12**: Shelf fungi, so called because they grow on trees in a stack, attack and digest the trunk or branches of a tree. While some shelf fungi are found only on dead trees, others can parasitize living trees and cause eventual death, so they are considered serious tree pathogens. (credit: Cory Zanker)

Mutualistic Relationships

Symbiosis is the ecological interaction between two organisms that live together. The definition does not describe the quality of the interaction. When both members of the association benefit, the symbiotic relationship is called mutualistic. Fungi form mutualistic associations with many types of organisms, including cyanobacteria, algae, plants, and animals.

One of the most remarkable associations between fungi and plants is the establishment of **mycorrhizae**. Mycorrhiza, which comes from the Greek words *myco* meaning fungus and *rhizo* meaning root, refers to the association between vascular plant roots and their symbiotic fungi. Somewhere between 80 and 90 percent of all plant species have mycorrhizal partners. In a mycorrhizal association, the fungal mycelia use their extensive network of hyphae and large surface area in contact with the soil to channel water and minerals from the soil into the plant. In exchange, the plant supplies the products of photosynthesis to fuel the metabolism of the fungus.

Lichens are not a single organism, but rather another example of mutualism, in which a fungus (usually a member of the Ascomycota or Basidiomycota phyla) lives in close contact with a photosynthetic organism (a eukaryotic alga or a prokaryotic cyanobacterium) (Figure **3.4.4.13**). Generally, neither the fungus nor the photosynthetic organism can survive alone outside of the symbiotic relationship.

Video



This 5-minute video provides an overview of mycorrhiza.
Question after watching: What are some of the functions of the common mycelium network?



Figure **3.4.4.13**: Lichens have many forms. They may be (a) crust-like, (b) hair-like, or (c) leaf-like. (credit a: modification of work by Jo Naylor; credit b: modification of work by "djpmapleferryman"/Flickr; credit c: modification of work by Cory Zanker)

Optional Activity 3.4.4.3

What term describes the close association of a fungus with the root of a tree?

A. a rhizoid
B. a lichen
C. a mycorrhiza
D. an endophyte

Answer

C. a mycorrhiza

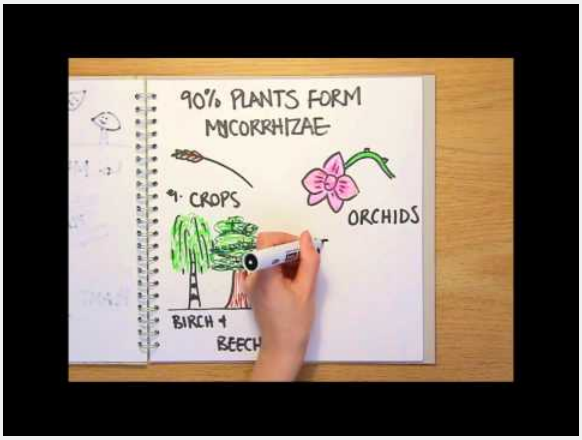
Evolution Connection: Coevolution of Land Plants and Mycorrhizae

Mycorrhizae are the mutually beneficial symbiotic association between roots of vascular plants and fungi. A well-accepted theory proposes that fungi were instrumental in the evolution of the root system in plants and contributed to the success of Angiosperms. The bryophytes (mosses and liverworts), which are considered the most primitive plants and the first to survive on dry land, do not have a true root system; some have mycorrhizae and some do not. They depend on a simple **rhizoid** (an underground organ) and cannot survive in dry areas. True roots appeared in vascular plants. Vascular plants that developed a system of thin extensions from the rhizoids (found in mosses) are thought to have had a selective advantage because they had a greater surface area of contact with the fungal partners than the mosses and liverworts, thus availing themselves of more nutrients in the ground.

Fossil records indicate that fungi preceded plants on dry land. The first association between fungi and photosynthetic organisms on land involved moss-like plants and endophytes. These early associations developed before roots appeared in plants. Slowly, the benefits of the endophyte and rhizoid interactions for both partners led to present-day mycorrhizae; up to about 90 percent of today's vascular plants have associations with fungi in their rhizosphere. The fungi involved in mycorrhizae display many characteristics of primitive fungi; they produce simple spores, show little diversification, do not have a sexual reproductive cycle, and cannot live outside of a mycorrhizal association. The plants benefited from the association because mycorrhizae allowed them to move into new habitats because of increased uptake of nutrients, and this gave them a selective advantage over plants that did not establish symbiotic relationships.

Video





This 5.5-minute video provides a review of the kingdom Fungi.
Question after watching: What are three things you learned in this section, two things you still have questions about, and one visual you created to summarize your learning?

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Unit 3.4.5 - Kingdom Animalia

- Please read and watch the following Learning Resources
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  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe the features that characterized the earliest animals and when they appeared on Earth
- Recognize the implications of mass animal extinctions that have occurred in evolutionary history
- List the features that distinguish the kingdom Animalia from other kingdoms
- Describe the types of data that scientists use to construct and revise animal phylogeny
- List some of the relationships within the modern phylogenetic tree that have been discovered as a result of modern molecular data
- Interpret the Animalia (metazoan) phylogenetic tree

Introduction

Animal evolution began in the ocean over 600 million years ago with tiny creatures that probably do not resemble any living organism today. Since then, animals have evolved into a diverse kingdom known as Animalia or Metazoa. Although over one million extant species of animals have been identified, scientists are continually discovering more species as they explore ecosystems around the world. The number of extant animal species is estimated to be between 3 and 30 million.

But what is an **animal**? While we can easily identify dogs, birds, fish, spiders, and worms as animals, other organisms, such as corals and sponges, are not as easy to classify. Animals vary in complexity—from sponges to crickets to chimpanzees—and scientists are faced with the difficult task of classifying them within a unified system. As with all classifications, they must identify traits that are common to all animals as well as traits that can be used to distinguish among related groups of animals. The animal classification system characterizes animals based on their anatomy, morphology, evolutionary history, features of embryological development, and genetic makeup. Classifications are constantly developing as new information about species arises. Understanding and classifying the great variety of living species help us better understand how to conserve the diversity of life on earth.

Even though members of the animal kingdom are diverse, most animals share features that distinguish them from organisms in other kingdoms. All animals are eukaryotic, multicellular organisms, and almost all animals have complex tissue structures with differentiated and specialized tissues. Most animals are motile, at least during certain life stages. All animals require a source of food and perform internal digestion. They are heterotrophic, ingesting other living or dead organisms, but different from fungi that perform external digestion. As consumers of other organisms, they are also distinguished from autotrophic organisms, such as plants, which synthesize their own nutrients through photosynthesis. Animals may be carnivores, herbivores, omnivores, scavengers, detritivores, or parasites (Figure **3.4.5.1**). Most animals reproduce sexually, although many can reproduce asexually, and the offspring pass through a series of developmental stages that establish a determined and fixed body plan. The body plan refers to the morphology of an animal, determined by developmental cues.



(a) (b)

Figure **3.4.5.1**: All animals are heterotrophs that derive energy from food. The (a) black bear is an omnivore, eating both plants and animals. The (b) heartworm *Dirofilaria immitis* is a parasite that derives energy from its hosts. It spends its larval stage in mosquitoes and its adult stage infesting the heart of dogs and other mammals. (credit a: modification of work by USDA Forest Service; credit b: modification of work by Clyde Robinson)

Many questions regarding the origins and evolutionary history of the animal kingdom continue to be researched and debated, as new fossil and molecular evidence change prevailing theories. Some of these questions include the following:

- How long have animals existed on Earth?
- What were the earliest members of the animal kingdom?
- What organism was their common ancestor?

While animal diversity increased during the Cambrian period of the Paleozoic era, 530 million years ago, modern fossil evidence suggests that primitive animal species existed much earlier.



Figure **3.4.5.2**: The leaf chameleon (*Brookesia micra*) was discovered in northern Madagascar in 2012. At just over one inch long, it is the smallest known chameleon. (credit: modification of work by Frank Glaw, et al., PLOS)

History of Animal Life

Animals of the Pre-Cambrian

It is hypothesized that early animal life, termed **Ediacaran biota**, evolved from protists during the period before the Cambrian, from about 635 Ma to 543 Ma, during the late Proterozoic Era. Some protist species called choanoflagellates closely resemble the choanocyte cells in the simplest animals, sponges. In addition to their morphological similarity, molecular analyses have revealed similar sequence homologies in their DNA.

The earliest animal biota was long believed to include only tiny, sessile, soft-bodied sea creatures. However, recently there has been increasing scientific evidence suggesting that more varied and complex animal species lived during this time, and possibly even before this period, known as the Ediacaran. Fossils believed to represent the oldest animals with hard body parts were recently discovered in South Australia. These sponge-like fossils, named *Coronacollina acula*, date back as far as 560 million years, and are believed to show the existence of hard body parts and spicules that extended 20–40 cm from the main body (estimated about 5 cm long). Other fossils from the Ediacaran period are shown in Figure **3.4.5.3**.



(a) (b)

Figure 3.4.5.3: Fossils of (a) *Cyclomedusa* and (b) *Dickinsonia* date to 650 million years ago, during the Ediacaran period. (credit: modification of work by "Smith609"/Wikimedia Commons)

Another recent fossil discovery may represent the earliest animal species ever found. While the validity of this claim is still under investigation, these primitive fossils appear to be small, one-centimeter long, sponge-like creatures. These fossils from South Australia date back 650 Ma, actually placing the putative animal before the great ice age extinction event that marked the transition between the **Cryogenian period** and the Ediacaran period. Until this discovery, most scientists believed that there was no animal life prior to the Ediacaran period. Many scientists now believe that animals may in fact have evolved during the Cryogenian period, which began 720 Ma.

Video





This 7-minute video provides an overview of the Ediacaran Period, an important moment in the evolution of animal life on earth.

Question after watching: What factors may have led to the diversification of life in this period?

The Cambrian Explosion

The Cambrian period, occurring between approximately 542–488 Ma, marks the most rapid evolution of new animal phyla and animal diversity in Earth's history. It is believed that most of the animal phyla in existence today had their origins during the **Cambrian explosion** (Figure 3.4.5.4). Echinoderms, mollusks, worms, arthropods, and chordates arose during this period (Figure 3.4.5.5). More evidence for this explosion of diversity can be found in Unit 2.2.2.



Figure 3.4.5.4: An artist's rendition depicts some organisms from the Cambrian period.

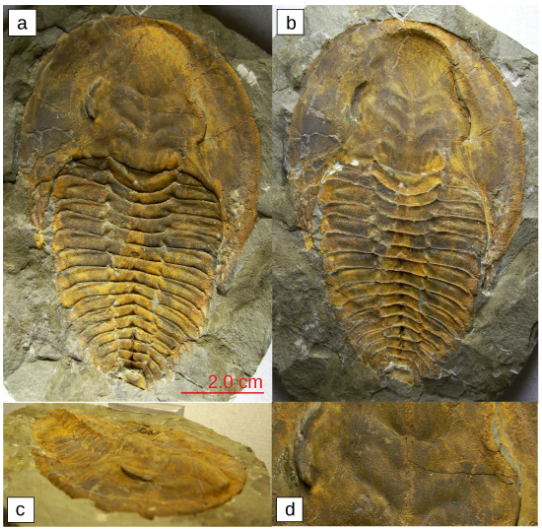
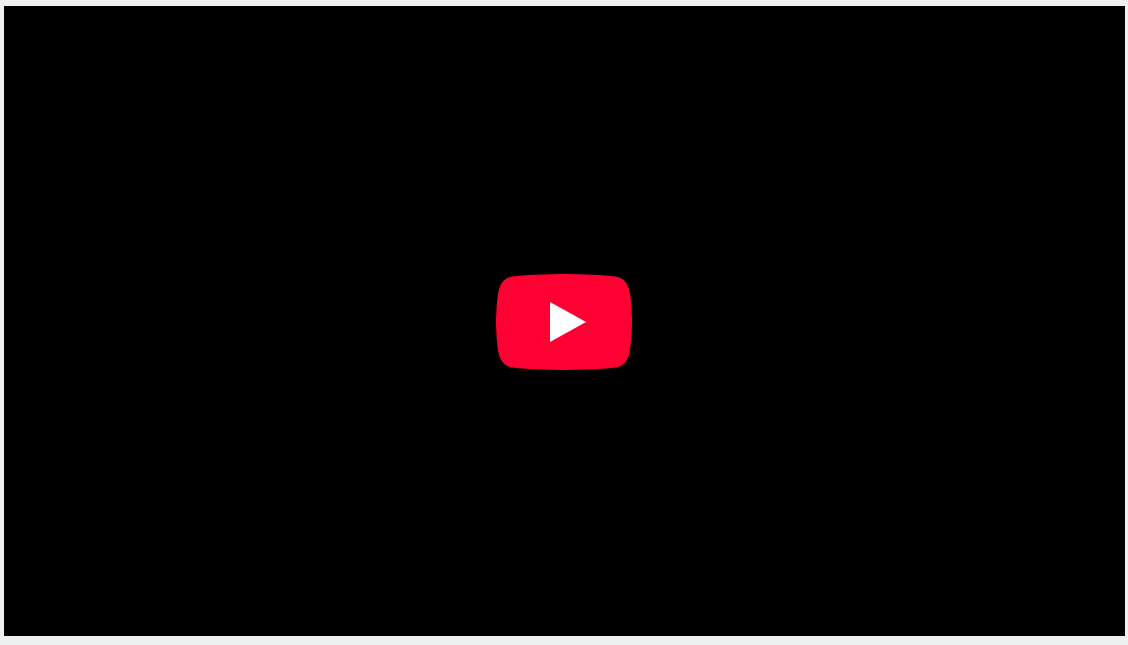


Figure **3.4.5.5**: These fossils (a–d) belong to trilobites, extinct arthropods that appeared in the early Cambrian period, 525 million years ago, and disappeared from the fossil record during a mass extinction at the end of the Permian period, about 250 million years ago.

The cause of the Cambrian explosion is still debated. There are many hypotheses that attempt to answer this question, including environmental changes, genetic developments, and new niches. Hypotheses that attempt to explain why the Cambrian explosion happened must be able to provide valid reasons for the massive animal diversification, as well as explain why it happened *when* it did. There is evidence that both supports and refutes each of the hypotheses described above, and the answer may very well be a combination of these and other hypotheses.

However, unresolved questions about the animal diversification that took place during the Cambrian period remain. For example, we do not understand how the evolution of so many species occurred in such a short period of time. Was there really an "explosion" of life at this particular time? Some scientists question the validity of this idea because there is increasing evidence to suggest that more animal life existed prior to the Cambrian period and that other similar species' adaptive radiation occurred earlier in history as well. Furthermore, the vast diversification of animal species that appears to have begun during the Cambrian period continued well into the following Ordovician period. Despite some of these arguments, most scientists agree that the Cambrian period marked a time of impressively rapid animal evolution and diversification that is unmatched elsewhere during history.

Video





This 12-minute video provides an overview of animal evolution during the Cambrian Period.
Questions after watching: What were some of the adaptations that evolved in animals in this period that persist to this day?
What event is thought to have caused the end of the Cambrian Period as well as an extinction event?

? Optional Activity 3.4.5.1

The time between 542–488 million years ago marks which period?

A. Cambrian period
B. Silurian period
C. Ediacaran period
D. Devonian period

Answer

A. Cambrian period

Post-Cambrian Evolution and Mass Extinctions

The periods that followed the Cambrian during the Paleozoic Era are marked by further animal evolution and the emergence of many new orders, families, and species. As animal phyla continued to diversify, new species adapted to new ecological **niches**, or roles within the ecosystem. During the Ordovician period, which followed the Cambrian period, plant life first appeared on land. This change allowed formerly aquatic animal species to invade land, feeding directly on plants or decaying vegetation. Continual changes in temperature and moisture throughout the remainder of the Paleozoic Era due to continental plate movements encouraged the development of new adaptations to terrestrial existence in animals, such as limbed appendages in amphibians and epidermal scales in reptiles.

Changes in the environment often create new niches that contribute to rapid speciation and increased diversity. On the other hand, cataclysmic events, such as volcanic eruptions and meteor strikes that obliterate life, can result in devastating losses of diversity. Such periods of mass extinction have occurred repeatedly in the evolutionary record of life, erasing some genetic lines while creating room for others to evolve into the empty niches left behind (Figure **3.4.5.6**).

The end of the Permian period (and the Paleozoic Era) was marked by the largest mass extinction event in Earth's history, a loss of roughly 95 percent of the extant species at that time. Some of the dominant phyla in the world's oceans, such as trilobites, disappeared completely. On land, the disappearance of some dominant species of Permian reptiles made it possible for a new line of reptiles to emerge, the dinosaurs. The warm and stable climatic conditions of the ensuing Mesozoic Era promoted an explosive diversification of dinosaurs into every conceivable niche in land, air, and water. Plants, too, radiated into new landscapes and empty niches, creating complex communities of producers and consumers, some of which became very large on the abundant food available.

Video



This 10-minute video describes how a branch of the animal kingdom grew to a huge size.
Questions after watching: What were the factors that led to the evolution of such an enormous size? What were the advantages of this large size for the animal?

Two other mass extinction events occurred: one that ended the Triassic period and one that ended the Cretaceous period, bringing the Mesozoic Era to an end (Figure **3.4.5.6**). The K-Pg (formerly K-T) event (discussed in Unit 3.3.1) led to the end of the dinosaurs as one of the dominant animal lifeforms. In the following Cenozoic Era, mammals radiated into terrestrial and aquatic niches once occupied by dinosaurs, and birds, the warm-blooded offshoots of one line of the ruling reptiles, became aerial specialists.

The appearance and dominance of flowering plants in the Cenozoic Era created new niches for insects, as well as for birds and mammals. Changes in animal species diversity during the late-Cretaceous and early Cenozoic were also promoted by a dramatic shift in Earth's geography, as continental plates slid over the crust into their current positions, leaving some animal groups isolated on islands and continents, or separated by mountain ranges or inland seas from other competitors. Early in the Cenozoic, new ecosystems appeared, with the evolution of grasses and coral reefs. Late in the Cenozoic, further extinctions followed by speciation occurred during ice ages that covered high latitudes with ice and then retreated, leaving new open spaces for colonization.

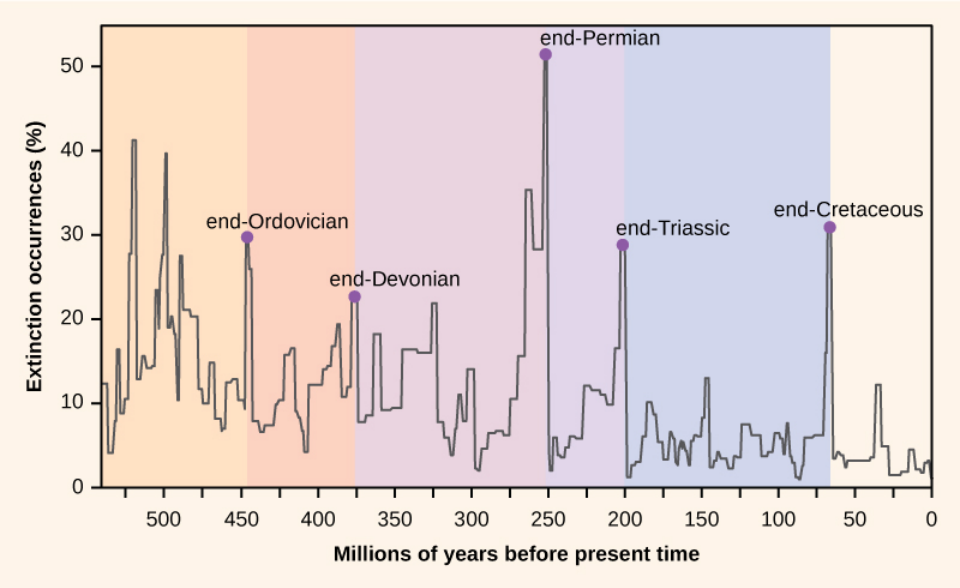


Figure **3.4.5.6**: Mass extinctions have occurred repeatedly over geological time.

Phylogeny of Animalia

The current understanding of evolutionary relationships between the phyla of animals begins with the distinction between the **Eumetazoa** (“true” animals with differentiated tissues) and the **Parazoa** (those like sponges that do not have differentiated tissues). Both Parazoa and Eumetazoa evolved from a common ancestral organism that resembles the modern-day protists called choanoflagellates. These protist cells strongly resemble the sponge choanocyte cells today (Figure **3.4.5.7**).

Most animals fall into the Eumetazoa. While the organisms in Parazoa (“beside animal”) do not contain specialized tissues they do possess specialized cells that perform different functions. Those cells are just not organized into tissues. These organisms are still considered animals since are eukaryotic and they lack the ability to make their own food.

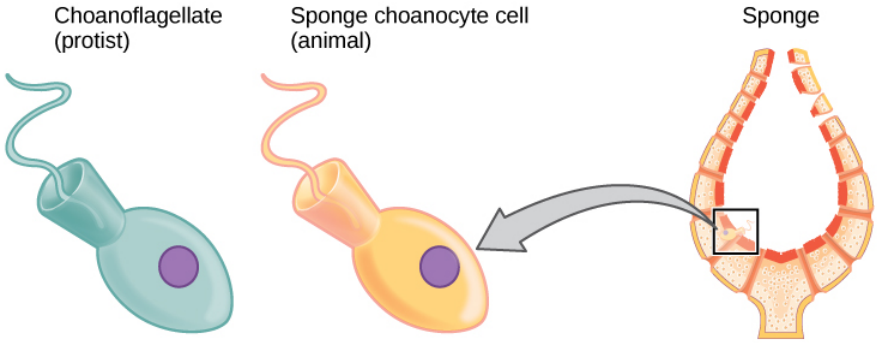


Figure **3.4.5.7**: Cells of the protist choanoflagellate resemble sponge choanocyte cells. Beating of choanocyte flagella draws water through the sponge so that nutrients can be extracted and waste removed.

Video



An overview of the classification of animals is presented in this 4-minute video.
Question after watching: Create a flowchart that would allow you to ask questions about animals at each node point and then allow you to pick one of the branches based on the answer.

Scientists have developed a classification scheme that categorizes all members of the animal kingdom, although there are exceptions to most "rules" governing animal classification. Animals are primarily classified according to morphological and developmental characteristics, such as a **body plan**. One of the most prominent features of the body plan of true animals is that they are morphologically symmetrical. This means that the distribution of body parts is balanced along an axis. Additional characteristics (see Unit 3.4.6) include the number of tissue layers formed during development, the presence or absence of an internal body cavity, and other features of embryological development, such as the origin of the mouth and anus.

Modern Phylogeny Techniques

Phylogenetic groupings are continually being debated and refined by evolutionary biologists. Each year, new evidence emerges that further alters the relationships described by a phylogenetic tree diagram (Figure **3.4.5.7**). Recall that until recently, only morphological characteristics and the fossil record were used to determine phylogenetic relationships among animals. Scientific understanding of the distinctions and hierarchies between anatomical characteristics provided much of this knowledge. Used alone, however, this information can be misleading.

Morphological characteristics may evolve multiple times, and independently, through evolutionary history. Analogous characteristics may appear similar between animals, but their underlying evolution may be very different. With the advancement of molecular technologies, modern phylogenetics is now informed by genetic and molecular analyses, in addition to traditional morphological and fossil data. Many evolutionary relationships in the modern tree have only recently been determined as new DNA and RNA analyses are performed on additional animal species.

Biologists strive to understand the evolutionary history and relationships of all life. The study of phylogeny aims to determine the evolutionary relationships between phyla. Currently, most biologists divide the animal kingdom into 35 to 40 phyla. Scientists develop phylogenetic trees, which serve as hypotheses about which species have evolved from which ancestors.

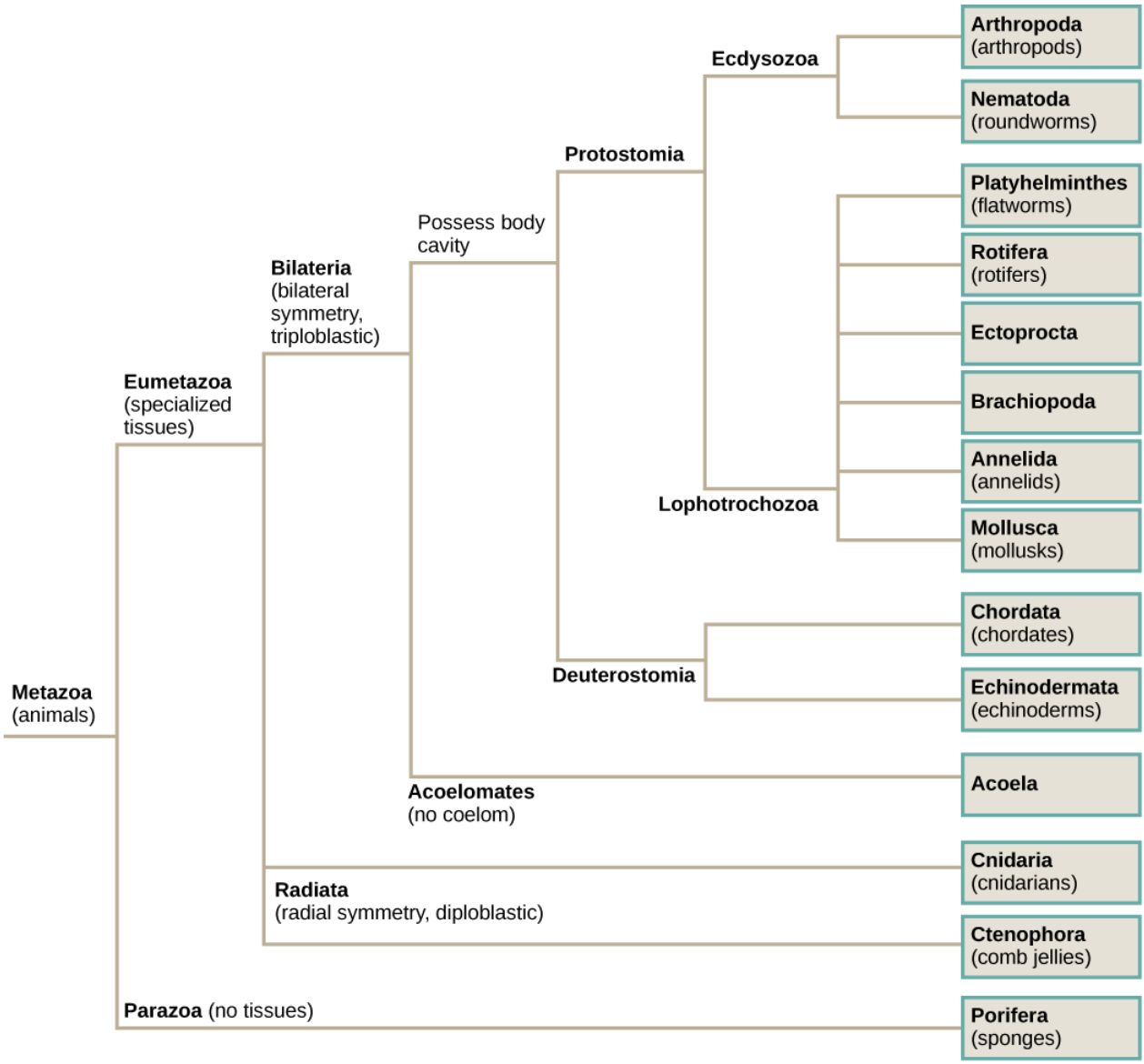


Figure 3.4.5.7: The phylogenetic tree of animals is based on morphological, fossil, and genetic evidence.

? Optional Activity 3.4.5.2

Figure 3.4.5.7: Which of the following statements is false?

A. Eumetazoans have specialized tissues and parazoans don't.
B. Lophotrochozoa and Ecdysozoa are both Bilataria.
C. Acoela and Cnidaria both possess radial symmetry.
D. Arthropods are more closely related to nematodes than they are to annelids.

Answer

C. Acoela and Cnidaria both possess radial symmetry.

? Optional Activity 3.4.5.3

Consulting the modern phylogenetic tree of animals, which of the following would not constitute a clade?

A. deuterostomes
B. lophotrochozoans
C. Parazoa
D. Bilateria

Answer

C. Parazoa

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Unit 3.4.6 - Kingdom Animalia

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Learning Objectives

- Explain the processes of animal reproduction and embryonic development
- Describe the roles that Hox genes play in development
- Explain the differences in animal body plans that support basic animal classification
- Compare and contrast the embryonic development of protostomes and deuterostomes

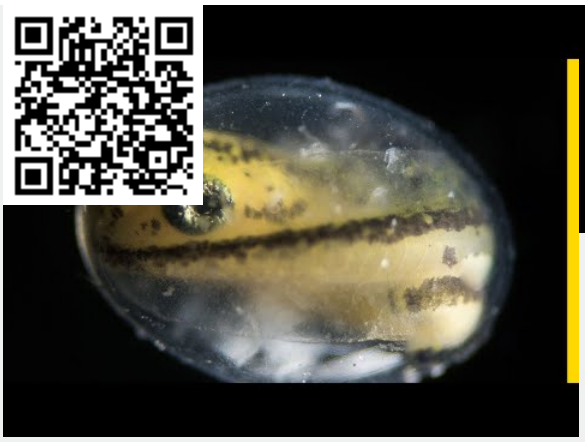
Introduction to Animal Reproduction and Development

Most animals are diploid organisms, meaning that their body (**somatic**) cells are diploid and haploid reproductive (**gamete**) cells are produced through meiosis. Some exceptions exist: For example, in bees, wasps, and ants, the male is haploid because it develops from unfertilized eggs. Most animals are able to undergo sexual reproduction. This fact distinguishes animals from fungi, protists, and bacteria, where asexual reproduction is common or exclusive. During sexual reproduction, the haploid gametes of the male and female individuals of a species combine in a process called fertilization. Typically, the small, motile male sperm fertilizes the much larger, sessile female egg. This process produces a diploid fertilized egg called a zygote. After fertilization, a series of developmental stages occur during which primary germ layers are established and reorganize to form an embryo. During this process, animal tissues begin to specialize and organize into organs and organ systems, determining their future morphology and physiology. The series of developmental stages of the embryo remains largely the same for most members of the animal kingdom.

Some animal groups are also able to reproduce asexually—including cnidarians, roundworms, echinoderms, as well as some insects, reptiles, and fish. The most common forms of asexual reproduction for stationary aquatic animals include budding and fragmentation, where part of a parent individual can separate and grow into a new individual. In contrast, a form of asexual reproduction found in certain insects and vertebrates is called **parthenogenesis** (or “virgin beginning”), where unfertilized eggs can develop into new offspring. This type of parthenogenesis is called **haplodiploidy**. These types of asexual reproduction produce genetically identical offspring, which is disadvantageous from the perspective of evolutionary adaptability because of the potential buildup of deleterious mutations. However, for animals that are limited in their capacity to attract mates, asexual reproduction can ensure genetic propagation.

Video

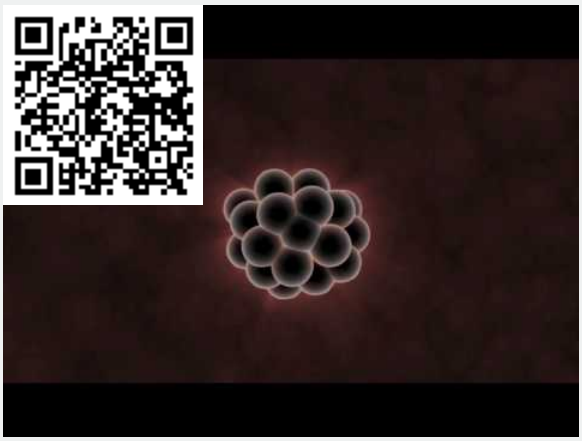




In this 7-minute time lapse video of embryogenic development, you will see a fertilized cell move through cell division and rearrangement of tissues to create a multicellular salamander.
Question after watching: What do you notice about how a one-celled organism becomes a whole animal? What appears to be stages of development?

Video





Watch the following 4-minute video to see how human embryonic development (after the blastula and gastrula stages of development) reflects evolution.

Question after watching: This video shows an animation of human development from a one-celled organism. Compare it to the time lapse video of a salamander's development taken with a microscope. At 0:38 seconds into this video, the animation shows the development of the notochord. When does this happen in the time lapse video of the salamander development? What does this become once the organism is fully formed?

The Role of Homeobox (*Hox*) Genes in Animal Development

Since the early 19th century, scientists have observed that many animals, from the very simple to the complex, shared similar embryonic morphology and development. A human embryo and a frog embryo, at a certain stage of embryonic development, look remarkably alike. For a long time, scientists did not understand why so many animal species looked similar during embryonic development but were very different in adults. They wondered what dictated the developmental direction that a fly, mouse, frog, or human embryo would take. Near the end of the 20th century, a particular class of genes was discovered that had this very job. These genes that determine animal structure are called "homeotic genes," and they contain DNA sequences called homeoboxes. The animal genes containing homeobox sequences are specifically referred to as ***Hox* genes**. This family of genes is responsible for determining the general body plan, such as the number of body segments of an animal, the number and placement of appendages, and animal head-tail directionality. The first *Hox* genes to be sequenced were those from the fruit fly (*Drosophila melanogaster*). A single *Hox* mutation in the fruit fly can result in an extra pair of wings or even appendages growing from the "wrong" body part.

While there are a great many genes that play roles in the morphological development of an animal, what makes *Hox* genes so powerful is that they serve as master control genes that can turn on or off large numbers of other genes. *Hox* genes are well conserved in the animal kingdom. That is, the genetic sequences of *Hox* genes and their positions on chromosomes are remarkably similar across most animals because they were strongly selected for in a common ancestor to nearly all and are not selected against today (Figure **3.4.6.1**). One of the contributions to increased animal body complexity is that *Hox* genes have undergone at least two duplication events during animal evolution (humans have undergone four duplication events), with the additional genes allowing for more complex body types to evolve.

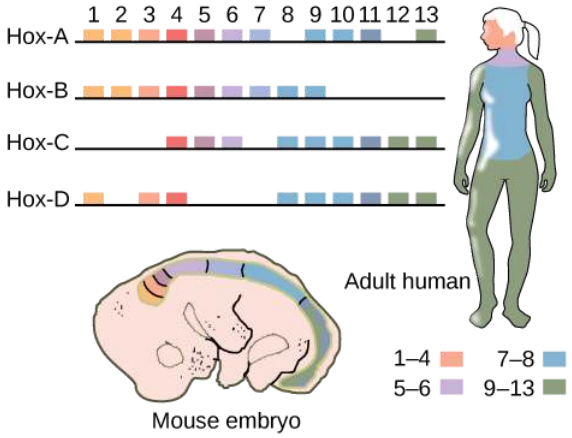


Figure **3.4.6.1**: Hox genes are highly conserved genes encoding transcription factors that determine the course of embryonic development in animals. In vertebrates, the genes have been duplicated into four clusters: *Hox-A*, *Hox-B*, *Hox-C*, and *Hox-D*. Genes within these clusters are expressed in certain body segments at certain stages of development. Shown here is the homology between *Hox* genes in mice and humans. Note how Hox gene expression, as indicated with orange, pink, blue and green shading, occurs in the same body segments in both the mouse and the human.

? Optional Activity **3.4.6.1**

Figure **3.4.6.1**: If a *Hox 13* gene in a mouse was replaced with a *Hox 1* gene, how might this alter animal development?

Answer

The animal might develop two heads and no tail.

Classifying Animalia

Complex Tissue Structure

As multicellular organisms, animals differ from plants and fungi in several ways. Animal cells do not have cell walls, their cells may be embedded in an extracellular matrix (such as bone, skin, or connective tissue), and their cells have unique structures for intercellular communication (such as gap junctions). In addition, animals possess unique tissues, absent in fungi and plants, which allow coordination (nerve tissue) of motility (muscle tissue). Animals are also characterized by specialized connective tissues that provide structural support for cells and organs. This connective tissue constitutes the extracellular surroundings of cells and is made up of organic and inorganic materials. The complex bodies and activities of vertebrates demand such supportive tissues.

The different types of tissues in the Eumetazoa are responsible for carrying out specific functions for the organism. This differentiation and specialization of tissues is part of what allows for such incredible animal diversity. For example, the evolution of nerve tissues and muscle tissues has resulted in animals' unique ability to rapidly sense and respond to changes in their environment. This allows animals to survive in environments where they must compete with other species to meet their nutritional demands.

Body Symmetry

At a very basic level of classification, true animals can be largely divided into three groups based on the type of symmetry of their body plan: radially symmetrical, bilaterally symmetrical, and asymmetrical. **Asymmetry** is a unique feature of Parazoa (Figure 3.4.6.2). Only a few animal groups display radial symmetry. All types of symmetry are well suited to meet the unique demands of a particular animal's lifestyle.

Radial symmetry is the arrangement of body parts around a central axis, as is seen in a drinking glass or pie. It results in animals having top and bottom surfaces but no left and right sides, or front or back. The two halves of a radially symmetrical animal may be described as the side with a mouth or "oral side," and the side without a mouth (the "aboral side"). This form of symmetry marks the body plans of animals in the phyla Ctenophora and Cnidaria, including jellyfish and adult sea anemones (Figure 3.4.6.2). Radial symmetry equips these sea creatures (which may be sedentary or only capable of slow movement or floating) to experience the environment equally from all directions.



Figure 3.4.6.2: The (a) sponge is asymmetrical. The (b) jellyfish and (c) anemone are radially symmetrical, and the (d) butterfly is bilaterally symmetrical. (credit a: modification of work by Andrew Turner; credit b: modification of work by Robert Freiburger; credit c: modification of work by Samuel Chow; credit d: modification of work by Cory Zanker)

Bilateral symmetry involves the division of the animal through a sagittal plane, resulting in two mirror images, right and left halves, such as those of a butterfly (Figure **3.4.6.3**), crab, or human body. Animals with bilateral symmetry have a “head” and “tail” (anterior vs. posterior), front and back (dorsal vs. ventral), and right and left sides. Most animals are bilaterally symmetrical. The evolution of bilateral symmetry that allowed for the formation of anterior and posterior (head and tail) ends promoted a phenomenon called cephalization, which refers to the collection of an organized nervous system at the animal’s anterior end. In contrast to radial symmetry, which is best suited for stationary or limited-motion lifestyles, bilateral symmetry allows for streamlined and directional motion. In evolutionary terms, this simple form of symmetry promoted active mobility and increased the sophistication of resource-seeking and predator-prey relationships.

Animals in the phylum Echinodermata (such as sea stars, sand dollars, and sea urchins) display radial symmetry as adults, but their larval stages exhibit bilateral symmetry. This is termed secondary radial symmetry. They are believed to have evolved from bilaterally symmetrical animals; thus, they are classified as bilaterally symmetrical.

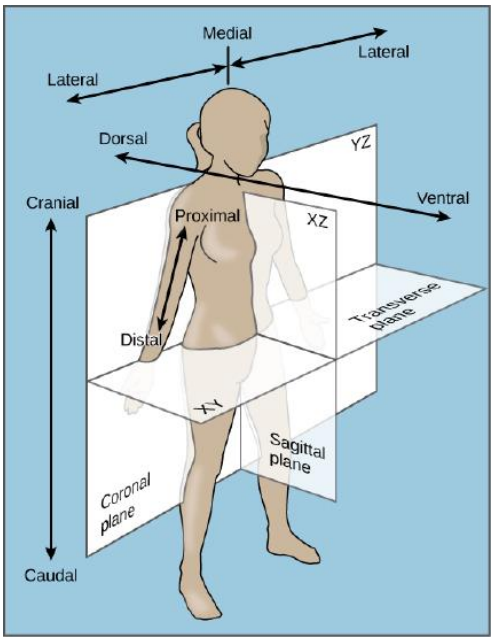
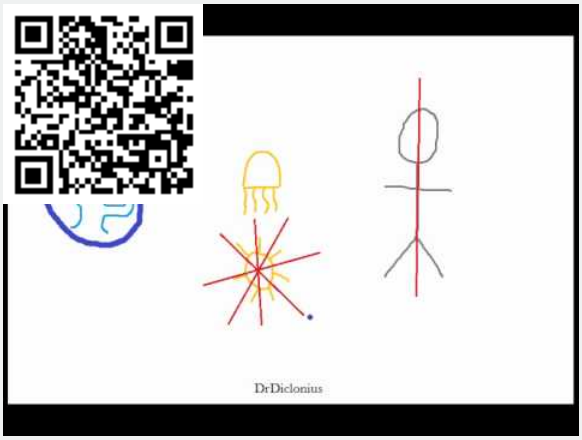


Figure **3.4.6.3**: The bilaterally symmetrical human body can be divided into planes.

https://bio.libretexts.org/@go/page/108077

Video



In this quick 1-minute video, you will review the three types of body symmetry.
Question after watching: What might be an advantage of bilateral symmetry? Why did it evolve? The video mentions that the left and right parts of our bodies are not identical. What are some examples of ways in which our two sides are not symmetrical?

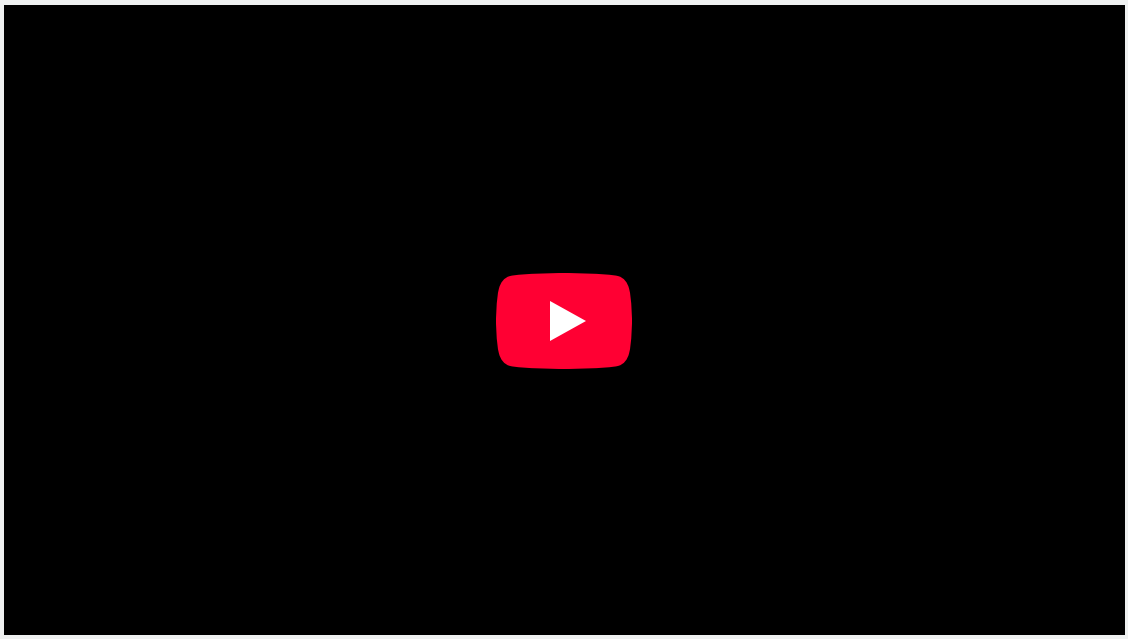
Embryological Development

Most animal species undergo a separation of tissues into germ layers during embryonic development. **Germ layers** are formed during **gastrulation** and they are predetermined to develop into the animal's specialized tissues and organs. Animals develop either two or three embryonic germ layers (Figure **3.4.6.4**). The animals that display radial symmetry develop two germ layers, an inner layer (endoderm) and an outer layer (ectoderm). These animals are called diploblasts. **Diploblasts** have a non-living layer between the endoderm and ectoderm. More complex animals (those with bilateral symmetry) develop three tissue layers: an inner layer (endoderm), an outer layer (ectoderm), and a middle layer (mesoderm). Animals with three tissue layers are called **triploblasts**.

Each of the three germ layers is programmed to give rise to particular body tissues and organs. In humans, the endoderm gives rise to the lining of the digestive tract (including the stomach, intestines, liver, and pancreas), as well as to the lining of the trachea, bronchi, and lungs of the respiratory tract, along with a few other structures. The ectoderm develops into the outer epithelial covering of the body surface, the central nervous system, and a few other structures. The mesoderm is the third germ layer; it forms between the endoderm and ectoderm in triploblasts. This germ layer gives rise to all muscle tissues (including the cardiac tissues

and muscles of the intestines), connective tissues such as the skeleton and blood cells, and most other visceral organs such as the kidneys and the spleen.

Video



deo provides an overview of human development from a fertilized egg until birth and highlights how tissues rearrange to create tubes as a strategy to form the body plan.

Question after watching: How is your body plan really just a tube? How does a tube come to be during animal development?

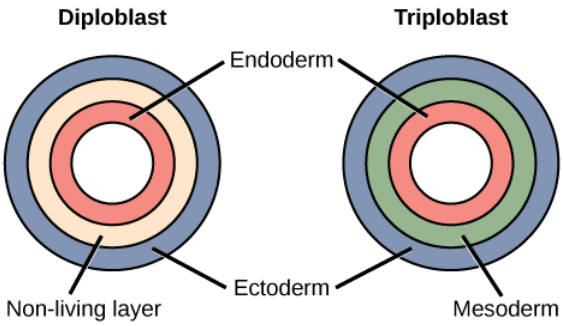


Figure 3.4.6.4: During embryogenesis, diploblasts develop two embryonic germ layers: an ectoderm and an endoderm. Triploblasts develop a third layer—the mesoderm—between the endoderm and ectoderm.

Optional Activity 3.4.6.1

Figure 3.4.6.5: Which of the following statements about diploblasts and triploblasts is false?

A. Animals that display radial symmetry are diploblasts.
B. Animals that display bilateral symmetry are triploblasts.
C. The endoderm gives rise to the lining of the digestive tract and the respiratory tract.
D. The mesoderm gives rise to the central nervous system.

Answer

D. The mesoderm gives rise to the central nervous system.

Coelom: Presence or Absence

Further subdivision of animals with three germ layers (triploblasts) results in the separation of animals that may develop an internal body cavity derived from mesoderm, called a **coelom**, and those that do not. This epithelial cell-lined coelomic cavity represents a space, usually filled with fluid, which lies between the visceral organs and the body wall. It houses many organs such as the digestive system, kidneys, reproductive organs, and heart, and contains the circulatory system. In some animals, such as mammals, the part of the coelom called the pleural cavity provides space for the lungs to expand during breathing. The evolution of the coelom is associated with many functional advantages. Primarily, the coelom provides cushioning and shock absorption for the major organ systems. Organs housed within the coelom can grow and move freely, which promotes optimal organ development and placement. The coelom also provides space for the diffusion of gases and nutrients, as well as body flexibility, promoting improved animal motility.

Triploblasts that do not develop a coelom are called **acoelomates**, and their mesoderm region is completely filled with tissue, although they do still have a gut cavity. Examples of acoelomates include animals in the phylum Platyhelminthes, also known as flatworms. Animals with a true coelom are called **eucoelomates** (or **coelomates**) (Figure **3.4.6.5**). A true coelom arises entirely within the mesoderm germ layer and is lined by an epithelial membrane. Annelids, mollusks, arthropods, echinoderms, and chordates are all eucoelomates. A third group of triploblasts has a slightly different coelom derived partly from mesoderm and partly from endoderm, which is found between the two layers. Although still functional, these are considered false coeloms, and those animals are called **pseudocoelomates**. The phylum Nematoda (roundworms) is an example of a pseudocoelomate.

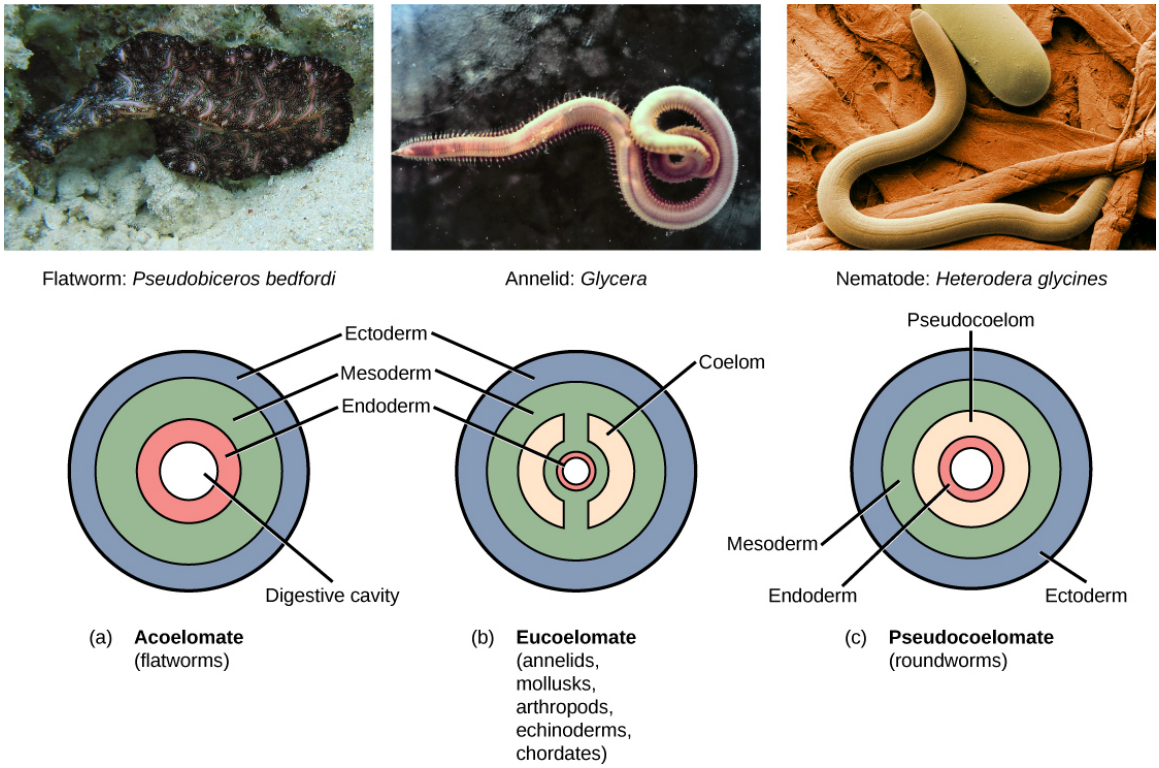


Figure **3.4.6.5**: Triploblasts may be (a) acoelomates, (b) eucoelomates, or (c) pseudocoelomates. Acoelomates have no body cavity. Eucoelomates have a body cavity within the mesoderm, called a coelom, which is lined with mesoderm. Pseudocoelomates also have a body cavity, but it is sandwiched between the endoderm and mesoderm. (credit a: modification of work by Jan Derk; credit b: modification of work by NOAA; credit c: modification of work by USDA, ARS)

Embryonic Development of the Mouth

Finally, true coelomates can be further characterized based on certain features of their early embryological development. Bilaterally symmetrical, tribloblastic eucoelomates can be further divided into two groups based on differences in their early embryonic development. Protostomes include arthropods, mollusks, and annelids. Deuterostomes include more complex animals such as chordates but also some simple animals such as echinoderms. These two groups are separated based on which opening of the

digestive cavity develops first: mouth or anus. The word **protostome** comes from the Greek word meaning “mouth first,” and **deuterostome** originates from the word meaning “mouth second” (in this case, the anus develops first).

The mouth or anus develops from a structure called the **blastopore** (Figure **3.4.6.6**). The blastopore is the indentation formed during the initial stages of gastrulation. In later stages, a second opening forms, and these two openings will eventually give rise to the mouth and anus. It has long been believed that the blastopore develops into the mouth of protostomes, with the second opening developing into the anus; the opposite is true for deuterostomes. Recent evidence has challenged this view of the development of the blastopore of protostomes, however, and the theory remains under debate.

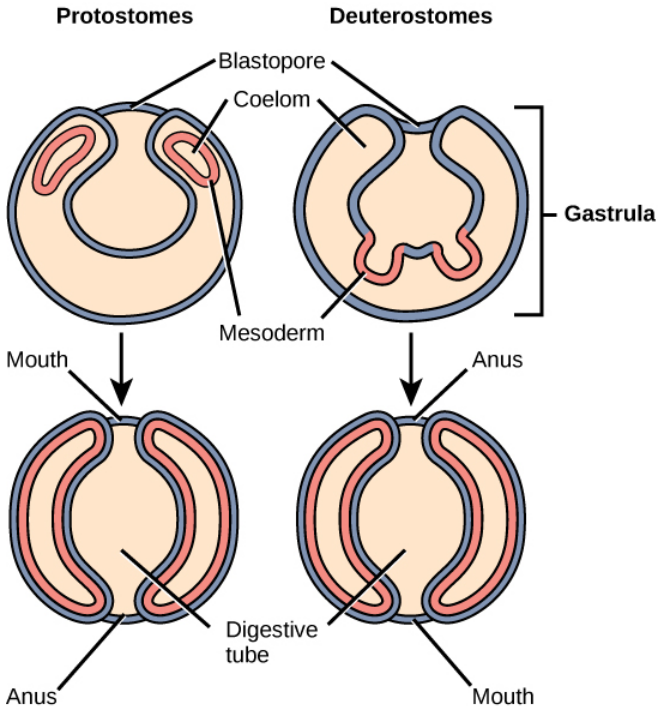


Figure **3.4.6.7**: Eucoelomates can be divided into two groups based on their early embryonic development. In protostomes, part of the mesoderm separates to form the coelom. In deuterostomes, the mesoderm pinches off to form the coelom.

? Optional Activity 3.4.6.2

Which of the following is not a feature common to *most* animals?

A. development into a fixed body plan
B. asexual reproduction
C. specialized tissues
D. heterotrophic nutrient sourcing

Answer

B. asexual reproduction

? Optional Activity 3.4.6.3

Which of the following is not possible?

A. radially symmetrical diploblast
B. diploblastic eucoelomate
C. protostomic coelomate
D. bilaterally symmetrical deuterostome

Answer

B. diploblastic eucoelomate

Indigenous Connections

'Namgis Treaty researcher Diana Jacobson reminds us of traditional knowledge embedded in story:

> *There's one woman who is a twin and she turns into a dog salmon. She told all about the fish carcasses that they had to be thrown back into the river. This way our old people knew that the carcasses fed the future fry by coming up when they emerged. This knowledge was passed on with the stories so anytime they cut up the fish and heads that they used, it went back into the river and it rotted …and it fed the fish. (personal interview, July 16, 2008)*

Despite fishing since time immemorial, Indigenous fisheries management in British Columbia was replaced with state regulation (Indigenous Foundations, 2009):

> When the first salmon canneries appeared on the BC coast in the 1870s, Indigenous peoples had already built flourishing economies based on salmon. The one-way spawning migrations of adult salmon to the stretch of river where they were born has always brought a crucial source of energy and nutrients from the ocean to freshwater and terrestrial environments, allowing people to preserve vast quantities of fish for winter use, and for trade with other Indigenous groups. Salmon were received by First Nations peoples as gift-bearing relatives, and were treated with great respect. Nick Claxton describes his community's traditional reef-net fishery as a successful collaboration between the fish and the people:
>
> > The WSÁNEC people successfully governed their traditional fisheries for thousands of years, prior to contact. This was not just because there were laws and rules in place, and that everybody followed them, but there was also a different way of thinking about fish and fishing, which included a profound respect. At the end of the net, a ring of willow was woven into the net, which allowed some salmon to escape. This is more than just a simple act of conservation (the main priority and narrow vision of the Department of Fisheries and Oceans). It represents a profound respect for salmon. It was believed that the runs of salmon were lineages, and if some were allowed to return to their home rivers, then those lineages would always continue. The WSÁNEC people believe that all living things were once people, and they are respected as such. The salmon are our relatives. Out of respect, when the first large sockeye was caught, a First Salmon Ceremony was conducted. This was the WSÁNEC way to greet and welcome the king of all salmon. The celebration would likely last up to ten days. Taking time to celebrate allowed for a major portion of the salmon stocks to return to their rivers to spawn, and to sustain those lineages or stocks. (2008)
>
> As lineages or stocks, salmon populations are enormously diverse, with many different life-history adaptations, such as the length of time spent in freshwater and in the ocean, the timing of spawning, and age and size at maturity. In addition, since fat content decreases with migration distance, processing techniques, such as drying and smoking, needed to be closely adapted to individual runs. Local ecology and culture worked together to produce highly specialized salmon food products for food and trade. Wind-drying of salmon in the Fraser Canyon, for example, depended on the temperature and humidity conditions created by this upriver canyon environment. In early July, when hot, dry winds blew into the canyon, salmon were fished from particular, family-owned spots, and then hung on giant racks perched on rock bluffs, where they could be dried before the arrival of blowflies and wasps (Carlson, 2001). Despite government intervention, and changes in technology to fishing by boat with gill nets, the practice of wind-drying continues to this day among some Stó:lō families, and wind-drying is consciously regarded as a traditional practice in need of protection (Butler, 1998).

Source: Adapted from Isaac (2016).

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Butler, C. (1998). *Regulating tradition: Sto:lo wind drying and Aboriginal rights* [Unpublished master's thesis]. University of British Columbia.

Carlson, K. T. (2001). History wars: Considering contemporary fishing site disputes. In K. T. Carson (Ed.), *A Sto:lo Coast Salish historical atlas* (p. 58). Douglas & McIntyre.

Claxton, N. X. (2008). ISTÁ SĆIÁNEW, ISTÁ SXOLE: 'To fish as formerly:' The Douglas Treaties and the WSÁNEĆ reef-net fisheries. In L. Simpson (Ed.), *Lighting the eighth fire: The liberation, resurgence, and protection of Indigenous nations* (pp. 54–55). Arbeiter Ring.

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Unit 3.4.7: Kingdom Plantae - Evolution and Phylogeny

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 90 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 3.4.8, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Identify the challenges to life on land for plants
- Describe the timeline of plant evolution and the impact of land plants on other living things
- Identify the main characteristics of bryophytes
- Identify the new traits that first appear in pterophytes
- Describe the type of seeds produced by gymnosperms, as well as other characteristics of gymnosperms
- State which period saw the first appearance of gymnosperms and explain when they were the dominant plant life
- List the four groups of modern-day gymnosperms and provide examples of each
- Explain why angiosperms are the dominant form of plant life in most terrestrial ecosystems
- Describe the two main groups of flowering plants

Introduction

The kingdom **Plantae** constitutes large and varied groups of organisms. All are eukaryotic, multicellular with differentiated tissues, and photosynthetic. There are more than 300,000 species of cataloged plants. Of these, more than 260,000 are seed plants. Mosses, ferns, conifers, and flowering plants are all members of the plant kingdom.

Evolutionary History of Plants

The major event to mark the Ordovician, more than 500 Ma, was the colonization of land by the ancestors of modern land plants. Fossilized cells, cuticles, and spores of early land plants have been dated as far back as the Ordovician period in the early Paleozoic era. The oldest-known vascular plants have been identified in deposits from the Devonian. One of the richest sources of information is the Rhynie chert, a sedimentary rock deposit found in Rhynie, Scotland, where embedded fossils of some of the earliest vascular plants have been identified (Figure **3.4.7.1**).



Figure **3.4.7.1**: This Rhynie chert contains fossilized material from vascular plants. The circles seen in the rock on the left are the cross sections of the root-like structures called rhizoids seen in the model on the right. Credit left: Peter Coxhead CC-BY-SA 3.0; right: Matteo De Stefano/MUSE CC-BY-SA 3.0.

Current evolutionary thought holds that green algae and land-dwelling plants are monophyletic. The evolutionary transition from water to land imposed severe constraints on plants. They had to develop strategies to avoid dehydration, disperse reproductive cells, support themselves without water, and capture and filter sunlight. These adaptations were required for the colonization of land begun by the **bryophytes** (seedless, non-vascular plants) and their ancestors. While seed plants developed adaptations that allowed them to populate even arid habitats, full independence from water did not happen in all plants. Most seedless plants still require a moist environment.

An incredible variety of seedless plants populates the terrestrial landscape (Figure **3.4.7.2**). Mosses may grow on a tree trunk, and horsetails may display their jointed stems and spindly leaves across the forest floor. Ferns dominate some forest floors. Today, seedless plants represent only a small fraction of the plants in our environment; yet, three hundred million years ago, seedless plants dominated the landscape and grew in the enormous swampy forests of the Carboniferous period. Their decomposition created large deposits of coal that we mine today.



Figure **3.4.7.2**: Seedless plants, like these horsetails (*Equisetum* sp.), thrive in damp, shaded environments under a tree canopy where dryness is rare. (credit: modification of work by Jerry Kirkhart)

Seeds and pollen, two critical adaptations, distinguish the seed plants from other (seedless) vascular plants. Seed plants, such as conifers and flowering plants, do not rely on water for reproduction like the seedless plants do (Figure **3.4.7.3**). They play an integral role in all aspects of life on the planet, shaping the physical terrain, influencing the climate, and maintaining life as we know it.

Fossils place the earliest distinct seed plants at about 350 Ma. The first reliable record of **gymnosperms** (the cone-bearing plants) dates their appearance to the Pennsylvanian period, about 319 Ma. Gymnosperms dominated the landscape in the early (Triassic) and middle (Jurassic) Mesozoic era. **Angiosperms** (the flowering plants) surpassed gymnosperms by the middle of the Cretaceous (about 100 Ma) in the late Mesozoic era, and today are the most abundant plant group in most terrestrial biomes.



(a) (b) (c) (d)

Figure **3.4.7.3**: Seed plants dominate the landscape and play an integral role in human societies. (a) Palm trees grow along the shoreline; (b) wheat is a crop grown in most of the world; (c) the flower of the cotton plant produces fibers that are woven into fabric; (d) the potent alkaloids of the beautiful opium poppy have influenced human life both as a medicinal remedy and as a dangerously addictive drug. (credit a: modification of work by Ryan Kozie; credit b: modification of work by Stephen Ausmus; credit c: modification of work by David Nance; credit d: modification of work by Jolly Janner)

The Major Divisions (i.e. Phyla) of Land Plants

The green algae and land plants are grouped together into a subphylum called the Streptophytina, and thus are called Streptophytes. In a further division, land plants are classified into two major groups (knowns as **Divisions** rather than phyla) according to the absence or presence of vascular tissue, as detailed in Figures **3.4.7.4**.

Plants that lack **vascular tissue** (the bryophytes), which is formed of specialized cells for the transport of water and nutrients, are referred to as non-vascular plants. Liverworts, mosses, and hornworts are **seedless, non-vascular plants** that likely appeared early in land plant evolution. Vascular plants developed a network of cells that conduct water and solutes.

The first vascular plants (the **tracheophytes**) appeared in the late Ordovician and were probably similar to **lycophytes**, which include club mosses (not to be confused with the mosses) and the **pterophytes** (ferns, horsetails, and whisk ferns). Lycophytes and pterophytes are referred to as **seedless vascular plants**, because they do not produce seeds.

The seed plants, or **spermatophytes**, form the largest group of all existing plants, and hence dominate the landscape. Seed plants include gymnosperms, most notably conifers, which produce “naked seeds,” and the most successful of all plants, the angiosperms, which produce flowers. Angiosperms protect their seeds inside chambers at the center of a flower; the walls of the chamber later develop into a fruit.

The evolutionary history of the development of each of these groups is detailed in the cladogram in Figure **3.4.7.5**. Each taxa is described in more detail below.

STREPTOPHYTES: THE GREEN PLANTS								
Charophytes	Embryophytes: The Land Plants							
	Non Vascular			Vascular				
	Seedless Plants Bryophytes			Seedless Plants		Seed Plants Spermatophytes		
				Lycophytes	Pterophytes			
	Liver-worts	Horn-worts	Mosses	Club Mosses	Whisk Ferns	Gymno-sperms	Angio-sperms	
				Quillworts	Horsetails			
				Spike Mosses	Ferns			

Figure 3.4.7.4: This table shows the major divisions of green plants.

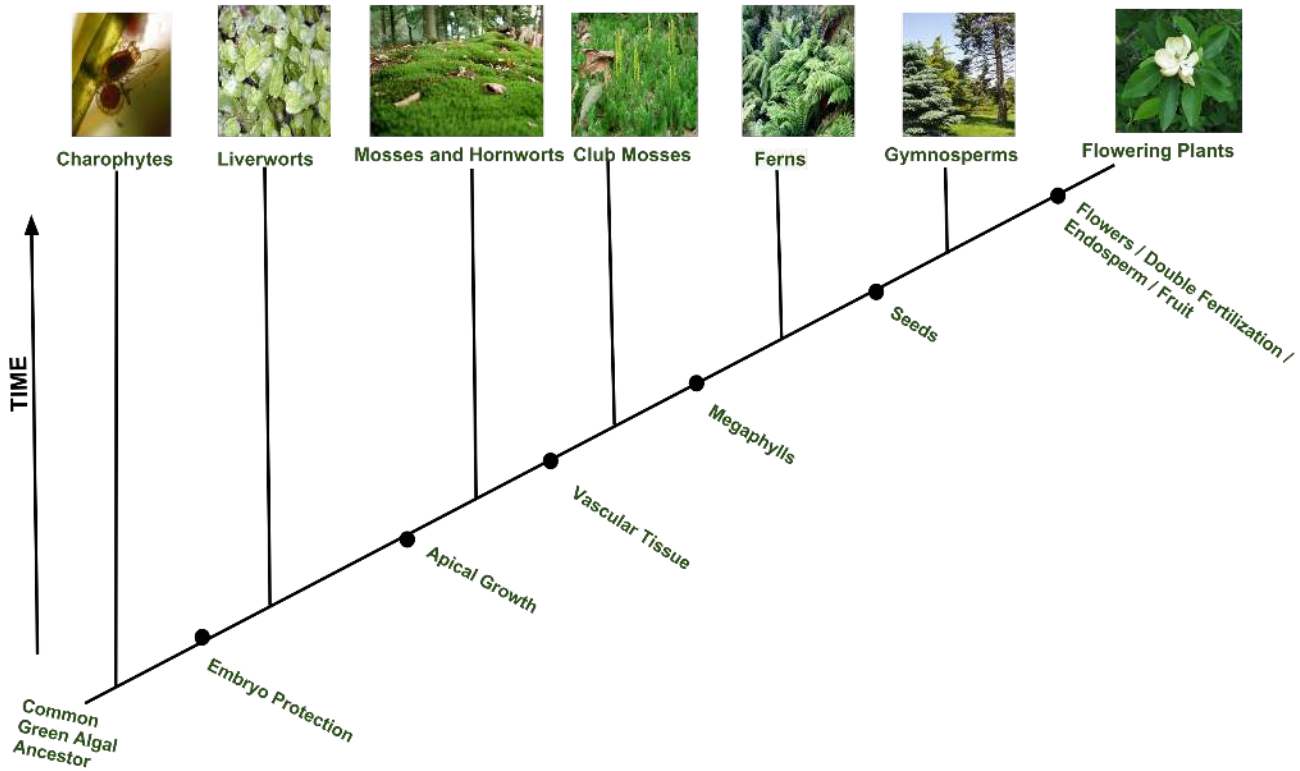


Figure 3.4.7.5: Evolutionary history of the kingdom Plantae.
Laurenprue216; CC-BY-SA 3.0

? Optional Activity 3.4.7.1

Figure 3.4.7.4: Which of the following statements about plant divisions is false?

A. Lycophytes and pterophytes are seedless vascular plants.
B. All vascular plants produce seeds.

C. All nonvascular embryophytes are bryophytes.
D. Seed plants include angiosperms and gymnosperms.

Answer

B.

Evolution Connection: Algae and Evolutionary Paths to Photosynthesis

Some scientists consider all algae to be plants, while others assert that only the **Charophytes** belong in the kingdom Plantae. These divergent opinions are related to the different evolutionary paths to photosynthesis selected for in different types of algae. While all algae are photosynthetic—that is, they contain some form of a chloroplast—they did not all become photosynthetic via the same path.

The ancestors to the green algae became photosynthetic by engulfing, but not metabolising, a green, photosynthetic bacterium about 1.65 billion years ago. That algal line evolved into the Charophytes, and eventually into the modern mosses, ferns, gymnosperms, and angiosperms. Their evolutionary trajectory was relatively straight and monophyletic. In contrast, the other algae—red, brown, golden, stramenopiles, and so on—all became photosynthetic by secondary, or even tertiary, endosymbiotic events; that is, they endosymbiosed cells that had already endosymbiosed a cyanobacterium. These latecomers to photosynthesis are parallels to the Charophytes in terms of autotrophy, but they did not expand to the same extent as the Charophytes, nor did they colonize the land.

The different views on whether all algae are Plantae arise from how these evolutionary paths are viewed. Scientists who solely track evolutionary straight lines, consider only the Charophytes as plants. To biologists who cast a broad net over living things that share a common characteristic (in this case, photosynthetic eukaryotes), all algae are plants.

Optional Activity 3.4.7.2

What evolved first: eukaryotic cells or cells capable of photosynthesis?

Answer

Bacteria capable of photosynthesis (cyanobacteria) evolved first and were engulfed by larger bacterial cells without being degraded. These photosynthetic cells evolved a mutualistic relationship with their hosts and are now known as chloroplasts within some eukaryotic cells.

The Seedless Plants

Bryophytes (Non-Vascular, Seedless Plants)

Bryophytes are the group of plants that are the closest extant relatives of early terrestrial plants. The first bryophytes (liverworts) most likely appeared in the Ordovician period, about 450 million years ago. Because of the lack of lignin and other resistant structures in these plants, the likelihood of bryophytes forming fossils is rather small. By the Silurian period, however, vascular plants had spread through the continents. This compelling fact is used as evidence that non-vascular plants must have preceded the Silurian period.

Today, more than 25,000 species of bryophytes thrive in mostly damp habitats, although some live in deserts. They constitute the major flora of inhospitable environments like the tundra, where their small size and tolerance to desiccation offer distinct advantages. They generally lack lignin and do not have **tracheids** (xylem cells specialized for forming conduits inside the plant to conduct water). Rather, water and nutrients circulate inside specialized conducting cells. Although the term non-tracheophyte is more accurate, bryophytes are commonly called nonvascular plants.

In a bryophyte, all the conspicuous vegetative organs—including the photosynthetic leaf-like structures, the thallus, stem, and the rhizoid that anchors the plant to its substrate—belong to the haploid organism or **gametophyte**. The **sporophyte** (the diploid organism) is barely noticeable. The gametes formed by bryophytes swim with a flagellum, as do gametes in a few of the tracheophytes. The **sporangium**, the multicellular sexual reproductive structure, is present in bryophytes and absent in the majority

of algae. The bryophyte embryo also remains attached to the parent plant, which protects and nourishes it. This is a characteristic of land plants.

Bryophytes may have been successful at the transition from an aquatic habitat to land, but they are still dependent on water for reproduction and absorb moisture and nutrients through the gametophyte surface. The lack of roots for absorbing water and minerals from the soil, as well as a lack of reinforced conducting cells, limits bryophytes to small sizes. Although they may survive in reasonably dry conditions, they cannot reproduce and expand their habitat range in the absence of water.

The bryophytes are divided into three phyla: the liverworts (**Marchantiophyta**), the hornworts (**Anthocerotophyta**), and the mosses (**Bryophyta**).

Video



Learn more about Bryophytes in this 8-minute video.
Questions after watching: How would you recognize a bryophyte next time you go on a hike in the forest? What are their distinctive features? If they have no root system, how do they take in water? What about other nutrients?

The Seedless Vascular Plants

The vascular plants, or tracheophytes, are the dominant and most conspicuous group of land plants. More than 260,000 species of tracheophytes represent more than 90 percent of Earth's vegetation. Several evolutionary innovations explain their success and their ability to spread to all habitats. Vascular plants can achieve enormous heights, thus competing successfully for light. Photosynthetic organs become leaves. Pipe-like cells or vascular tissues transport water, minerals, and macromolecules (especially carbohydrates) throughout the organism.

By the late Devonian period, plants had evolved vascular tissue, well-defined leaves, and root systems. With these advantages, plants increased in height and size. During the Carboniferous period, swamp forests of club mosses (**Lycopodiophyta**) and ferns, horsetails, and whisk ferns (**Pteridophyta**), with some specimens reaching heights of more than 30 m, covered most of the land. These forests gave rise to the extensive coal deposits that gave the Carboniferous its name.

Water is still required for the fertilization of *seedless vascular plants*, and most favor a moist environment as the sperm must swim on a layer of moisture to reach the egg. This step in reproduction explains why ferns and their relatives are more abundant in damp environments. Modern-day seedless tracheophytes include club mosses, horsetails, ferns, and whisk ferns. In seedless vascular plants, the diploid sporophyte is the dominant phase of the lifecycle. The gametophyte is now an inconspicuous, but still independent, organism. Throughout plant evolution, there is an evident reversal of roles in the dominant phase of the lifecycle.

Video



Learn more about lycophytes in this 5.5-minute video.
Questions after watching: What's unique about the "plumbing system" of lycophytes? What is the most significant impact that lycophytes have had on our society?

Video



In this 7-minute video, you will learn more about monilophytes (a smaller clade of the Pteridophyta).
Question after watching: How are monilophytes different to the lycophytes you just heard about in the last video?

Gymnosperms

The fossil plant *Elkinsia polymorpha*, a "seed fern" from the Devonian period, about 400 Ma, is considered the earliest seed plant currently known. Seed ferns produced their seeds along their branches without specialized structures (Figure **3.4.7.6**). They are the first true seed plants due to structures called **cupules** that enclose and protect the **ovule**, the female gametophyte, and associated tissues, which then developed into a seed upon fertilization. Seed plants resembling modern tree ferns became more numerous and diverse in the swamps of the Carboniferous period.

Following the wet Mississippian and Pennsylvanian periods, which were dominated by giant fern trees, the Permian period was dry. This gave a reproductive edge to seed plants, which are better adapted to survive dry spells. The Ginkgoales, a group of gymnosperms with only one surviving species, *Gingko biloba*, were the first gymnosperms to appear during the lower Jurassic. Gymnosperms expanded in the Mesozoic era (about 240 Ma), supplanting ferns in the landscape, and reaching their greatest diversity during this time. The Jurassic period was as much the age of the cycads (palm-tree-like gymnosperms) as the age of the dinosaurs. Gingkoales and the more familiar conifers also dotted the landscape.

Gymnosperms, meaning “naked seeds,” are a diverse group of seed plants and are paraphyletic. Their characteristics include naked seeds, separate female and male gametes, pollination by wind, and tracheids (which transport water and solutes in the vascular

system). Gymnosperm seeds are not enclosed in an **ovary**; rather, they are exposed on cones or modified leaves. **Sporophylls** are specialized leaves that produce sporangia. The term **strobilus** describes a tight arrangement of sporophylls around a central stalk, as seen in cones. Some seeds are enveloped by sporophyte tissues upon maturation.

Modern gymnosperms are classified into four taxa: **Coniferophyta** (the conifers), **Cycadophyta** (the cycads), and **Ginkgophyta** (the ginko) are similar in their production of **secondary cambium** (cells that generate the vascular system of the trunk or stem and are partially specialized for water transportation) and their pattern of seed development. However, the three phyla are not closely related phylogenetically to each other. **Gnetophyta** (a group of 70 species of three genera) are considered the closest group to angiosperms because they produce true xylem tissue with vessel elements.



Figure **3.4.7.6**: This fossilized leaf is from *Glossopteris*, a seed fern that thrived during the Permian age (290–240 million years ago). (credit: D.L. Schmidt, USGS)

Although angiosperms (flowering plants) are the major form of plant life in most biomes, gymnosperms still dominate some ecosystems, such as the taiga (boreal forests - see Unit 4.4.3) and the alpine forests at higher mountain elevations because of their adaptation to cold temperatures and dry growth conditions (Figure **3.4.7.7**).



Figure **3.4.7.7**: This boreal forest (taiga) has low-lying plants and conifer trees. Government of Canada: Boreal Forest

Angiosperms (The Flowering Plants)

Undisputed fossil records place the massive appearance and diversification of angiosperms in the middle to late Mesozoic era. Angiosperms (“seed in a vessel”) produce a flower containing male and/or female reproductive structures. Fossil evidence indicates that flowering plants first appeared in the Lower Cretaceous, about 125 million years ago, and were rapidly diversifying by the Middle Cretaceous, about 100 Ma (Figure **3.4.7.8**). Earlier traces of angiosperms are scarce but fossilized pollen recovered from Jurassic geological material has been attributed to possible angiosperms. A few early Cretaceous rocks show clear imprints of leaves resembling angiosperm leaves. By the mid-Cretaceous, a staggering number of diverse flowering plants crowd the fossil record. The same geological period is also marked by the appearance of many modern groups of insects, including pollinating insects that likely played a key role in ecology and the evolution of flowering plants.

Although several hypotheses have been offered to explain this sudden profusion and variety of flowering plants, none have garnered the consensus of paleobotanists (scientists who study ancient plants). New data in comparative genomics and paleobotany have, however, shed some light on the evolution of angiosperms. Rather than being derived from gymnosperms, angiosperms formed a sister clade that developed in parallel with the gymnosperms. The two innovative structures of flowers and fruit represent an improved reproductive strategy that served to protect the embryo, while increasing genetic variability and range. Paleobotanists debate whether angiosperms evolved from small woody bushes, or were basal angiosperms related to tropical grasses. Both views

draw support from cladistics studies, and the so-called woody magnoliid hypothesis, which proposes that the early ancestors of angiosperms were shrubs, also offers molecular biological evidence.



Figure **3.4.7.8**: This leaf imprint shows a *Ficus speciosissima*, an angiosperm that flourished during the Cretaceous period. (credit: W. T. Lee, USGS)

From their humble and still obscure beginning during the early Jurassic period, the angiosperms—or flowering plants—have evolved to dominate most terrestrial ecosystems. With more than 250,000 species, the angiosperm phylum (Anthophyta) is second only to insects in terms of diversification. The success of angiosperms is due to two novel reproductive structures: flowers and fruit (Figure **3.4.7.9**). The function of the **flower** is to facilitate **pollination**, which helps plants mix up their genes with that of other plants to produce offspring. Flowers also provide protection for the ovule and developing embryo inside a receptacle. The function of the **fruit** is seed dispersal. They also protect the developing seed and assist with germination. Different fruit structures or tissues on fruit—such as sweet flesh, wings, parachutes, or spines that grab—reflect the dispersal strategies that help spread seeds.



Figure **3.4.7.9**: These flowers grow in the Sunken Gardens at Butchart Gardens in Victoria, BC. Flowering plants dominate terrestrial landscapes. The vivid colors of flowers are an adaptation to pollination by animals such as insects and birds. Jeffrey Beall; CC BY-ND 2.0.

Angiosperms are classified in a single phylum: the Anthophyta. Modern angiosperms appear to be a monophyletic group, which means that they originate from a single ancestor. Flowering plants are divided into two major groups, according to the structure of the **cotyledons** (the first leaves formed after germination), veins (the vascular tissue of xylem and phloem), pollen grains (haploid sperm cells), and other structures such as flower petal numbers (Table **3.4.7.1**). **Monocots** include grasses and lilies, and **eudicots** or dicots form a polyphyletic group. **Basal angiosperms** are a group of plants that are believed to have branched off before the separation into monocots and eudicots because they exhibit traits from both groups. They are categorized separately in many

classification schemes. The *Magnoliidae* (magnolia trees, laurels, and water lilies) and the *Piperaceae* (peppers) belong to the basal angiosperm group.

Table **3.4.7.1**: Comparison of Structural Characteristics of Monocots and Eudicots

Characteristic	Monocot	Eudicot
Cotyledon	One	Two
Veins in Leaves	Parallel	Network (branched)
Stem Vascular Tissue	Scattered	Arranged in ring pattern
Roots	Network of adventitious roots	Tap root with many lateral roots
Pollen	Monosulcate	Trisulcate
Flower Parts	Three or multiple of three	Four, five, multiple of four or five and whorls

Highlight: Sweetgrass (Angiosperm)

According to *The Canadian Encyclopedia* (Turner, 2018):

> Sweetgrass is a fragrant grass with long, satiny leaves. Also known as vanillagrass, mannagrass, and holy grass, it is well known to [some] Indigenous people in Canada and the United States as a material for baskets, as well as a scent, medicine, and smudge. Two closely related species are native to Canada: common sweetgrass (*Hierochloë hirta* subspecies *arctica*) and alpine sweetgrass (*H. alpina*). As a widely used and revered sacred plant, sweetgrass is still harvested today and continues to play an important role in Indigenous cultures.
>
> Sweetgrass is a perennial grass, in the family Poaceae. Usually placed in the genus *Hierochloë*, it is sometimes included within the genus *Anthoxanthum*. It has often been treated as one species, *Hierochloë odorata*, but currently taxonomists recognize up to four species, two of which grow in Canada: common sweetgrass (*Hierochloë hirta* subspecies *arctica*) and alpine sweetgrass (*H. alpina*).
>
> The flat, bright green leaves can grow up to half a metre long or more and have a distinctively reddish colour at their base. The flowers are small and greenish and grow in branching clusters at the top of slender, upright stalks. The seeds are small and often infertile and rarely germinate to create new plants. Sweetgrass's most common means of reproduction comes from its creeping, underground stems. These stems, known as rhizomes, grow horizontally under the earth, creating dense patches of grass that can be manually divided up to produce new plants.
>
> Sweetgrass (*Hierochloë*) thrives in diverse habitats and is circumpolar in distribution. Members of the genus are native to northern Eurasia, Greenland, Iceland, Canada, and the United States (except in the south central and southeastern regions). In Canada, common sweetgrass (*Hierochloë hirta* subsp. *arctica*) grows near rivers, lake edges, and wet meadows, often forming dense patches, from sea level to subalpine zones. Alpine sweetgrass (*Hierochloë alpina*) grows near sea level in the Arctic and in meadows and on rocky slopes in subalpine and alpine areas in other parts of Canada, especially in the Pacific Coastal and Rocky Mountains.

References

Turner, N. (2018, November 23). Sweetgrass. In *The Canadian Encyclopedia*. https://www.thecanadianencyclopedia....cle/sweetgrass



Figure 3.4.7.10: Sweetgrass (Matt Lavin; CC BY-SA 2.0)

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Unit 3.4.8: Kingdom Plantae - Adaptations

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to the Unit 3 Glossary, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Discuss the challenges to plant life on land
- Describe the adaptations that allowed plants to colonize the land
- Discuss the importance of adaptations to life on land
- Discuss the type of seeds produced by gymnosperms, as well as other characteristics of gymnosperms
- Describe the main parts of a flower and their purpose
- Detail the life cycle of an angiosperm
- Discuss the two main groups of flowering plants

Introduction

As plants adapted to life on land, they had to contend with several challenges in the terrestrial environment, the largest being a lack of easy access to water as compared to an aquatic environment.

Plant Adaptations to Life on Land

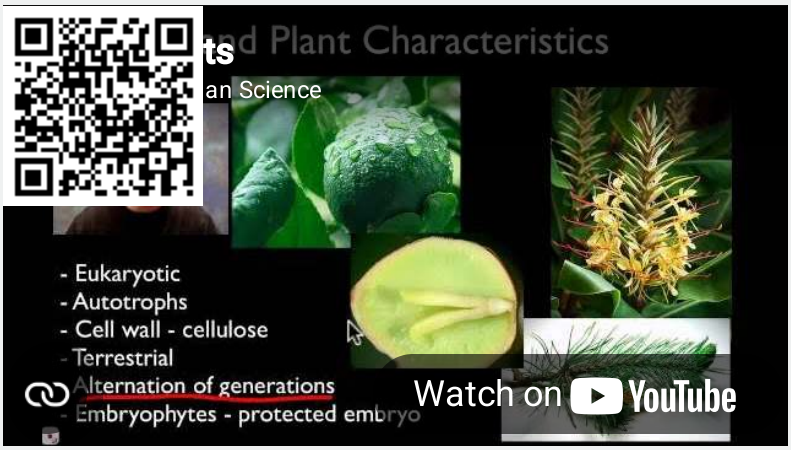
Water has been described as the “universal solvent.” The cell’s interior is a watery soup: in this medium, most small molecules dissolve and diffuse, and the majority of the chemical reactions of metabolism take place. Desiccation, or drying out, is a constant danger for an organism on land when exposed to air. Even when parts of a plant are close to a source of water, the aerial structures are likely to dry out. Water also provides buoyancy to organisms and there is no need for structural support to help the organism maintain a shape or orientation. On land, plants needed to develop structural support since air does not provide the same lift as water. The organism is also subject to bombardment by mutagenic radiation, because air does not filter out as many of the ultraviolet rays of sunlight as water. Additionally, the male gametes must reach the female gametes using new strategies, because swimming is no longer possible. Therefore, both gametes *and* zygotes must be protected from desiccation. The successful land plants developed strategies to deal with all of these challenges. Not all adaptations appeared at once. Some species never moved very far from the aquatic environment, whereas others went on to conquer the driest environments on Earth.

To balance these survival challenges, life on land offers several advantages. First, sunlight is abundant. Water filters sunlight, altering the spectral quality and reducing the amount of light absorbed by the photosynthetic pigment chlorophyll. Soils provide nutrients where the plants grow, rather than depending on currents and diffusion to bring them. Finally, land plants evolved before land animals; therefore, plants were initially able to evolve without herbivores (although they did have pathogens). As some animals evolved to land-dwelling, plants developed strategies to deter predation: from spines and thorns to toxic chemicals.

Early land plants, like the early land animals, did not live very far from an abundant source of water and developed survival strategies to combat dryness. One of these strategies is called tolerance. Many mosses, for example, can dry out to a brown and brittle mat, but as soon as rain or a flood makes water available, mosses will absorb it and are restored to their healthy green appearance. Another strategy is to colonize environments with high humidity, where droughts are uncommon. Ferns, which are considered an early lineage of plants, thrive in damp and cool places such as the understory of temperate forests. Later, plants moved away from moist or aquatic environments using resistance to desiccation, rather than tolerance. These plants, like cacti, minimize the loss of water to such an extent they can survive in extremely dry environments.

The most successful adaptation was the development of new structures that gave plants the advantage when colonizing new and dry environments. Four major adaptations are found in all terrestrial plants: the alternation of generations, a sporangium in which the spores are formed, a gametangium that produces haploid cells, and apical meristem tissue in roots and shoots. The evolution of a waxy cuticle and a cell wall containing **lignin**, a complex polymer impermeable to water, also contributed to the success of land plants. These adaptations are noticeably lacking in the closely related green algae—another reason for the debate over their placement in the plant kingdom.

Video



In this 7.5-minute video from Bozeman Science, you will be taken through an overview of plants, their unique characteristics, and their classification.

Questions after watching: Based on the information you learned in this video, create an evolutionary tree of plants containing the 4 groups: bryophytes, ferns and relatives, gymnosperms, and angiosperms. Include the adaptation that evolved at each node and led to the diversification of the plant groups at the appropriate location.

Alternation of Generations

Alternation of generations describes a life cycle in which an organism has both haploid and diploid multicellular stages (Figure 3.4.8.1).

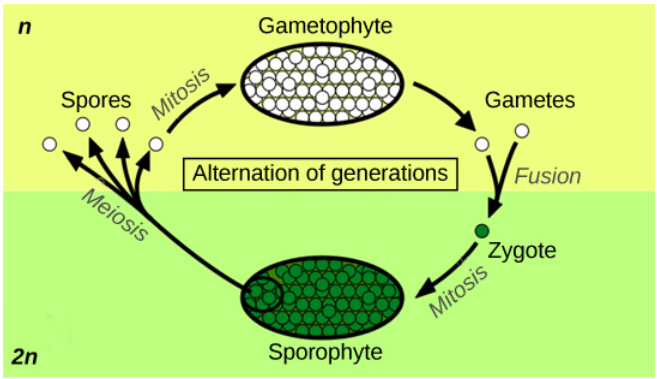


Figure 3.4.8.1: Alternation of generations between the 1*n* gametophyte and 2*n* sporophyte is shown. (credit: Peter Coxhead)

Haplontic refers to a lifecycle in which there is a dominant haploid stage, and **diplontic** refers to a lifecycle in which the diploid is the dominant life stage. Humans are diplontic. Most plants exhibit alternation of generations, which is described as **haplodiplodontic:** the haploid multicellular form, known as a gametophyte, is followed in the development sequence by a multicellular diploid organism: the sporophyte. The gametophyte gives rise to the gametes by mitosis. This can be the most obvious phase of the life cycle of the plant, as in the bryophytes, or it can occur in a microscopic structure, such as a pollen grain, in vascular plants. The sporophyte stage is barely noticeable in the non-vascular plants.

? Optional Activity 3.4.8.1

Alternation of generations means that plants produce:

1. only haploid multicellular organisms
2. only diploid multicellular organisms
3. only diploid multicellular organisms with single-celled haploid gametes
4. both haploid and diploid multicellular organisms

Answer

D

Sporangia and Gametangia

Gametangia (singular, gametangium) are structures observed on multicellular haploid gametophytes. In the gametangia, precursor cells give rise to gametes by mitosis. The male gametangium (**antheridium**) releases sperm. Many seedless plants produce sperm equipped with flagella that enable them to swim in a moist environment to the **archegonia**: the female gametangium. The embryo develops inside the archegonium as the sporophyte. Gametangia are prominent in seedless plants, but are very rarely found in seed plants.

The sporophyte bears the sporangia (singular, sporangium): organs that first appeared in the land plants. The term "sporangia" literally means "spore in a vessel," as it is a reproductive sac that contains spores (Figure **3.4.8.2**). The spores are later released by the sporangia and disperse in the environment. Two different types of spores are produced in land plants, the megaspore (female) and the microspore (male), resulting in the separation of sexes at different points in the lifecycle.



Figure **3.4.8.2**: Spore-producing sacs called sporangia grow at the ends of long, thin stalks in this photo of the moss *Esporangios bryum*. (credit: Javier Martin)

Seedless Plants

The sporophyte of seedless plants is diploid and results from fusion of two gametes. Seedless non-vascular plants produce only one kind of spore and are called **homosporous**. The gametophyte phase is dominant in these plants. After germinating from a spore, the resulting gametophyte produces both male and female gametangia, usually on the same individual. In contrast, heterosporous plants produce two morphologically different types of spores. The male spores are called **microspores**, because of their smaller size, and develop into the male gametophyte; the comparatively larger **megaspores** develop into the female gametophyte. Heterospory is observed in a few seedless vascular plants and in all seed plants.

When the haploid spore germinates in a hospitable environment, it generates a multicellular gametophyte by mitosis. The gametophyte supports the zygote formed from the fusion of gametes and the resulting young sporophyte (vegetative form). The cycle then begins anew.

Seed Plants

Gymnosperms are seed plants that use an exposed seed to reproduce. This contrasts to angiosperms, or flowering plants, that enclose the seeds in fruits or nuts. The life cycle of gymnosperm alternates between sporophyte (2n) and gametophyte (1n) stages. The bulk of their lives are spent in the sporophyte stage, but while they do the organism hosts a female gametophyte. You can think of it as the sex organs of the plant, or its ovaries (Figure **3.4.8.3**). All gymnosperms are heterosporous. The male and female

reproductive organs can form in cones or strobili. Male and female sporangia are produced either on the same plant, described as **monoecious** (“one home” or bisexual), or on separate plants, referred to as **dioecious** (“two homes” or unisexual).

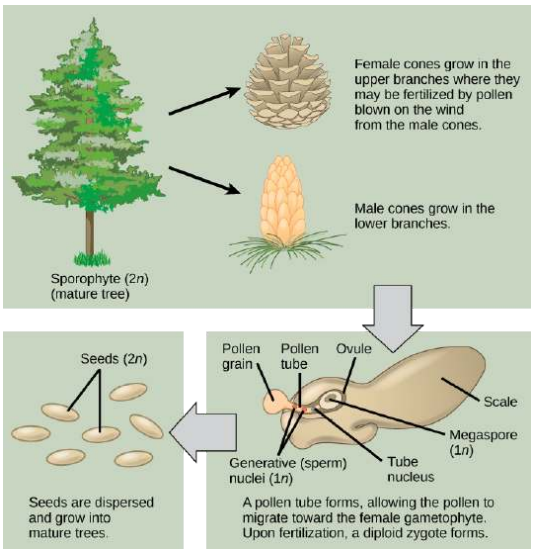


Figure **3.4.8.3**: This image shows the life cycle of a conifer. Pollen from male cones blows up into upper branches, where it fertilizes female cones.

Optional Activity 3.4.8.2

Figure **3.4.8.3**: At what stage does the diploid zygote form?

A. When the female cone begins to bud from the tree
B. At fertilization
C. When the seeds drop from the tree
D. When the pollen tube begins to grow

Answer

B. The diploid zygote forms after the pollen tube has finished forming, so that the male generative nuclei can fuse with the female gametophyte.

Video



In this 6-minute video, explore the long-distance pollination process of naked seed plants, the gymnosperms. Questions after watching: What is the difference between male cones and female cones in a pine tree? If the gametes of pine trees are inside cones, how do the female and male gametes meet to achieve fertilization?

The adult, or sporophyte, phase is the main phase of an angiosperm's life cycle (Figure **3.4.8.4**). Like gymnosperms, angiosperms are heterosporous. Therefore, they generate microspores, which will generate pollen grains as the male gametophytes, and megaspores, which will form an ovule that contains female gametophytes. Inside the anthers' **microsporangia**, male gametophytes divide by meiosis to generate haploid microspores, which, in turn, undergo mitosis and give rise to pollen grains. Each pollen grain contains two cells: one generative cell that will divide into two sperm and a second cell that will become the pollen tube cell. The ovary contains the female **megasporangia** which will give rise to the haploid megaspores.

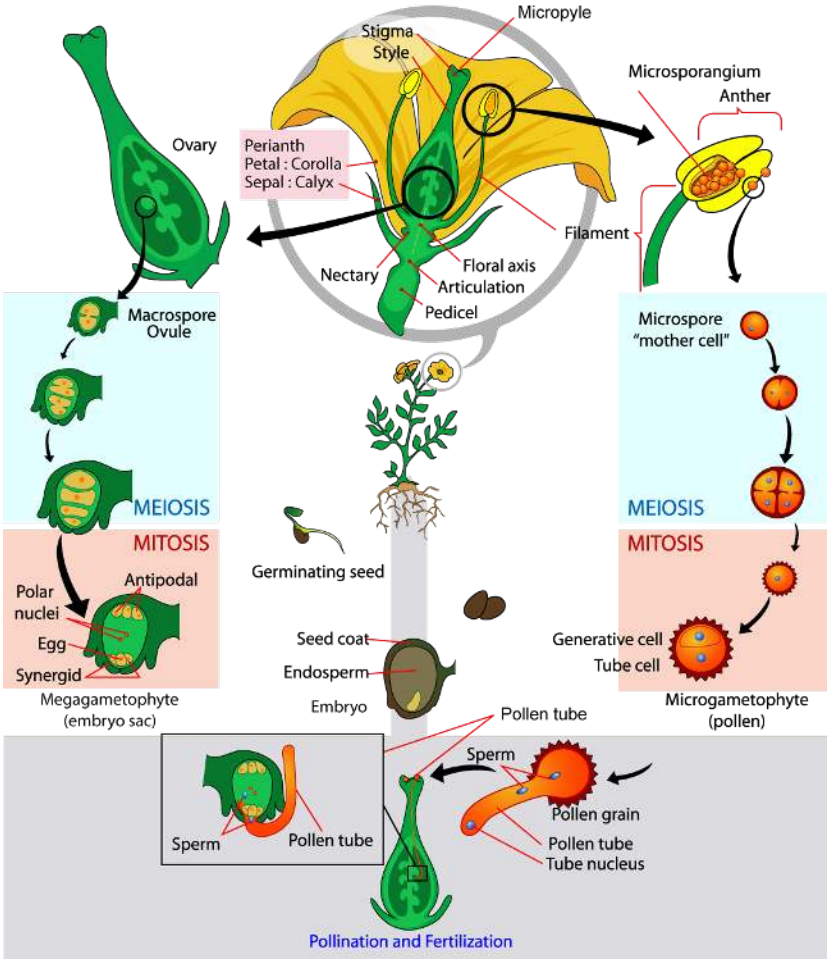


Figure **3.4.8.4**: The life cycle of an angiosperm is shown. Anthers and carpels are structures that shelter the actual gametophytes: the pollen grain and embryo sac. Double fertilization is a process unique to angiosperms. (credit: modification of work by Mariana Ruiz Villareal)

Apical Meristems

Shoots and roots of plants increase in length through rapid cell division in a tissue called the **apical meristem**, which is a small zone of cells found at the shoot tip or root tip (Figure **3.4.8.5**). The apical meristem is made of undifferentiated cells that continue to proliferate throughout the life of the plant. Elongation of the shoots and roots allows a plant to access additional space and resources: light in the case of the shoot, and water and minerals in the case of roots. A separate meristem, called the **lateral meristem**, produces cells that increase the diameter of tree trunks.

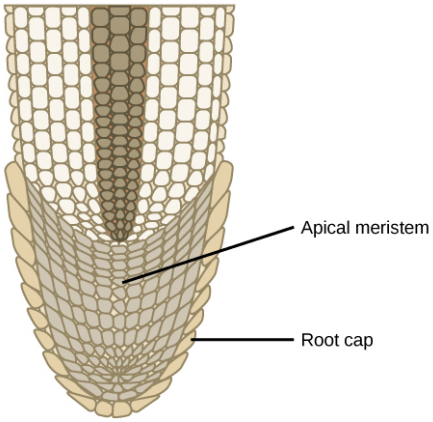


Figure **3.4.8.5**: Addition of new cells in a root occurs at the apical meristem. Subsequent enlargement of these cells causes the organ to grow and elongate. The root cap protects the fragile apical meristem as the root tip is pushed through the soil by cell elongation.

Additional Land Plant Adaptations

Seeds and Pollen

Protection of the embryo is a major requirement for land plants. The vulnerable embryo must be sheltered from desiccation and other environmental hazards. In both seedless and seed plants, the female gametophyte provides protection and nutrients to the embryo as it develops into the new generation of sporophyte. This distinguishing feature of land plants gave the group its alternate name of embryophytes.

Unlike bryophyte and fern spores (which are haploid cells dependent on moisture for rapid development of gametophytes), seeds contain a diploid embryo that will germinate into a sporophyte. Storage tissue to sustain growth and a protective coat give seeds their superior evolutionary advantage. Several layers of hardened tissue prevent desiccation, and free reproduction from the need for a constant supply of water. Furthermore, seeds remain in a state of dormancy, induced by desiccation and the hormone abscisic acid, until conditions for growth become favorable. Whether blown by the wind, floating on water, or carried away by animals, seeds are scattered in an expanding geographic range, thus avoiding competition with the parent plant.

Pollen grains are male gametophytes and are carried by wind, water, or a pollinator. The whole structure is protected from desiccation and can reach the female organs without dependence on water, a major evolutionary development for land-based plants. Male gametes reach female gametophyte and the egg cell gamete though a pollen tube: an extension of a cell within the pollen grain. The sperm of modern gymnosperms lack flagella, but in cycads and the *Gingko*, the sperm still possess flagella that allow them to swim down the pollen tube to the female gamete; however, they are enclosed in a pollen grain.

Cuticle

In land plants, a waxy, waterproof cover called a **cuticle** protects the leaves and stems from desiccation. However, the cuticle also prevents intake of carbon dioxide needed for the synthesis of carbohydrates through photosynthesis. To overcome this, **stomata**, or pores that open and close to regulate gases and water vapor, appeared in plants as they moved away from moist environments into drier habitats.

UVB Filters

Water filters ultraviolet-B (UVB) light, which is harmful to all organisms, especially those that must absorb light to survive. This filtering does not occur for land plants. This presented an additional challenge to land colonization, which was met by the evolution of biosynthetic pathways for the synthesis of protective flavonoids and other compounds: pigments that absorb UV wavelengths of light and protect the aerial parts of plants from photodynamic damage.

Secondary Metabolites

Plants cannot avoid being eaten by animals. Instead, they synthesize a large range of poisonous **secondary metabolites**: complex organic molecules such as alkaloids, whose noxious smells and unpleasant taste deter animals. These toxic compounds can also cause severe diseases and even death, thus discouraging predation. Humans have used many of these compounds for centuries as

drugs, medications, or spices. In contrast, as plants co-evolved with animals, the development of sweet and nutritious metabolites lured animals into providing valuable assistance in dispersing pollen grains, fruit, or seeds. Plants have been enlisting animals to be their helpers in this way for hundreds of millions of years.

Vascular Tissue: Xylem and Phloem

As plants adapted to dry land and evolved strategies for dealing with the dry environment, new organs and structures made their appearance. Early land plants did not grow more than a few inches off the ground, competing for light on these low mats. By developing a shoot and growing taller, individual plants captured more light. Because air offers substantially less support than water, land plants incorporated more rigid molecules in their stems (and later, tree trunks). In small plants such as single-celled algae, simple diffusion suffices to distribute water and nutrients throughout the organism. However, for plants to evolve larger forms, the evolution of vascular tissue for the distribution of water and solutes was a prerequisite. The vascular system contains xylem and phloem tissues. **Xylem** conducts water and minerals absorbed from the soil up to the shoot, while **phloem** transports food derived from photosynthesis throughout the entire plant. A root system evolved to take up water and minerals from the soil and to anchor the increasingly taller shoot in the soil.

Roots: Support for the Plant

Roots are not well preserved in the fossil record. Nevertheless, it seems that roots appeared later in evolution than vascular tissue. The development of an extensive network of roots represented a significant new feature of vascular plants. Thin **rhizoids** attached bryophytes to the substrate, but these rather flimsy filaments did not provide a strong anchor for the plant; neither did they absorb substantial amounts of water and nutrients. In contrast, roots, with their prominent vascular tissue system, transfer water and minerals from the soil to the rest of the plant. The extensive network of roots that penetrates deep into the soil to reach sources of water also stabilizes trees by acting as a ballast or anchor. The majority of roots establish a symbiotic relationship with fungi, forming mycorrhizae, which benefit the plant by greatly increasing the surface area for absorption of water and soil minerals and nutrients.

Leaves, Sporophylls, and Strobili

The appearance of true leaves in the pterophytes improved plants' photosynthetic efficiency. Leaves capture more sunlight with their increased surface area by employing more chloroplasts to trap light energy and convert it to chemical energy, which is then used to fix atmospheric carbon dioxide into carbohydrates. The carbohydrates are exported to the rest of the plant by the conductive cells of phloem tissue.

In addition to photosynthesis, leaves play another role in the life of plants. Pine cones, mature fronds of ferns, and flowers are all sporophylls, leaves that were modified structurally to bear sporangia. Strobili are cone-like structures that contain sporangia. They are prominent in conifers and are commonly known as pine cones.

Flowers and Fruits

Angiosperms produce their gametes in separate organs, which are usually housed in a flower (Figure **3.4.8.6**). Both fertilization and embryo development take place inside this anatomical structure that provides a stable system of sexual reproduction largely sheltered from environmental fluctuations. Flowering plants are the most diverse phylum on Earth after insects; flowers come in a bewildering array of sizes, shapes, colors, smells, and arrangements. Most flowers have a mutualistic pollinator, with the distinctive features of flowers reflecting the nature of the pollination agent. The relationship between pollinator and flower characteristics is one of the great examples of coevolution.

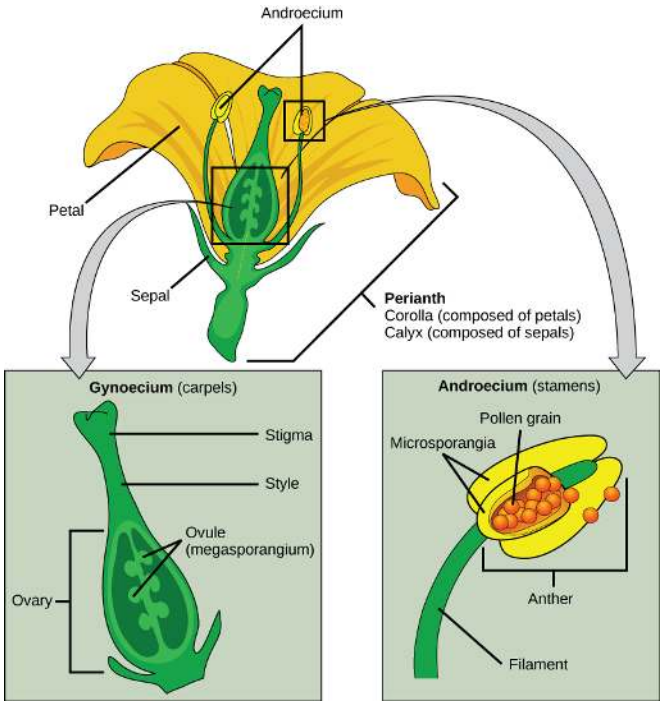


Figure **3.4.8.6**: This image depicts the structure of a perfect flower. Perfect flowers produce both male and female floral organs. The flower shown has only one **carpel**, but some flowers have a cluster of carpels. Together, all the carpels make up the **gynoecium**. (credit: modification of work by Mariana Ruiz Villareal)

Following fertilization, the ovule grows into a **seed**. The surrounding tissues of the ovary thicken, developing into a fruit that will protect the seed inside and often ensure its dispersal over a wide geographic range. Not all fruits develop from an ovary; such structures are "false fruits." Like flowers, fruit can vary tremendously in appearance, size, smell, and taste. Tomatoes, walnut shells, and avocados are all examples of fruit. As with pollen and seeds, fruits also act as agents of dispersal. Some may be carried away by the wind. Many attract animals that will eat the fruit and pass the seeds through their digestive systems, then deposit the seeds in another location. Cockleburs are covered with stiff, hooked spines that can hook into fur (or clothing) and hitch a ride on an animal for long distances. The cockleburs that clung to the velvet trousers of an enterprising Swiss hiker, George de Mestral, inspired his invention of the loop and hook fastener he named Velcro.

? Optional Activity 3.4.8.3

Besides the seed, what other major structure diminishes a plant's reliance on water for reproduction?

A. flower
B. fruit
C. pollen
D. spore

Answer

C. pollen

Career Connection: Paleobotanist

How organisms acquired traits that allow them to colonize new environments—and how the contemporary ecosystem is shaped—are fundamental questions of evolution. Paleobotany (the study of extinct plants) addresses these questions through the analysis of fossilized specimens retrieved from field studies, reconstituting the morphology of organisms that disappeared long ago. **Paleobotanists** trace the evolution of plants by following the modifications in plant morphology: shedding light on the connection between existing plants by identifying common ancestors that display the same traits. This field seeks to find transitional species that bridge gaps in the path to the development of modern organisms. Fossils are formed when organisms

are trapped in sediments or environments where their shapes are preserved. Paleobotanists collect fossil specimens in the field and place them in the context of the geological sediments and other fossilized organisms surrounding them. The activity requires great care to preserve the integrity of the delicate fossils and the layers of rock in which they are found.

One of the most exciting recent developments in paleobotany is the use of analytical chemistry and molecular biology to study fossils. Preservation of molecular structures requires an environment free of oxygen, since oxidation and degradation of material through the activity of microorganisms depend on its presence. One example of the use of analytical chemistry and molecular biology is the identification of oleanane, a compound that deters pests. Up to this point, oleanane appeared to be unique to flowering plants; however, it has now been recovered from sediments dating from the Permian, much earlier than the current dates given for the appearance of the first flowering plants. Paleobotanists can also study fossil DNA, which can yield a large amount of information, by analyzing and comparing the DNA sequences of extinct plants with those of living and related organisms. Through this analysis, evolutionary relationships can be built for plant lineages.

Some paleobotanists are skeptical of the conclusions drawn from the analysis of molecular fossils. For example, the chemical materials of interest degrade rapidly when exposed to air during their initial isolation, as well as in further manipulations. There is always a high risk of contaminating the specimens with extraneous material, mostly from microorganisms. Nevertheless, as technology is refined, the analysis of DNA from fossilized plants will provide invaluable information on the evolution of plants and their adaptation to an ever-changing environment.

? Optional Activity 3.4.8.4

How did the development of a vascular system contribute to the increase in size of plants?

Answer

Plants became able to transport water and nutrients and not be limited by rates of diffusion. Vascularization allowed the development of leaves, which increased efficiency of photosynthesis and provided more energy for plant growth.

Indigenous Connections

Sweetgrass (*Hierochloë odorata*) is an aromatic angiosperm that belongs to the order Poales, which contains many of the grasses and sedges. It is a hardy perennial monocot that is found from the plains of North America to the Arctic Circle. As an **herbaceous** plant, it grows to approximately 100 cm and reproduces primarily vegetatively through rhizomes, modified stems that grow underground (Figure **3.4.8.7**).



Figure **3.4.8.7**: Hierochloë odorata (Sally and Andy Wasowski; CC-BY-SA)

According to *The Canadian Encyclopedia* (Turner, 2018):

> Sweetgrass is revered as a sacred plant. For many it is a cultural keystone species, reflecting a group's cultural identity and embodying their values and beliefs. Sweetgrass leaves at the harvestable stage are bright green, and, depending on

when they are picked and how quickly they are dried, turn light green to straw-coloured. For weaving into baskets, the dried leaves are soaked and then coiled or twined, alone or with other materials as the foundation. Experienced weavers often mix sweetgrass dried in different ways to create subtle designs or add a few dyed leaves as coloured decorations.

On the Great Plains [of southern Alberta], the Siksika (Blackfoot) and their relatives have many uses for sweetgrass, which they call *sipátsimo*. They use it as a ceremonial incense during daily prayers, burn it at major tribal events such as the Sundance, and use the smoke to purify tribal dancers. Siksika also used sweetgrass leaves to treat saddle sores on their horses, packed braided sweetgrass leaves into saddles, and fed their horses sweetgrass to give them stamina. They also inhaled sweetgrass smoke or drank an infusion of the plant for colds, coughs, and sore throats and used water in which the stems had been soaked as an eyewash.

Sweetgrass was used to make a hair wash and hair tonic, not only by the Siksika, but by the Nlaka'pamux (Thompson) of British Columbia, who call sweetgrass *xásxast* (literally, 'good-good'). The Nlaka'pamux were said to have traded for sweetgrass braids from the Siksika. Other Interior Salish Peoples, as well as the Ktunaxa of British Columbia, also use sweetgrass for ceremonial and medicinal purposes. On the far West Coast of Canada, the Nuxalk (Bella Coola) have been using sweetgrass from the estuary of the Bella Coola River for ceremonial purposes for generations; according to some, they also learned about using sweetgrass from the Siksika, who were said to have visited the Nuxalk at some point in the early 20th century.

References

Turner, N. (2018, November 23). Sweetgrass. In *The Canadian Encyclopedia*. https://www.thecanadianencyclopedia....cle/sweetgrass



In this 16-minute video, you will be introduced to the usage and cultural significance of sweetgrass for the Mi'kmaw culture. You will also be introduced to the natural history of sweetgrass.
Question after watching: What practice did the Indigenous population engage in that might have contributed to the spread of sweetgrass?

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3.G: Unit 3 Glossary

Unit 3.2

basal taxon
A lineage on a phylogenetic tree that evolved early from the root and remains unbranched over time

binomial nomenclature
a system of two-part scientific names for an organism, which includes genus and species names

branch point
see: node

cladogram
one of most common representations of phylogeny; based in cladistics

clades
groups of organisms that descended from a single ancestor

cladistics
comparison of homologous and analogous traits of various organisms

class
the category in the taxonomic classification system that falls within phylum and includes orders

common ancestor
a single branch point at the bottom of many phylogenetic trees, indicating a common origin species from which all others derive

domain
the highest level category in the classification system and that includes all taxonomic classifications below it; it is the most inclusive taxon

family
the category in the taxonomic classification system that falls within order and includes genera

genus
the category in the taxonomic classification system that falls within family and includes species; the first part of the scientific name

ingroup
in cladistics, the group of taxa being analyzed

kingdom
the category in the taxonomic classification system that falls within domain and includes phyla

maximum parsimony
the likeliest order of events in phylogeny is probably the simplest shortest path

molecular characters
includes differences in the amino-acid sequence of a protein, shapes of a protein, RNA, location of a gene, differences in the individual nucleotide sequence of a gene, or differences in the arrangements of genes

molecular systematics

describes the use of information on the molecular level including DNA sequencing

monophyletic group
a single clade including all descendants from a branch point

node
a point on a phylogenetic tree where a single lineage splits to distinct new ones

order
the category in the taxonomic classification system that falls within class and includes families

outgroup
in cladistics, a species or group of species that diverged before the lineage containing the group(s) of interest

phylogenetic tree
diagram used to reflect the evolutionary relationships between organisms or groups of organisms

phylogeny
evolutionary history and relationship of an organism or group of organisms

phylum
the category in the taxonomic classification system that falls within kingdom and includes classes

polytomy
a node with more than two lineages

rooted
describing a phylogenetic tree with a single ancestral lineage to which all organisms represented in the diagram relate

scientific name
the genus and species name of an organism, italicized

sister taxa
two lineages that diverged from the same branch point

shared ancestral character
trait shared by all species of a group

shared derived character
trait shared by only some species within a group

species
the most specific category of classification

systematics
the science of determining the evolutionary relationships of organisms

taxon
a single level in the taxonomic classification system

taxonomy
the science of classifying organisms

Unit 3.3

accessory pigments
chlorophyll *a* and a range of other pigments capable of harvesting energy from light

acidophile
acid-loving prokaryotes

aerobic respiration
cellular respiration in the presence of oxygen

ages
smallest unit of geologic time

alkilophile
alkaline-loving prokaryotes

alpha-proteobacteria
a group of bacteria that were likely the LCA of the endosymbiont that became mitochondria

Alvarez Hypothesis
a giant asteroid or comet striking the Earth 66 million years ago caused the massive die-off at the end of the Cretaceous Period

Anthropocene
proposed epoch to include the impact of humans on Earth

biofilm
a microbial mat comprised of colonies of organisms along with and extracellular matrix

chloroplasts
photosynthetic plastids of plants

continental drift
the theory that the continents of the Earth have moved over geologic time

Domain Archaea
comprises all archaeans

Domain Bacteria
comprises all eubacteria

Domain Eukarya
comprises all eukaryotes including protists, fungi, animals, and plants

eon
the broadest category of geological time

endosymbiosis
engulfment of one cell within another such that the engulfed cell survives, and both cells benefit; the process responsible for the evolution of mitochondria and chloroplasts in eukaryotes

endosymbiotic theory
theory that states that eukaryotes may have been a product of one cell engulfing another, one living within another, and evolving over time until the separate cells were no longer recognizable as such

epochs
subdivisions of periods in geologic time

era
second longest unit of geologic time

extant
species that are currently living

extinct
no longer existing species

extracellular matrix
proteins and carbohydrates which help affix the organisms in a biofilm to each other and to a surface

extremophiles
organisms that have adapted to life in extreme conditions not suitable for most forms of life

geologic time scale
a reference and communication system for comparing rocks and fossils from throughout the world and important in identifying the milestones in the history of life

Gondwanaland
southern continent that formed when Pangaea broke apart

Great Oxygenation Event (GOE)
about 2 billion years ago geological evidence shows that oxygen built up to higher concentrations in the atmosphere due to the evolution of cyanobacteria

halophile
salt-loving prokaryotes

hydrothermal vent
a fissure in the Earth's surface that releases geothermally-heated water and chemicals leached from rocks in the Earth's interior

hypersaline
concentrated saltwater

K-Pg boundary
the interface between the rocks of the Cretaceous and those of the Paleogene Epoch

Laurasia
northern continent that formed when Pangaea broke apart

mass extinctions
when large numbers of species go extinct all within a very short period of geologic time

mitochondria
a eukaryotic organelle capable of generating ATP from organic molecules

Pangaea
a single, massive landmass composed of all modern continents that existed during the Mesozoic era

period

subdivision of eras in geologic time

Phanerozoic
the current eon; comprised of the Paleozoic, Mesozoic, and Cenozoic eras

photosynthesis
use of energy from sunlight to power the formation of organic compounds

Precambrian
the Hadean, Archean, and Proterozoic eons combined

prokaryote
single-celled organisms without a nucleus or membrane-bound organelles that were the first inhabitants on Earth

ribozymes
certain RNA molecules have enzymatic activity on their own

RNA World Hypothesis
ribozyme (RNA) molecules have enzymatic activity, can store information, and may have been able to synthesize the proteins that life needed

Stanley Miller
created an apparatus that mimicked the Earth's early conditions and atmosphere and proposed a hypothesis for the origin of life

stromatolite
a sedimentary structure formed when minerals are precipitated out of water by prokaryotes in a microbial mat

Unit 3.4

Unit 3.4.1

acellular
biological entities without a cellular structure

apoptosis
programmed cell death

bacteriophages
viruses that infect bacteria

Baltimore classification
groups viruses according to how the mRNA is produced during the replicative cycle of the virus

budding
viral reproductive process where virions leave the cell individually

capsid
a protective layer of proteins on the external surface of a virus

cytopathic
causes cell damage

lysis
cell bursting

pathogen
agent with the ability to cause disease

permissive
cells that a virus may use to replicate

prion
infectious particle that consists of proteins that replicate without DNA or RNA

progressive hypothesis
hypothesis that viruses originated from RNA and DNA molecules that escaped from a host cell

regressive hypothesis
hypothesis that viruses evolved from free-living cells that progressively lost the ability to reproduce and metabolize on their own

segments
pieces of genetic material in some viruses (versus a single nucleic acid)

viral receptor
for a cell to be permissive, this surface molecule must be found on the host cell surface for the virus to attach

virions
single virus particles outside of the cell

viroid
plant pathogen that produces only a single, specific RNA

virus
acellular parasitic entities that are not classified within any domain or kingdom

virus core
contains total genome of the virus

virus molecular systematics
field of study which aims to determine whether the progressive or regressive hypothesis is correct through comparisons of sequenced genetic material

Unit 3.4.2

ammonification
process by which ammonia is released during the decomposition of nitrogen-containing organic compounds

autotroph
organisms that can fix inorganic carbon into organic molecules

bacilli
bacteria that are rod-shaped

binary fission
replication of the prokaryotic chromosome and separation of the bacterial cell into two identical copies

capsule (prokaryotes)
external structure that enables a prokaryote to attach to surfaces and protects it from dehydration

cell wall (prokaryotes)

a protective layer that surrounds some cells and gives them shape and rigidity; contains peptidoglycan; chemical composition varies between Archaea and Bacteria and between bacterial species

chemoautotrophs

obtain their energy from chemical compounds

chemolitotrophs

chemoautotrophs that use inorganic compounds as energy sources

chemoorganotrophs

chemoautotrophs that can use organic compounds as energy sources

cocci

bacteria that are spherically-shaped

conjugation

process by which prokaryotes move DNA from one individual to another using a pilus

denitrification

the reduction of nitrate from the soils to gaseous compounds such as N_2O, NO, and N_2

fix

transforming nitrogen gas (N_2) into a form useable for other life forms

Gram-negative

bacterium whose cell wall contains little peptidoglycan but has an outer membrane

Gram-positive

bacterium that contains mainly peptidoglycan in its cell walls

heterotroph

obtain carbon from organic compounds

nitrification

conversion of ammonium to nitrite and nitrate

peptidoglycan

polysaccharide chains cross-linked by peptides

pilus

surface appendage of some prokaryotes used for attachment to surfaces including other prokaryotes

photoautotrophs

obtain their energy from sunlight

pseudopeptidoglycan

component of archaea cell walls that is similar to peptidoglycan in morphology but contains different sugars

S-layer

surface-layer protein present on the outside of cell walls of archaea and bacteria

spirilli

bacteria that are spiral-shaped

teichoic acid
polymer associated with the cell wall of Gram-positive bacteria

transduction
process by which a bacteriophage moves DNA from one prokaryote to another

transformation
process by which a prokaryote takes in DNA found in its environment that is shed by other prokaryotes

Unit 3.4.3

cyst (protist)
a protective, resting stage of the life cycle

mixotroph
obtaining nutrition by photoautotrophic or heterotrophic routes, depending on whether sunlight or organic nutrients are available

paraphyletic group
a taxonomic group that does not contain all descendants of its common ancestor

pellicle
interlocking protein strips that function like a flexible coat of armor, preventing tearing or piercing

phagocytosis
when the cell membrane engulfs a food particle and brings it inward, pinching off an intracellular membranous sac

phototaxis
movement toward light

Protista
a paraphyletic group of diverse eukaryotes

pseudopodia
cytoplasmic extensions which allow movement

saprobe
organism that derives nutrients from decaying organic matter; also saprophyte

supergroup
taxonomic divisions of the Domain Eukaryota that are hypothesized to be monophyletic

Unit 3.4.4

ascocarp
fruiting body of ascomycetes, composed of millions of asci

asci
spore-forming sacs of Ascomycota

Ascomycota
(also, sac fungi) phylum of fungi that store spores in a sac called ascus

basidiocarp
fruiting body that protrudes from the ground and bears the basidia

Basidiomycota
(also, club fungi) phylum of fungi that produce club-shaped structures (basidia) that contain spores

basidium
club-shaped fruiting body of basidiomycetes; many fuse together into basidiocarp

Chytridiomycota
(also, chytrids) primitive phylum of fungi that live in water and produce gametes with flagella

coenocytic hypha
single hypha that lacks septa and contains many nuclei

conidiospores
unicellular or multicellular spores that are released directly from the tip or side of the hypha

decomposer
organism that carries out the decomposition of dead organisms

Eucomycota
true fungi belonging to the Kingdom Fungi

exoenzymes
enzymes transported by the hyphae into the environment for external digestion

faculative anaerobes
organisms that can perform both aerobic and anaerobic respiration and can survive in oxygen-rich and oxygen-poor environment

fungus
comes from the Latin word for mushrooms

Glomeromycota
phylum of fungi that form symbiotic relationships with the roots of trees

heterothallic
describes when only one mating type is present in an individual mycelium

homothallic
describes when both mating types are present in mycelium

hypha
fungal filament composed of one or more cells

imperfect fungi
reproduce asexually

karyogamy
fusion of nuclei

lichen
close association of a fungus with a photosynthetic alga or bacterium that benefits both partners

mycelium
mass of fungal hyphae

mycology
scientific study of fungi

mycorrhizae
a mutualistic relationship between a plant and a fungus; are connections between fungal hyphae, which provide soil minerals to the plant, and plant roots, which provide carbohydrates to the fungus

obligate aerobes
organisms that require oxygen to survive

obligate anaerobes
organisms that only use anaerobic respiration because oxygen will disrupt their metabolism

oenology
science of wine-making

perfect fungi
reproduce sexually and asexually

polycyclic aromatic hydrocarbons (PAHs)
toxic chemicals that are a byproduct of some industrial processes

plasmogamy
fusion of cytoplasm

rhizoid
underground organ

septa
cell wall division between hyphae

sessile
seemingly immobile

sporangiospores
produced in a sporangium

sporangium
reproductive sac that contains spores

spore
a haploid cell that can undergo mitosis to form a multicellular, haploid individual

symbiosis
ecological interaction between two organisms that live together

thallus
vegetative body of a fungus

yeast
general term used to describe unicellular fungi

Zygomycota
(also, conjugated fungi) phylum of fungi that form a zygote contained in a zygospore

zygospore
structure with thick cell wall that contains the zygote in zygomycetes

zoospore
asexual spores of chytrids

Unit 3.4.5

animal
eukaryotic, heterotrophic, motile (at least at certain life stages), multicellular organisms, with differentiated and specialized tissues; require a source of food and perform internal digestion

body plan
morphology or constant shape of an organism

Cambrian explosion
time during the Cambrian period (542–488 million years ago) when most of the animal phyla in existence today evolvedni

Cryogenian period
geologic period (850–630 million years ago) characterized by a very cold global climate

Ediacaran biota
oldest definite multicellular organisms with tissues that evolved geological period (630–542 million years ago)

Eumetazoa
group of animals with true differentiated tissues

Metazoa
group containing all animals

niche
an organisms's role within an ecosystem

Parazoa
group of animals without true differentiated tissues

Unit 3.4.6

acoelomate
animal without a body cavity

asymmetry
unique feature of Parazoa

bilateral symmetry
type of symmetry in which there is only one plane of symmetry, so the left and right halves of an animal are mirror images

blastopore
indentation formed during gastrulation, evident in the gastrula stage

coelom
lined body cavity

deuterostome
blastopore develops into the anus, with the second opening developing into the mouth

diploblast
animal that develops from two germ layers

eucoelomate
animal with a body cavity completely lined with mesodermal tissue

gamete
haploid reproductive cells produced through meiosis

gastrulation
stage of animal development characterized by the formation of the digestive cavity

germ cell
collection of cells formed during embryogenesis that will give rise to future body tissues, more pronounced in vertebrate embryogenesis

Hox gene
(also, homeobox gene) master control gene that can turn on or off large numbers of other genes during embryogenesis

parthenogenesis
unfertilized eggs can develop into new offspring

protostome
blastopore develops into the mouth of protostomes, with the second opening developing into the anus

pseudocoelomate
animal with a body cavity located between the mesoderm and endoderm

radial symmetry
type of symmetry with multiple planes of symmetry, with body parts (rays) arranged around a central disk

somatic
diploid body cells produced through mitosis

triploblast
animal that develops from three germ layers

Unit 3.4.7

angiosperm
flowering plants

Anthocerotophyta
the hornworts

Anthophyta
division to which angiosperms belong

basal angiosperms
a group of plants that probably branched off before the separation of monocots and eudicots

bryophytes
seedless, non-vascular plants; liverworts, hornworts, and mosses

Bryophyta

the mosses

charophyte
other term for green algae; considered the closest relative of land plants

club mosses
earliest group of seedless vascular plants

Coniferophyta
dominant division of gymnosperms with the most variety of trees

cotyledon
primitive leaf that develop in the zygote; monocots have one cotyledon, and dicots have two cotyledons

cupule
enclose and protect the ovule in gymnosperms

Cycadophyta
gymnosperm that grows in tropical climates and resembles a palm tree

Division
taxonomic category of plants used in place of phyla

eudicot
related group of angiosperms whose embryos possess two cotyledons

fern
seedless vascular plant that produces large fronds; the most advanced group of seedless vascular plants

flower
helps to facilitate pollination

fruit
functions in seed protection, dispersal, and germination

gametophyte
haploid portion of the plant

Gingkophyta
gymnosperm with one extant species, the *Gingko biloba*; a tree with fan-shaped leaves

Gnetophyta
gymnosperm shrub with varied morphological features that produces vessel elements in its woody tissues; the division includes the genera *Ephedra*, *Gnetum* and *Welwitschia*

gymnosperm
seed plant with naked seeds (seeds exposed on modified leaves or in cones)

hornworts
group of non-vascular plants in which stomata appear

horsetail
seedless vascular plant characterized by joints

liverworts
most primitive group of the non-vascular plants

lycophyte
club moss

Lycopodiophyta
the club mosses

Marchantiophyta
the liverworts

monocot
related group of angiosperms that produce embryos with one cotyledon and pollen with a single ridge

mosses
group of bryophytes in which a primitive conductive system appears

non-vascular plant
plant that lacks vascular tissue, which is formed of specialized cells for the transport of water and nutrients

ovary
chamber that contains and protects the ovule or female megasporangium

ovule
the female gametophyte

Plantae
the Kingdom of plants including all organisms that are eukaryotic, multicellular with differentiated tissues, and photosynthetic; mosses, ferns, conifers, and flowering plants are all members of the plant kingdom

pollination
the process of genetic recombination through sexual reproduction in some plants

Pteridophyta
the ferns, horseetails, and whisk ferns

pterophyte
seedless, vascular plants; ferns, horsetails, and whisk ferns

secondary cambium
cells that generate the vascular system of the trunk or stem and are partially specialized for water transportation

seedless vascular plant
plant that does not produce seeds; club mosses, ferns, horsetails, and whisk ferns

spermatophytes
seed-bearing plants

sporangium
reproductive sac that contains spores

sporophyll
leaf modified structurally to bear sporangia

sporophyte
diploid portion of the plant

strobili
cone-like structures that contain the sporangia

strobilus
plant structure with a tight arrangement of sporophylls around a central stalk, as seen in cones or flowers; the male strobilus produces pollen, and the female strobilus produces eggs

tracheid
xylem cells specialized for forming conduits inside the plant to conduct water

tracheophyte
vascular plant

vascular plant
plant containing a network of cells that conducts water and solutes through the organism

whisk fern
seedless vascular plant that lost roots and leaves by reduction

Unit 3.4.8

alternation of generations
a life cycle in which an organism has both haploid and diploid multicellular stages; haplodiplodonitc

antheridium
male gametangium

anther
sac-like structure at the tip of the stamen in which pollen grains are produced

apical meristem
tissue that increases the length of shoots and roots through rapid cell division

archegonium
female gametangium

calyx
whorl of sepals

carpel
single unit of the pistil

corolla
collection of petals

cuticle
protects the leaves and stems from desiccation

dioecious
describes a species in which the male and female reproductive organs are carried on separate specimens

diplontic

a lifecycle in which the diploid is the dominant life stage

embryo
a diploid structure that germinates into a sporophyte; contained within a protective coat making it a seed

embryophyte
other name for land plant; embryo is protected and nourished by the sporophyte

filament
thin stalk that links the anther to the base of the flower

gametangium
structure on the gametophyte in which gametes are produced

gynoecium
(also, carpel) structure that constitute the female reproductive organ

haplodiplodontic
a life cycle in which haploid and diploid stages alternate; alternation of generations

haplontic
a lifecycle in which the haploid stage is the dominant stage

herbaceous
grass-like plant noticeable by the absence of woody tissue

homosporous
refers to the one type of spore produced by the seedless, non-vascular plants

lateral meristem
tissue that produces cells that increase the diameter of tree trunks

lignin
complex polymer impermeable to water

megaspore
female spore

megasporocyte
megaspore mother cell; larger spore that germinates into a female gametophyte in a heterosporous plant

microspore
male spore

microsporocyte
smaller spore that produces a male gametophyte in a heterosporous plant

monoecious
describes a species in which the male and female reproductive organs are on the same plant

paleobotanist
traces the evolution of plants by following the modifications in plant morphology

perianth

part of the plant consisting of the calyx (sepals) and corolla (petals)

petal
modified leaf interior to the sepals; colorful petals attract animal pollinators

phloem
tissue responsible for transport of sugars, proteins, and other solutes

pistil
fused group of carpels

pollen
male gametophytes

rhizoids
thin filaments that anchor the plant to the substrate

secondary metabolites
complex organic molecules such as alkaloids, whose noxious smells and unpleasant taste deter animals

seed
contains the embryo protected by a coat

sepal
modified leaf that encloses the bud; outermost structure of a flower

stamen
structure that contains the male reproductive organs

stigma
uppermost structure of the carpel where pollen is deposited

stomata
pores that open and close to regulate gases and water vapor

style
long, thin structure that links the stigma to the ovary

xylem
tissue responsible for long-distance transport of water and nutrients

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3.S: Unit 3 Summary

Unit 3.2

Scientists continually obtain new information that helps to understand the evolutionary history of life on Earth. Historically, organisms were organized into a taxonomic classification system. Each group of organisms went through its own evolutionary journey, called its phylogeny. Each organism shares relatedness with others and, based on morphologic and genetic evidence, scientists attempt to map the evolutionary pathways of all life on Earth. However, today many scientists build phylogenetic trees to illustrate evolutionary relationships; the taxonomic classification system is expected to reflect evolutionary relationships.

To build phylogenetic trees, scientists must collect character information that allows them to make evolutionary connections between organisms. Using morphologic and molecular data, scientists work to identify homologous characteristics and genes. Similarities between organisms can stem either from shared evolutionary history (homologies) or from separate evolutionary paths (analogies). After homologous information is identified, scientists use cladistics to organize these events as a means to determine an evolutionary timeline.

Many disciplines within the study of biology contribute to understanding how past and present life evolved over time, and together they contribute to building, updating, and maintaining the “tree of life.” Information gathered may include data collected from fossils, from studying morphology, from the structure of body parts, or from molecular structure, such as the sequence of amino acids in proteins or DNA nucleotides. By considering the trees generated by different sets of data scientists can put together the phylogeny of a species. Scientists continue to discover new species of life on Earth as well as new information about already identified species. Thus, phylogenetic trees change as new data arrive.

Unit 3.3

The geological time scale is a result of hundreds of years of investigation and remains very much a work in progress. The Earth has gone through periodic cycles of increases and decreases in temperature. During the past 2000 years, the Medieval Climate Anomaly was a warmer period, while the Little Ice Age was unusually cool. Both of these irregularities can be explained by natural causes of changes in climate, and, although the temperature changes were small, they had significant effects. Natural drivers of climate change include Milankovitch cycles, changes in solar activity, and volcanic eruptions. None of these factors, however, leads to rapid increases in global temperature or sustained increases in carbon dioxide. The burning of fossil fuels is an important source of greenhouse gases, which plays a major role in the greenhouse effect. Long ago, global warming resulted in the Permian extinction: a large-scale extinction event that is documented in the fossil record. Currently, modern-day climate change is associated with the increased melting of glaciers and polar ice sheets, resulting in a gradual increase in sea level. Plants and animals can also be affected by global climate change when the timing of seasonal events, such as flowering or pollination, is affected by global warming.

The oldest fossil evidence of eukaryotes is about 2 billion years old. Fossils older than this all appear to be prokaryotes. It is probable that today’s eukaryotes are descended from an ancestor that had a prokaryotic organization. The last common ancestor of today’s Eukarya had several characteristics, including cells with nuclei that divided mitotically and contained linear chromosomes where the DNA was associated with histones, a cytoskeleton and endomembrane system, and the ability to make cilia/flagella during at least part of its life cycle. It was aerobic because it had mitochondria that were the result of an aerobic alpha-proteobacterium that lived inside a host cell. Whether this host had a nucleus at the time of the initial symbiosis remains unknown. The last common ancestor may have had a cell wall for at least part of its life cycle, but more data are needed to confirm this hypothesis. Today’s eukaryotes are very diverse in their shapes, organization, life cycles, and number of cells per individual.

Unit 3.4

Acellular Entities

Viruses are tiny, acellular entities that can usually only be seen with an electron microscope. Their genomes contain either DNA or RNA—never both—and they replicate using the replication proteins of a host cell. Viruses are diverse, infecting archaea, bacteria, fungi, plants, and animals. Viruses consist of a nucleic acid core surrounded by a protein capsid with or without an outer lipid envelope. The capsid shape, presence of an envelope, and core composition dictate some elements of the classification of viruses.

The most commonly used classification method, the Baltimore classification, categorizes viruses based on how they produce their mRNA. Viral replication within a living cell always produces changes in the cell, sometimes resulting in cell death and sometimes slowly killing the infected cells. There are six basic stages in the virus replication cycle: attachment, penetration, uncoating, replication, assembly, and release. A viral infection may be productive, resulting in new virions, or nonproductive, which means that the virus remains inside the cell without producing new virions.

Prions are infectious agents that consist of protein, but no DNA or RNA, and seem to produce their deadly effects by duplicating their shapes and accumulating in tissues. They are thought to contribute to several progressive brain disorders, including mad cow disease and Creutzfeldt-Jakob disease. Viroids are single-stranded RNA pathogens that infect plants. Their presence can have a severe impact on the agriculture industry.

Kingdoms Bacteria and Archaea

Prokaryotes (domains Archaea and Bacteria) are single-celled organisms lacking a nucleus. They have a single piece of circular DNA in the nucleoid area of the cell. Most prokaryotes have a cell wall that lies outside the boundary of the plasma membrane. Some prokaryotes may have additional structures such as a capsule, flagella, and pili. Bacteria and Archaea differ in the lipid composition of their cell membranes and the characteristics of the cell wall. In archaeal membranes, phytanyl units, rather than fatty acids, are linked to glycerol. Some archaeal membranes are lipid monolayers instead of bilayers.

The cell wall is located outside the cell membrane and prevents osmotic lysis. The chemical composition of cell walls varies between species. Bacterial cell walls contain peptidoglycan. Archaean cell walls do not have peptidoglycan, but they may have pseudopeptidoglycan, polysaccharides, glycoproteins, or protein-based cell walls. Bacteria can be divided into two major groups: Gram-positive and Gram-negative, based on the Gram stain reaction. Gram-positive organisms have a thick cell wall, together with teichoic acids. Gram-negative organisms have a thin cell wall and an outer envelope containing lipopolysaccharides and lipoproteins.

Prokaryotes are metabolically diverse organisms. There are many different environments on Earth with various energy and carbon sources, and variable conditions. Prokaryotes have been able to live in every environment by using whatever energy and carbon sources are available. Prokaryotes fill many niches on Earth, including being involved in nutrient cycles such as nitrogen and carbon cycles, decomposing dead organisms, and thriving inside living organisms, including humans. The very broad range of environments that prokaryotes occupy is possible because they have diverse metabolic processes.

Protists

Protists are extremely diverse in terms of their biological and ecological characteristics, partly because they are an artificial assemblage of phylogenetically unrelated groups. Protists display highly varied cell structures, several types of reproductive strategies, virtually every possible type of nutrition, and varied habitats. Most single-celled protists are motile, but these organisms use diverse structures for transportation.

Kingdom Fungi

Fungi are eukaryotic organisms that appeared on land more than 450 million years ago. They are heterotrophs and contain neither photosynthetic pigments such as chlorophyll nor organelles such as chloroplasts. Because fungi feed on decaying and dead matter, they are saprobes. Fungi are important decomposers that release essential elements into the environment. External enzymes digest nutrients that are absorbed by the body of the fungus, which is called a thallus. A thick cell wall made of chitin surrounds the cell. Fungi can be unicellular as yeasts or develop a network of filaments called a mycelium, which is often described as mold. Most species multiply by asexual and sexual reproductive cycles and display an alternation of generations. Another group of fungi do not have a sexual cycle.

Kingdom Animalia

The most rapid diversification and evolution of animal species in all of history occurred during the Cambrian period of the Paleozoic Era, a phenomenon known as the Cambrian explosion. Until recently, scientists believed that there were only very few tiny and simplistic animal species in existence before this period. However, recent fossil discoveries have revealed that additional, larger, and more complex animals existed during the Ediacaran period, and even possibly earlier, during the Cryogenian period.

Still, the Cambrian period undoubtedly witnessed the emergence of the majority of animal phyla that we know today, although many questions remain unresolved about this historical phenomenon.

The remainder of the Paleozoic Era is marked by the growing appearance of new classes, families, and species, and the early colonization of land by certain marine animals. The evolutionary history of animals is also marked by numerous major extinction events, each of which wiped out a majority of extant species. Some species of most animal phyla survived these extinctions, allowing the phyla to persist and continue to evolve into species that we see today.

Animals constitute an incredibly diverse kingdom of organisms. Although animals range in complexity from simple sea sponges to human beings, most members of the animal kingdom share certain features. Animals are eukaryotic, multicellular, heterotrophic organisms that ingest their food and usually develop into motile creatures with a fixed body plan. A major characteristic unique to the animal kingdom is the presence of differentiated tissues, such as nerve, muscle, and connective tissues, which are specialized to perform specific functions. Most animals undergo sexual reproduction, leading to a series of developmental embryonic stages that are relatively similar across the animal kingdom. A class of transcriptional control genes called *Hox* genes directs the organization of the major animal body plans, and these genes are strongly homologous across the animal kingdom.

Organisms in the animal kingdom are classified based on their body morphology and development. True animals are divided into those with radial versus bilateral symmetry. Generally, the simpler and often non-motile animals display radial symmetry. Animals with radial symmetry are also generally characterized by the development of two embryological germ layers, the endoderm and ectoderm, whereas animals with bilateral symmetry are generally characterized by the development of a third embryological germ layer, the mesoderm. Animals with three germ layers, called triploblasts, are further characterized by the presence or absence of an internal body cavity called a coelom. The presence of a coelom affords many advantages, and animals with a coelom may be termed true coelomates or pseudocoelomates, depending on which tissue gives rise to the coelom. Coelomates are further divided into one of two groups called protostomes and deuterostomes, based on a number of developmental characteristics, including differences in zygote cleavage and method of coelom formation.

Scientists are interested in the evolutionary history of animals and the evolutionary relationships among them. There are three main sources of data that scientists use to create phylogenetic evolutionary tree diagrams that illustrate such relationships: morphological information (which includes developmental morphologies), fossil record data, and, most recently, molecular data. The details of the modern phylogenetic tree change frequently as new data are gathered, and molecular data has recently contributed to many substantial modifications of the understanding of relationships between animal phyla.

Kingdom Plantae

Land plants acquired traits that made it possible to colonize land and survive out of the water. All land plants share the following characteristics: alternation of generations, with the haploid plant called a gametophyte, and the diploid plant called a sporophyte; protection of the embryo, formation of haploid spores in a sporangium, formation of gametes in a gametangium, and an apical meristem. Vascular tissues, roots, leaves, cuticle cover, and a tough outer layer that protects the spores contributed to the adaptation of plants to dry land. Land plants appeared about 500 million years ago in the Ordovician period.

Seedless nonvascular plants are small, having the gametophyte as the dominant stage of the lifecycle. Without a vascular system and roots, they absorb water and nutrients on all their exposed surfaces. Collectively known as bryophytes, the three main groups include the liverworts, the hornworts, and the mosses. Liverworts are the most primitive plants and are closely related to the first land plants. Hornworts developed stomata and possess a single chloroplast per cell. Mosses have simple conductive cells and are attached to the substrate by rhizoids. They colonize harsh habitats and can regain moisture after drying out. The moss sporangium is a complex structure that allows the release of spores away from the parent plant.

The pterophytes are seedless, vascular plants. Vascular systems consist of xylem tissue, which transports water and minerals, and phloem tissue, which transports sugars and proteins. With the development of the vascular system, there appeared leaves to act as large photosynthetic organs, and roots to access water from the ground. Small uncomplicated leaves are microphylls. Large leaves with vein patterns are megaphylls. Modified leaves that bear sporangia are sporophylls. Some sporophylls are arranged in cone structures called strobili.

Seed plants appeared about one million years ago, during the Carboniferous period. Two major innovations—seed and pollen—allowed seed plants to reproduce in the absence of water. The gametophytes of seed plants shrank, while the sporophytes became

prominent structures and the diploid stage became the longest phase of the lifecycle. Gymnosperms became the dominant group during the Triassic. In these, pollen grains and seeds protect against desiccation. The seed, unlike a spore, is a diploid embryo surrounded by storage tissue and protective layers. It is equipped to delay germination until growth conditions are optimal. Angiosperms bear both flowers and fruit. The structures protect the gametes and the embryo during its development. Angiosperms appeared during the Mesozoic era and have become the dominant plant life in terrestrial habitats.

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CHAPTER OVERVIEW

Unit 4: Ecology

Ecology is the study of the interactions of living organisms with their environment. One core goal of ecology is to understand the distribution and abundance of living things in the physical environment. Attainment of this goal requires the integration of scientific disciplines inside and outside of biology, such as biochemistry, physiology, evolution, biodiversity, molecular biology, geology, and climatology.

Unit 4 introduces students to the general concepts of ecology including population ecology, community ecology, and ecosystem ecology, and biogeography. Vignettes on Indigenous Science and the ecology of British Columbia are included.

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4.1: Unit 4 Introduction

Unit 4 Introduction

This unit introduces ecology, the study of the interactions of living organisms with their environment. One core goal of ecology is to understand the distribution and abundance of living things in the physical environment. Attainment of this goal requires the integration of scientific disciplines inside and outside of biology, such as biochemistry, physiology, evolution, biodiversity, molecular biology, geology, and climatology. Unit 4 introduces students to the general concepts of ecology including population ecology, community ecology, and ecosystem ecology, and biogeography. Vignettes on Indigenous Science and the ecology of British Columbia are included.

Unit 4 Learning Outcomes

By the end of this Unit, you will be able to:

- Discuss important processes and interactions leading to the structure of natural communities, especially natural selection, population growth, competition, nutrient cycling, and behavioural ecology.
- Be familiar with the major ecosystems on land and in water.
- Critically discuss the role of humans as a force of change in the biosphere.
- Understand and articulate the principles and processes of scientific inquiry.
- Think critically about the principles of biology studied and communicate your thinking clearly and concisely in speaking and in writing.

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Unit 4 Assessments

If you are a TRU student using this resource, all of your assessed learning activities and assignments are in your course Moodle site.

This unit introduces learners to the scale and scope of the study of ecology, from populations and communities to ecosystems and biomes.

Video



In this 10.5-minute video, the field of ecology is introduced, the topic of this unit.
Question after watching: What is the difference between population, communities, ecosystems, biomes, and biosphere?
Think of a specific region in British Columbia. Identify what might fit into each of these categories in that region.

Please click on the blue arrow on the right to start Unit 4: Chapter 4.2. If you are on mobile, use the navigation links at the bottom of this page.

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SECTION OVERVIEW

4.2: Population Ecology

Learning Objectives

- Describe how ecologists measure population size and density
- Summarize the types of population distribution
- Identify how the carrying capacity of habitats may change
- Describe how natural selection and environmental adaptation led to the evolution of particular life history patterns
- Explain the characteristics of and differences between exponential and logistic growth patterns
- Identify how population growth is regulated
- Predict the ecological consequences of unregulated growth
- Analyze the factors leading to exponential human population growth and its impacts

Video



This 12-minute video summarizes much of the content of Unit 4.2

Question after watching: As you watch this video, consider how the West Nile Virus outbreak in Dallas, Texas illustrates the usefulness of population ecology. How would you explain what population ecology is and why it is useful to a sibling or friend?

4.2.1: The Scope of Ecology

4.2.2: What is Population Ecology?

4.2.3: Life Histories and Natural Selection

4.2.4: Population Demography

4.2.5: Population Models

4.2.6: Human Population Growth

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Unit 4.2.1 - The Scope of Ecology

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 45 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.2.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Define ecology and the four levels of ecological research
- Describe examples of the ways in which ecology requires the integration of different scientific disciplines
- Distinguish between abiotic and biotic components of the environment
- Recognize the relationship between abiotic and biotic components of the environment

Introduction

Ecology is the study of the interactions of living organisms with their environment. One core goal of ecology is to understand the distribution and abundance of living things in the physical environment. Attainment of this goal requires the integration of scientific disciplines inside and outside of biology, such as biochemistry, physiology, evolution, biodiversity, molecular biology, geology, and climatology. Some ecological research also applies aspects of chemistry and physics, and it frequently uses mathematical models.

Levels of Ecological Study

When a discipline such as biology is studied, it is often helpful to subdivide it into smaller, related areas. For instance, cell biologists interested in cell signaling need to understand the chemistry of the signal molecules (which are usually proteins) as well as the result of cell signaling. Ecologists interested in the factors that influence the survival of an endangered species might use mathematical models to predict how current conservation efforts affect endangered organisms. To produce a sound set of management options, a conservation biologist needs to collect accurate data, including current population size, factors affecting reproduction (like physiology and behavior), habitat requirements (such as plants and soils), and potential human influences on the endangered population and its habitat (which might be derived through studies in sociology and urban ecology). Within the discipline of ecology, researchers work at four specific levels, sometimes discretely and sometimes with overlap: organism, population, community, and ecosystem (Figure **4.2.1.1**).

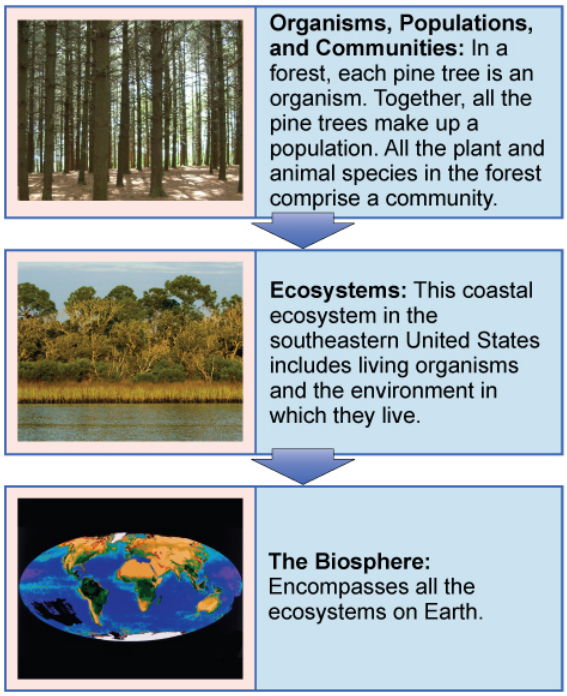


Figure 4.2.1.1: Ecologists study within several biological levels of organization. (credit “organisms”: modification of work by "Crystl"/Flickr; credit “ecosystems”: modification of work by Tom Carlisle, US Fish and Wildlife Service Headquarters; credit “biosphere”: NASA)

Optional Activity 4.2.1.1

Which of the following are arranged from least inclusive to most inclusive?

a. population>ecosystem>community>biosphere
b. ecosystem < population < biosphere < community
c. biosphere < ecosystem < community < population
d. population < community < ecosystem < biosphere

Answer

d. population < community < ecosystem < biosphere

Organismal Ecology

Researchers studying the level of **organismal ecology** are interested in the adaptations that enable individuals to live in specific habitats. These adaptations can be morphological, physiological, and behavioral. For instance, the Karner blue butterfly (*Lycaeides melissa samuelis*) (Figure 4.2.1.2) is considered a specialist because the females preferentially oviposit (that is, lay eggs) on wild lupine. This preferential adaptation means that the Karner blue butterfly is highly dependent on the presence of wild lupine plants for its continued survival.



Figure **4.2.1.2**: The Karner blue butterfly (*Lycaeides melissa samuelis*) is a rare butterfly that lives only in open areas with few trees or shrubs, such as pine barrens and oak savannas. It can only lay its eggs on lupine plants. (credit: modification of work by J & K Hollingsworth, USFWS)

After hatching, the larval caterpillars emerge and spend four to six weeks feeding solely on wild lupine (Figure **4.2.1.3**). The caterpillars pupate (undergo metamorphosis) and emerge as butterflies after about four weeks. The adult butterflies feed on the nectar of flowers of wild lupine and other plant species. A researcher interested in studying Karner blue butterflies at the organismal level might, in addition to asking questions about egg laying, ask questions about the butterflies' preferred temperature (a physiological question) or the behavior of the caterpillars when they are at different larval stages (a behavioral question).



Figure **4.2.1.3**: The wild lupine (*Lupinus perennis*) is the host plant for the Karner blue butterfly.

Population Ecology

A **population** is a group of interbreeding organisms that are members of the same species living in the same area at the same time (organisms that are all members of the same species are called **conspecifics**). A population is identified, in part, by where it lives, and the area where it lives may have natural or artificial boundaries: natural boundaries might be rivers, mountains, or deserts, while examples of artificial boundaries include mowed grass, manmade structures, or roads. The study of **population ecology** focuses on the number of individuals in an area and how and why population size changes over time. Population ecologists are particularly interested in counting the Karner blue butterfly, for example, because it is classified as federally endangered. However, the distribution and density of this species is highly influenced by the distribution and abundance of wild lupine. Researchers might ask questions about the factors leading to the decline of wild lupine and how these affect Karner blue butterflies. For example, ecologists know that wild lupine thrives in open areas where trees and shrubs are largely absent. In natural settings, intermittent wildfires regularly remove trees and shrubs, helping to maintain the open areas that wild lupine requires. Mathematical models can be used to understand how wildfire suppression by humans has led to the decline of this important plant for the Karner blue butterfly.

Community Ecology

A biological **community** consists of the different species within an area, typically a three-dimensional space, and the interactions within and among these species. Community ecologists are interested in the processes driving these interactions and their consequences. Questions about conspecific interactions often focus on competition among members of the same species for a limited resource. Ecologists also study interactions among various species; members of different species are called **heterospecifics**. Examples of heterospecific interactions include predation, parasitism, herbivory, competition, and pollination. These interactions can have regulating effects on population sizes and can impact ecological and evolutionary processes affecting diversity.

For example, Karner blue butterfly larvae form mutualistic relationships with ants. Mutualism is a form of a long-term relationship that has coevolved between two species and from which each species benefits. For mutualism to exist between individual organisms, each species must receive some benefit from the other as a consequence of the relationship. Researchers have shown that there is an increase in the probability of survival when Karner blue butterfly larvae (caterpillars) are tended by ants. Scientists are currently unsure of the mechanism but this might be because the larvae spend less time in each life stage when tended by ants, which provides some advantages for the larvae. Meanwhile, the Karner blue butterfly larvae secrete a carbohydrate-rich substance that is an important energy source for the ants. Both the Karner blue larvae and the ants benefit from their interaction.

Ecosystem Ecology

Ecosystem ecology is an extension of organismal, population, and community ecology. The **ecosystem** is composed of all the **biotic** components (living things) in an area along with the abiotic components (non-living things) of that area. Some of the **abiotic** components include air, water, and soil. Ecosystem biologists ask questions about how nutrients and energy are stored and how they move among organisms and the surrounding atmosphere, soil, and water.

The Karner blue butterflies and the wild lupine live in an oak-pine barren habitat. This habitat is characterized by natural disturbance and nutrient-poor soils that are low in nitrogen. The availability of nutrients is an important factor in the distribution of the plants that live in this habitat. Researchers interested in ecosystem ecology could ask questions about the importance of limited resources and the movement of resources, such as nutrients, through the biotic and abiotic portions of the ecosystem.

Career Connection: Ecologist

A career in ecology contributes to many facets of human society. Understanding ecological issues can help society meet the basic human needs of food, shelter, and health care. Ecologists can conduct their research in the laboratory and outside in natural environments (Figure **4.2.1.4**). These natural environments can be as close to home as the stream running through your campus or as far away as the hydrothermal vents at the bottom of the Pacific Ocean. Ecologists manage natural resources such as white-tailed deer populations (*Odocoileus virginianus*) for hunting or aspen (*Populus* spp.) timber stands for paper production. Ecologists also work as educators who teach children and adults at various institutions including universities, high schools, museums, and nature centers. Ecologists may also work in advisory positions assisting local, provincial, and federal policymakers to develop laws that are ecologically sound, or they may develop those policies and legislation themselves. Becoming an ecologist requires an undergraduate degree, usually in a natural science. The undergraduate degree is often followed by specialized training or an advanced degree, depending on the area of ecology selected. Ecologists should also have a broad background in the physical sciences, as well as a sound foundation in mathematics and statistics.



Figure **4.2.1.4**: This landscape ecologist is releasing a black-footed ferret into its native habitat as part of a study. (credit: USFWS Mountain Prairie Region, NPS)

Video



Watch this 3-minute video about Chantal Ouimet, an ecologist from Parks Canada, as she discusses her role as an ecologist and how she decided on ecology as a career.
Question after watching: What aspects of being an ecologist are interesting or surprising?

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Unit 4.2.2 - What is Population Ecology?

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.2.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
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Introduction

Thousands of bird species breed and reproduce in North America. Some, like the American Robin (*Turdus migratorius*), are widespread, and can be found building nests and raising their young throughout North America. Others, like Kirtland's Warbler (*Setophaga kirtlandii)* breed almost entirely within a single state within the United States. A few, like the Cozumel thrasher (*Toxostoma guttatum*) and Socorro mockingbird (*Mimus graysoni*) are found only on single small islands. Population ecologists study what determines the occurrence and abundance of species in space and time: their geographic ranges, population sizes and densities, and what factors result in them being so rare or common.

A **species** is typically defined as a group of organisms capable of interbreeding. For some species, all of the members of the species occur in the same geographic area and could potentially meet and interbreed during their lifetimes. Most species, however, can be divided into geographically separate populations. Individuals within a single population are likely to interact and perhaps inter-breed, while those from different populations will only come into contact if there is long-range movement between the populations, known as **dispersal**.

? Optional Activity 4.2.2.1

The study of population ecology focuses on the _____.

a. number of individuals of one species in an area and how and why that number changes over time
b. processes driving interactions within and among different species within an area
c. adaptations that enable individuals to live in specific habitats
d. Plants and animals living in an enclosed area

Answer

a. number of individuals of one species in an area and how and why that number changes over time

Populations

Populations can be described by their size, density, or spatial extent. One species that currently consists of a single population is the Kirtland's warbler (*Setophaga kirtlandii*), a North American songbird. Almost all members of this species occur in the northern part of Michigan and eastern Wisconsin in the United States and southern Ontario (Fig. **4.2.2.1**). In contrast, the Spotted Owl (*Strix occidentalis*) is a species with many distinct populations throughout the western United States, southern Canada, and central Mexico.



Figure **4.2.2.1**: Left: A male Kirtland's Warbler in Michigan, USA. Right: Core habitat area of Kirtland's Warbler. Sources: Left - Photo by J. Trick, US Fish and Wildlife Service and accessed via Wikipedia https://bit.ly/KIWA_01. Used under the Creative Commons License CC BY 2.0. Right - Google Earth: https://bit.ly/3ofgDK1

For both species and populations, patterns of distribution and abundance can be measured in several ways. These include:

1. Size: How many total individuals are there?
2. Density: How many individuals can be found per unit of area?
3. Dispersion: How are individuals in a population arranged spatially relative to one another? Do they occur in clumps or are they evenly spread apart?
4. Occupancy: Does a species or member of a population occur in a given habitat, or is it absent?
5. Population distribution: Where does a population occur in space?
6. Geographic range: What are the furthest geographic limits of where a species occurs?

In addition to static characteristics of size and distribution, populations are dynamic and 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. To study these many facets of a population's biology, ecologists use both systematic field observations to determine its current status, and mathematical tools to characterize how it responds to changes in the biotic and abiotic environments.

Population size

Population size is the number of organisms in a population. This is often of great interest to biologists – especially those working in forestry, wildlife management and conservation – and most of our basic population models work with population sizes. A **complete census** is one way to determine population size and entails counting each individual present within the population. This occurs in some well-studied populations, such as the Kasekela population of chimpanzees in Gombe National Park, Tanzania (Pusey et al. 2008), and the Seychelles Warbler on islands in the Indian Ocean off the coast of East Africa (Burt et al. 2016).

Although it is the most accurate methodology, counting every individual in a population can be difficult, if not impossible. In most cases, ecologists can only attempt to estimate the population size, "**N**", by using well-designed field studies and statistics. Indeed, some population ecologists specialize in developing mathematical and statistical models to accurately estimate population size, such as mark-recapture models and camera-trapping methods (detailed in Unit 4.2.4). Often, however, we do not have good estimates of the size of a population itself, but factors that should be correlated with the population size, such as the number of animals harvested by hunters or trapped by ecologists or the density of dung found during a survey.

Data that ecologists think correlates with abundance of individuals constitutes a **population index**. Index data are cheaper to collect than the data needed for formal estimates of population size such as the mark-recapture methods discussed below, but can be biased and provide an inaccurate sense of the status of a population (Stephens et al. 2015). Ideally, an index should be validated by checking its correlation with rigorous estimates of population size. For example, the abundance of large mammals such as lions, elephants, and tigers is frequently indexed by the frequency of their tracks or scat. To determine the reliability of an indirect measure of population size, Belant et al. (2019) compared an index based on lion tracks to a formal estimate of population size. Unfortunately, the commonly used index of lion abundance based on their tracks overestimated abundance.

When species become endangered, researchers often try to determine - or at least estimate - the number of individuals surviving. For example, with only approximately 4,000 individuals, Kirtland's Warbler is the rarest species breeding in the continental United States and a small portion of Canada. It was considered critically endangered throughout most of the 20th century. Researchers, therefore, worked each spring to determine as best as possible how many male warblers had established territories and were trying to attract mates.

British Columbia Connection

Species that are economically important or are central players in ecosystem functioning are also often monitored intensively. Since the middle of the 20th century, the abundance of Wildebeest (*Connochaetes taurinus*) in the Serengeti ecosystem of East Africa has been intensively monitored by aircraft (Fig. **4.2.2.2**). A Canadian ecologist, Dr. Tony Sinclair, Professor Emeritus at the University of British Columbia, began the first quantitative studies on wildebeest and their benefits to the ecosystem. The population was considered to be small in the 1960s when it numbered around 250,000, but by the 1990s had grown to over 1 million. Learn more about Dr. Sinclair's work here: https://beatymuseum.ubc.ca/2013/11/20/fifty-years-in-serengeti/



Figure 4.2.2.2 Wildebeest in Maasi Mara. Source: Photo by Bjørn Christian Tørrissen, http://bjornfree.com/galleries.html.

In this 8-minute video, Dr. Sinclair discusses his work on the ecology of Serengeti and how data on animal populations are collected through time.

Questions after watching: What does Dr. Sinclair mean by Living Data? What are the benefits to having openly accessible data for ecological studies?

Population density

While population size is a total count of individuals, **population density** is how many individuals occur in a given area of space. It is therefore a measure of **relative abundance**. For animals and trees, this is often the estimated number of animals per hectare (a hectare is 100 m by 100 m). For plants, insects, and other smaller organisms this is often the number per square meter.

Estimates of population density are often easier to obtain than estimates of total population size. Population density can be converted to a rough estimate population size through simple multiplication. If there are 1.4 pairs per hectare of good habitat, and there are 2800 hectares of habitat, we can calculate the number of pairs as 1.4*2000 = 2800 pairs. Two things are key to this calculation: first, the estimate of density is accurate, and second, the estimate of the amount of good habitat is accurate.

Occupancy

Occupancy is simply whether a given species or member of a population occurs in a habitat patch, fragment, or area. Often it can be very difficult to count the number of individuals or determine their density; instead of asking a question like "*How many owls are there in this forest?*" it's relatively easier to ask "*Are there* any *owls present in this forest?*" It can be very time-consuming to do counts or determine density, which can limit researchers' ability to study multiple sites or locations. Focusing on determining just the presence or absence of a population in a habitat often allows researchers to study a larger area.

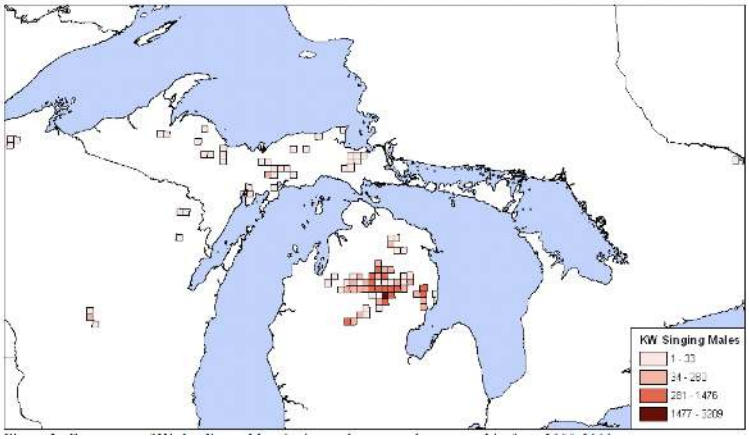


Figure 4.2.2.4: Frequency of Kirtland's warbler singing males counted per township from 2000-2011. Source: U.S. Fish and Wildlife Service.

Kirtland's Warbler is currently increasing its population size and is being found in stands of Jack Pine outside of the state of Michigan (Figure 4.2.2.4). Since the warbler's population is increasing, researchers are more interested in doing occupancy surveys to determine which patches of forest warblers are occurring in rather than determining exactly how many warblers are in these forests (Richards 2008).

Camera traps and occupancy studies can be used to determine if a species has become locally extinct. Giodano, Tumenta and Iongh (2017) carried out a camera-trap based occupancy study of Waza National Park in Cameroon. While they confirmed the occupancy of lions in the park, no leopards (*Panthera pardus*) were photographed. Since lions and leopards are typically similarly difficult to detect and lions were detected, they concluded that there were no longer any leopards occupying the park.

Distribution

In addition to measuring simple density, further information about a population can be obtained by looking at the distribution of the individuals. Species **distribution patterns** summarize 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 population 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, distributed randomly with no predictable pattern, or clustered in groups. These are known as uniform, random, and clumped distribution patterns, respectively (Fig. 4.2.2.5). **Uniform distribution** can occur in plants and is thought to result from competition for below-ground resources such as water, or secretion of substances inhibiting the growth of nearby individuals, a phenomenon called **allelopathy**. In animals like penguins that nest in large colonies, uniform dispersion can occur due to territorial behavior. An example of **random distribution** occurs with dandelion and other plants that have wind-dispersed seeds that germinate wherever they happen to fall in a favorable environment. A **clumped distribution** 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 distribution may also be a function of habitat heterogeneity. Thus, the distribution pattern 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.

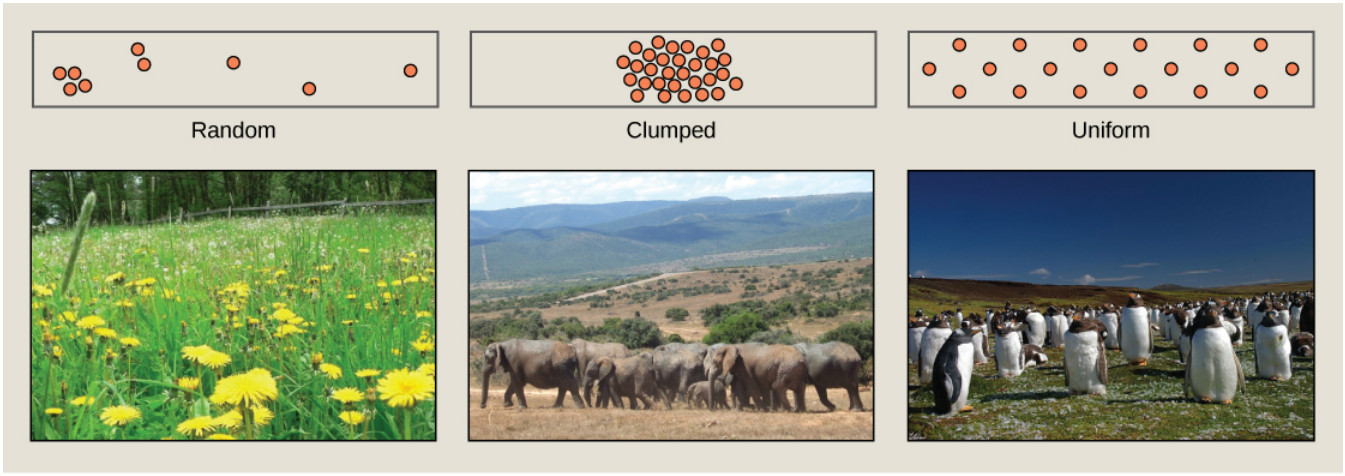


Figure 4.2.2.5: Species may have random, clumped, or uniform distribution. Plants such as dandelions with wind-dispersed seeds tend to be randomly distributed. Animals such as elephants that travel in groups exhibit clumped distribution. Territorial birds such as penguins tend to have uniform distribution. (credit a: modification of work by Rosendahl; credit b: modification of work by Rebecca Wood; credit c: modification of work by Ben Tubby)

Video



In this 3-minute video, see examples of the various types of distribution patterns populations exhibit across space (note that "aggregated" in the film is the same as clumped in the text above).
Question after watching: Which example is surprising to you and why?

Niches

Population distributions are limited to suitable habitats. In ecology, a **niche** is the match of a species to a specific environmental condition. It describes how an organism or population responds to the distribution of environmental resources (abiotic components of the environment) and predators, pathogens, and competitors (biotic components of the environment). An early study on ecological niches conducted by Joseph H. Connell analyzed the environmental factors that limit the range of a barnacle (*Chthamalus stellatus*) on Scotland's Isle of Cumbrae (Connell 1961).

In his experiments, Connell described the dominant features of *C. stellatus* niches and provided explanation for their distribution on intertidal zone of the rocky coast of the Isle. Connell described the upper portion of C. stellatus's range as limited by the barnacle's ability to resist dehydration during periods of low tide. The lower portion of the range was limited by interspecific interactions,

namely competition with a cohabiting barnacle species and predation by a snail (Connell 1961). By removing the *B. balanoides*, Connell showed that *C. stellatus* was able to extend the lower edge of its realized niche in the absence of competition. These experiments demonstrate how biotic and abiotic factors limit the distribution of an organism.

Range and Habitat

Population distribution is the geographic area where a particular population of a species occurs. This area of occupancy is determined by the local availability of appropriate habitat. The **geographic range** of a species can be viewed as a spatial reflection of its niche, along with characteristics of the geographic template and the species that influence its potential to colonize. The **fundamental geographic range** of a species is the area it occupies in which environmental conditions are favorable, without restriction from barriers to disperse or colonize. A species will be confined to its **realized geographic range** when confronting biotic interactions or abiotic barriers that limit dispersal, a more narrow subset of its larger fundamental geographic range.

A term that can sometimes be confused with geographic range is home range. Geographic range refers to the entire spatial area a species can be found in, while a **home range** refers to an area utilized and perhaps defended by a single organism. A species' current geographic range is often very different from its historical range. Factors such as habitat loss, hunting, and climate change can all reduce the distribution of populations and the species' overall geographic range. For example, lions previously ranged broadly over Africa, Western Asia, the Middle East and India (Figure **4.2.2.6**).

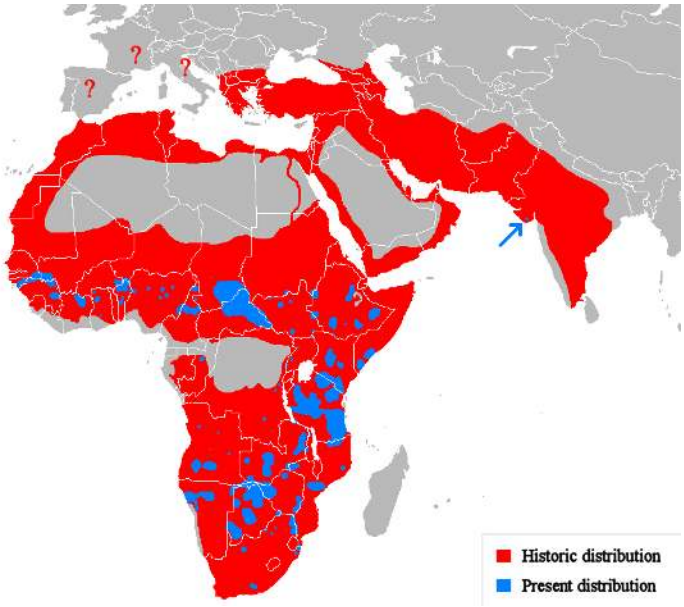


Figure **4.2.2.6**: Historical (red) and present (blue) distribution of lions (*Panthera leo*). Source: Tommyknocker (Wikipedia), based on a map created by 'The African Lion Environmental Research Trust (ALERT).

Some species are **habitat generalists** (species that can thrive in a wide variety of environmental conditions) and their populations spread out almost continuously across a landscape. American Robins, for example, can breed in parks, urbanized areas, farms, and the edges of forest. Bald eagles can be found breeding in almost every state of the USA and most provinces of Canada. Their geographic range, therefore, encompasses almost all of North America north of Mexico.

In contrast, Golden Eagles breed almost exclusively in western Canada, the western United States, and Mexico. The Golden Eagle's range is restricted to the western part of the continent and Mexico. Aquatic species also often occur in isolated populations because their habitat is necessarily bounded by the extent of the lake, wetland, or waterway they occur in.

Kirtland's Warbler is a habitat **specialist** (species that can thrive in a specialized subset of environmental conditions) and only nests in forests dominated by a single conifer, the Jack Pine (*Pinus banksiana*). Moreover, it only nests in Jack Pines of a certain age (5-20 years) and density (>3000 pines per hectare; Donner et al. 2018). When conditions are optimal, there is usually one breeding pair of warblers per 70 hectares, or 1.4 pairs per 100 hectares (Densities are usually reported for standard areas such as 1 square meter, 100 hectares, etc.).

The Northern Spotted Owl is a subspecies of spotted owl that is a habitat specialist that only occurs in old-growth forests in the Pacific Northwest of North America (British Columbia, Washington, Oregon, California). While much of the Pacific Northwest is still forested, most forests are less than 100 years old and don't have the large, old trees that the owls nest in. The extent of each population of owls is therefore limited by the size of each patch of old-growth forest.

As noted above, Kirtland's warblers are habitat specialists, which means that the species only reside in the Jack Pine Forests of northern Michigan and a few adjacent states and Canadian provinces. Subsequently, this phenomenon is referred to by biologists as a **restricted range**. A restricted range species refers to a species in which the range is so small, there is basically a single population. This results in the population distribution and geographic range is essentially the same.

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Unit 4.2.3 - Life Histories and Natural Selection

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1.5 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.2.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe how life history patterns are influenced by natural selection
- Explain different life history patterns and how different reproductive strategies affect species' survival
- Describe how natural selection and environmental adaptation lead to the evolution of particular life-history patterns

Introduction

Life history theory is an analytical framework designed to study the diversity of life history strategies used by different organisms throughout the world, as well as the causes and results of the variation in their life cycles. It is a theory of biological evolution that seeks to explain aspects of organisms' anatomy and behavior by reference to the way that their life histories—including their reproductive development and behaviors, post-reproductive behaviors, and lifespan (length of time alive)—have been shaped by natural selection. A life history strategy is the "age- and stage-specific patterns" and timing of events that make up an organism's life, such as birth, weaning, maturation, death, etc. These events, notably juvenile development, age of sexual maturity, first reproduction, number of offspring and level of parental investment, senescence and death, depend on the physical and ecological environment of the organism.

Video



In this 4-minute video, learn how life history traits include significant life events of a species, such as reproductive rate and reproductive lifespan.
Question after watching: How do these life history traits relate to natural selection?

The theory was developed in the 1950s and is used to answer questions about organism size, age of maturation, number of offspring, lifespan, and many others. In order to study these topics, life history strategies must be identified, and then models are constructed to study their effects. Finally, predictions about the importance and role of the strategies are made, and these predictions are used to understand how evolution affects the ordering and length of life history events in an organism's life, particularly the lifespan and period of reproduction. Life history theory draws on an evolutionary foundation, and studies the effects

of natural selection on organisms, both throughout their lifetime and across generations. It also uses measures of evolutionary fitness to determine if organisms are able to maximize or optimize this fitness, by allocating resources to a range of different demands throughout the organism's life.

Organisms have evolved a great variety of life histories, from Pacific salmon, which produce thousands of eggs at one time and then die, to human beings, who produce a few offspring over the course of decades. The theory depends on principles of evolutionary biology and ecology and is widely used in other areas of science.



Figure **4.2.3.1**: A swallowtail butterfly hatches from a chrysalis. Image: Pixabay

Video



This 15-minute video introduces Pacific salmon and their life cycle. Keep these fish in mind as you read through the sections below.

Question after watching: What adaptations are noted in the video? Which do you notice that are not explicitly stated?

Life cycle

All organisms follow a specific sequence in their development, known as the **life cycle**. All events and adaptations of life cycle comprise the life history strategy of that species. The major events in this life cycle are often shaped by the demographic qualities of the organism. Some are more obvious than others, like teeth erupting in young children, while some events may have little variation between individuals, such as the length of gestation. Other events may show a lot of variation between individuals, such as age at first reproduction. Life cycles across all life forms can be divided into two major stages: growth and reproduction. These two cannot take place at the same time, so once reproduction has begun, growth usually ends. This shift is important because it can also affect other aspects of an organism's life, such as the organization of its group or its social interactions.

Each species has its own pattern and timing for these events, often known as its **ontogeny**, and the variety produced by this is what life history theory addresses. Evolution then works upon these stages to ensure that an organism adapts to its environment. For example, a human, between being born and reaching adulthood, will pass through an assortment of life stages, which include: birth, infancy, weaning, childhood and growth, adolescence, sexual maturation, reproduction, and senescence. All of these are defined in a specific biological way. In life history theory, evolution works on the life stages of particular species (e.g., length of juvenile

period) but is also discussed for a single organism's functional, lifetime adaptation. In both cases, researchers assume adaptation—processes that establish fitness.

Traits

There are at least seven traits that are traditionally recognized as important in life history theory. The trait that is seen as the most important for any given organism is the one where a change in that trait creates the most significant difference in that organism's level of fitness. In this sense, an organism's fitness is determined by its changing life history traits. The way in which evolutionary forces act on these life history traits serves to limit the genetic variability and heritability of the life history strategies, although there are still large varieties that exist in the world.

Commonly studied life history traits:

1. size at birth (animals)
2. size of seeds/spores (plants and animals)
3. growth pattern
4. age and size at maturity
5. number, size, and sex ratio of offspring
6. age- and size-specific reproductive investments
7. age- and size-specific mortality schedules
8. length of life.

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 and 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 may provide little if any care for the offspring. Most of their reproductive 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 trade-offs 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 **4.2.3.3**a), 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 **4.2.3.3**b). 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 **4.2.3.3**c).



a b



c

Figure 4.2.3.2: 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)

? Optional Activity 4.2.3.1

Which of the following is associated with long-term parental care?

a. few offspring
b. many offspring
c. semelparity
d. fecundity

Answer

a. few offspring

Trade-offs

>An essential component of studying life history strategies is identifying the trade-offs[that take place for any given organism. Energy use in life history strategies is regulated by thermodynamics and the conservation of energy, and the "inherent scarcity of resources", so not all traits or tasks can be invested in at the same time. Thus, organisms must choose between tasks, such as growth, reproduction, and survival, prioritizing some and not others. For example, there is a trade-off between maximizing body size and maximizing lifespan, and between maximizing offspring size and maximizing offspring number. This is also sometimes seen as a choice between quantity and quality of offspring. These choices are the trade-offs that life history theory studies.

One significant trade-off is between **somatic effort** (towards growth and maintenance of the body) and **reproductive effort** (towards producing offspring). Since an organism cannot put energy towards doing these simultaneously, many organisms have a period where energy is put just toward growth, followed by a period where energy is focused on reproduction, creating a separation of the two in the life cycle. Thus, the end of the period of growth marks the beginning of the period of reproduction. Another fundamental trade-off associated with reproduction is between mating effort and parenting effort. If an organism is focused on raising its offspring, it cannot devote that energy to pursuing a mate.

An important trade-off in the dedication of resources to breeding has to do with predation risk: organisms that have to deal with an increased risk of predation often invest less in breeding. This is because it is not worth as much to invest much in breeding when the benefit of such investment is uncertain.

These trade-offs, once identified, can then be put into models that estimate their effects on different life history strategies and answer questions about the selection pressures that exist on different life events. Over time, there has been a shift in how these models are constructed. Instead of focusing on one trait and looking at how it changed, scientists are looking at these trade-offs as part of a larger system, with complex inputs and outcomes.

The idea of **constraints** is closely linked to the idea of trade-offs discussed above. Because organisms have a finite amount of energy, the process of trade-offs acts as a natural limit on the organism's adaptations and potential for fitness. These limits can be physical, developmental, or historical, and they are imposed by the existing traits of the organism.

Populations can adapt and thereby achieve an "optimal" life history strategy that allows the highest level of fitness possible (fitness maximization). There are several methods from which to approach the study of **optimality**, including energetic and demographic. Achieving optimal fitness also encompasses multiple generations, because the optimal use of energy includes both the parents and the offspring. For example, "optimal investment in offspring is where the decrease in total number of offspring is equaled by the increase of the number who survive". Optimality is important for the study of life history theory because it serves as the basis for many of the models used, which work from the assumption that natural selection, as it works on a life history traits, is moving towards the most optimal group of traits and use of energy. This base assumption, that over the course of its lifespan an organism is aiming for optimal energy use, then allows scientists to test other predictions. However, actually gaining this optimal life history strategy cannot be guaranteed for any organism.

An organism's allocation of resources ties into several other important concepts, such as trade-offs and optimal strategies. The best possible allocation of resources is what allows an organism to achieve an optimal life history strategy and obtain the maximum level of fitness, and making the best possible choices about how to allocate energy to various trade-offs contributes to this. The allocation of resources also plays a role in variation, because the different resource allocations by different species create the variety of life history strategies.

Unpredictable environments

Many factors can determine the evolution of an organism's life history, especially the unpredictability of the environment. A very unpredictable environment—one in which resources, hazards, and competitors may fluctuate rapidly—selects for organisms that produce more offspring earlier in their lives, because it is never certain whether they will survive to reproduce again. **Mortality rate**, the number of individuals who die per 1,000 over a given time, might be the best indicator of a species' life history: organisms with high mortality rates—the usual result of an unpredictable environment—typically mature earlier than those species with low mortality rates, and give birth to more offspring at a time.

Early Theories about Life History: *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. "*K*" is the biological term for carrying capacity and "r" indicates a focus on reproductive effort (see Unit 4.2.5)

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 the length of life and survivorship factors as well. For this analysis,

population biologists have grouped species into two large categories—*K*-selected and *r*-selected—although they are really two ends of a continuum (Table **4.2.3.1**).

Table **4.2.3.1**: 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

***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. 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 **4.2.3.3**a).

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 (*K*-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).



(a) K-selected species



(b) r-selected species

Figure **4.2.3.3**: (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.

In contrast, ***r*-selected** species have a large number of small offspring (hence their *r* designation (Table **4.2.3.1**). 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 **4.2.3.3**b). Dandelions have small seeds that are wind dispersed over 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.

? Optional Activity 4.2.3.2

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.

Answer

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.

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. A highly unpredictable environment can lead to plasticity, in which individual organisms can shift along the spectrum of r-selected vs. K-selected life histories to suit the environment. 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 and population age structure and mortality factors. These are discussed in the next sections.

Indigenous Connections: The Life Histories of Salmon

Salmon play a significant role in interconnectedness (First Nations Education Steering Committee & First Nations Schools Association, 2019):

> Salmon is an essential resource to many First Nations people and communities in BC. Salmon is found in almost every part of BC, with the exception of northeast regions that are in the Peace and McKenzie River watersheds. For thousands of years, First Nations peoples have developed an intricate understanding and knowledge about salmon, including the interconnectedness of salmon with other life forms. Before contact, salmon was a foundational trade item, contributing significantly to the economy and social structure of First Nations societies. Salmon helped to ensure the sustenance of large, vibrant populations of people. First Nations developed a myriad of technologies to capture and preserve the salmon. The value and respect that the people had for the salmon is reflected in the representation of salmon in traditional stories, songs, dances, and art throughout BC.

The life cycle of salmon is important to understand in order to appreciate the impact this keystone species has on the environment (Pacific Salmon Foundation, n.d.):

> The Pacific salmon life cycle depends on the species. Some spend hardly any time in natal streams; some spend years. Some mature at two years of age; some mature at five. Some live for only a couple of years; others live for ten. And some, like Steelhead and Cutthroat, can spawn more than once. Despite these variations, we can still make some general observations about the life stages of salmon.
>
> All Pacific salmon are anadromous, which means they start in freshwater (streams, lakes, rivers, etc.), migrate to the ocean, then return home to spawn and die.

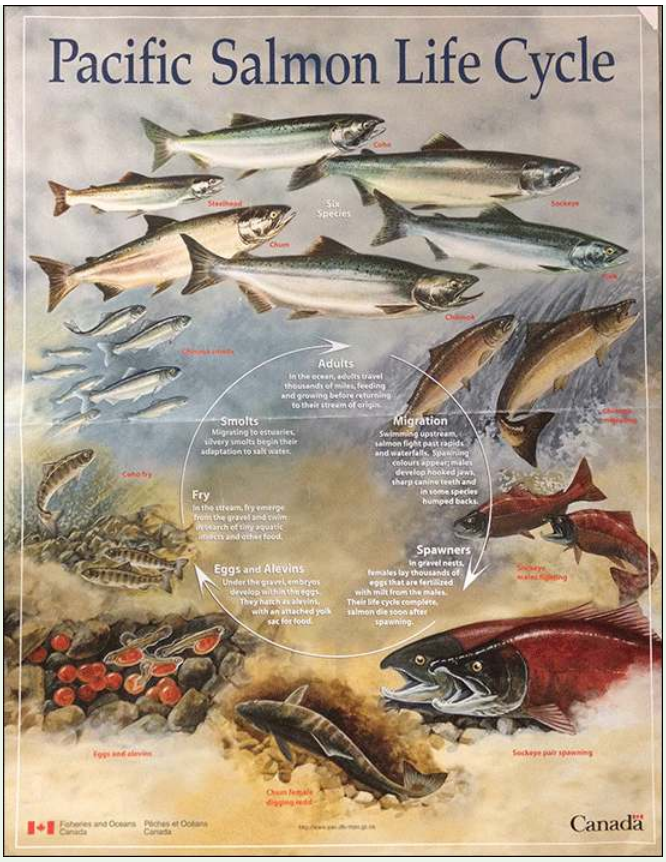


Figure 4.2.3.4: Pacific Salmon Life Cycle Poster (Fisheries and Oceans Canada, n.d.)

Adult spawners often journey for hundreds of miles to return to the waters their parents spawned in, and where they themselves were born. If they make it back, evading all sorts of obstacles—predation, competition, environmental impediments, the males and females court, and ultimately breed. At the crucial moment, the male releases sperm and the female releases eggs… at precisely the same time!

The eggs and sperm float in a fog of milt to the bottom of the stream or lake bed where the female has painstakingly prepared a redd (aka nest), which, covered with gravel, is expected to protect the eggs until they are ready to hatch.

While new salmon are preparing to enter the world, their parents die (usually only days after spawning), making them semelparous. Their bodies remain in the water or along the shore to decay and/or be eaten by other species. In this way, they continue to nourish the environment around them.



Figure 4.2.3.5: Indigenous wooden eagle and salmon sculpture ("Capilano Suspension Bridge, West Vancouver, BC" by Yuta Koike; CC-BY-SA)

References

First Nations Education Steering Committee & First Nations Schools Association. (2019). *Secondary science First Peoples teacher resource guide*. https://www.fnesc.ca/wp/wp-content/u...y-TRG-2019.pdf

Fisheries and Oceans Canada. (n.d.). *Pacific salmon life cycle poster*. Government of Canada. https://www.pac.dfo-mpo.gc.ca/educat...-cycle-eng.pdf

Pacific Salmon Foundation. (n.d.). *Species & lifecycle*. https://psf.ca/learn/species-lifecycle



This 7-minute short is about the importance and life cycle of wild Pacific salmon.



This 15-minute video showcases the St'at'imc: The Salmon People.

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Unit 4.2.4 - Population Demography

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
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  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe how ecologists measure population size and density
- Describe three different patterns of population distribution
- Use life tables to estimate mortality rates
- Describe the three types of survivorship curves and relate them to specific populations

Introduction

Populations are dynamic entities. Populations consist of a 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 identify the life expectancies of individuals within a population and are discussed in more detail in a later section, 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 **4.2.4.1**, smaller organisms tend to be more densely distributed than larger organisms.

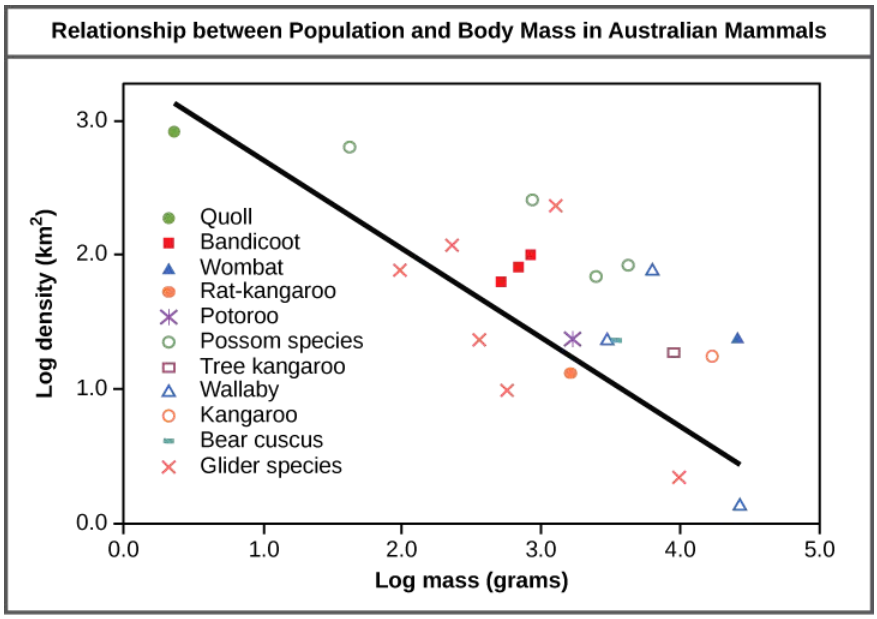


Figure 4.2.4.1: Australian mammals show a typical inverse relationship between population density and body size.

? Optional Activity 4.2.4.1

Figure 4.2.4.1: As this graph shows, population density typically decreases with increasing body size. Why do you think this is the case?

Answer

Smaller animals require less food and other resources, so the environment can support more of them.

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.

Video



Ecologists are interested in the distribution of organisms within habitats, and use transects, quadrants, and other sampling methods to collect quantitative data, as you will see in this 5-minute video.
Question after watching: What type of technique would be used for mobile organisms?

Quadrat Sampling

For immobile organisms such as plants, or for very small and slow-moving organisms, a quadrat may be used. 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 (Figure **4.2.4.2**). 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.

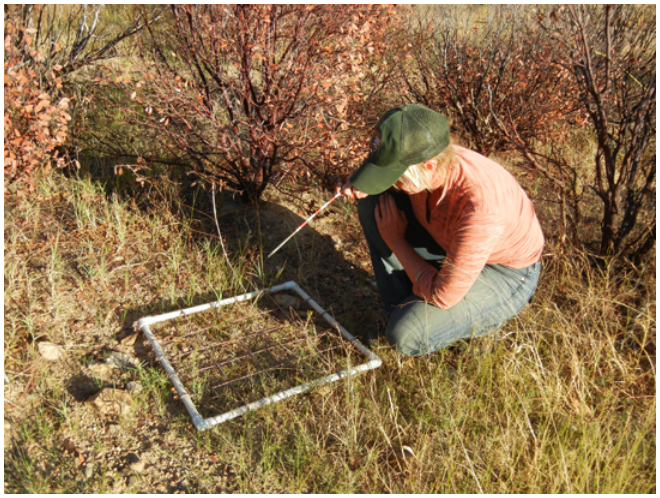


Figure **4.2.4.2**: A scientist uses a quadrat to measure population size and density. (credit: NPS Sonoran Desert Network)

Distance Sampling Methods

Other techniques for sampling populations to estimate density or abundance are distance sampling methods (Figure **4.2.4.3**). The main methods are based on **line transects** or **point transects**. Distance-based methods are frequently used for animals with observers making their observations while walking, riding in trucks, or in low-flying aircraft. They can also be used for tasks such as surveying for very rare trees or plants.

In this method of sampling, the data collected are the distances of the objects being surveyed from these randomly placed lines or points, and the objective is to estimate the average density of the objects within a region. When using line transects, the observer randomly places a straight line or follows some pre-planned route through the habitat of the population of interest, then walks the line or route. Whenever the researcher observes an object of interest (e.g., an animal of the type being surveyed), they record the observation, the distance from their current position to the object (r), as well as the angle of the detection to the transect line (θ). The distance of the object to the transect can then be calculated using trigonometry as $x = r * \sin(\theta)$. These distances x are the detection distances that will be analyzed in further modeling aspects of the population (e.g., population distribution in space).

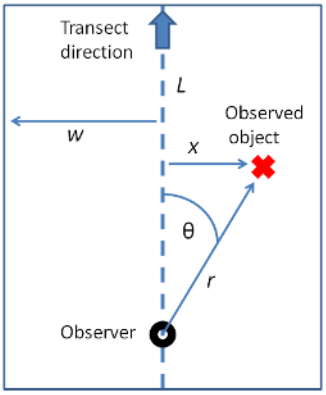
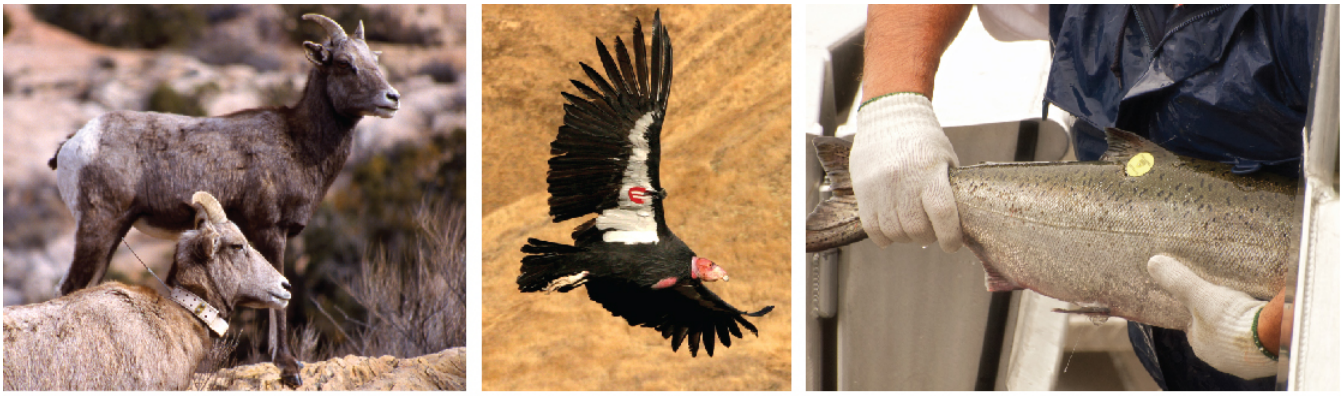


Figure 4.2.4.3: Basic distance sampling survey approach using line transects. A field observer detects an object and records distance *r* and angle *θ* to the transect line. This allows the calculation of object distance to the transect (*x*). All *x* from the survey are used to model how detectability decreases with distance from the transect, which allows estimation of total population density in the surveyed area. (Elmidae; CC-BY-4.0)

Mark and Recapture

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 (recaptured) and some individuals that are unmarked (Figure 4.2.4.4).



(a) (b) (c)

Figure 4.2.4.4: 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.

To begin, the ratio of the proportions looks like this \[\frac{\text{number marked first catch} {\text{total population}} = \ [\frac{\text{number marked second catch} {\text{total caught in second sample}}].

We can rearrange the ratios to solve for an unknown, in this case the total population.

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, we will start with 80 deer that are captured, tagged, and released into the forest.

Later, 100 deer are captured and 20 of them are already marked. From this, we can determine the population size (*N*) using the following equation:

$$\frac{\textbf{number marked first catch} * \textbf{total number of second catch}}{\textbf{number marked second catch}} = N$$

Using our example above, 80 would be the number marked first catch, 100 would be the total number of second catch, and 20 would be the number of them already marked.

The calculation of this formula leads to the number 400.

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

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.

Camera Traps

Recently, great progress in estimating animal density has been made using camera traps (Figure **4.2.4.5**). These are especially useful for studying rare and nocturnal animals, such as predators. For example, lions (*Panthera leo*) are considered vulnerable to extinction and are most threatened in West Africa, where they are restricted to a few small national parks. In western-most West Africa lions occur only in Niokolo-Koba National Park in south-eastern Senegal. Mamadou Kane used camera traps to estimate the density of lions in Niokolo-Koba. While the entire park is 9130 km^2, Kane sampled an area of approximately 285.4 square kilometers within the highest quality lion habitat of the park. Kane estimated that there are about 3 lions per 100 square kilometers in this high-quality habitat (100 square kilometers is an area 10 km by 10 km). Three lions per 100 km^2 equals 0.03 per km^2. We can therefore estimate the total abundance in the study area as 0.03*285.4 = 8.6 lions.



Figure **4.2.4.5**: A camera trap, for taking pictures of game on trails. This model is for hunting. Motion detector on top, lens in the middle, flash on the bottom, with a little LCD for showing how many pictures taken/left on the left. By Hustvedt CC BY-SA 3.0

British Columbia Connection

Many camera traps have been distributed throughout BC to collect data on everything from animal abundance to phenology.

You can view some of these camera trap projects online:

- Parks Canada: https://www.pc.gc.ca/en/nature/science/controle-monitoring/cameras
- Wildlife Cameras for Adaptive Management: https://wildcams.ca/projects/

Optional Activity 4.2.4.2

Which of the following methods will tell an ecologist about both the size and density of a population?

a. mark and recapture

b. line transect
c. quadrat
d. camera trap

Answer

c. quadrat sampling

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 the 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 **4.2.4.1** 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 1,000), 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 1,000.

$$\text{mortality rate} = \frac{\text{number of individuals dying}}{\text{number of individuals surviving}} * 1,000$$

For example, between ages three and four, 12 individuals die out of the 776 that were remaining from the original 1,000 sheep. This number is then multiplied by 1,000 to get the mortality rate per thousand.

$$\text{mortality rate} = \frac{12}{776} * 1,000 \approx 15.5$$

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 the last column.

Table **4.2.4.1**: Life Table of Dall Mountain Sheep[1]

Age interval (years)	Number dying in age interval out of 1,000 born	Number surviving at beginning of age interval out of 1,000 born	Mortality rate per 1,000 alive at beginning of age interval	Life expectancy or mean lifetime remaining to those attaining age interval
Column A	Column B	Column C	Column D	Column E
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

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 **4.2.4.6**). 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 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.

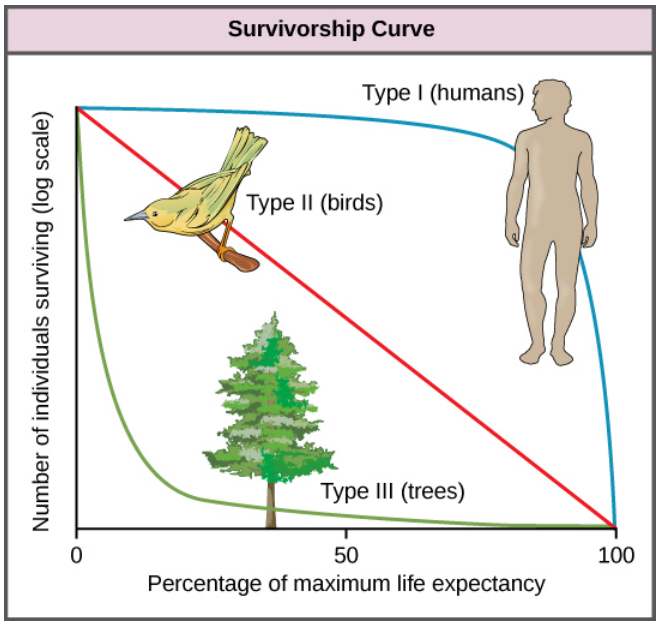


Figure **4.2.4.6**: Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. 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.

? Optional Activity 4.2.4.3

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

Answer

c. salmon

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Unit 4.2.5 - Population Models

- Please read and watch the following Learning Resources
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Learning Objectives

- Compare and contrast density-dependent growth regulation and density-independent growth regulation, giving examples
- Explain the characteristics of and differences between exponential and logistic growth patterns
- Give examples of exponential and logistic growth in wild animal populations

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.

Population Dynamics

Changes in population size over time and the processes that cause these to occur are called **population dynamics**. How populations change in abundance over time is a major concern of population ecology, wildlife ecology, and conservation biology, and is related to questions asked in evolutionary biology. The processes and mechanisms that drive population change are varied and include intraspecific competition with members of the same population, interspecific competition between species, the availability of food or other resources, extreme weather, inbreeding, predators or parasites.

We can consider changes in populations from various measures of populations. For example, Kirtland's Warbler (*Setophaga kirtlandii*) in North America is currently:

1. Increasing in the overall number of individuals (population size).
2. Increasing in the number of occupied habitat patches (occupancy).
3. Increasing in the geographic area it occurs in (population distribution and species range).

Importantly, since the warbler prefers a certain density of Jack Pine, its density within an occupied habitat also changes. Jack Pine stands are naturally prone to burning in forest fires, and are also logged for timber. As the density of trees changes due to these disturbances, the density of warblers changes. After a fire or logging there are few if any mature pine trees and therefore few warblers. Approximately five years after seedlings have sprouted and grown up to be the proper size, the density of warblers can increase. When pine forests get too old habitat conditions are not ideal for the warbler and their abundance declines.

Population Size Over Time

Though there are many dimensions to spatial and temporal population dynamics, discussions of population dynamics often center on changes in population size over time. Changes in population size are often displayed in a time series graph with time on the x-axis (usually in years) and population size (N) on the y-axis. General patterns of population dynamics in terms of population size include:

1. Growth: Growing larger than the current size (Snail kites: Figure **4.2.5.1**a)
2. Decline: Decreasing in abundance (Elk: **4.2.5.1**b)
3. Stability: Staying approximately the same size over time (Wolves: **4.2.5.1**c)

4. Recovery: Stability or growth following a period of decline. (Impala: 4.2.5.1d)
5. Extirpation (local extinction): Decline of one or more populations of a species to 0 (Kirtland's Warbler, 4.2.5.2a).
6. Extinction: Decline of all members of a species to 0 (Northern White Rhino, 4.2.5.2b).
7. Cycles: repeated patterns of growth followed by decline (Lynx: 4.2.5.2c)

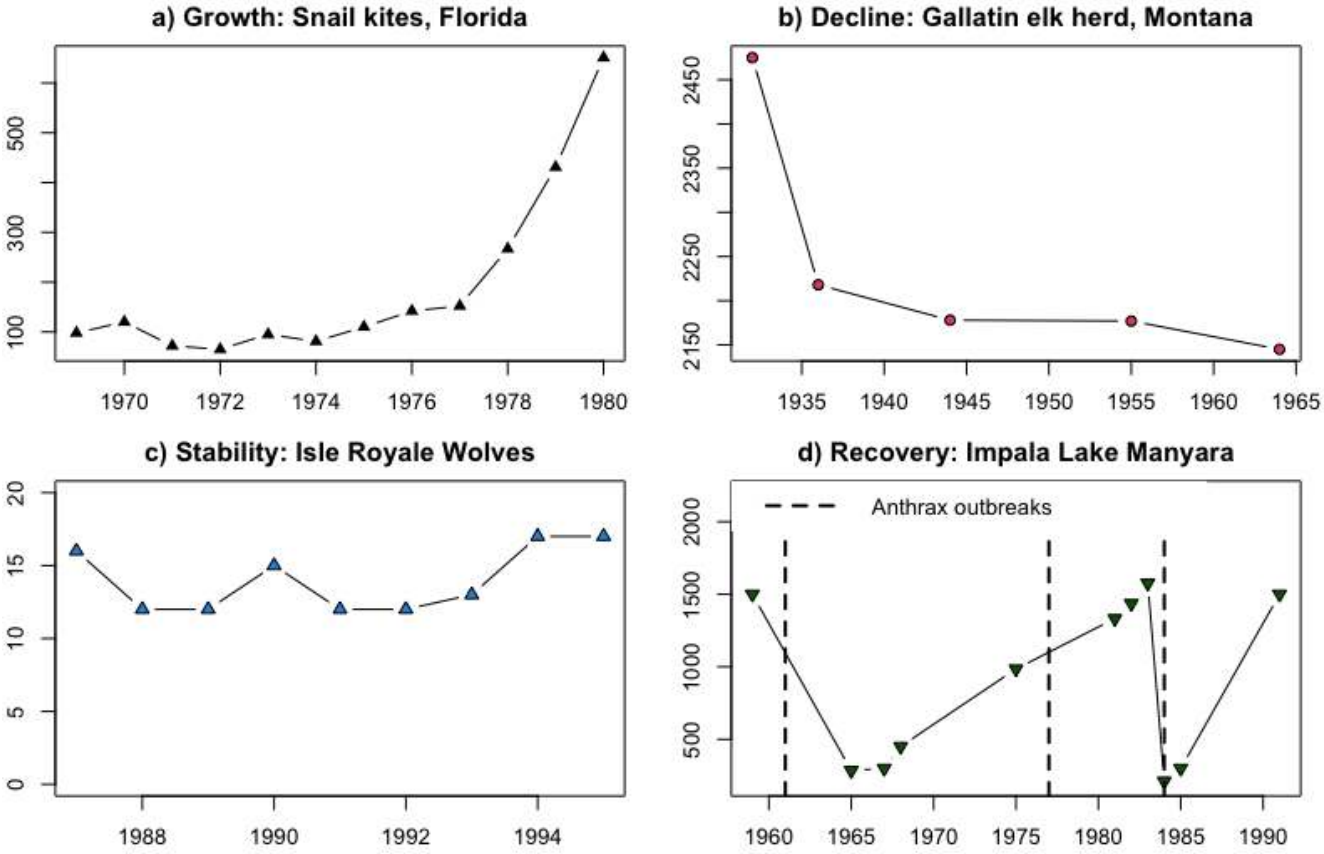


Figure 4.2.5.1: Common patterns of population change. The x-axis in all panels is the year and the y-axis is the number of individuals. a) Growth in a Florida Snail Kite (*Rostrhamus sociabilis*) population from 1970s to 1980s; b) Decline of the Gallatin, Montana herd of elk (*Cervus canadensis*) from the 1920s to 1960s; c) Stability of the Isle Royale, Michigan pack of wolves (*Canis lupus*) in the 1980s and 1990s; d) Recovery after population crashes in the Lake Manyara National Park, Tanzania herd of impala.

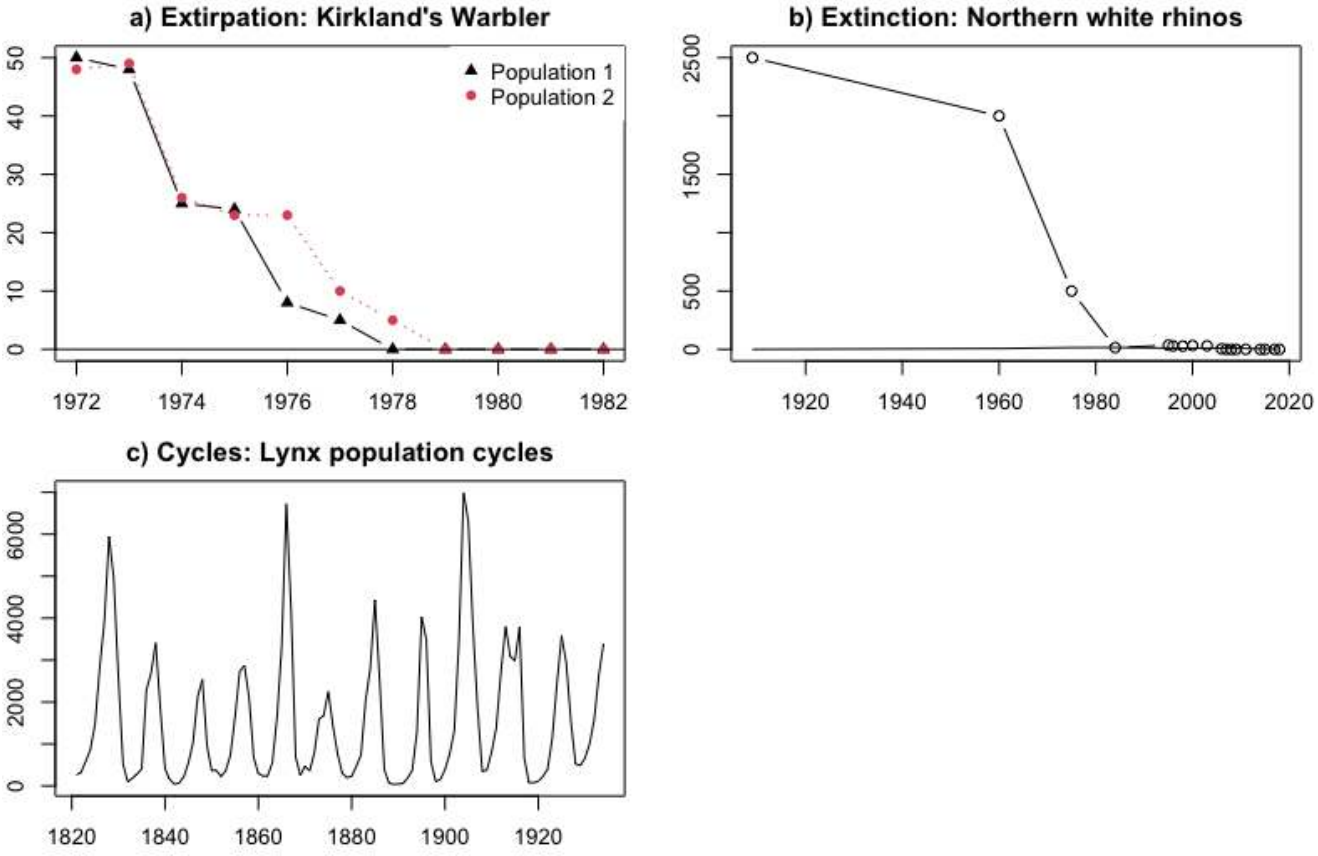


Figure **4.2.5.2**: Common patterns of population change. The x-axis in all panels is the year. a) Decline to extirpation (local extinction) of Kirtland's Warbler in two populations. The y-axis is the number of singing males; b) Decline to global extinction of the Northern White Rhinoceros (*Ceratotherium simum cottoni*), one of two subspecies of White Rhinos. The y-axis is the total number of rhinos in the wild. c) Repeated cycling of the Canada lynx (*Lynx canadensis)*. The y-axis is the number of lynx trapped, an index of population size.

Mixed Dynamics

Over the course of many years, a single population can display many of these dynamics. For example, Kirtland's Warbler populations were monitored by determining the number of males defending territories in their summer breeding habitat in the Great Lakes region North America, primarily Michigan. There were about 500 males with territories in the 1950s (**4.2.5.3**). The following changes occurred over the next 50 years after the species began being protected by the Endangered Species Act in the United States:

1. Decline over the course of the 1960s to ~200 territories.
2. A period of stability at ~200 territories from 1975 to 1990.
3. Steady growth to >2500 from 1990 through 2020.

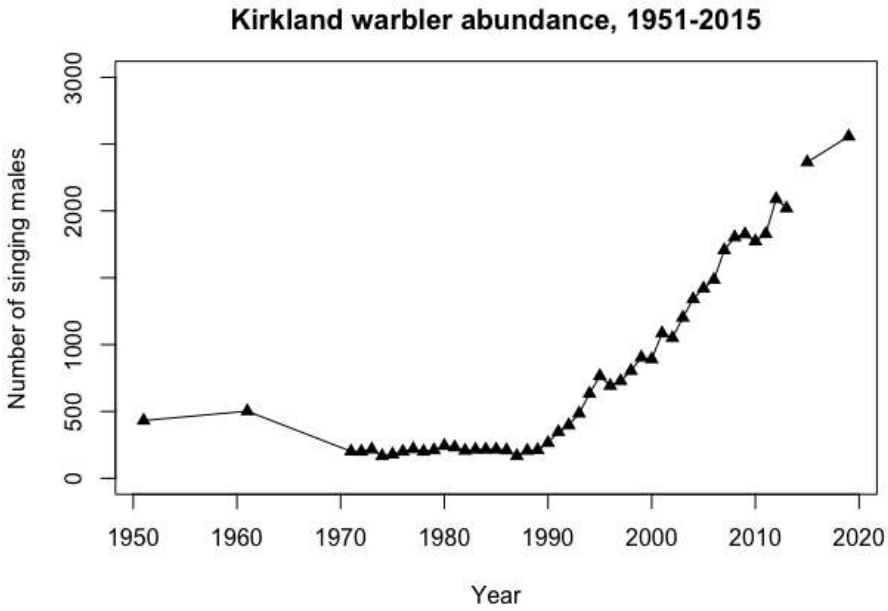


Figure 4.2.5.3: Number of singing Kirtland's Warbler (*Setophaga kirtlandii*) males, 1950 to 2020.

Population Modeling

Researchers who study population dynamics often use mathematical models to describe and predict population dynamics and understand what factors are driving those changes. For example, if there are 2500 Kirtland's Warblers in Michigan this year, can we predict how many will be around next year, or 10 years from now? Due to its small population size, the Kirtland's Warbler was listed as an Endangered Species in the United States in 1967. In 2019, it was de-listed and now is considered "near-threatened." Ecologists are very interested in using models to predict how large the Kirtland's Warbler population will be in the future, and what factors cause it to increase and decrease. Below, we explore the conceptual and mathematical tools ecologists use to understand population dynamics and predict their future trajectories.

Types of Growth: Exponential and Logistic

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 1,000 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 2,000 organisms—an increase of 1,000. In another hour, each of the 2,000 organisms will double, producing 4,000, an increase of 2,000 organisms. After the third hour, there should be 8,000 bacteria in the flask, an increase of 4,000 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 1,000 to more than 16 billion. When the population size, *N*, is plotted over time, a **J-shaped growth curve** is produced (Figure 4.2.5.4).

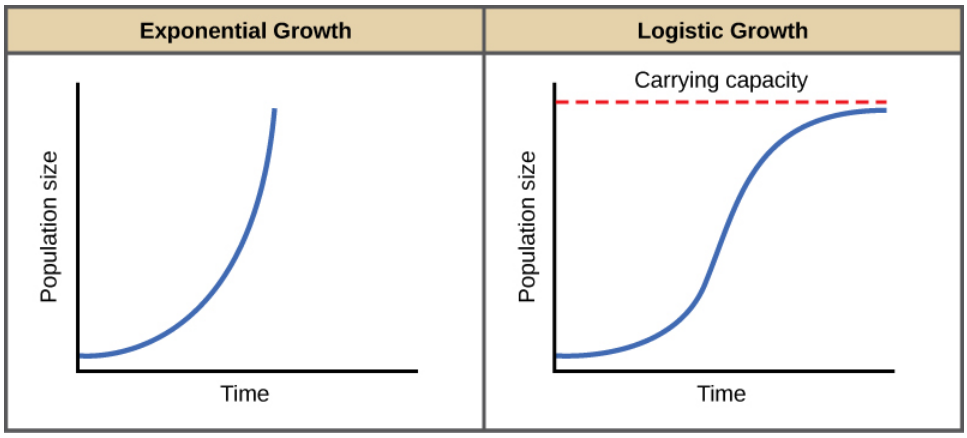


Figure **4.2.5.4**: When resources are unlimited, populations exhibit exponential growth, resulting in a J-shaped curve. When resources are limited, populations exhibit logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity of the environment is reached, resulting in an S-shaped curve.

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). While it is not necessary for you to know the math behind this equation, it is helpful to see how ecologists utilize math to build their models. This equation for exponentially growing population is shown here:

$$\frac{\Delta N \text{ (change in number)}}{\Delta T \text{ (change in time)}} = B \text{ (birth rate)} - D \text{ (death rate)}$$

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:

$$\frac{dN}{dT} = r_{\max}N$$

Video



In this 3-minute video, you will be introduced to some of the factors that limit population growth.
Question after watching: What are some of the factors that may be limiting the population growth of humans? How might they act to limit population growth?

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 DNA) to the next generation at a greater rate (natural selection). To model the reality of limited resources, population ecologists developed the **logistic growth model**.

Video



This 3-minute video will introduce you to the concept of carrying capacity.
Question after watching: Why are diseases considered a factor in carrying capacity?

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 4.2.5.4). 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 (again, the math is not important but seeing how the model is built is):

$$\frac{dN}{dT} = r_{\max}\frac{dN}{dT}$$
$$= r_{\max}N\frac{(K-N)}{K}$$

Notice that when N is very small, $(K-N)/K$ 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, $(K-N)/K$ 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 4.2.5.4), 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 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 and alcoholic beverages, exhibits the classical S-shaped curve when grown in a test tube (Figure 4.2.5.5a). 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 4.2.5.5b). 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.

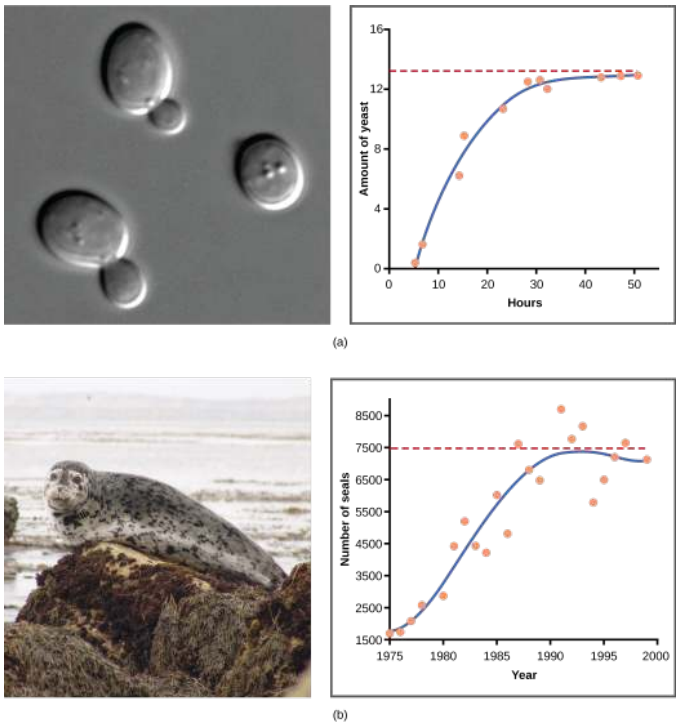


Figure **4.2.5.5**: (a) Yeast grown in ideal conditions in a test tube show a classical S-shaped logistic growth curve, whereas (b) a natural population of seals shows real-world fluctuation.

Video



This 3-minute video reviews the various demographic models.

Question after watching: Which type of model should be applied to a perennial plant species that is introduced to a new environment without any herbivores or diseases?

Optional Activity 4.2.5.1

Figure **4.2.5.2**b If the major food source of the seals declines due to pollution or overfishing, which of the following would likely occur?

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.

Answer

A

? Optional Activity 4.2.5.2

The maximum rate of growth of a species is called its _____.

a. limit
b. carrying capacity
c. biotic potential
d. exponential growth pattern

Answer

b. biotic potential

Population Limitations

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 winter is much lower than it is during 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.

Video



In this 4-minute video, you will learn about density-dependent and density-independent factors that limit the growth of populations.

Question after watching: Disease is listed as a density-dependent factor limiting a population's growth. How might disease be density-dependent?

Density-Dependent Regulation

Most density-dependent factors are biological in nature (biotic) and include predation, inter- and intraspecific competition, stress, 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 4.2.5.6 with results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite of humans and other mammals. 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 that indicated that female weight had no influence. The actual cause of the density-dependence of fecundity in this organism is still unclear and awaiting further investigation.

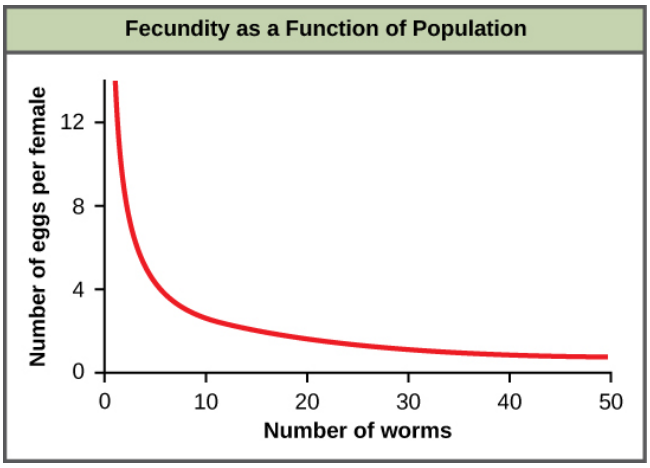


Figure 4.2.5.6: In this population of roundworms *Ascaris lumbricoides*, fecundity (number of eggs) decreases with population density (Croll et al. 1982).

Density-Independent Regulation

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.

Video

In this 2-minute video, you will explore biotic and abiotic limiting factors.
Question after watching: The video provides the example of a fish bowl and lists limiting factors on the growth of its fish population. Now apply this to a human population living in the "bowl" of a small town. List density-dependent, density-independent, biotic, and abiotic factors that will limit the human population's growth in that small town.

Optional Activity 4.2.5.3

Species with limited resources usually exhibit a(n) ____ growth curve.

a. logistic
b. logical
c. experimental
d. exponential

Answer

a. logistic

Evolution Connection: Why Did the Woolly Mammoth Go Extinct?

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.



a b c

Figure **4.2.5.7**: 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)

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 **4.2.5.7**). 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 like northern Canada. 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 both climate change and human hunting led to their extinction. A 2008 study estimated that climate change reduced the mammoths' range from 8,000,000 square kilometers 42,000 years ago down to 800,000 square kilometers 6,000 years ago.[4] It is also well documented that humans hunted these animals. A 2012 study indicated that no single factor was exclusively responsible for the extinction of these magnificent creatures.[5] 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. We once contributed to a species' decline using only primitive hunting technology.

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- **45.4: Population Dynamics and Regulation** by OpenStax is licensed CC BY 4.0.

Unit 4.2.6 - Human Population Growth

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to the Unit Glossary and Summary, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Discuss how human population growth can be exponential
- Explain how humans have expanded the carrying capacity of their habitat
- Relate population growth and age structure to the level of economic development in different countries
- Discuss the long-term implications of unchecked human population growth

Introduction

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 their 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. More is discussed in Unit 5. 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 **4.2.6.1**). 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.

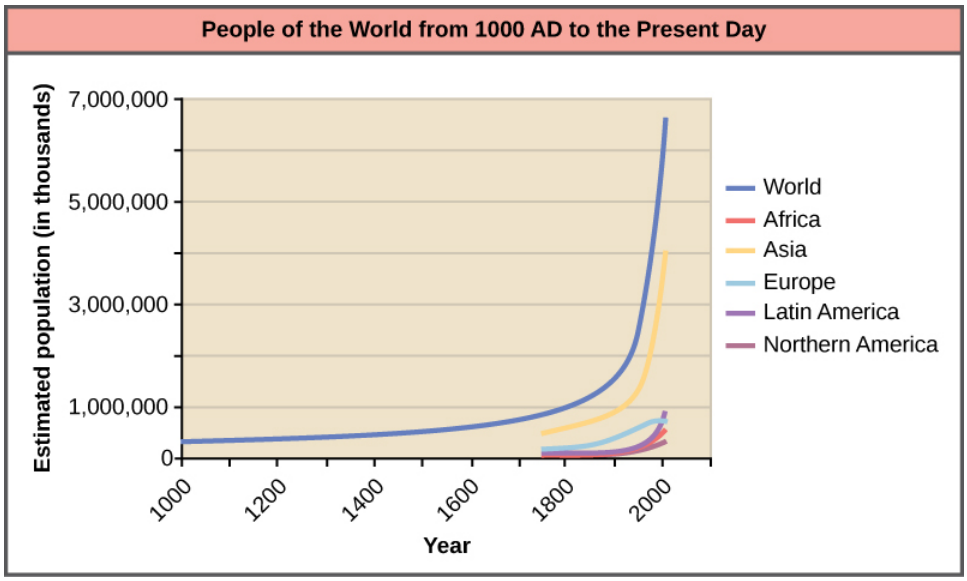


Figure **4.2.6.1**: Human population growth since 1000 AD is exponential (dark blue line). Notice that while the population in Asia (yellow line), which has many economically underdeveloped countries, is increasing exponentially, the population in Europe (light blue line), where most of the countries 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 **4.2.6.2** shows that 123 years were necessary to add 1 billion humans in 1930, but it took only 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.

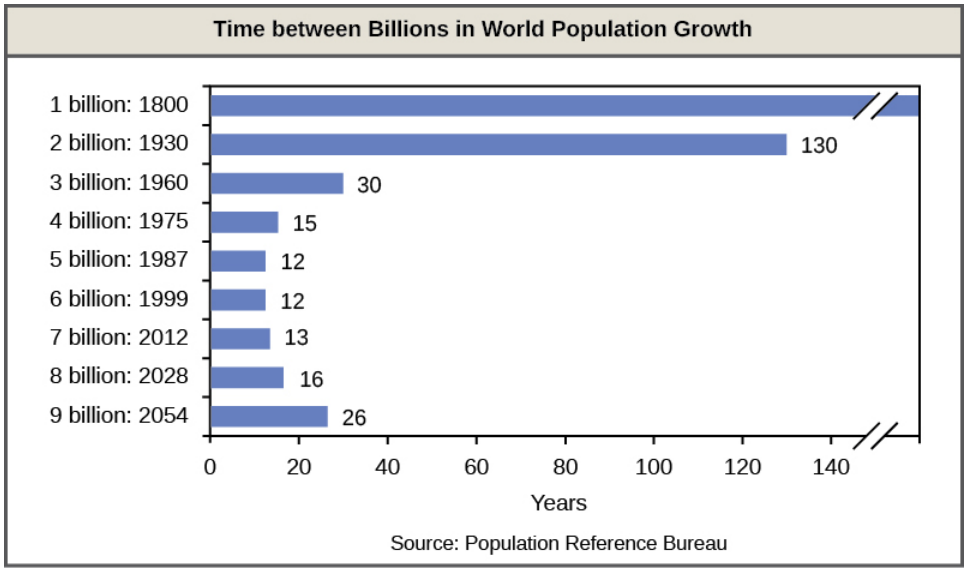


Figure **4.2.6.2**: The time between the addition of each billion human beings to Earth decreased in 1999, and has since been increasing (indicating slowing growth). (credit: modification of work by Ryan T. Cragun)

Video



In this 4-minute video, you will explore the historical pace of human population growth.
Questions after watching: Do we have an ethical obligation to limit human population growth? Why? If so, how might we do it ethically? If not, how should we distribute dwindling resources for the growing population?

Video



In this 6-minute video of the American Museum of Natural History, you will follow human population and distribution on a world map for the past 200,000 years.
Question after watching: In watching this video, what appears to have contributed to sharp rises in the human population throughout history?

Optional Activity 4.2.6.1

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.

Answer

d. By increasing their own carrying capacity, humans have enabled their population to grow exponentially.

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/culture, and communication. Humans can construct shelters 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 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 plague 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. Compared to some of the epidemics of the past, the percentage of the world's population killed by infectious diseases between 1993 and 2002 decreased from 0.30 percent of the world's population to 0.24 percent. It appears that the influence of infectious diseases on human population growth is becoming less significant, although the SARS-CoV-2 pandemic may be a harbinger of things to come due to globalization and anti-vaccination movements.

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 **4.2.6.3**). This pattern is most often observed in underdeveloped countries where individuals do not live to old age because of sub-optimal living conditions such as Mali (Stage 1). Age structures of areas with slow growth, including some developed countries such as Canada, still have a pyramidal or even arched structure, but with many fewer young and reproductive-aged individuals and a greater proportion of older individuals (Stages 2-3) (Figure **4.2.6.4**). Other developed countries, such as Italy and Japan, have zero or even negative population growth. The age structure of these populations is more conical, with more middle-aged and older individuals than young people. The actual growth rates in different countries are shown in Figure **4.2.6.5**, with the highest rates tending to be in the less economically developed countries within Africa and Asia.

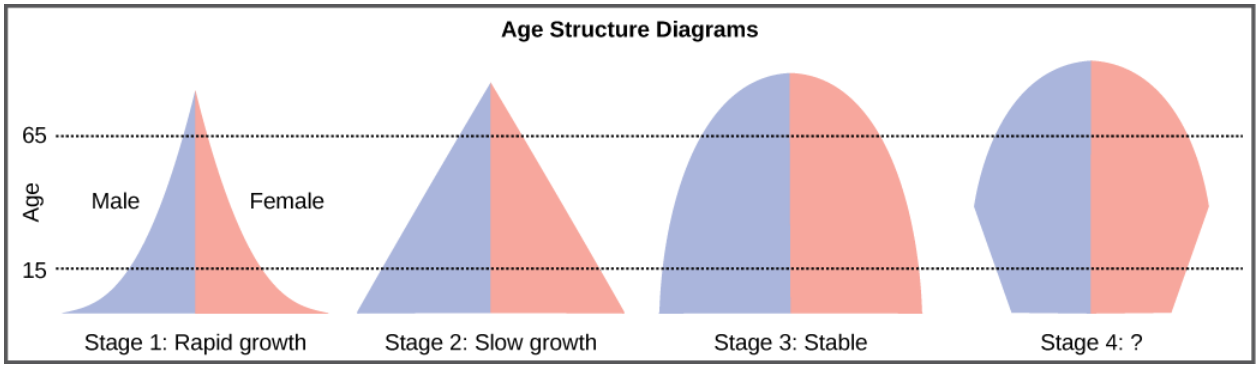


Figure **4.2.6.3**: Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing that the number of individuals per age group decreases gradually, and then increases for the older part of the population.

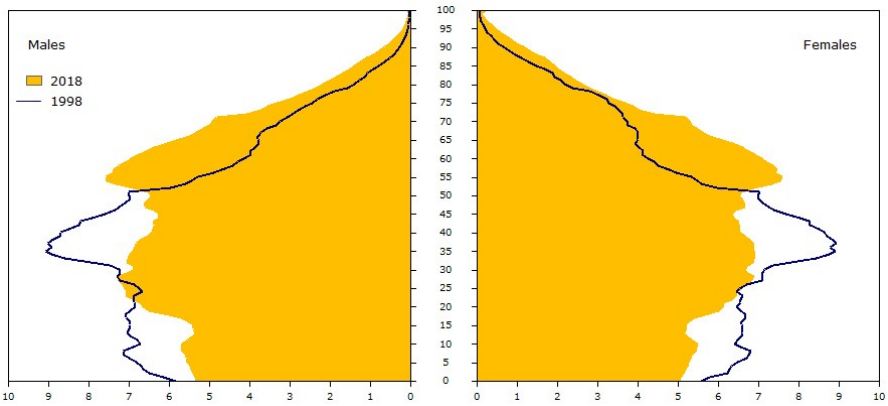


Figure **4.2.6.4**: This graph compares the age structure of the 1998 and the 2018 population of Canada at July 1st in relative value. The left side shows males and the right side shows females. The horizontal axis shows the population in relative value and the vertical axis shows age. (Copyright 2018 Statistics Canada)

Video



In this 5-minute TED-Ed video, you will explore population statistics applied to human populations and learn to interpret the population pyramid.

Question after watching: Now that you have learned more about how to interpret a population pyramid, explain what is happening in a Stage 4 structure diagram. Which is the diagram portrayed in Figure 4.2.6.3 does Canada's population fit?

Optional Activity 4.2.6.2

Figure **4.2.6.3**: Age structure diagrams for rapidly growing, slow growing and stable populations are shown in stages 1 through 3. What type of population change do you think stage 4 represents?

Answer

Stage 4 represents a population that is decreasing.

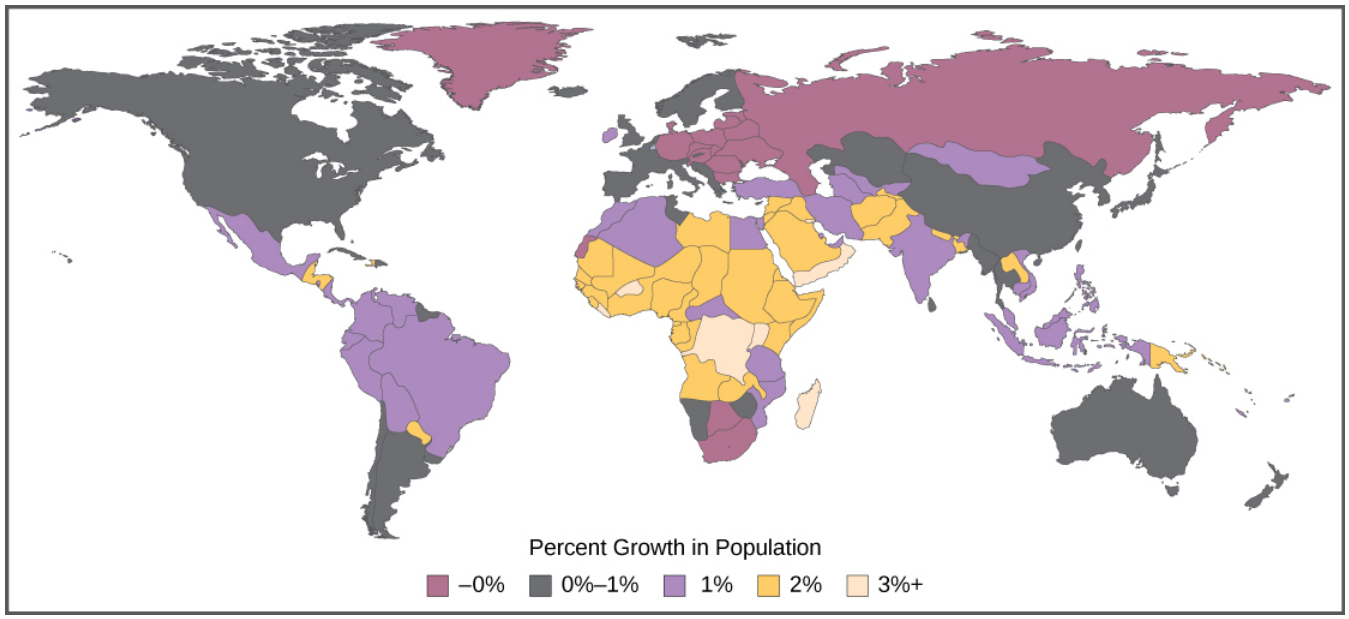


Figure **4.2.6.5**: The percent growth rate of population in different countries is shown. Notice that the highest growth is occurring in less economically developed countries within Africa and Asia.

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."[1] 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. In turn, the planet may be able to support larger numbers of humans that live with less of a collective **ecological footprint**. However, more and more individuals around the world have adopted consumerist lifestyles, and the Earth may not be able to support as many humans as it once might have been able to due to resource depletion, pollution, etc.

Video



In this 11-minute video, you will explore in more depth human population growth.
Questions after watching: Water and oil are listed as essential resources for humans, over which populations fight. Would you agree that each of these is an essential resource for human populations; that they have the potential to limit population growth? Why?

In spite of population control policies in some countries, nearly all of which have now been phased out, the human population continues to grow. At some point, food supplies may be increasingly scarce because of the subsequent need to produce more and more food to feed our population, even more challenging with the crisis of climate change. 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 emissions of greenhouse gases like 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 (Unit 5.3) has become a hotly debated socio-political issue in some developed countries. Thus, we enter the future with considerable uncertainty about our ability to curb human population growth and protect our environment.

Video



In this 10-minute video, you will learn how population geographers view human population growth.
Question after watching: In this video, you learned that many countries are encouraging populations to increase their birth rate, which is at odds with some of the data about humans having exceeded our carrying capacity on this planet. What is driving these seemingly contradictory messages?

Optional Activity **4.2.6.3**

Predict and explain the effects of the 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.

Answer

a. Biodiversity will decline as human population increases because of habitat loss, increased pollution, and climate change.

Video



In this 4.5-minute video, you will continue to explore population dynamics. You will learn about birth and death rates and how they impact the population as a whole.

Questions after watching: This video mentions that the growth rate = births - deaths. What is another factor that can impact growth rates? Why is this factor particularly important in Canada?

Footnotes

1. 1 Paul R. Erlich, prologue to *The Population Bomb*, (1968; repr., New York: Ballantine, 1970).

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SECTION OVERVIEW

4.3: Community Ecology

Learning Objectives

- Discuss the predator-prey cycle
- Discuss the many levels of interaction such as predation, herbivory, competition, and symbiosis between living organisms within a population, within a community, and within an ecosystem
- Predict patterns of succession following natural and anthropogenic disturbance

Video



This 11.5-minute video summarizes much of the content of Unit 4.3

Question after watching: What are some of the strategies provided in the video that organisms use to reduce competition?

4.3.1: Introduction to Community Ecology

4.3.2: Antagonistic Interactions

4.3.3: Symbiotic Interactions

4.3.4: Ecological Succession

4.3.5: Community Structure and Dynamics

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Unit 4.3.1 - Introduction to Community Ecology

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 30 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.3.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Develop an appreciation of the interconnected nature of ecological communities
- Organize species interactions based on their impacts on the species involved

Introduction to Species Interactions

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: multiple 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. Below, some of the interactions in these communities are introduced.

Video



Learn about ecological communities in this 6-minute video.
Question after watching: In BC, old-growth and second-growth forests are often discussed. How would these correspond to the concepts of succession mentioned in this video? Which do you think is likely to have the highest level of biodiversity?

The interactions among populations of different species play a major role in regulating population growth and abundance. A **species interaction** is an effect that a pair of organisms living together in a community have on each other as seen in Figure **4.3.1.1**. Interactions range from mutualism, which benefits both species involved, to competition (Figure **4.3.1.2**), which harms both species involved. Interactions can be indirect, through intermediaries such as shared resources or common enemies. All of these interactions can be organized by the effects the species have on each other Figure **4.3.1.1**.

Species interactions may be short-term, like pollination and predation (Figure **4.3.1.3**), or long-term; both often strongly influence the evolution of the species involved. Short-term interactions are short-lived in terms of the duration of a single interaction: a predator kills and eats a prey; a pollinator transfers pollen from one flower to another; but they are extremely durable in terms of their influence on the evolution of both partners. As a result, the partners coevolve.

Interaction	Species 1	Species 2	Example
Competition	-	-	Blue mussels (Species 1) competing with barnacles (Species 2) for space in the intertidal zone
Mutualism	+	+	Zooxanthellae (Species 1) providing coral (Species 2) with photosynthate and gaining nutrients from the coral
Antagonistic (Predation, Parasitism, Herbivory)	-	+	An antelope (Species 1) killed and consumed by a lion (Species 2)
Amensalism	-	0	Insects (Species 1) crushed by a walking elephant (Species 2)
Commensalism	+	0	Remora (Species 1) catching a ride on a large shark (Species 2)
Neutralism	0	0	Two species without niche overlap sharing a habitat

Figure **4.3.1.1**: Summary of species interactions, showing how each species is impacted by the interaction. ("-" indicates the species experiences an overall cost from the interaction, "+" indicates the species experiences an overall benefit from the interaction, "0" indicates the species does not experience either a benefit or a cost from the interaction...the interaction is neutral). Produced by N. Gownaris.



Figure **4.3.1.2**: The black walnut secretes a chemical from its roots that harms neighboring plants, an example of competition.



Figure **4.3.1.3**: Predation is a short-term interaction, in which the predator, here an osprey, kills and eats its prey.

Video



This 4-minute overview of species interactions will prepare you for the next sections of this Chapter.
Question after watching: Which of these topics do you think you will need to spend extra time to understand?

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Unit 4.3.2 - Antagonistic Interactions

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.3.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
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Learning Objectives

- Explain the predator-prey cycle
- Give examples of defenses against predation and herbivory
- Describe the competitive exclusion principle
- Identify adaptations of pathogens

Introduction to Antagonistic Interactions

Video



Recognize predation and the many ways prey organisms have developed to avoid it in this 10-minute video.
Question after watching: What is meant when Hank says that predator-prey interactions are an "evolutionary arms race"?

Predation

Predation is a biological interaction where one organism, the **predator**, kills and eats another organism, its **prey**. It is one of a family of common feeding behaviors that includes parasitism and micropredation (which usually do not kill the host) and parasitoidism (which always does, eventually). It is distinct from scavenging on dead prey, though many predators also scavenge. Predation and herbivory overlap because seed predators and destructive frugivores kill their “prey." The concept of predation is broad, defined differently in different contexts, and includes a wide variety of feeding methods

Predators are adapted and often highly specialized for hunting, with acute senses such as vision, hearing, or smell. Many predatory animals, both vertebrate and invertebrate, have sharp claws or jaws to grip, kill, and cut up their prey. Other adaptations include stealth and aggressive mimicry that improve hunting efficiency. When prey is detected, the predator assesses whether to attack it. Predators may actively search for or pursue prey (**pursuit predation**) or sit and wait for prey (**ambush predation**), often concealed, prior to attack. If the attack is successful, the predator kills the prey, removes any inedible parts like the shell or spines, and eats it.

Predation has a powerful selective effect on prey, and prey evolve anti-predator adaptations such as warning coloration, alarm and other calls, camouflage, copying (**mimicry**) of well-defended species, and defensive spines and chemicals. Sometimes predator and prey find themselves in an **evolutionary arms race**, a cycle of adaptations and counter-adaptations.

Some relationships that result in the prey's death are not generally called predation. A **parasitoid**, such as an ichneumon wasp, lays its eggs in or on its host; the eggs hatch into larvae, which eat the host, and it inevitably dies. Zoologists generally call this a form of parasitism, though conventionally parasites are thought not to kill their hosts. A predator can be defined to differ from a parasitoid in that it has many prey, captured over its lifetime, where a parasitoid's larva has just one, or at least has its food supply provisioned for it on just one occasion.

Predator-Prey Cycles

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 **4.3.2.1**). 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 the 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.

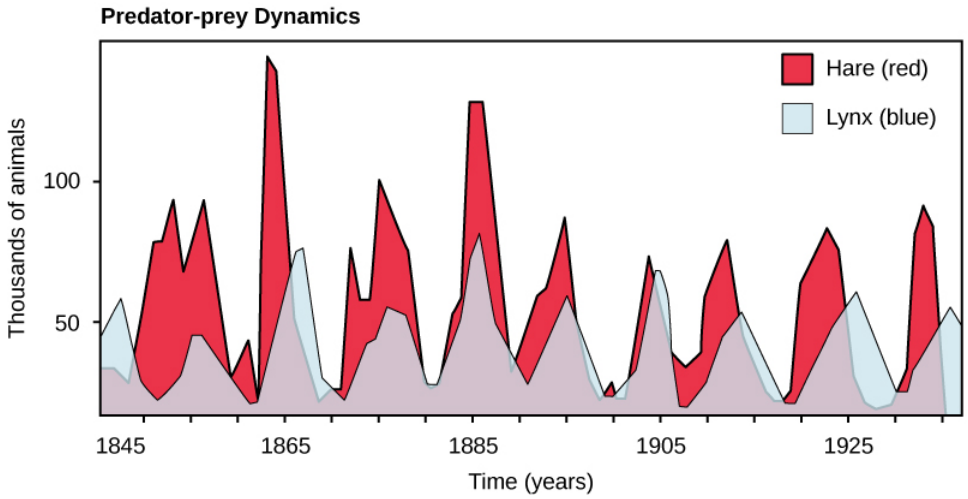


Figure **4.3.2.1**: The cycling of lynx and snowshoe hare populations in Northern Ontario is an example of predator-prey dynamics.

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 cycling, in addition to predation. One possibility is that 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 communities are studied, the more complexities are found, allowing ecologists to derive more accurate and sophisticated models of population dynamics.

? Optional Activity **4.3.2.1**

Pick from the statements below to best 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.

Answer

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.

Herbivory

Herbivory is a form of consumption in which an organism principally eats autotrophs such as plants, algae and photosynthesizing bacteria. Herbivory describes the consumption of plants by insects and other animals, and it is another interspecific relationship that affects populations. More generally, organisms that feed on autotrophs are known as **primary consumers.** Herbivory is usually limited to animals that eat plants. Fungi, bacteria, and protists that feed on living plants are usually termed plant pathogens (plant diseases), while fungi and microbes that feed on dead plants are described as saprotrophs. Flowering plants that obtain nutrition from other living plants are usually termed parasitic plants.

Two herbivore feeding strategies are **grazing** (e.g. cows) and **browsing** (e.g. moose). For a terrestrial mammal to be called a grazer, at least 90% of the forage has to be grass, and for a browser at least 90% tree leaves and twigs. An intermediate feeding strategy is called "**mixed-feeding**". In their daily need to take up energy from forage, herbivores of different body masses may be selective in choosing their food. "Selective" means that herbivores may choose their forage source depending on environmental conditions such as season or food availability, but also that they may choose high-quality (and consequently highly nutritious) forage before lower quality. The latter especially is determined by the body mass of the herbivore, with small herbivores selecting for high-quality forage, and with increasing body mass animals are less selective.

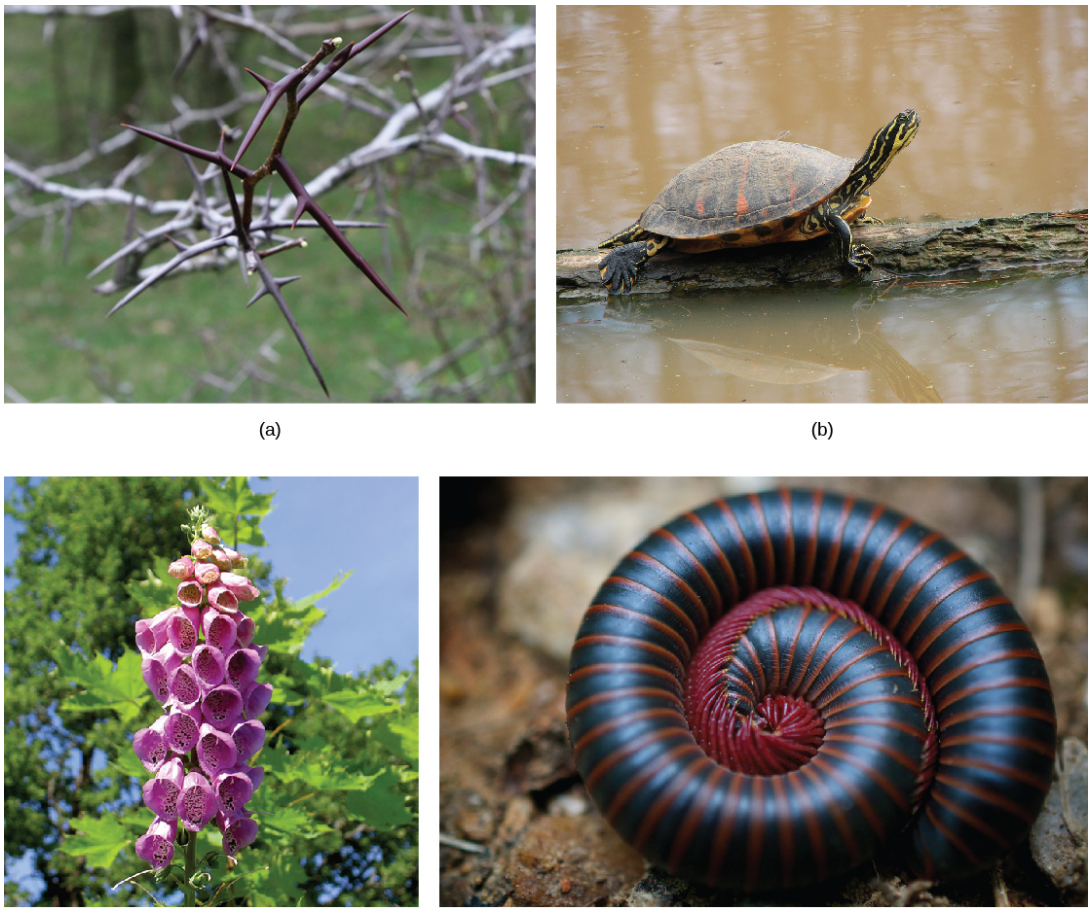
Unlike animals, most plants cannot outrun predators or use mimicry to hide from hungry animals. Coevolution and phylogenetic correlation between herbivores and plants are important aspects of the influence of herbivore and plant interactions on communities and ecosystem functioning, especially in regard to herbivorous insects. This is apparent in the adaptations plants develop to tolerate and/or defend from insect herbivory and the responses of herbivores to overcome these adaptations. 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. The evolution of antagonistic and mutualistic plant-herbivore interactions do not exclude one another and may co-occur.

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 and Chemical Defenses

Mechanical defenses, such as the presence of thorns on plants or the hard shell of 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 4.3.2.2 shows some organisms' defenses against predation and herbivory.



(a) (b)

(c) (d)

Figure **4.3.2.2**: 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)

Crypsis

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 **4.3.2.3**a). In another example, the chameleon can change its color to match its surroundings (Figure **4.3.2.3**b). Both of these are examples of **crypsis**, or avoiding detection by blending in with the background.



a b

Figure 4.3.2.3: (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)

Warning Coloration

Some species use . This type of defensive mechanism is called **aposematic coloration**, or warning coloration (Figure 4.3.2.4). 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.



(a) (b)

Figure 4.3.2.4: (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)

Mimicry

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 4.3.2.5).



a b

Figure 4.3.2.5: 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 4.3.2.6 shows a variety of foul-tasting butterflies with similar coloration.



Figure 4.3.2.6: 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.)

? Optional Activity 4.3.2.2

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 a 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.

Answer

d. Mullerian mimicry because it involves different species that both produce toxins and display similar warning coloration.

Video



Explore some of the many internal and external defenses that make plants less appealing to herbivores in this 6-minute video. Question after watching: What are the different physical barriers that plants use to repel microscopic bacteria, fungi, and herbivores?

Competition

Competition can be defined as an interaction between organisms or species, in which both require a resource that is in limited supply (such as food, water, or territory). Competition lowers the fitness of both organisms involved, since the presence of one of the organisms always reduces the amount of the resource available to the other. Competition among members of the same species is known as intraspecific competition, while competition between individuals of different species is known as **interspecific competition**.

According to the **competitive exclusion principle**, no two species with the same ecological niche can coexist, and the species less suited to compete for resources should either adapt or die out. Competition within and between species for resources plays a critical role in natural selection. Ecologists model competition using the Lotka-Volterra competition model, and use this model to predict the conditions under which two species will coexist or one species outcompetes the other.

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 **4.3.2.7**, with two protozoan species, *Paramecium aurelia* and *Paramecium caudatum*. In this famous experiment by Gause (1934), 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.

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.

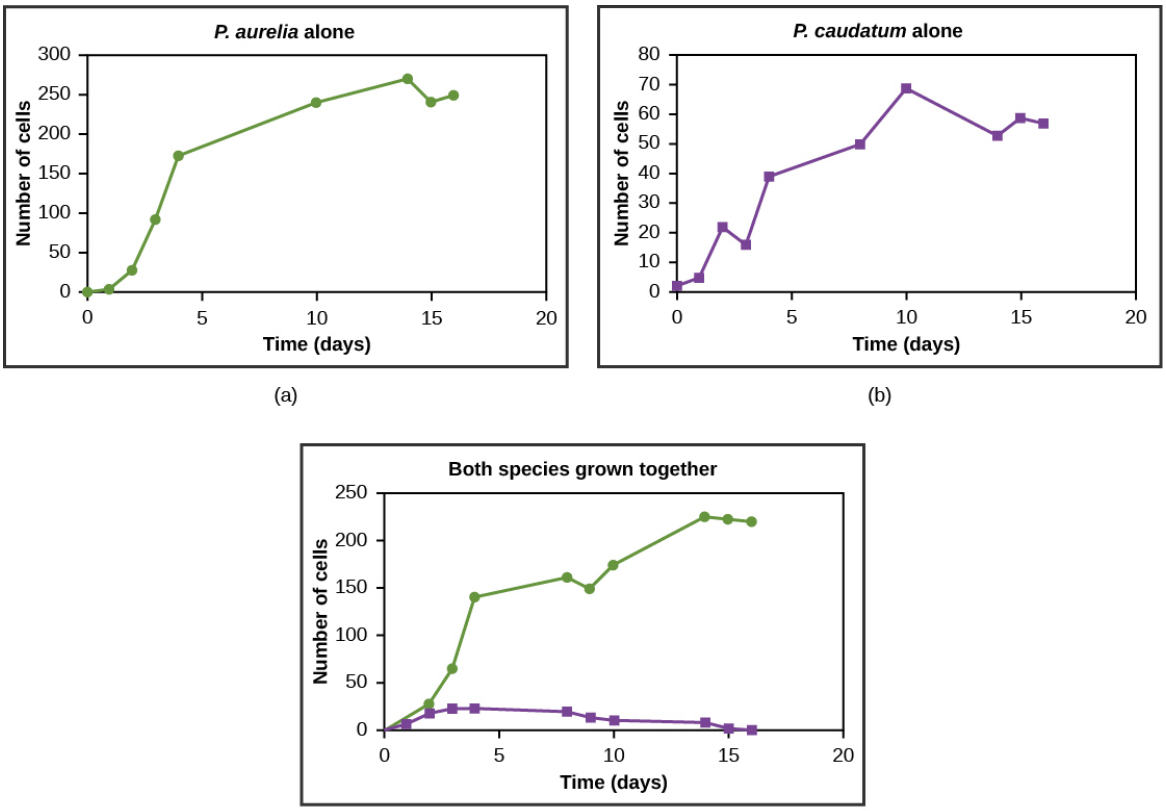


Figure 4.3.2.7: Paramecium aurelia and *Paramecium caudatum* grow well individually, but when they compete for the same resources, the *P. aurelia* outcompetes the *P. caudatum*.

In the study of community ecology, competition within and between members of a species is an important biological interaction. Competition is one of many interacting biotic and abiotic factors that affect community structure, species diversity, and population dynamics (shifts in a population over time). Competition within and between species for resources is important in natural selection.

? Optional Activity 4.3.2.3

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.

Answer

c. Two species can coexist in the same habitat as long as they do not share the same resources.

Pathogens and Infection

All organisms, from bacteria to trees to humans are capable of getting infections. An **infection** is the invasion of an organism's body tissues by disease-causing agents (**pathogens**), the pathogen's multiplication, and the reaction of host tissues to the pathogens and the toxins the pathogens produce. An **infectious disease**, also known as **transmissible disease** or **communicable disease**, is an illness resulting from an infection.

Infections can be caused by a wide range of pathogens, most prominently bacteria and viruses. Hosts can fight infections using an immune system.

There is a general chain of events that applies to infections, sometimes called the **chain of infection** (Figure 4.3.2.8). The chain of events involves several steps – which include the infectious agent, reservoir, entering a susceptible host, exit, and transmission to new hosts. Each link must be present in chronological order for an infection to develop. Understanding these steps helps health-care workers target the infection and prevent it from occurring in the first place.

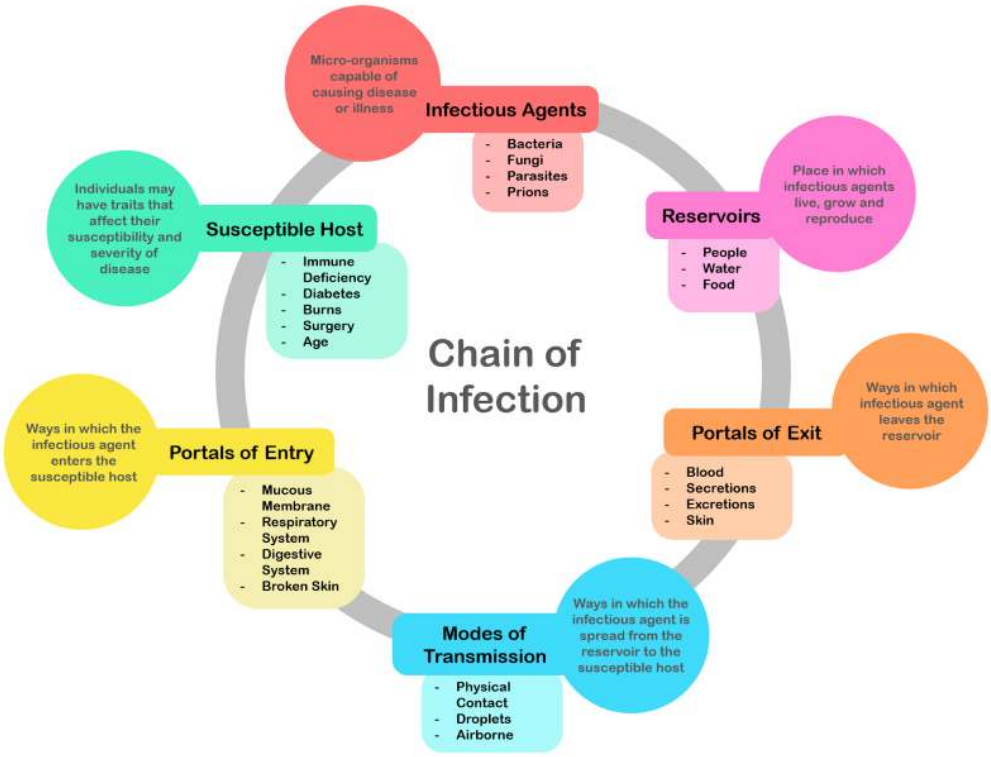


Figure 4.3.2.8: The chain of events that lead to infection.

Disease can arise if the host's protective immune mechanisms are compromised and the organism inflicts damage on the host. Microorganisms can cause tissue damage by releasing a variety of toxins or destructive enzymes. For example, *Clostridium tetani* release a toxin that paralyzes muscles, and *Staphylococcus sp.* releases toxins that produce shock and sepsis. Not all infectious agents cause disease in all hosts. For example, less than 5% of individuals infected with the polio virus develop the disease. On the other hand, some infectious agents are highly virulent. The prion-causing mad cow disease and Creutzfeldt–Jakob disease invariably kills all animals and people that are infected.

Persistent infections occur because the body is unable to clear the organism after the initial infection. Persistent infections are characterized by the continual presence of the infectious organism, often as latent infection with occasional recurrent relapses of active infection. There are some viruses that can maintain a persistent infection by infecting different cells of the body. Some viruses once acquired never leave the body. A typical example is the *Herpes zoaster* virus (that causes chickenpox and shingles), which tends to hide in nerves and become reactivated when specific circumstances arise.

Reference

Gause, G.F. 1934. Experimental analysis of vito volterra's mathematical theory of the struggle for existence. *Science*, 79(2036), 16-17. https://doi.org/10.1126/science.79.2036.16.b

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Unit 4.3.3 - Symbiotic Interactions

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 30 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
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Learning Objectives

- Describe the types of symbiotic relationships between species

Introduction

Symbiotic relationships, or **symbioses** (plural), are close interactions between individuals of different species over an extended period of time that 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.

Video



In this 10-minute video, learn how evolutionary biologists understand symbiosis, all its different forms, and why it matters. Question after watching: what other examples of commensalism, mutualism, and parasitism can you think of?

Commensalism

A **commensal relationship** occurs when one species benefits from a close prolonged interaction, while the other neither benefits nor is harmed. Birds nesting in trees provide an example of a commensal relationship (Figure **4.3.3.1**). 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. Many potential commensal relationships are difficult to identify because it is difficult to prove that one partner does not derive some benefit from the presence of the other.



Figure 4.3.3.1: The southern masked-weaver 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

Mutualism occurs when two species benefit from their interaction. For example, termites have a mutualistic relationship with protists that live in the insects' gut (Figure 4.3.3.2a). The termite benefits from the ability of the protists to digest cellulose. The termite itself cannot do this: without the protozoa, it would not be able to obtain energy from its food (cellulose from the wood it chews and eats). The protozoa benefit by having a protective environment and a constant supply of food from the wood-chewing actions of the termite. In turn, the protists benefit from the enzymes provided by their bacterial endosymbionts, while the bacteria benefit from a doubly protective environment and a constant source of nutrients from two hosts.

Lichen are a mutualistic relationship between a fungus and photosynthetic algae or cyanobacteria (Figure 4.3.3.2b). 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. The algae of lichens can live independently given the right environment, but many of the fungal partners are unable to live on their own.



(a) (b)

Figure 4.3.3.2: (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 in close association. (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 (Figure **4.3.3.3**). 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.



Figure **4.3.3.3**: A fish parasite, the isopod *Cymothoa exigua*, replacing the tongue of a Lithognathus

Like predation, **parasitism** is a type of consumer-resource interaction, but unlike predators, parasites (with the exception of parasitoids) are typically much smaller than their hosts, do not kill them, and often live in or on their hosts for an extended period. Parasites of animals are highly specialized and reproduce at a faster rate than their hosts. Classic examples include interactions between vertebrate hosts and tapeworms, flukes, the malaria-causing *Plasmodium* species, and fleas.

Parasites reduce host fitness by general or specialized pathology, from parasitic castration to modification of host behavior. Parasites increase their own fitness by exploiting hosts for resources necessary for their survival, in particular by feeding on them and by using intermediate (secondary) hosts to assist in their transmission from one definitive (primary) host to another. Although parasitism is often unambiguous, it is part of a spectrum of interactions between species, grading via parasitoidism into predation, through evolution into mutualism, and in some fungi, shading into being saprophytic.

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 **4.3.3.4**). 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 15m long by adding segments. The parasite moves from species to species in a cycle, making two hosts necessary to complete its life cycle.

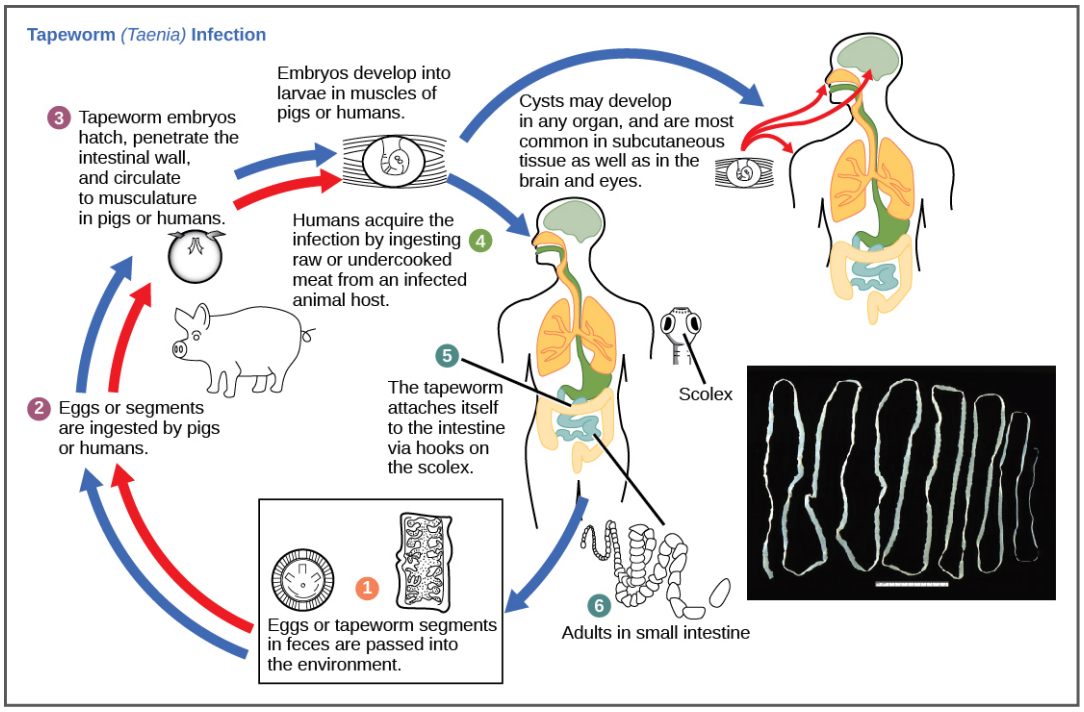


Figure **4.3.3.4**: This diagram shows the life cycle of a pork tapeworm (*Taenia solium*), a human worm parasite. (credit: modification of work by CDC)

? Optional Activity 4.3.3.1

A symbiotic relationship where both of the coexisting species benefit from the interaction is called _____.

a. commensalism
b. parasitism
c. mutualism
d. communism

Answer

c. mutualism

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Unit 4.3.4 - Ecological Succession

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 45 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
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Learning Objectives

- Describe community structure and succession

Ecological **succession** is the process of change in the species structure of an ecological community over time. It is a process by which an ecological community undergoes more or less orderly and predictable changes following a disturbance or the initial colonization of a new habitat. Succession may be initiated either by formation of new, unoccupied habitat, such as from a lava flow or a severe landslide, or by some form of disturbance of a community, such as from a fire, severe windthrow, or logging. Succession that begins in new habitats, uninfluenced by pre-existing communities is called primary succession, whereas succession that follows disruption of a pre-existing community is called secondary succession.

The trajectory of successional change can be influenced by site conditions by the type of events initiating succession, the interactions of the species present, and/or more stochastic factors such as the availability of larvae or weather conditions at the time of disturbance. Some of these factors contribute to the predictability of succession dynamics.

Community Dynamics

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.

Ecological Disturbance

Changes in community structure and composition over time 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. 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. Thus, disturbance can initiate successional change.

Species that are well adapted for exploiting disturbance sites are referred to as **pioneers** or **early successional species**. In forests, these shade-intolerant species are able to photosynthesize at high rates and, as a result, grow quickly. Their fast growth is usually balanced by short life spans. Furthermore, although these species often dominate immediately following a disturbance, they are unable to compete with shade-tolerant species later on and are replaced by these species through succession. However these shifts may not reflect the progressive entry to the community of the taller long-lived forms, but instead, the gradual emergence and dominance of species that may have been present, but inconspicuous directly after the disturbance. Disturbances have also been shown to be important facilitators of non-native plant invasions.

While plants must deal directly with disturbances because of their lack of mobility, many animals are mobile and thus are not as immediately affected by disturbance. For example, some animals could successfully evade the initial destruction of a forest fire, but can later return to the burned area and thrive on new growth on the forest floor. Disturbed communities (such as a forest after a fire) often support a wider variety of plants compared to pre-disturbance vegetation. The plants in turn support a variety of wildlife, temporarily increasing biological diversity in the forest.

British Columbia Connection

An example familiar to many people who drive on the side of a highway in BC is fireweed (Figure **4.3.4.1**). Fireweed, a fast grower, is often one of the first plants to populate the area after the habitat is disturbed to put down the road. As a pioneering species, this vibrantly colored plant with bright flowers can be seen before most other species. Other species eventually move in as new soil is made.



Figure **4.3.4.1**: Fireweed (*Chamerion angustifolium*).

Intermediate Disturbance Hypothesis

The **intermediate disturbance hypothesis (IDH)** suggests that local species diversity is maximized when ecological disturbances are neither too rare nor too frequent (Figure **4.3.4.2**). At low levels of disturbance, more competitive organisms will push subordinate species to extinction and dominate the ecosystem. At high levels of disturbance, due to frequent forest fires or human impacts like deforestation, all species are at risk of going extinct. According to IDH, at intermediate levels of disturbance, diversity is thus maximized because species that thrive at both early and late successional stages can coexist. IDH is a nonequilibrium model used to describe the relationship between disturbance and species diversity.

IDH is based on the following premises:

1. ecological disturbances have major effects on **species richness** (the total number of different species) within the area of disturbance,
2. interspecific competition results from one species driving a competitor to extinction and becoming dominant in the ecosystem, and
3. moderate ecological scale disturbances prevent interspecific competition.

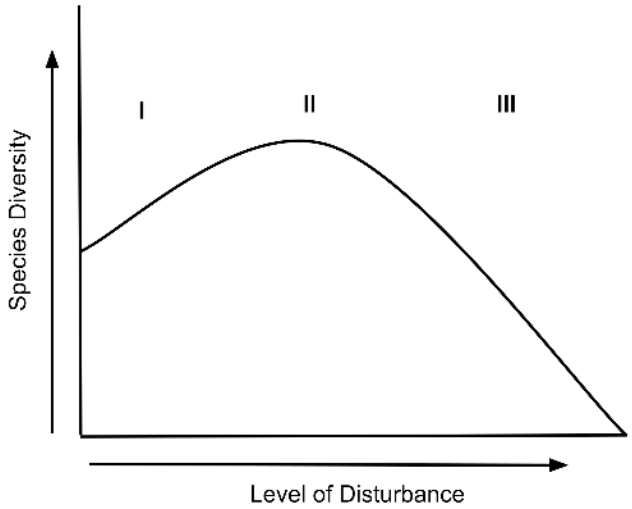


Figure 4.3.4.2: I. at low levels of ecological disturbance species richness decreases as competitive exclusion increases, II. at intermediate levels of disturbance, diversity is maximized because species that thrive at both early and late successional stages can coexist, III. at high levels of disturbance species richness is decreased due to an increase in species movement. (CC-SA-BY Wikimedia)

Disturbances act to disrupt stable ecosystems and clear species' habitats. As a result, disturbances lead to species movement into the newly cleared area (secondary succession). Once an area is cleared there is a progressive increase in species richness and competition between species takes place. Once the conditions that create a disturbance are gone, and competition between species in the formerly disturbed area increases, species richness decreases as competitive exclusion increases.

Primary Succession and Pioneer Species

Primary succession occurs when new substrate 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 are added each year. First, weathering and other natural forces break down the substrate enough for the establishment of pioneer species such as hearty plants and lichens with few soil requirements (Figure 4.3.4.3). These species help to further break down the mineral-rich lava into the 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.

In primary succession, pioneer species like lichen, algae, and fungi as well as abiotic factors like wind and water start to develop soil and initiate other important mechanisms for greater diversity to flourish. These pioneer species are then replaced by plants better adapted to less harsh conditions, these plants include vascular plants like grasses and some shrubs that are able to live in thin soils that are often mineral-based. Water and nutrient levels increase with the amount of succession exhibited.

The early stages of primary succession are dominated by species with small propagules (seed and spores), which can be dispersed long distances. The early colonizers—often algae, fungi, and lichens—stabilize the substrate. Nitrogen supplies are limited in new soils, and nitrogen-fixing species tend to play an important role early in primary succession.



Figure **4.3.4.3**: 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 **4.3.4.4**). 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.

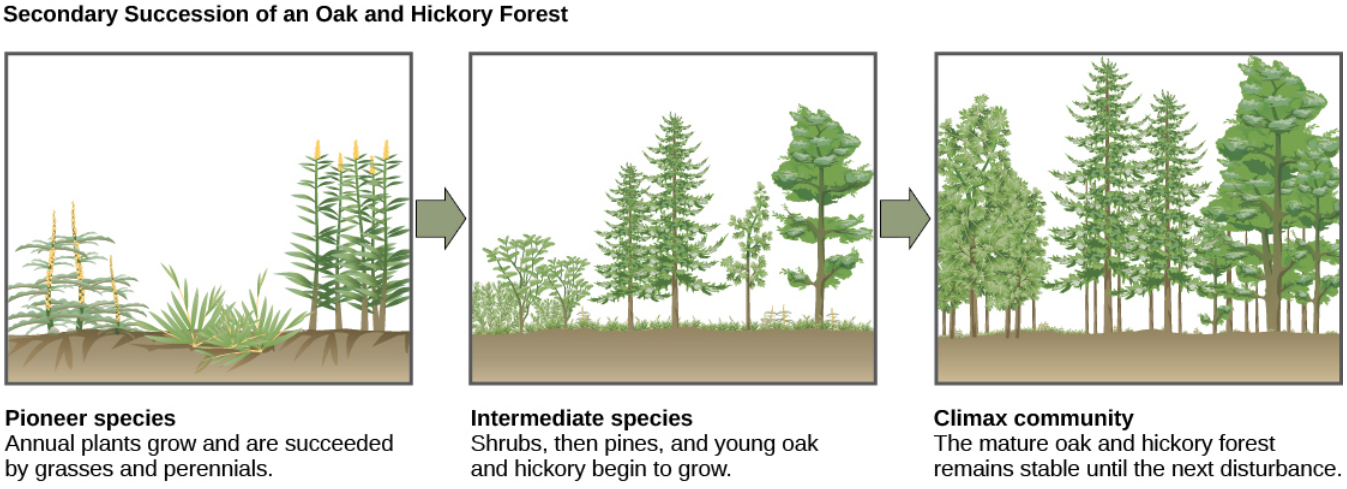


Figure **4.3.4.4**: Secondary succession is shown in an oak and hickory forest after a forest fire.

Climatic factors may be very important, but on a much longer time-scales than any other. Changes in temperature and rainfall patterns will promote changes in communities. As the climate warmed at the end of each ice age, great successional changes took place. The tundra vegetation and bare glacial till deposits underwent succession to mixed deciduous forest. The greenhouse effect resulting in increased temperatures is likely to bring profound community changes in the next century (Unit 5.3.3). Geological and climatic catastrophes such as volcanic eruptions, earthquakes, avalanches, meteors, floods, fires, and high winds also bring successional changes.

In general, communities in early succession will be dominated by fast-growing, well-dispersed species (opportunist, fugitive, or r-selected life histories). As succession proceeds, these species will tend to be replaced by more competitive (K-selected) species (See Unit 4.2.3). Trends in ecosystem and community properties in succession have been suggested, but few appear to be general. For example, species diversity almost necessarily increases during early succession as new species arrive, but may decline in later succession as competition eliminates opportunistic species and leads to dominance by locally superior competitors.

Dynamics in secondary succession are strongly influenced by pre-disturbance conditions, including soil development, seed banks, remaining organic matter, and residual living organisms. Because of residual fertility and pre-existing organisms, community change in early stages of secondary succession can be relatively rapid. Secondary succession is much more commonly observed and studied than primary succession. Particularly common types of secondary succession include responses to natural disturbances such as fire, flood, and severe winds, and to human-caused disturbances such as logging and agriculture.

Unlike in primary succession, the species that dominate secondary succession, are usually present from the start of the process. In some systems, the successional pathways are fairly consistent, and thus, are easy to predict. In others, there are many possible pathways, potentially leading to **alternate stable states**.

Climax Communities?

Ecological succession was formerly seen as having a stable end-stage called the **climax**, sometimes referred to as the 'potential vegetation' of a site, and shaped primarily by the local climate Figure 4.3.4.5. This idea has been largely abandoned by modern ecologists in favor of non-equilibrium ideas of ecosystem dynamics. Most natural ecosystems experience disturbance at a rate that makes a "climax" community unattainable. Climate change often occurs at a rate and frequency sufficient to prevent arrival at a climax state. Additions to available species pools through range expansions and introductions can also continually reshape communities.

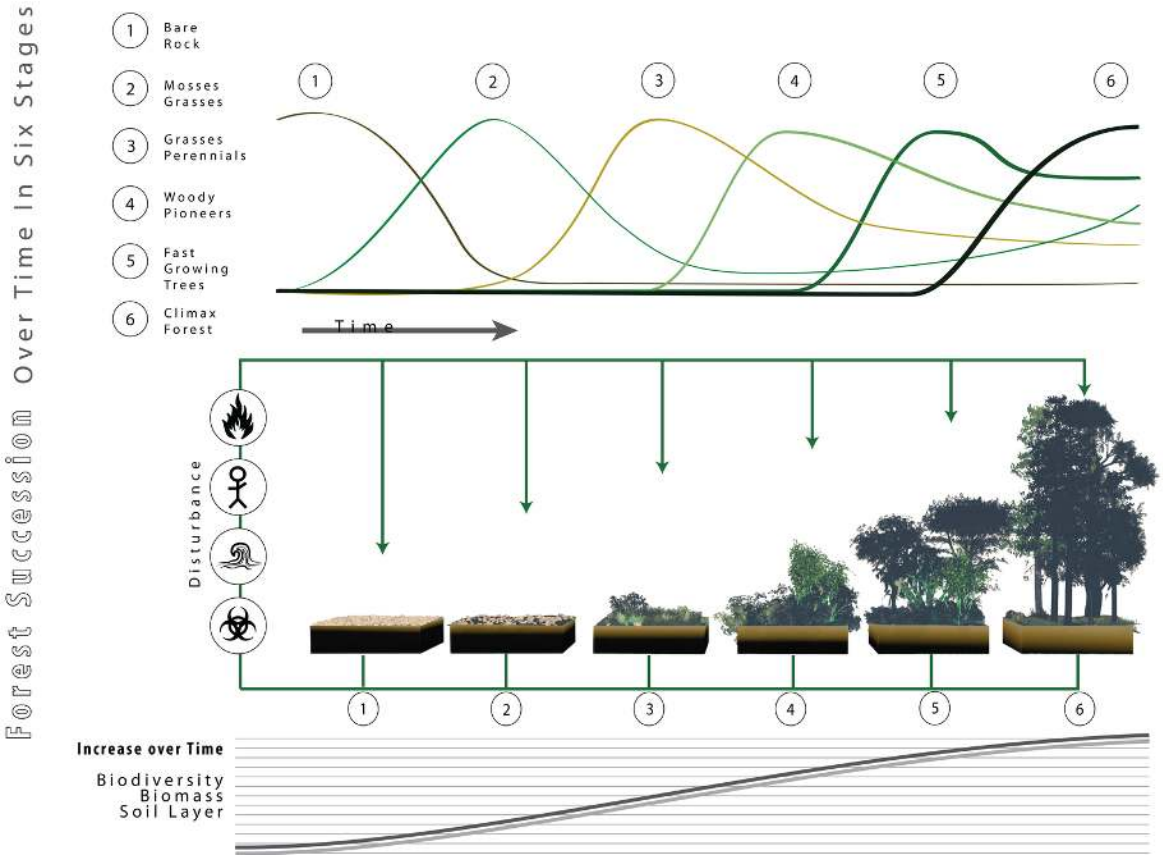


Figure 4.3.4.5: Trajectory of forest secondary succession following an intense disturbance, resulting in nearly no original biomass, to a mature forest state. Biodiversity, biomass, and soil depth all increase with time, and community composition changes. (CC-SA-BY Wikimedia)

Optional Activity 4.3.4.1

The first species to live on new land, such as that formed from volcanic lava, are called _____.

a. climax community
b. keystone species
c. foundation species
d. pioneer species

Answer

d. pioneer species

Video



Change is good for communities, as you will see in this 10-minute video.
Question after watching: What are two examples given in the video of how disturbance can lead to higher biodiversity?

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Unit 4.3.5 - Community Structure and Dynamics

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 45 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
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Learning Objectives

- Develop an appreciation of the interconnected nature of ecological communities
- Organize species interactions based on their impacts on the species involved
- Understand some of the factors that structure ecological communities

Overview of Community Structure and Dynamics

Communities are complex entities that can be characterized by their **community structure** (the types and numbers of species present) and **community dynamics** (how communities change over time). Understanding community structure and community dynamics enables 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. For example, kelp, a type of brown algae, is a foundation species, forming the basis of the kelp forests off the coast of British Columbia.

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 **4.3.5.1**). Corals themselves are not photosynthetic, but harbor symbionts within their body tissues (dinoflagellates called **zooxanthellae**) that perform photosynthesis; this is another example of 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 **4.3.5.1**: Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

British Columbia Connection

An example of foundation species in British Columbia would be the sponge reefs of the Strait of Georgia and Howe Sound. These unique ecosystems are based on the foundation species of glass sponges, which live at the bottom of the sea and create habitats for other marine creatures such as prawns, rockfish, crabs, salmon and halibut, and sharks. In a way, they function like coral reefs in shallow tropical seas but occur in deeper areas of the ocean.



Figure 4.3.5.1: Glass sponges. BC Gov Photos CC BY-NC-ND 2.0

You can read more about these rare and unique ecosystems of BC here:

- Parks Canada: https://www.dfo-mpo.gc.ca/oceans/ceccsr-cerceef/closures-fermetures-eng.html
- CPAWS: https://cpawsbc.org/glass-sponge-reefs/
- The Royal BC Museum: https://learning.royalbcmuseum.bc.ca/pathways/glass-sponges/

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 Pacific Coast, is a keystone species (Figure 4.3.5.2). 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 **4.3.5.2**: The *Pisaster ochraceus* sea star is a keystone species. (credit: Jerry Kirkhart)

Video



Find out what gray wolves, elephants, and parrotfish have in common in this 5-minute video.
Question after watching: What is an example of a keystone species in British Columbia?

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 North America, as shown in Figure **4.3.5.3** below. Whether enjoying a forest hike, taking a summer boat trip, or simply walking down an urban street, you have likely encountered an invasive species.

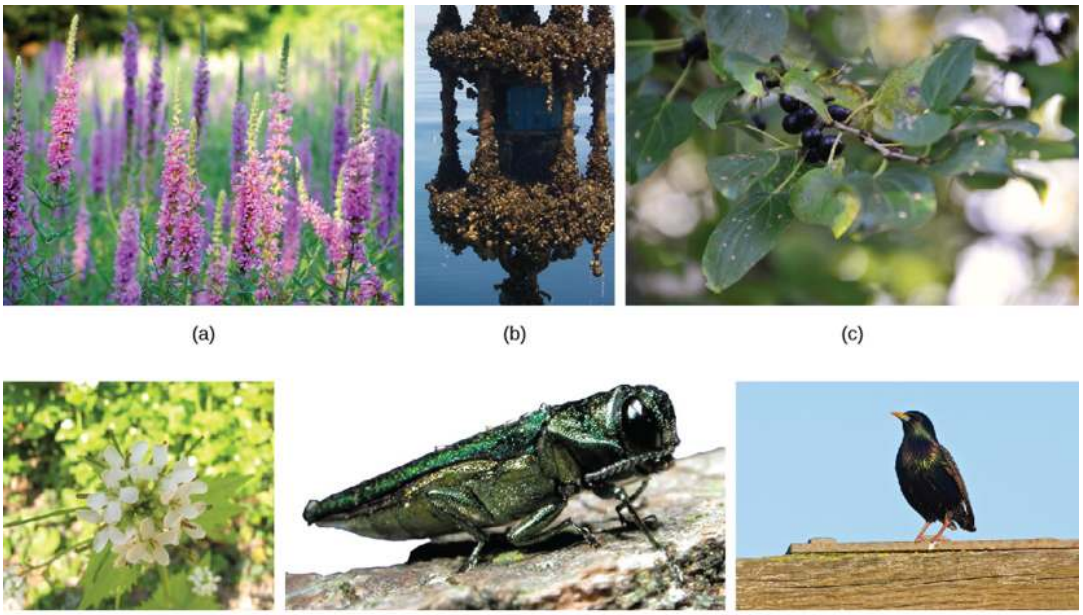


Figure **4.3.5.3**: In North America, invasive species like (a) purple loosestrife (*Lythrum salicaria*) and the (b) zebra mussel (*Dreissena polymorpha*) threaten certain aquatic ecosystems. Some forests are threatened by the spread of (c) common buckthorn (*Rhamnus cathartica*), (d) garlic mustard (*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 Great Lakes 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).

Video



Identify the problems that invasive species pose to ecosystems in this 5-minute video
Question after watching: Explain the role that limiting factors play in keeping population sizes in check. What invasive species exist in British Columbia?

Biodiversity, Species Richness, and Relative Species Abundance

Biodiversity describes a community's biological complexity: it is measured in many ways, the simplest of which is by the number of different species (**species richness**) in a particular area and their relative abundance. Species richness varies across the globe. 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 (Figure 4.3.5.4). 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 which inspired Darwin. Foundation species often have the highest relative abundance or biomass of all species in a community. Much more on biodiversity is discussed in Unit 5.2.

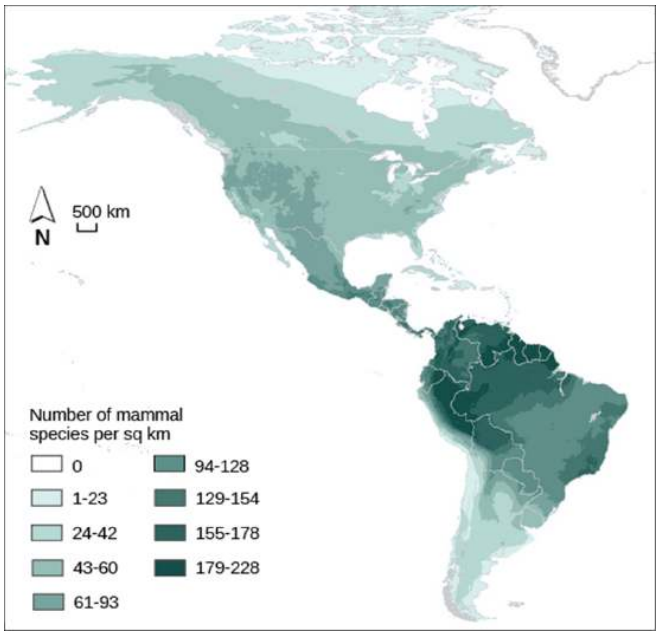


Figure 4.3.5.4:
The greatest species richness for mammals in North and South America is associated with the equatorial latitudes. (credit: modification of work by NASA, CIESIN, Columbia University)

Video

Review some of the hypotheses on why there is more species diversity near the equator in this 8-minute video.
Question after watching: Which of these hypotheses would you like to explore further?

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SECTION OVERVIEW

4.4: Ecosystems and the Biosphere

Learning Objectives

- Discuss how life and the planet exist as a system
- Outline the flow of energy through an ecosystem using trophic dynamics theory
- Describe the basic ecosystem types
- Explain the methods that ecologists use to study ecosystem structure and dynamics
- Identify the different methods of ecosystem modeling

Video



In this 10-minute video, Hank will provide an overview of ecosystem ecology and its various subfields.
Question after watching: After watching this video, make a list of questions that you have about ecosystems.

4.4.1: Ecology of Ecosystems

4.4.2: Energy Flow through Ecosystems

4.4.3: Terrestrial Biomes

4.4.4: Aquatic Biomes

4.4.5: Biogeochemical Cycles

4.4.6: Biogeography

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Unit 4.4.1 - Ecology of Ecosystems

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 30 minutes.
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Learning Objectives

- Describe the basic types of ecosystems on Earth
- Explain the methods that ecologists use to study ecosystem structure and dynamics
- Identify the different methods of ecosystem modeling
- Differentiate between food chains and food webs and recognize the importance of each

Introduction to Ecosystems

Video



Learn about feedback loops in this 5-minute TED-Ed video.
Question after watching: Describe at least one other example of positive feedback, and one example of negative feedback in the world (not necessarily in ecology).

Life in an ecosystem is often about competition for limited resources, a characteristic of the theory of natural selection. Competition in communities (all living things within specific habitats) is observed both within species and among different species. The resources for which organisms compete include organic material from living or previously living organisms, sunlight, and mineral nutrients, which provide the energy for living processes and the matter to make up organisms' physical structures. Other critical factors influencing community dynamics are the components of its physical and geographic environment: a habitat's latitude, amount of rainfall, topography (elevation), and available species. These are all important environmental variables that determine which organisms can exist within a particular area.

As was defined in Unit 4.2, an ecosystem is a community of living organisms and their interactions with their abiotic (non-living) environment. Ecosystems can be small, such as the tide pools found near the rocky shores of many oceans (such as on the coast of British Columbia), or large, such as the Amazon Rainforest in Brazil (Figure **4.4.1.1**).



(a) (b)

Figure 4.4.1.1: A (a) tidal pool ecosystem in Matinicus Island in Maine, USA is a small ecosystem, while the (b) Amazon Rainforest in Brazil is a large ecosystem. (credit a: modification of work by “takomabibelot”/Flickr; credit b: modification of work by Ivan Mlinaric)

There are three broad categories of ecosystems based on their general environment: freshwater, marine (ocean), and terrestrial. Within these broad categories are individual ecosystem types based on the organisms present and the type of environmental habitat.

Ocean ecosystems are the most common, comprising 75 percent of the Earth's surface and consisting of three basic types: shallow ocean, open ocean surface water, and deep ocean (the low-depth areas of the deep oceans). The shallow ocean ecosystems include extremely biodiverse coral reef ecosystems, and the open ocean surface is known for its large numbers of plankton and krill (small crustaceans) that support it. These two environments are especially important to producers worldwide as the phytoplankton that live there (protist and bacterial producers) are responsible for 40 percent of all photosynthesis on Earth. Although not as diverse as the other two, deep ocean ecosystems contain a wide variety of marine organisms. Ecosystems exist even at the bottom of the ocean where light is unable to penetrate through the water such as sponge reefs in the Georgia Strait and deep-sea hydrothermal vents in the Juan de Fuca Ridge.

Freshwater ecosystems are the rarest, occurring on only 1.8 percent of the Earth's surface. These are made of lakes, rivers, streams, and springs; they are quite diverse and support a variety of fish, amphibians, reptiles, insects, phytoplankton, fungi, and bacteria.

Terrestrial ecosystems, also known for their diversity, are grouped into large categories, such as tropical rain forests, savannas, deserts, coniferous forests, deciduous forests, and tundra. Grouping these ecosystems into just a few categories obscures the great diversity of the individual ecosystems within them. For example, there is great variation in desert vegetation: the saguaro cacti and other plant life in the Sonoran Desert, in the United States, are relatively abundant compared to the desolate rocky desert of Boa Vista, an island off the coast of Western Africa (Figure 4.4.1.2).



(a)



(b)

Figure **4.4.1.2**: Desert ecosystems, like all ecosystems, can vary greatly. The desert in (a) Saguaro National Park, Arizona, has abundant plant life, while the rocky desert of (b) Boa Vista island, Cape Verde, Africa, is devoid of most plant life. (credit a: modification of work by Jay Galvin; credit b: modification of work by Ingo Wölbern)

Ecosystems are complex with many interacting parts. They are routinely exposed to various disturbances, or changes, in the environment that may affect their compositions. For example, yearly variations in rainfall and temperature and the slow processes of plant regrowth in response. Many of these disturbances are a result of natural processes. For example, when lightning causes a forest fire and destroys part of a forest ecosystem, the ground is eventually populated by grasses, then by bushes and shrubs, and later by mature trees, restoring the forest to its former state. The impact of environmental disturbances caused by human activities is as important as the changes wrought by natural processes. Human agricultural practices, air pollution, acid rain, global deforestation, overfishing, eutrophication, oil spills, and illegal dumping on land and into the ocean are all issues of concern to conservationists (Unit 5.2.3).

Equilibrium is the steady state of an ecosystem where all organisms are in balance with their environment and with each other. In ecology, two parameters are used to measure changes in ecosystems: resistance and resilience. The ability of an ecosystem to remain at equilibrium in spite of disturbances is called **resistance**. The speed at which an ecosystem recovers equilibrium after being disturbed is called its **resilience**. Ecosystem resistance and resilience are especially important when considering the impacts of humans. The nature of an ecosystem may change to such a degree that it can lose its resilience entirely. This process can lead to the complete destruction or irreversible altering of the ecosystem.

Evolution Connection: Three-spined Stickleback

It is well established by the theory of natural selection that changes in the environment play a major role in the evolution of species within an ecosystem. However, little is known about how the evolution of species within an ecosystem can alter the ecosystem environment. In 2009, Dr. Luke Harmon, from the University of Idaho in Moscow, published a paper that, for the first time, showed that the evolution of organisms into subspecies can have direct effects on their ecosystem environment.[1]

The three-spined stickleback (*Gasterosteus aculeatus*) is a freshwater fish that evolved from a saltwater fish to live in freshwater lakes about 10,000 years ago, which is considered a recent development in evolutionary time (Figure **4.4.1.3**). Over the last 10,000 years, these freshwater fish then became isolated from each other in different lakes. Depending on which lake population was studied, findings showed that these sticklebacks either remained as one species or evolved into two species. The divergence of species was made possible by their use of different areas of the pond for feeding called micro niches.

Dr. Harmon and his team created artificial pond microcosms in 250-gallon tanks and added muck from freshwater ponds as a source of zooplankton and other invertebrates to sustain the fish. In different experimental tanks, they introduced one species of stickleback from either a single-species or double-species lake.

Over time, the team observed that some of the tanks bloomed with algae while others did not. This puzzled the scientists, and they decided to measure the water's dissolved organic carbon (DOC), which consists of mostly large molecules of decaying

organic matter that gives pond water its slightly brownish color. It turned out that the water from the tanks with two-species fish contained larger particles of DOC (and hence darker water) than water with single-species fish. This increase in DOC blocked the sunlight and prevented algal blooming. Conversely, the water from the single-species tank contained smaller DOC particles, allowing more sunlight penetration to fuel the algal blooms.

This change in the environment, which is due to the different feeding habits of the stickleback species in each lake type, probably greatly impacts the survival of other species in these ecosystems, especially other photosynthetic organisms. Stickleback species are, therefore, acting as foundational species. Thus, the study shows that, at least in these ecosystems, the environment and the evolution of populations have reciprocal effects that may now be factored into simulation models.



Figure 4.4.1.3: The three-spined stickleback evolved from a saltwater fish to freshwater fish. (credit: Barrett Paul, USFWS)

Ecosystem Research: Experimentation and Modeling

The study of the changes in ecosystem structure caused by changes in the environment (disturbances) or by internal forces is called **ecosystem dynamics**. Ecosystems are characterized using a variety of research methodologies. Some ecologists study ecosystems using controlled experimental systems, while some study entire ecosystems in their natural state, and others use both approaches.

Holistic Model and Experimentation

A **holistic ecosystem model** attempts to quantify the composition, interaction, and dynamics of entire ecosystems; it is a model of the most representative ecosystem in its natural state. A food web (Unit 4.4.2) is an example of a holistic ecosystem model. However, this type of study is limited by time and expense, as well as the fact that it is neither feasible nor ethical to do experiments on large natural ecosystems. To quantify all different species in an ecosystem and the dynamics in their habitat is difficult, especially when studying large habitats such as the Amazon Rainforest, which covers 1.4 billion acres (5.5 million km^2) of the Earth's surface.

For these reasons, scientists study ecosystems under more controlled conditions. Experimental systems usually involve either partitioning a part of a natural ecosystem that can be used for experiments, termed a **mesocosm**, or re-creating an ecosystem entirely in an indoor or outdoor laboratory environment, which is referred to as a **microcosm**. A major limitation to these approaches is that removing individual organisms from their natural ecosystem or altering a natural ecosystem through partitioning may change the dynamics of the ecosystem. These changes are often due to differences in species numbers and diversity and also to environmental alterations caused by partitioning (mesocosm) or re-creating (microcosm) the natural habitat. Thus, these types of experiments are not totally predictive of changes that would occur in the ecosystem from which they were gathered.

As both of these approaches have their limitations, some ecologists suggest that results from these experimental systems should be used only in conjunction with holistic ecosystem studies to obtain the most representative data about ecosystem structure, function, and dynamics.

Scientists use the data generated by these experimental studies to develop ecosystem models that demonstrate the structure and dynamics of ecosystems. Three basic types of ecosystem modeling are routinely used in research and ecosystem management: a conceptual model, an analytical model, and a simulation model. A conceptual model describes ecosystem structure and dynamics and shows how environmental disturbances affect the ecosystem; however, its ability to predict the effects of these disturbances is limited. Analytical and simulation models, in contrast, are mathematical methods of describing ecosystems that are indeed capable

of predicting the effects of potential environmental changes without direct experimentation, although with some limitations as to accuracy.

Conceptual Models

Conceptual models are ecosystem models that consist of flow charts to show interactions of different compartments of the living and nonliving components of the ecosystem. Conceptual models are useful for describing ecosystem structure and dynamics and for demonstrating the relationships between different organisms in a community and their environment. The organisms and their resources are grouped into specific compartments with arrows showing the relationship and transfer of energy or nutrients between them. Thus, these diagrams are sometimes called compartment models.

To model the cycling of mineral nutrients, organic and inorganic nutrients are subdivided into those that are bioavailable (ready to be incorporated into biological macromolecules) and those that are not (Unit 4.4.5). For example, in a terrestrial ecosystem near a deposit of coal, carbon will be available to the plants of this ecosystem as carbon dioxide gas in a short-term period, not from the carbon-rich coal itself. However, over a longer period, microorganisms capable of digesting coal will incorporate its carbon or release it as natural gas (methane, CH_4), changing this unavailable organic source into an available one. This conversion is greatly accelerated by the combustion of fossil fuels by humans, which releases large amounts of carbon dioxide into the atmosphere. This is thought to be a major factor in the rise of atmospheric carbon dioxide levels in the industrial age. The carbon dioxide released from burning fossil fuels is produced faster than photosynthetic organisms can use it. This process is intensified by the reduction of photosynthetic trees because of worldwide deforestation. Most scientists agree that high atmospheric carbon dioxide is a major cause of global climate change.

Conceptual models are also used to show the flow of energy through particular ecosystems. Figure **4.4.1.4** is based on Howard T. Odum's classical study of the Silver Springs, Florida, holistic ecosystem in the mid-twentieth century.[2] This study shows the energy content and transfer between various ecosystem compartments.

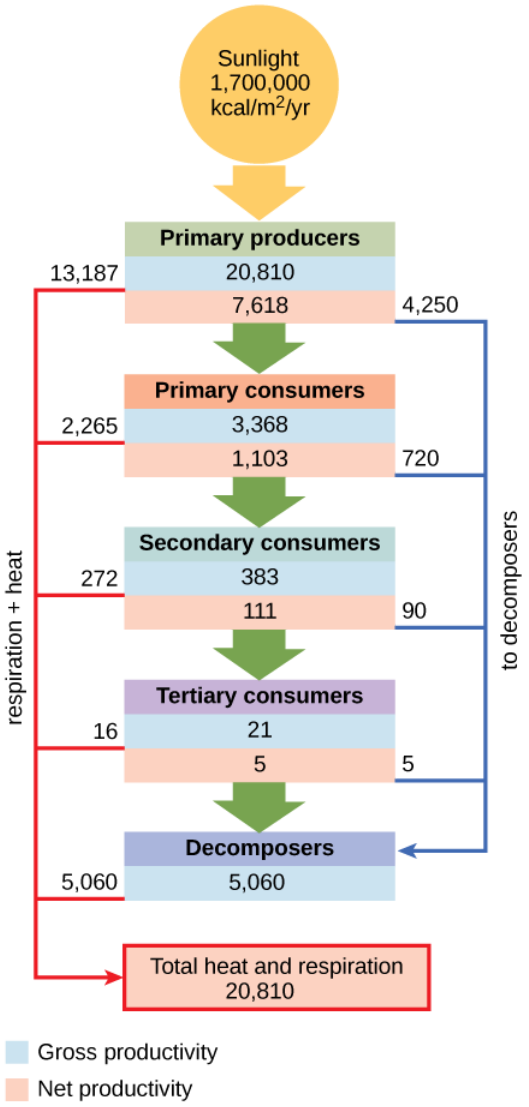


Figure **4.4.1.4**: This conceptual model shows the flow of energy through a spring ecosystem in Silver Springs, Florida. Notice that the energy decreases with each increase in trophic level.

Analytical and Simulation Models

An **analytical model** is an ecosystem model that is created using simple mathematical formulas to predict the effects of environmental disturbances on ecosystem structure and dynamics. Analytical models often use simple, linear components of ecosystems, such as food chains, and are known to be complex mathematically; therefore, they require a significant amount of mathematical knowledge and expertise. An example would be a model that predicts the effects of primary production (g C/m^2) on a wetland on decomposition and consumption rates (g C/m^2/y). Although analytical models have great potential, their simplification of complex ecosystems is thought to limit their accuracy. Simulation models that use computer programs can better deal with the complexities of ecosystem structure.

A **simulation model** is an ecosystem model that is created using complex computer algorithms to holistically model ecosystems and predict the effects of environmental disturbances on ecosystem structure and dynamics. Ideally, these models are accurate enough to determine which components of the ecosystem are particularly sensitive to disturbances, and they can serve as a guide to ecosystem managers (such as conservation ecologists or fisheries biologists) in the practical maintenance of ecosystem health. Climate models are simulation models. A recent development in simulation modeling uses supercomputers to create and run individual-based simulations, which account for the behavior of individual organisms and their effects on the ecosystem as a whole. These simulations are considered to be the most accurate and predictive of the complex responses of ecosystems to disturbances.

Footnotes

1. 1 *Nature* (Vol. 458, April 1, 2009)
2. 2 Howard T. Odum, “Trophic Structure and Productivity of Silver Springs, Florida,” *Ecological Monographs* 27, no. 1 (1957): 47–112.

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Unit 4.4.2 - Energy Flow through Ecosystems

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 90 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.4.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe how organisms acquire energy in a food web and in associated food chains
- Explain how the efficiency of energy transfers between trophic levels affects ecosystem structure and dynamics
- Discuss trophic levels and how ecological pyramids are used to model them

Introduction

All living things require energy in one form or another. Energy is required by most complex metabolic pathways (often in the form of adenosine triphosphate, ATP), especially those responsible for building large molecules from smaller compounds, and life itself is an energy-driven process. Living organisms would not be able to assemble macromolecules (proteins, lipids, nucleic acids, and complex carbohydrates) from their monomeric subunits without constant energy input.

It is important to understand how organisms acquire energy and how that energy is passed from one organism to another through food webs and their constituent food chains. Food webs illustrate how energy flows directionally through ecosystems, including how efficiently organisms acquire it, use it, and how much remains for use by other organisms of the food web.

Food Chains and Food Webs

The term “food chain” is sometimes used metaphorically to describe human social situations. In this sense, food chains are thought of as a competition for survival, such as “who eats whom?” Someone eats and someone is eaten. Therefore, it is not surprising that in our competitive society, individuals who are considered successful are seen as being at the top of the food chain, consuming all others for their benefit, whereas the less successful are seen as being at the bottom.

The scientific understanding of a food chain is more precise than in its everyday usage. In ecology, a **food chain** is a linear sequence of organisms through which nutrients and energy pass: primary producers, primary consumers, and higher-level consumers are used to describe ecosystem structure and dynamics. There is a single path through the chain. Each organism in a food chain occupies what is called a trophic level. Depending on their role as producers or consumers, species or groups of species can be assigned to various trophic levels.

In many ecosystems, the bottom of the food chain consists of photosynthetic organisms (plants and/or phytoplankton), which are called **primary producers**. The organisms that consume the primary producers are herbivores: the primary consumers. **Secondary consumers** are usually carnivores that eat the primary consumers. **Tertiary consumers** are carnivores that eat other carnivores. Higher-level consumers feed on the next lower tropic levels, and so on, up to the organisms at the top of the food chain: the **apex consumers**. In the Lake Ontario food chain shown in Figure **4.4.2.1**, the Chinook salmon is the apex consumer at the top of this food chain.

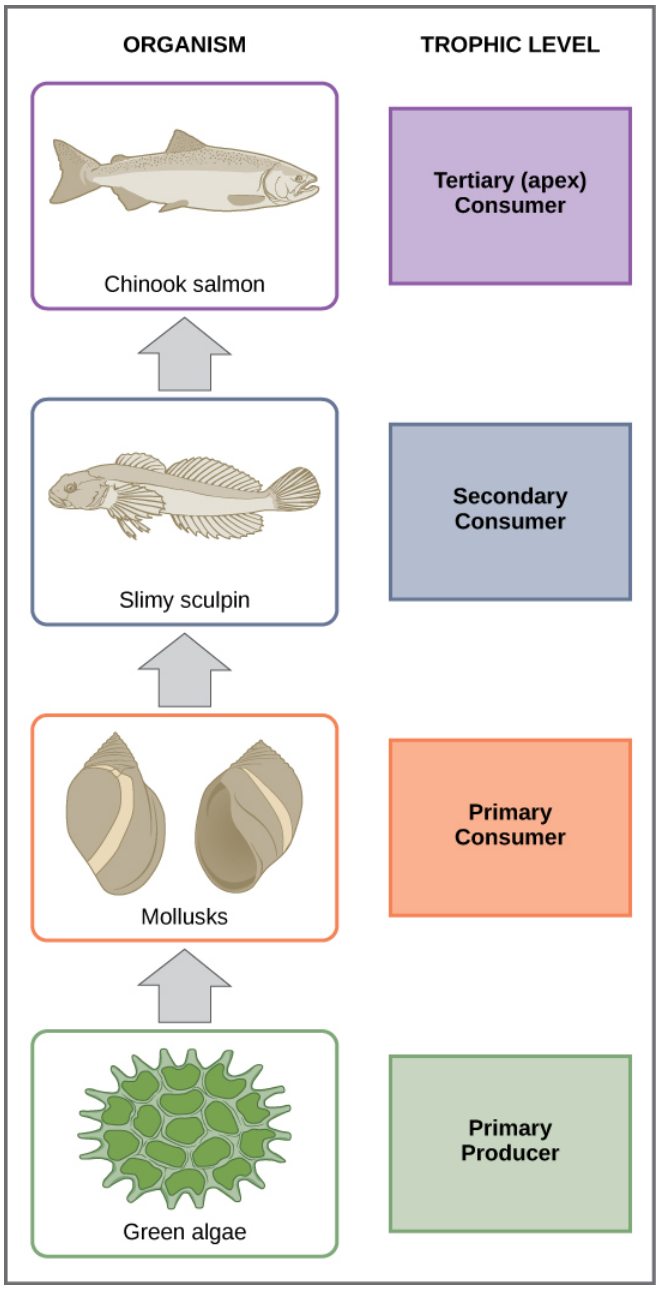


Figure **4.4.2.1**: These are the trophic levels of a food chain in Lake Ontario at the border with the United States. Energy and nutrients flow from photosynthetic green algae at the bottom to the top of the food chain: the Chinook salmon.

One major factor that limits the length of food chains is energy. An average of 90% of energy is lost as heat between each trophic level due to the second law of thermodynamics. Thus, after a limited number of trophic energy transfers, the amount of energy remaining in the food chain may not be great enough to support viable populations at yet a higher trophic level. When one organism eats another, most of the energy is dissipated as heat and is not used to make more of the consumer. For example, when someone eats a potato, most of the energy available in the chemical bonds of the potato does not become energy to make new molecules in the individual. Only about 10% of the potato's energy is available to be assimilated into the individual eating the potato.

The loss of energy between trophic levels is illustrated by the pioneering studies of Howard T. Odum in the Silver Springs, Florida, ecosystem in the 1940s (Figure **4.4.2.2**). The primary producers generated 20,819 kcal/m^2/yr (kilocalories per square meter per year), the primary consumers generated 3368 kcal/m^2/yr, the secondary consumers generated 383 kcal/m^2/yr, and the tertiary consumers only generated 21 kcal/m^2/yr. Thus, there is little energy remaining for another level of consumers in this ecosystem.

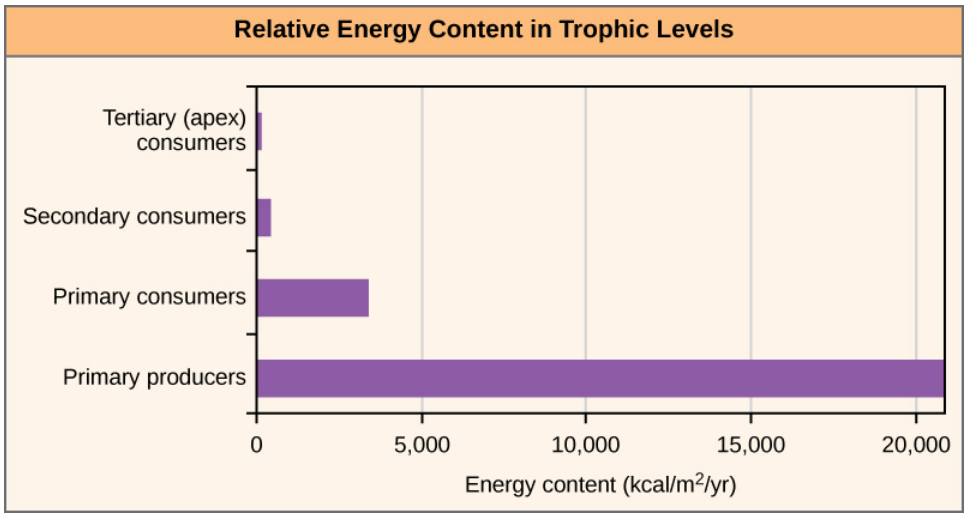


Figure **4.4.2.2**: The relative energy in trophic levels in a Silver Springs, Florida, ecosystem is shown. Each trophic level has less energy available and supports fewer organisms at the next level.

There is a BIG problem when using food chains to accurately describe most ecosystems. Even when all organisms are grouped into appropriate trophic levels, many of these organisms can feed on species from more than one trophic level; likewise, some of these organisms can be eaten by species from multiple trophic levels. In other words, the linear model of ecosystems, the food chain, is not very descriptive of ecosystem structure, is not appropriate to truly understand ecosystem relationships, and is not generally used in ecosystem studies.

A holistic model—which accounts for all the interactions between different species and their complex interconnected relationships with each other and with the environment—is more accurate and descriptive for ecosystems. A **food web** is a graphic representation of a holistic, non-linear web of primary producers, primary consumers, and higher-level consumers used to describe ecosystem structure and dynamics (Figure **4.4.2.3**).

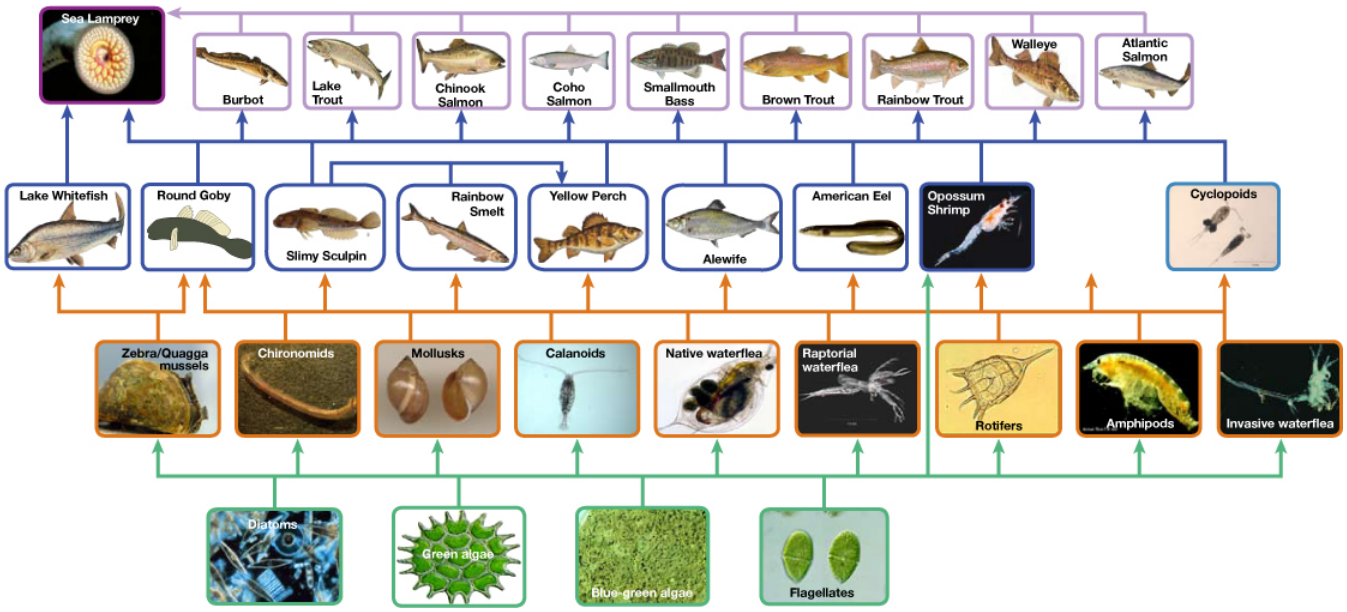


Figure **4.4.2.3**: This food web shows the interactions between organisms across trophic levels in the Lake Ontario ecosystem. Primary producers are outlined in green, primary consumers in orange, secondary consumers in blue, and tertiary (apex) consumers in purple. Arrows point from an organism that is consumed to the organism that consumes it. Notice how some lines point to more than one trophic level. For example, the opossum shrimp eats both primary producers and primary consumers. (credit: NOAA, GLERL)

A comparison of the two types of structural ecosystem models shows strength in both. Food chains are more flexible for analytical modeling, are easier to follow, and are easier to learn from, whereas food web models more accurately represent ecosystem

structure and dynamics, and data can be directly used as input for simulation modeling.

Two general types of food webs are often shown interacting within a single ecosystem. A **grazing food web** (such as the Lake Ontario food web in Figure **4.4.2.3**) has plants or other photosynthetic organisms at its base, followed by herbivores and various carnivores. As all ecosystems require a method to recycle material from dead organisms, most grazing food webs have an associated detrital food web. A **detrital food web** consists of a base of organisms that feed on decaying organic matter (dead organisms); these can be either decomposers or detritivores. **Decomposers** are bacteria or fungi that recycle organic material back into the ecosystem as they themselves are consumed by other organisms. **Detritivores** break larger materials such as leaves, dung, hides, etc., into material for decomposers.

Both grazing and detrital food webs exist in the same ecosystem at the same time. For example, in a meadow ecosystem, plants may support a grazing food web of different organisms, primary and other levels of consumers, while at the same time supporting a detrital food web of bacteria, fungi, and detrivorous invertebrates feeding off dead plants and animals.

How Organisms Acquire Energy in a Food Web

Energy is acquired by living things in three ways: photosynthesis, chemosynthesis, and the consumption and digestion of other living or previously living organisms by heterotrophs.

Photosynthetic and chemosynthetic organisms are both grouped into a category known as autotrophs: organisms capable of synthesizing their own food (more specifically, capable of using inorganic carbon as a carbon source). Photosynthetic autotrophs (**photoautotrophs**) use sunlight as an energy source, whereas chemosynthetic autotrophs (**chemoautotrophs**) use inorganic molecules as an energy source. Autotrophs are critical for all ecosystems. Without these organisms, energy would not be available to other living organisms and life itself would not be possible.

Photoautotrophs, such as plants, algae, and photosynthetic bacteria, serve as the energy source for a majority of the world's ecosystems. These ecosystems are often described by grazing food webs. Photoautotrophs harness the solar energy of the sun by converting it to chemical energy in the form of ATP (and NADP). The energy stored in ATP is used to synthesize complex organic molecules, such as glucose.

Chemoautotrophs are primarily bacteria that are found in rare ecosystems where sunlight is not available, such as in those associated with dark caves or hydrothermal vents at the bottom of the ocean (Figure **4.4.2.4**). Many chemoautotrophs at hydrothermal vents use hydrogen sulfide (H_2S), a source of chemical energy released from the vents. This allows chemoautotrophs to synthesize complex organic molecules, such as glucose, for their own energy and in turn supplies energy to the rest of the ecosystem.

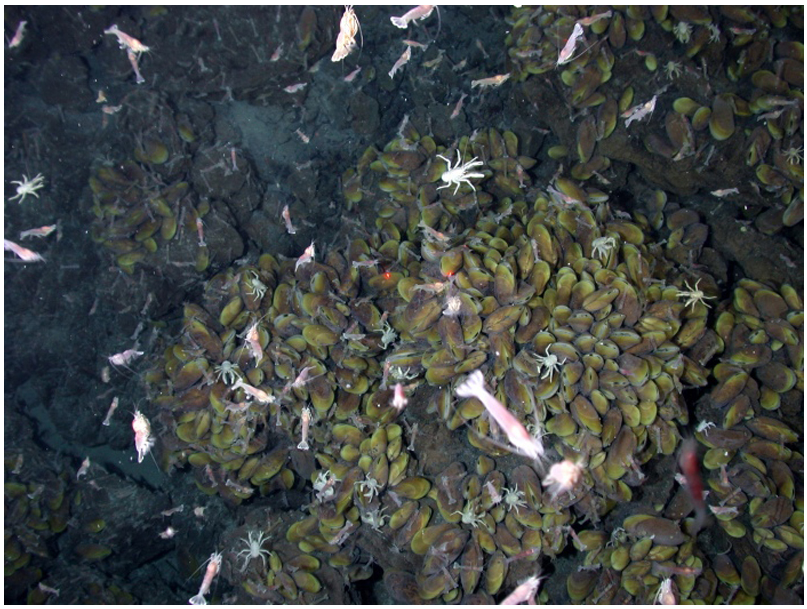


Figure 4.4.2.4: Swimming shrimp, a few squat lobsters, and hundreds of vent mussels are seen at a hydrothermal vent at the bottom of the ocean. As no sunlight penetrates to this depth, the ecosystem is supported by chemoautotrophic bacteria and organic material that sinks from the ocean's surface. This picture was taken in 2006 at the submerged NW Eifuku volcano off the coast of Japan by the National Oceanic and Atmospheric Administration (NOAA). The summit of this highly active volcano lies 1535 m below the surface.

Productivity within Trophic Levels

Productivity within an ecosystem can be defined as the percentage of energy entering the ecosystem incorporated into biomass in a particular trophic level. **Biomass** is the total mass, in a unit area at the time of measurement, of living or previously living organisms within a trophic level. Ecosystems have characteristic amounts of biomass at each trophic level. For example, in the English Channel ecosystem the primary producers account for biomass of 4 g/m^2 (grams per meter squared), while the primary consumers exhibit biomass of 21 g/m^2.

The productivity of the primary producers is especially important in any ecosystem because these organisms bring energy to other living organisms by photoautotrophy or chemoautotrophy. The rate at which photosynthetic primary producers incorporate energy from the sun is called **gross primary productivity**. An example of gross primary productivity is shown in the pyramid of energy within the Silver Springs aquatic ecosystem as shown (Figure 4.4.2.5)C. In this ecosystem, gross primary productivity was shown to be 20,810 $kcal/m^2/yr$.

Because all organisms need to use some of this energy for their own functions (like respiration and resulting metabolic heat loss) scientists often refer to the net primary productivity of an ecosystem. **Net primary productivity** is the energy that remains in the primary producers after accounting for the organisms' respiration and heat loss. In terrestrial environments, net primary productivity is estimated by measuring the **aboveground biomass** per unit area, which is the total mass of living plants, excluding roots. This means that a large percentage of underground plant biomass is not included in this measurement. Net productivity is available to the primary consumers at the next trophic level. In our Silver Spring example, 13,187 of the 20,810 $kcal/m^2/yr$ were used for respiration or were lost as heat, leaving 7,632 $kcal/m^2/yr$ of energy for use by the primary consumers.

Modeling Ecosystems Energy Flow: Ecological Pyramids

The structure of ecosystems can be visualized with ecological pyramids, which were first described by the pioneering studies of Charles Elton in the 1920s. Ecological pyramids show the relative amounts of various parameters (such as number of organisms, energy, and biomass) across trophic levels.

Pyramids of numbers can be either upright or inverted, depending on the ecosystem. As shown in Figure 4.4.2.5B, typical grassland during the summer has a base of many plants and the number of organisms decreases at each trophic level. However, during the summer in a temperate forest, the base of the pyramid consists of few trees compared with the number of primary consumers, mostly insects. Because trees are large, they have great photosynthetic capability, and dominate other plants in this

ecosystem to obtain sunlight. Even in smaller numbers, primary producers in forests are still capable of supporting other trophic levels.

Another way to visualize ecosystem structure is with **pyramids of biomass**. This pyramid measures the amount of energy converted into living tissue at the different trophic levels. Using the Silver Springs ecosystem example, this data exhibits an upright biomass pyramid (Figure **4.4.2.5**)A, whereas the pyramid from the English Channel example is inverted. The plants (primary producers) of the Silver Springs ecosystem make up a large percentage of the biomass found there. However, the phytoplankton in the English Channel example make up less biomass than the primary consumers, the zooplankton. As with inverted pyramids of numbers, this inverted pyramid is not due to a lack of productivity from the primary producers, but results from the high turnover rate of the phytoplankton. The phytoplankton are consumed rapidly by the primary consumers, thus, minimizing their biomass at any particular point in time. However, phytoplankton reproduce quickly, thus they are able to support the rest of the ecosystem.

Pyramid ecosystem modeling can also be used to show energy flow through the trophic levels in **pyramids of energy** (Figure **4.4.2.5**)C. Notice that these numbers are the same as those used in the energy flow compartment diagram in Unit 4.4.1. Pyramids of energy are always upright, and an ecosystem without sufficient primary productivity cannot be supported. All types of ecological pyramids are useful for characterizing ecosystem structure. However, in the study of energy flow through the ecosystem, pyramids of energy are the most consistent and representative models of ecosystem structure.

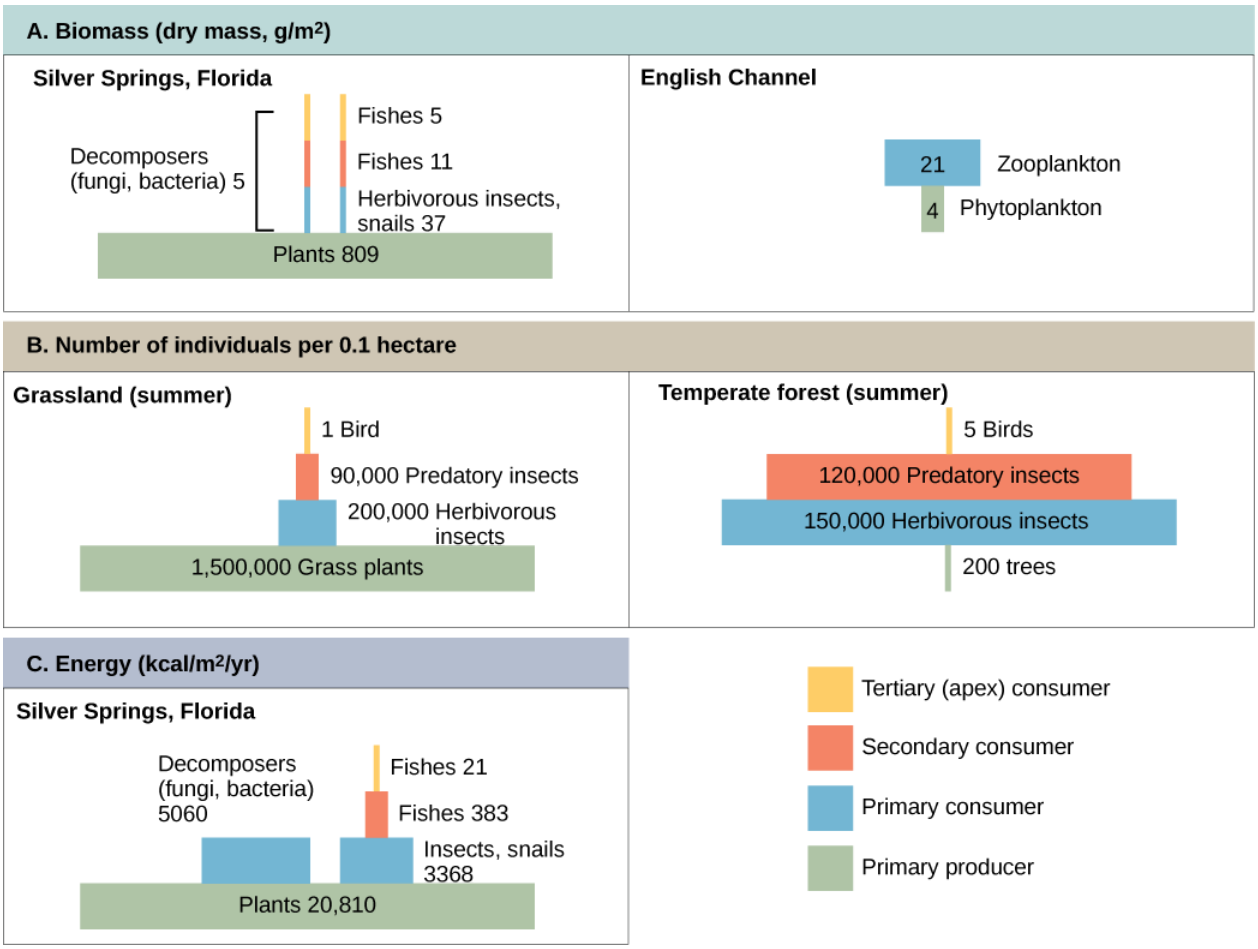


Figure **4.4.2.5**: Ecological pyramids depict the (a) biomass, (b) number of organisms, and (c) energy in each trophic level. Note that in aquatic environments (English Channel) the biomass pyramids are often inverted due to the high turnover in populations of producers. The temperate forest number of organisms pyramid is inverted due to the presence of few, very large trees supporting production for the higher trophic levels versus many individual grasses in the grassland.

Ecological Efficiency: The Transfer of Energy between Trophic Levels

As illustrated in Figure **4.4.2.5**C, large amounts of energy are lost from the ecosystem from one trophic level to the next level as energy flows from the primary producers through the various trophic levels of consumers and decomposers. The main reason for

this loss is the **second law of thermodynamics**, which states that whenever energy is converted from one form to another, there is a tendency toward disorder (entropy) in the system. In biological systems, this means a great deal of energy is lost as metabolic heat when the organisms from one trophic level consume the next level. In the Silver Springs ecosystem example (Figure **4.4.2.5**C), we see that the primary consumers produced 1103 kcal/m^2/yr from the 7618 kcal/m^2/yr of energy available to them from the primary producers. The measurement of energy transfer efficiency between two successive trophic levels is termed the **trophic level transfer efficiency** (TLTE) and is defined by the formula:

$$\text{TLTE} = \frac{\text{production at present trophic level}}{\text{production at previous trophic level}} * 100$$

In Silver Springs, the TLTE between the first two trophic levels was approximately 14.8 percent. The low efficiency of energy transfer between trophic levels is usually the major factor that limits the length of food chains observed in a food web. The fact is, after four to six energy transfers, there is not enough energy left to support another trophic level's need to grow, survive, and reproduce.

Ecologists have many different methods of measuring energy transfers within ecosystems. Some transfers are easier or more difficult to measure depending on the complexity of the ecosystem and how much access scientists have to observe the ecosystem. In other words, some ecosystems are more difficult to study than others, and sometimes the quantification of energy transfers has to be estimated.

Another main parameter that is important in characterizing energy flow within an ecosystem is the net production efficiency. **Net production efficiency (NPE)** allows ecologists to quantify how efficiently organisms of a particular trophic level incorporate the energy they receive into biomass; it is calculated using the following formula:

$$\text{NPE} = \frac{\text{net consumer productivity}}{\text{assimilation}} * 100$$

Net consumer productivity is the energy content available to the organisms at the next trophic level. **Assimilation** is the biomass (energy content generated per unit area) of the present trophic level after accounting for the energy lost due to incomplete ingestion of food, energy used for respiration, and energy lost as waste. **Incomplete ingestion** refers to the fact that some consumers eat only a part of their food. For example, when a lion kills an antelope, it will eat everything except the hide and bones. The lion is missing the energy-rich bone marrow inside the bone, so the lion does not make use of all the calories its prey could provide.

Thus, NPE measures how efficiently each trophic level uses and incorporates the energy from its food into biomass to fuel the next trophic level. In general, organisms whose internal temperature is externally regulated (**ectotherms**), such as invertebrates, fish, amphibians, and reptiles, use less of the energy they obtain for respiration and heat than organisms that internally regulate their temperature (**endotherms**), such as birds and mammals. The extra heat generated in endotherms, although an advantage in terms of the activity of these organisms in colder environments, is a major disadvantage in terms of NPE. Therefore, many endotherms have to eat more often than ectotherms to get the energy they need for survival. In general, NPE for ectotherms is an order of magnitude (10x) higher than for endotherms. For example, the NPE for a caterpillar eating leaves has been measured at 18 percent, whereas the NPE for a squirrel eating acorns may be as low as 1.6 percent.

The inefficiency of energy use by endotherms has broad implications for the world's food supply. It is widely accepted that the meat industry uses large amounts of crops to feed livestock, and because the NPE is low, much of the energy from animal feed is lost. For example, it costs about $0.01 to produce 1,000 dietary calories (kCcal) of corn or soybeans, but approximately $0.19 to produce a similar number of calories growing cattle for beef consumption. The same energy content of milk from cattle is also costly, at approximately $0.16 per 1,000 Kcal. Much of this difference is due to the low NPE of cattle. Thus, there has been a growing movement worldwide to promote the consumption of non-meat and non-dairy foods so that less energy is wasted feeding animals for the meat industry.

? Optional Activity 4.4.2.1

Pyramids depicting the number of organisms or biomass may be inverted, upright, or even diamond-shaped. Energy pyramids, however, are always upright. Why?

Answer

Pyramids of numbers may be inverted or diamond-shaped because a large organism, such as a tree, can sustain many smaller organisms. Likewise, a low biomass of producers can sustain a larger biomass at the next trophic level because the producers may reproduce rapidly and thus supply continuous nourishment. Pyramids of energy, however, must always be upright because of the laws of thermodynamics. The second law of thermodynamics states that, during the transfer of energy, some energy is always lost as heat; thus, less energy is available at each higher trophic level.

Consequences of Food Webs: Biological Magnification

One of the most important environmental consequences of ecosystem dynamics is biomagnification. **Biomagnification** is the increasing concentration of persistent, toxic substances in organisms at each trophic level, from the primary producers to the apex consumers. Many substances have been shown to **bioaccumulate**, including classical studies with the pesticide **d**ichloro**d**iphenyl**t**richloroethane (DDT). The results of these observations and analyses were published in the 1960s bestseller, *Silent Spring*, by Rachel Carson. DDT was a commonly used pesticide before its dangers became known. In some aquatic ecosystems, organisms from each trophic level consumed many organisms of the lower level, which caused DDT to increase in birds (apex consumers) that ate fish. Thus, the birds accumulated sufficient amounts of DDT to cause fragility in their eggshells. This effect increased egg breakage during nesting and was shown to have adverse effects on these bird populations. The use of DDT was banned in the United States in the 1970s.

Other substances that biomagnify are polychlorinated biphenyls (PCBs), which were used in coolant liquids in the United States until their use was banned in 1979, and heavy metals, such as mercury, lead, and cadmium. These substances were best studied in aquatic ecosystems, where fish species at different trophic levels accumulate toxic substances brought through the ecosystem by the primary producers. As illustrated in a study performed by the National Oceanic and Atmospheric Administration (NOAA) in the Saginaw Bay of Lake Huron (Figure **4.4.2.6**), PCB concentrations increased from the ecosystem's primary producers (phytoplankton) through the different trophic levels of fish species. The apex consumer (walleye) has more than four times the amount of PCBs compared to phytoplankton. Also, based on results from other studies, birds that eat these fish may have PCB levels at least one order of magnitude higher than those found in the lake fish.

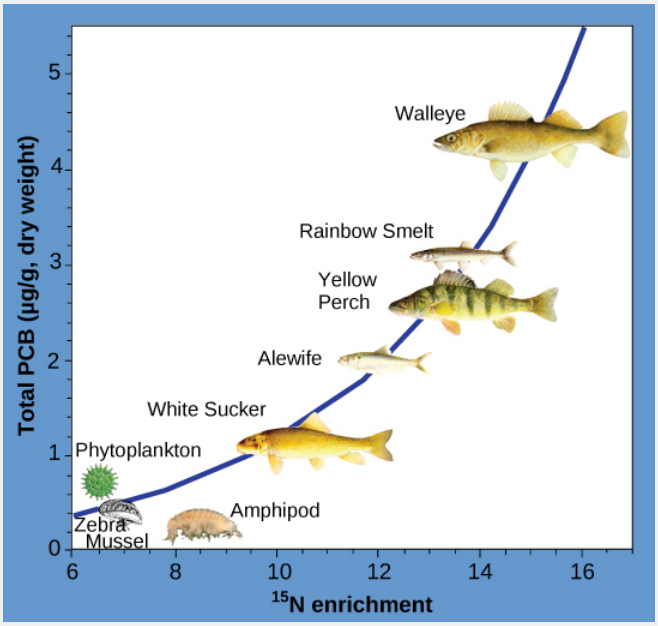


Figure **4.4.2.6**: This chart shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Numbers on the x-axis reflect enrichment with heavy isotopes of nitrogen (^{15}N), which is a marker for increasing trophic level. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels. (credit: Patricia Van Hoof, NOAA, GLERL)

Other concerns have been raised by the accumulation of heavy metals, such as mercury and cadmium, in certain types of seafood. The United States Environmental Protection Agency (EPA) recommends that pregnant women and young children should not consume any swordfish, shark, king mackerel, or tilefish because of their high mercury content. These individuals

> are advised to eat fish low in mercury: salmon, tilapia, shrimp, pollock, and catfish. Biomagnification is a good example of how ecosystem dynamics can affect our everyday lives, even influencing the food we eat.

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Unit 4.4.3 - Terrestrial Biomes

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.4.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Identify the two major abiotic factors that determine terrestrial biomes
- Recognize distinguishing characteristics of each of the eight major terrestrial biomes

Introduction

A **biome** is an ecological community of organisms that are adapted to a characteristic set of environmental conditions. The Earth's biomes are categorized into two major groups: terrestrial and aquatic. Terrestrial biomes are based on land, while aquatic biomes include both ocean and freshwater biomes. The eight major terrestrial biomes on Earth are each distinguished by characteristic temperatures and amount of precipitation. Comparing the annual totals of precipitation and fluctuations in precipitation from one biome to another provides clues as to the importance of abiotic factors in the distribution of biomes. Temperature variation on a daily and seasonal basis is also important for predicting the geographic distribution of the biome and the vegetation type in the biome. The distribution of these biomes shows that the same biome can occur in geographically distinct areas with similar climates (Figure **4.4.3.1**).

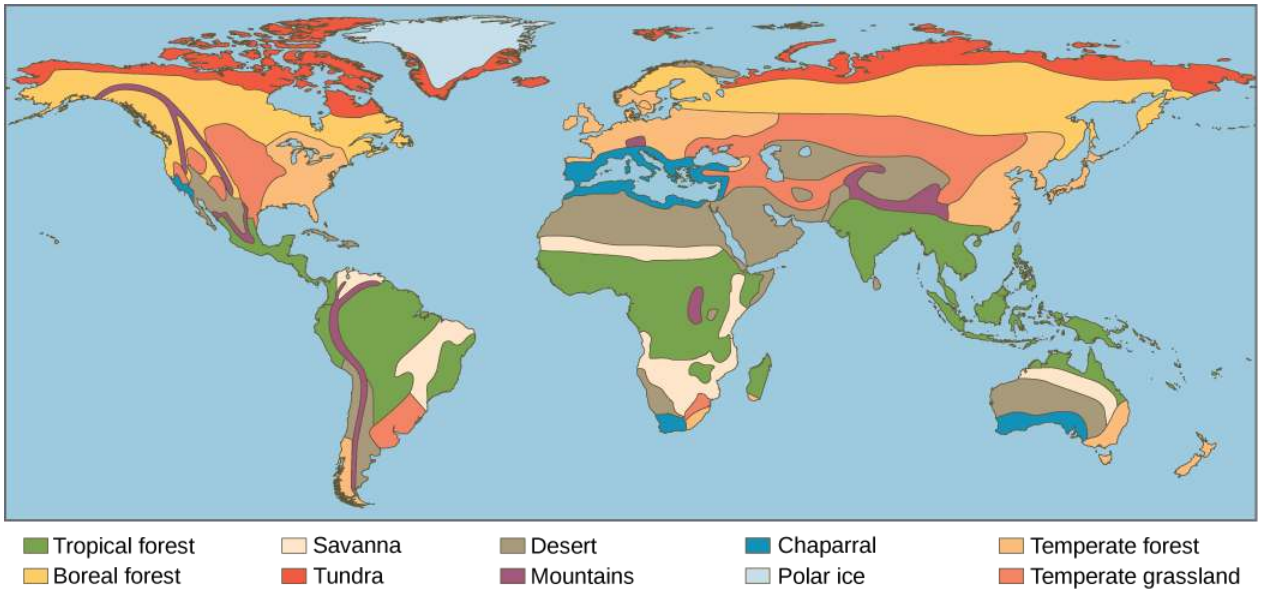


Figure **4.4.3.1**: Each of the world's major biomes is distinguished by characteristic temperatures and amounts of precipitation. Polar ice and mountains are also shown.

Video



In this 7.5-minute video, you will review the characteristics of the eight terrestrial biomes.
Questions after watching: In which biome is your home located? Why do you think it is in this biome?

Tropical Wet Forest

Tropical wet forests are also referred to as tropical rainforests. This biome is found in equatorial regions (Figure **4.4.3.1**). The vegetation is characterized by plants with broad leaves that fall off throughout the year. Unlike the trees of deciduous forests, the trees in this biome do not have a seasonal loss of leaves associated with variations in temperature and sunlight; these forests are "evergreen" year-round.

The temperature and sunlight profiles of tropical wet forests are very stable in comparison to that of other terrestrial biomes, with temperatures ranging from 20 °C to 34 °C. When one compares the annual temperature variation of tropical wet forests with that of other forest biomes, the lack of seasonal temperature variation in the tropical wet forest becomes apparent. This lack of seasonality leads to year-round plant growth, rather than the seasonal (spring, summer, and fall) growth seen in other biomes. In contrast to other ecosystems, tropical ecosystems do not have long days and short days during the yearly cycle. Instead, a constant daily amount of sunlight (11–12 hrs per day) provides more solar radiation, thereby, a longer period of time for plant growth.

The annual rainfall in tropical wet forests ranges from 125 to 660 cm with some monthly variation. While sunlight and temperature remain fairly consistent, annual rainfall is highly variable. Tropical wet forests have wet months in which there can be more than 30 cm of precipitation, as well as dry months in which there are fewer than 10 cm of rainfall. However, the driest month of a tropical wet forest still exceeds the *annual* rainfall of some other biomes, such as deserts.

Tropical wet forests have high net primary productivity because the annual temperatures and precipitation values in these areas are ideal for plant growth. Therefore, the extensive biomass present in the tropical wet forest leads to plant communities with very high species diversities (Figure **4.4.3.2**). Tropical wet forests have more species of trees than any other biome; on average between 100 and 300 species of trees are present in a single hectare of South America. One way to visualize this is to compare the distinctive horizontal layers within the tropical wet forest biome. On the forest floor is a sparse layer of plants and decaying plant matter. Above that is an **understory** of short shrubby foliage. A layer of trees rises above this understory and is topped by a closed **upper canopy**—the uppermost overhead layer of branches and leaves. Some additional trees emerge through this closed upper canopy. These layers provide diverse and complex habitats for the variety of plants, fungi, animals, and other organisms within the tropical wet forests. For instance, **epiphytes** are plants that grow on other plants, which typically are not harmed. Epiphytes are found throughout tropical wet forest biomes. Many species of animals use the variety of plants and the complex structure of the tropical wet forests for food and shelter. Some organisms live several meters above ground and have adapted to this arboreal lifestyle.



Figure **4.4.3.2**: Tropical wet forests, such as these forests of Madre de Dios, Peru, near the Amazon River, have high species diversity. (credit: Roosevelt Garcia)

Savannas

Savannas are grasslands with scattered trees, and they are located in Africa, South America, and northern Australia (Figure **4.4.3.3**). Savannas are hot, tropical areas with temperatures averaging from 24 °C to 29 °C and an annual rainfall of 10–40 cm. Savannas have an extensive dry season; for this reason, forest trees do not grow as well as they do in tropical wet forests (or other forest biomes). As a result, within the grasses and **forbs** (herbaceous flowering plants) that dominate the savanna, there are relatively few trees (Figure **4.4.3.3**). Since fire is an important source of disturbance in this biome, plants have evolved well-developed root systems that allow them to quickly re-sprout after a fire.



Figure **4.4.3.3**: Savannas, like this one in Taita Hills Wildlife Sanctuary in Kenya, are dominated by grasses. (credit: Christopher T. Cooper)

Subtropical Deserts

Subtropical deserts exist between 15° and 30° north and south latitude and are centered on the Tropics of Cancer and Capricorn (Figure **4.4.3.4**). This biome is very dry; in some years, evaporation exceeds precipitation. Subtropical hot deserts can have daytime soil surface temperatures above 60°C and nighttime temperatures approaching 0°C. In cold deserts, temperatures can be as high as 25°C and can drop below -30°C. Subtropical deserts are characterized by low annual precipitation of fewer than 30 cm with little monthly variation and a lack of predictability in rainfall. In some cases, the annual rainfall can be as low as 2 cm in subtropical deserts located in central Australia (“the Outback”) and northern Africa.

The vegetation and low animal diversity of this biome are closely related to this low and unpredictable precipitation. Very dry deserts lack perennial vegetation that lives from one year to the next; instead, many plants are annuals that grow quickly and reproduce when rainfall does occur, then they die. Many other plants in these areas are characterized by having a number of

adaptations that conserve water, such as deep roots, reduced foliage, and water-storing stems (Figure 4.4.3.4). Seed plants in the desert produce seeds that can be in dormancy for extended periods between rains. Adaptations in desert animals include **nocturnal** behavior (being awake at night) and burrowing.



Figure 4.4.3.4: To reduce water loss, many desert plants have tiny leaves or no leaves at all. The leaves of ocotillo (*Fouquieria splendens*), shown here in the Sonora Desert near Gila Bend, Arizona, appear only after rainfall, and then are shed.

Chaparral

The **chaparral** is also called the scrub forest and is found in California, along the Mediterranean Sea, and along the southern coast of Australia (Figure 4.4.3.5). The annual rainfall in this biome ranges from 65 cm to 75 cm, and the majority of the rain falls in the winter. Summers are very dry and many chaparral plants are dormant during the summertime. The chaparral vegetation, shown in Figure 4.4.3.5, is dominated by shrubs and is adapted to periodic fires, with some plants producing seeds that only germinate after a hot fire. The ashes left behind after a fire are rich in nutrients like nitrogen that fertilize the soil and promote plant regrowth.



Figure 4.4.3.5: The chaparral is dominated by shrubs. (credit: Miguel Vieira)

Temperate Grasslands

Temperate grasslands are found throughout central North America, where they are also known as prairies; they are also in Eurasia, where they are known as steppes (Figure **4.4.3.6**). Temperate grasslands have pronounced annual fluctuations in temperature with hot summers and cold winters. The annual temperature variation produces specific growing seasons for plants. Plant growth is possible when temperatures are warm enough to sustain plant growth and when ample water is available, which occurs in the spring, summer, and fall. During much of the winter, temperatures are low, and water, which is stored in the form of ice, is not available for plant growth.

Annual precipitation ranges from 25-75 cm. Because of relatively lower annual precipitation in temperate grasslands, there are few trees except for those found growing along rivers or streams. The dominant vegetation tends to consist of grasses and some prairies sustain populations of grazing animals Figure **4.4.3.6**. The vegetation is very dense and the soils are fertile because the subsurface of the soil is packed with the roots and rhizomes (underground stems) of these grasses. The roots and rhizomes act to anchor plants into the ground and replenish the organic material (**humus**) in the soil when they die and decay.



Figure **4.4.3.6**: The prairies in Alberta.

Fires, mainly caused by lightning, are a natural disturbance in temperate grasslands. When fire is suppressed in temperate grasslands, the vegetation eventually converts to scrub and dense forests. Often, the restoration or management of temperate grasslands requires the use of controlled burns to suppress the growth of trees and maintain the grasses.

Temperate Forests

Temperate forests are the most common biome in eastern North America, Western Europe, Eastern Asia, Chile, and New Zealand (Figure **4.4.3.7**). This biome is found throughout mid-latitude regions. Temperatures range between -30 °C and 30 °C and drop to below freezing on an annual basis. These temperatures mean that temperate forests have defined growing seasons during the spring, summer, and early fall. Precipitation is relatively constant throughout the year and ranges between 75 cm and 150 cm.

Because of the moderate annual rainfall and temperatures, deciduous trees are the dominant plant in this biome (Figure **4.4.3.7**). Deciduous trees lose their leaves each fall and remain leafless in the winter. Thus, no photosynthesis occurs in deciduous trees during the dormant winter period. Each spring, new leaves appear as the temperature increases. Because of the dormant period, the net primary productivity of temperate forests is less than that of tropical wet forests. In addition, temperate forests show less diversity of tree species than tropical wet forest biomes.



Figure **4.4.3.7**: Deciduous trees are the dominant plant in the temperate forest. (credit: Oliver Herold)

The trees of the temperate forests leaf out and shade much of the ground; however, this biome is more open than tropical wet forests because trees in temperate forests do not grow as tall as the trees in tropical wet forests. The soils of temperate forests are rich in inorganic and organic nutrients. This is due to the thick layer of leaf litter on forest floors. As this leaf litter decays, nutrients are returned to the soil. The leaf litter also protects soil from erosion, insulates the ground, and provides habitats for invertebrates (such as the pill bug or roly-poly, *Armadillidium vulgare*) and their predators, such as the red-backed salamander (*Plethodon cinereus*).

Boreal Forests

The **boreal forest**, also known as taiga or coniferous forest, is found south of the Arctic Circle and across most of Canada, Alaska, Russia, and northern Europe (Figure **4.4.3.8**). This biome has cold, dry winters and short, cool, wet summers. The annual precipitation is from 40 cm to 100 cm and usually takes the form of snow. Little evaporation occurs because of the cold temperatures. In British Columbia, you can find them surrounding the towns of Fort St. John, Fort Nelson, and Telegraph Creek, at the northern and eastern tip of the province. It comprises 5% of Canada's boreal forest.

The long and cold winters in the boreal forest have led to the predominance of cold-tolerant cone-bearing plants. These are evergreen coniferous trees like pines, spruce, and fir, which retain their needle-shaped leaves year-round. Evergreen trees can photosynthesize earlier in the spring than deciduous trees because less energy from the sun is required to warm a needle-like leaf than a broad leaf. This benefits evergreen trees, which grow faster than deciduous trees in the boreal forest. In addition, soils in boreal forest regions tend to be acidic with little available nitrogen. Leaves are a nitrogen-rich structure and deciduous trees must produce a new set of these nitrogen-rich structures each year. Therefore, coniferous trees that retain nitrogen-rich needles may have a competitive advantage over broad-leafed deciduous trees.

The net primary productivity of boreal forests is lower than that of temperate forests and tropical wet forests. The aboveground biomass of boreal forests is high because these slow-growing tree species are long-lived and accumulate standing biomass over time. Plant species diversity is less than that seen in temperate forests and tropical wet forests. Boreal forests lack the pronounced elements of the layered forest structure seen in tropical wet forests. The structure of a boreal forest is often only a tree layer and a ground layer (Figure **4.4.3.8**). When conifer needles are dropped, they decompose more slowly than broad leaves; therefore, fewer nutrients are returned to the soil to fuel plant growth.



Figure **4.4.3.8**: The boreal forest (taiga) range in North America. Government of Canada - Boreal Forest

Arctic Tundra

The **Arctic tundra** lies north of the subarctic boreal forest and is located throughout the Arctic regions of the northern hemisphere (Figure **4.4.3.9**). The average winter temperature is -34°C and the average summer temperature is from 3°C to 12°C. Plants in the arctic tundra have a very short growing season of approximately 10–12 weeks. However, during this time, there are almost 24 hours of daylight and plant growth is rapid. The annual precipitation of the Arctic tundra is very low with little annual variation in precipitation. And, as in the boreal forests, there is little evaporation due to the cold temperatures.

Plants in the Arctic tundra are generally low to the ground (Figure **4.4.3.9**). There is little species diversity, low net primary productivity, and low aboveground biomass. The soils of the Arctic tundra may remain in a perennially frozen state referred to as **permafrost**. The permafrost makes it impossible for roots to penetrate deep into the soil and slows the decay of organic matter, which inhibits the release of nutrients from organic matter. During the growing season, the ground of the Arctic tundra can be completely covered with plants or lichens.

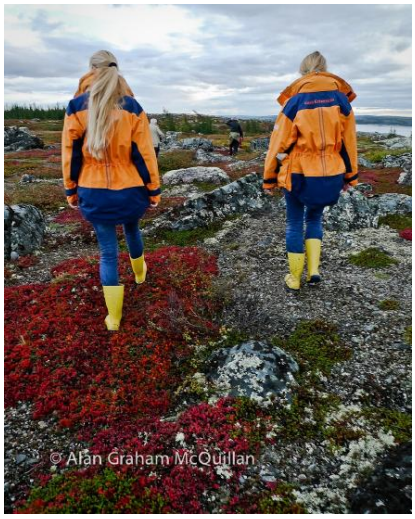


Figure **4.4.3.9:** Low-growing plants dominate the tundra landscape. Alan877 CC BY-NC-ND 2.0.

Optional Activity 4.4.3.1

Figure 4.4.3.1: Which of the following statements about biomes is false?

A. Chaparral is dominated by shrubs.
B. Savannas and temperate grasslands are dominated by grasses.
C. Boreal forests are dominated by deciduous trees.
D. Lichens are common in the arctic tundra.

Answer

C. Boreal forests are not dominated by deciduous trees.

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Unit 4.4.4 - Aquatic Biomes

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
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Learning Objectives

- Describe the effects of abiotic factors on the composition of plant and animal communities in aquatic biomes
- Compare and contrast the characteristics of the ocean zones
- Summarize the characteristics of standing water and flowing water freshwater biomes

Introduction

Like terrestrial biomes, aquatic biomes are influenced by a series of abiotic factors. The aquatic medium—water— has different physical and chemical properties than air. Even if the water in a pond or other body of water is perfectly clear (there are no suspended particles), water, on its own, absorbs light. As one descends into a deep body of water, there will eventually be a depth at which sunlight cannot reach. While there are some abiotic and biotic factors in a terrestrial ecosystem that might obscure light (like fog, dust, or insect swarms), usually these are not permanent features of the environment. The importance of light in aquatic biomes is central to the communities of organisms found in both freshwater and marine ecosystems. In freshwater systems, **stratification** due to differences in density is perhaps the most critical abiotic factor and is related to the energy aspects of light. The thermal properties of water (rates of heating and cooling) are significant to the function of marine systems and have major impacts on global climate and weather patterns. Marine systems are also influenced by large-scale physical water movements, such as currents; these are less important in most freshwater lakes.

Video



In this 6-minute video, review aquatic biomes which encompass the majority of the Earth.
Question after watching: The terrestrial biomes are distinguished by climate, whereas this is not the case for aquatic biomes. Why is this?

Marine Biomes

The ocean is the largest marine biome. It is a continuous body of salt water that is relatively uniform in chemical composition; it is a weak solution of mineral salts and decayed biological matter. Within the ocean, coral reefs are a second kind of marine biome. Estuaries, coastal areas where salt water and fresh water mix, form a third unique marine biome.

Ocean

The ocean is categorized by several areas or zones (Figure 4.4.4.1). The physical diversity of the ocean is a significant influence on plants, animals, and other organisms. The ocean is categorized into different zones based on how far light reaches into the water. Each zone has a distinct group of species adapted to the biotic and abiotic conditions particular to that zone.

All of the ocean's open water is referred to as the **pelagic realm** (or zone). The **benthic realm** (or zone) extends along the ocean bottom from the shoreline to the deepest parts of the ocean floor. Within the pelagic realm is the **photic zone**, which is the portion of the ocean that light can penetrate (approximately 200 m). At depths greater than 200 m, light cannot penetrate; thus, this is referred to as the **aphotic zone**. The majority of the ocean is aphotic and lacks sufficient light for photosynthesis. The deepest part of the ocean, the Challenger Deep (in the Mariana Trench, located in the western Pacific Ocean), is about 11,000 m deep. To give some perspective on the depth of this trench, the ocean is, on average, 4,267 m deep. These realms and zones are relevant to freshwater lakes as well.

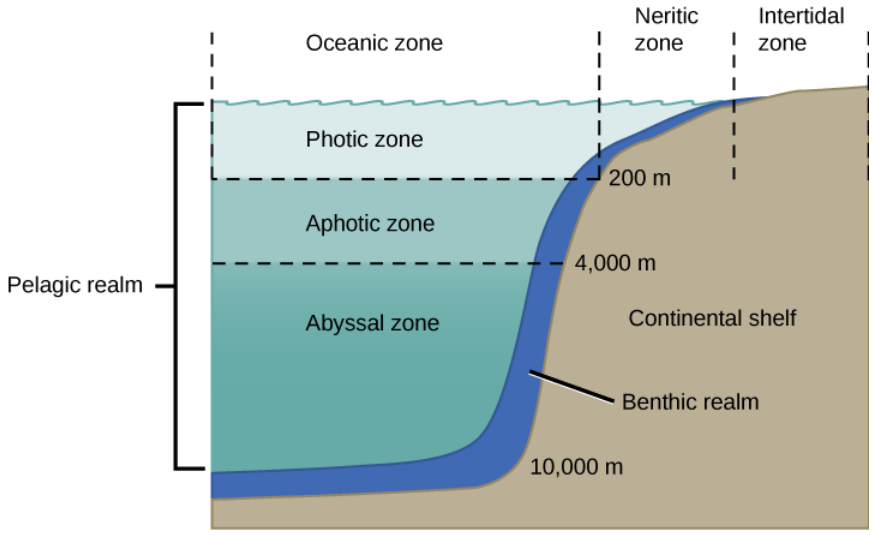


Figure 4.4.4.1: The ocean is divided into different zones based on water depth and distance from the shoreline.

? Optional Activity 4.4.4.1

Figure 4.4.4.1: In which of the following regions would you expect to find photosynthetic organisms?

A. the aphotic zone, the neritic zone, the oceanic zone, and the benthic realm
B. the photic zone, the intertidal zone, the neritic zone, and the oceanic zone
C. the photic zone, the benthic zone, the neritic zone, and the oceanic zone
D. the pelagic realm, the aphotic zone, the neritic zone, and the oceanic zone

Answer

C. Photosynthetic organisms would be found in the photic, benthic, neritic, and oceanic zones.

The **intertidal zone**, which is the zone between high and low tide, is the oceanic region that is closest to land (Figure 4.4.4.1). Generally, most people think of this portion of the ocean as a sandy beach. In some cases, the intertidal zone is indeed a sandy beach, but it can also be rocky or muddy. The intertidal zone is an extremely variable environment because of tides. Organisms are exposed to air and sunlight at low tide and are underwater most of the time, especially during high tide. Therefore, living things that thrive in the intertidal zone are adapted to being dry for long periods of time. The shore of the intertidal zone is also repeatedly

struck by waves, and the organisms found there are adapted to withstand damage from the pounding action of the waves (Figure 4.4.4.2). The exoskeletons of shoreline crustaceans (such as the shore crab, *Carcinus maenas*) are tough and protect them from desiccation (drying out) and wave damage. Another consequence of the pounding waves is that few algae and plants establish themselves in the constantly moving rocks, sand, or mud.



Figure 4.4.4.2: Sea urchins, mussel shells, and leather and purple sea stars are often found in the intertidal zone of BC. This photo was takenin Kachemak Bay, Alaska, but it is representative of BC intertidal life. (credit: NOAA)

The **neritic zone** (Figure 4.4.4.1) extends from the intertidal zone to depths of about 200 m at the edge of the continental shelf. Since light can penetrate this depth, photosynthesis can occur in the neritic zone. The water here contains silt and is well-oxygenated, low in pressure, and stable in temperature. Phytoplankton and floating *Sargassum* (a type of free-floating marine seaweed) provide a habitat and food source for some sea life found in the neritic zone. Zooplankton, protists, small fishes, and shrimp are found in the neritic zone and are the base of the food chain for most of the world's fisheries.

Beyond the neritic zone is the open ocean area known as the **oceanic zone** (Figure 4.4.4.1). Within the oceanic zone there is thermal stratification where warm and cold waters mix because of ocean currents. Abundant plankton serve as the base of the food chain for larger animals such as whales and dolphins. Nutrients are scarce and this is a relatively less productive part of the marine biome. When photosynthetic organisms and the protists and animals that feed on them die, their bodies fall to the bottom of the ocean where they remain; unlike freshwater lakes, the open ocean lacks a process for bringing the organic nutrients back up to the surface. The majority of organisms in the aphotic zone include sea cucumbers (phylum Echinodermata) and other organisms that survive on the nutrients contained in the dead bodies of organisms in the photic zone.

Beneath the pelagic zone is the benthic realm, the deepwater region beyond the continental shelf (Figure 4.4.4.1). The bottom of the benthic realm is comprised of sand, silt, and dead organisms. Temperature decreases, remaining above freezing, as water depth increases. This is a nutrient-rich portion of the ocean because of the dead organisms that fall from the upper layers of the ocean. Because of this high level of nutrients, a diversity of fungi, sponges, sea anemones, marine worms, sea stars, fishes, and bacteria exist.

The deepest part of the ocean is the **abyssal zone**, which is at depths of 4,000 m or greater. The abyssal zone (Figure 4.4.4.1) is very cold and has very high pressure, high oxygen content due to stratification, and low nutrient content. There are a variety of invertebrates and fishes found in this zone, but the abyssal zone does not have plants because of the lack of light. Hydrothermal vents are found primarily in the abyssal zone; chemosynthetic bacteria utilize the hydrogen sulfide and other minerals emitted from the vents. These chemosynthetic bacteria use hydrogen sulfide as an energy source and serve as the base of the food chain found in the abyssal zone.

Coral Reefs

Coral reefs are ocean ridges formed by marine invertebrates living in warm shallow waters within the photic zone of the ocean. They are found within 30˚ north and south of the equator. The Great Barrier Reef is a well-known reef system located several miles off the northeastern coast of Australia. Other coral reef systems are fringing islands, which are directly adjacent to land, or atolls, which are circular reef systems surrounding a former landmass that is now underwater. The coral organisms (members of phylum Cnidaria) are colonies of saltwater polyps that secrete a calcium carbonate skeleton. These calcium-rich skeletons slowly

accumulate, forming the underwater reef (Figure **4.4.4.3**). Corals found in shallower waters (at a depth of approximately 60 m) have a mutualistic relationship with photosynthetic unicellular algae (dinoflagellates known as zooxanthellae). The relationship provides corals with the majority of the nutrition and the energy they require. The waters in which these corals live are nutritionally poor and, without this mutualism, it would not be possible for large corals to grow. Some corals living in deeper and colder water do not have a mutualistic relationship with algae; these corals attain energy and nutrients using stinging cells on their tentacles to capture prey.

It is estimated that more than 4,000 fish species inhabit coral reefs. These fishes can feed on coral, the **cryptofauna** (invertebrates found within the calcium carbonate substrate of the coral reefs), or the seaweed and algae that are associated with the coral. In addition, some fish species inhabit the boundaries of a coral reef; these species include predators, herbivores, or **planktivores** (that eat plankton).



Figure **4.4.4.3**: Coral reefs are formed by the calcium carbonate skeletons of coral organisms, which are marine invertebrates in the phylum Cnidaria. (credit: Terry Hughes)

Evolution Connection: Global Decline of Coral Reefs

It takes a long time to build a coral reef. The animals that create coral reefs have evolved over millions of years, continuing to slowly deposit the calcium carbonate that forms their characteristic ocean homes. Bathed in warm tropical waters, the coral animals and their symbiotic algal partners evolved to survive at the upper limit of ocean water temperature.

Together, climate change and human activity pose dual threats to the long-term survival of the world's coral reefs. Excessive sea surface temperatures due to climate change cause the reefs to expel their symbiotic, food-producing algae, resulting in a phenomenon known as **bleaching**. When bleaching occurs, the reefs lose much of their characteristic color as the algae and the coral animals die if loss of the symbiotic zooxanthellae is prolonged.

In addition, as CO_2 dissolves in ocean waters, it lowers the pH and increases ocean acidity. As acidity increases, it interferes with the calcification that normally occurs as coral animals build their calcium carbonate homes. When a coral reef begins to die, species diversity plummets as animals lose food and shelter. Coral reefs are also economically important tourist destinations, so the decline of coral reefs poses a serious threat to coastal economies.

Human population growth has damaged corals in other ways, too. As human coastal populations increase, the runoff of sediment and agricultural chemicals has increased causing some of the once-clear tropical waters to become cloudy. At the same time, overharvesting has allowed the predator species that eat corals to go unchecked.

Although a rise in global temperatures of 1–2˚C (a conservative projection) in the coming decades may not seem large, it is significant to this biome. When change occurs rapidly, species can become extinct before evolution leads to new adaptations. Many scientists believe that climate change, with its rapid (in terms of evolutionary time) and inexorable increases in temperature, is tipping the balance beyond the point at which many of the world's coral reefs can recover.

More is covered in (Unit 5.3)

Estuaries

Estuaries are biomes that occur where a source of fresh water, such as a river, meets the ocean. Therefore, both fresh water and salt water are found in the same vicinity; mixing results in a diluted (**brackish**) saltwater. Estuaries form protected areas where many of the young offspring of crustaceans, mollusks, and fish begin their lives. Salinity is a very important factor that influences the organisms and the adaptations of the organisms found in estuaries. The salinity of estuaries varies and is based on the rate of flow of its freshwater sources. Once or twice a day, high tides bring salt water into the estuary. Low tides occurring at the same frequency reverse the current of salt water.

The short-term and rapid variation in salinity due to the mixing of fresh water and salt water is a difficult physiological challenge for the plants and animals that inhabit estuaries. Many estuarine plant species are **halophytes**: plants that can tolerate salty conditions. Halophytic plants are adapted to deal with the salinity resulting from saltwater on their roots or from sea spray. In some halophytes, filters in the roots remove the salt from the water that the plant absorbs. Other plants are able to pump oxygen into their roots. Animals, such as mussels and clams (phylum Mollusca), have developed behavioral adaptations that expend a lot of energy to function in this rapidly changing environment. When these animals are exposed to low salinity, they stop feeding, close their shells, and switch from aerobic respiration (in which they use gills) to anaerobic respiration (a process that does not require oxygen). When high tide returns to the estuary, the salinity and oxygen content of the water increases, and these animals open their shells, begin feeding, and return to aerobic respiration.

Freshwater Biomes

Freshwater biomes include lakes and ponds (standing water) as well as rivers and streams (flowing water). They also include wetlands, which will be discussed below. Humans rely on freshwater biomes to provide aquatic resources for drinking water, crop irrigation, sanitation, and industry. These various roles and human benefits are referred to as ecosystem services. Lakes and ponds are found in terrestrial landscapes and are, therefore, connected with abiotic and biotic factors influencing these terrestrial biomes.

Lakes and Ponds

Lakes and ponds can range in area from a few square meters to thousands of square kilometers. Temperature is an important abiotic factor affecting living things found in lakes and ponds. In the summer, thermal stratification of lakes and ponds occurs when the upper layer of water is warmed by the sun and does not mix with deeper, cooler water. Light can penetrate within the photic zone of the lake or pond. Phytoplankton (algae and cyanobacteria) are found here and carry out photosynthesis, providing the base of the food web of lakes and ponds. Zooplankton, such as rotifers and small crustaceans, consume phytoplankton. At the bottom of lakes and ponds, bacteria in the aphotic zone break down dead organisms that sink to the bottom.

Nitrogen and phosphorus are important limiting nutrients in lakes and ponds. Because of this, they are density-dependent factors for phytoplankton growth in lakes and ponds. When there is a large input of nitrogen and phosphorus known as **eutrophication** (from sewage and runoff from fertilized lawns and farms, for example), the growth of algae skyrockets, resulting in a large accumulation of algae called an algal bloom. **Algal blooms** can become so extensive that they reduce light penetration in water (Figure 4.4.4.4). As a result, the lake or pond becomes aphotic and photosynthetic plants cannot survive. When the algae die and decompose, severe oxygen depletion of the water occurs. Fishes and other organisms that require oxygen are then more likely to die, and resulting dead zones are found across the globe (Unit 4.4.5). Lake Erie and the Gulf of Mexico represent freshwater and marine habitats where phosphorus control and stormwater runoff pose significant environmental challenges.



Figure 4.4.4.4: The uncontrolled growth of algae in this lake has resulted in an **algal bloom**. (credit: Jeremy Nettleton)

Rivers and Streams

Rivers and streams are continuously moving bodies of water that carry large amounts of water from the source, or headwater, to a lake or ocean. The largest rivers include the Nile River in Africa, the Amazon River in South America, and the Mackenzie River in the Northern Territories.

Abiotic features of rivers and streams vary along the length of the river or stream. Streams begin at a point of origin referred to as **source water**. The source water is usually cold, low in nutrients, and clear. The **channel** (the width of the river or stream) is narrower than at any other place along the length of the river or stream. Because of this, the current is often faster here than at any other point of the river or stream.

The fast-moving water results in minimal silt accumulation at the bottom of the river or stream; therefore, the water is clear. Photosynthesis here is mostly attributed to algae that are growing on rocks; the swift current inhibits the growth of phytoplankton. An additional input of energy can come from leaves or other organic material that falls into the river or stream from trees and other plants that border the water. When the leaves decompose, the organic material and nutrients in the leaves are returned to the water. Plants and animals have adapted to this fast-moving water. For instance, leeches (phylum Annelida) have elongated bodies and suckers on both ends. These suckers attach to the substrate, keeping the leech anchored in place. Freshwater trout species (phylum Chordata) are important predators in these fast-moving rivers and streams.

As the river or stream flows away from the source, the width of the channel gradually widens and the current slows. This slow-moving water, caused by the gradient decrease and the volume increase as tributaries unite, has more sedimentation. Phytoplankton can also be suspended in slow-moving water. Therefore, the water will not be as clear as it is near the source. The water is also warmer. Worms (phylum Annelida) and insects (phylum Arthropoda) can be found burrowing into the mud. The higher-order predator vertebrates (phylum Chordata) include waterfowl, frogs, and fishes. These predators must find food in these slow-moving, sometimes murky, waters, and, unlike the trout in the waters at the source, these vertebrates may not be able to use vision as their primary sense to find food. Instead, they are more likely to use taste or chemical cues to find prey.

Wetlands

Wetlands are environments in which the soil is either permanently or periodically saturated with water. Wetlands are different from lakes because wetlands are shallow bodies of water whereas lakes vary in depth. **Emergent vegetation** consists of wetland plants that are rooted in the soil but have portions of leaves, stems, and flowers extending above the water's surface. There are several types of wetlands including marshes, swamps, bogs, mudflats, and salt marshes (Figure 4.4.4.5). The three shared characteristics among these types—what makes them wetlands—are their hydrology, hydrophytic vegetation, and hydric soils.



Figure 4.4.4.5: Located in southern Florida, Everglades National Park is a vast array of wetland environments, including sawgrass marshes, cypress swamps, and estuarine mangrove forests. Here, a great egret walks among cypress trees. (credit: NPS)

Freshwater **marshes and swamps** are characterized by slow and steady water flow. **Bogs** develop in depressions where water flow is low or nonexistent. Bogs usually occur in areas where there is a clay bottom with poor percolation. **Percolation** is the movement of water through the pores in the soil or rocks. The water found in a bog is stagnant and oxygen depleted because the oxygen that is used during the decomposition of organic matter is not replaced. As the oxygen in the water is depleted, decomposition slows. This leads to organic acids and other acids building up and lowering the pH of the water. At a lower pH, nitrogen becomes unavailable to plants. This creates a challenge for plants because nitrogen is an important limiting resource. Some types of bog plants (such as sundews, pitcher plants, and Venus flytraps) capture insects and extract nitrogen from their bodies. Bogs have low net primary productivity because the water found in bogs has low levels of nitrogen and oxygen.

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Unit 4.4.5 - Biogeochemical Cycles

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 90 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 4.3.6, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Discuss the biogeochemical cycles of water, carbon, nitrogen, phosphorus, and sulfur
- Explain how human activities have impacted these cycles and the potential consequences for Earth

Introduction

Energy flows directionally through ecosystems, entering as sunlight (or inorganic molecules for chemoautotrophs) and leaving as heat during the many transfers between trophic levels. However, the matter that makes up living organisms is conserved and recycled. The six most common elements associated with organic molecules—carbon, nitrogen, hydrogen, oxygen, phosphorus, and sulfur—take a variety of chemical forms and may exist for long periods in the atmosphere, on land, in water, or beneath the Earth's surface. Geologic processes through the **geosphere**, or rock of the Earth, such as weathering, erosion, water drainage, and the **subduction** of the continental plates, all play a role in this recycling of materials. Because geology and chemistry have major roles in the study of this process, the recycling of inorganic matter between living organisms and their environment is called a **biogeochemical cycle**.

Water contains hydrogen and oxygen, which is essential to all living processes. The **hydrosphere** is the area of the Earth where water movement and storage occurs: as liquid water on the surface and beneath the surface or frozen (rivers, lakes, oceans, groundwater, polar ice caps, and glaciers), and as water vapor in the atmosphere. Carbon is found in all organic macromolecules and is an important constituent of fossil fuels. Nitrogen is a major component of our nucleic acids and proteins and is critical to human agriculture. Phosphorus, a major component of nucleic acid (along with nitrogen), is one of the main ingredients in artificial fertilizers used in agriculture and their associated environmental impacts on our surface water. Sulfur, critical to the three-dimensional folding of proteins (as in disulfide binding), is released into the atmosphere by the burning of fossil fuels, such as coal.

The cycling of these elements is interconnected. For example, the movement of water is critical for the leaching of nitrogen and phosphate into rivers, lakes, and oceans. Furthermore, the ocean itself is a major reservoir for carbon. Thus, mineral nutrients are cycled, either rapidly or slowly, through the entire biosphere, from one living organism to another, and between the biotic and abiotic world.

Video

In this 6-minute video, you will examine how chemicals (nutrients) are recycled in an ecosystem and how energy flows through the ecosystem.

Questions after watching: A house plant in a terrarium with good soil is an isolated ecosystem. Is this closed ecosystem capable of recycling all of its needed chemicals? What are its sources of nutrients (chemicals) and energy?

The Water (Hydrologic) Cycle

Water is the basis of all living processes. The human body is more than 50% water and human cells are more than 70% water. Thus, most land animals need a supply of fresh water to survive. However, when examining the stores of water on Earth, 97.5 percent of it is non-potable salt water (Figure 4.4.5.1). Of the remaining water, 99 percent is locked underground as water or as ice. Thus, less than 1% of fresh water is easily accessible from lakes and rivers. Many living things, such as plants, animals, and fungi, are dependent on the small amount of fresh surface water supply, a lack of which can have massive effects on ecosystem dynamics. Humans, of course, have developed technologies to increase water availability, such as digging wells to harvest groundwater, storing rainwater, and using desalination to obtain drinkable water from the ocean. Although this pursuit of drinkable water has been ongoing throughout human history, the supply of fresh water is still a major issue in modern times.

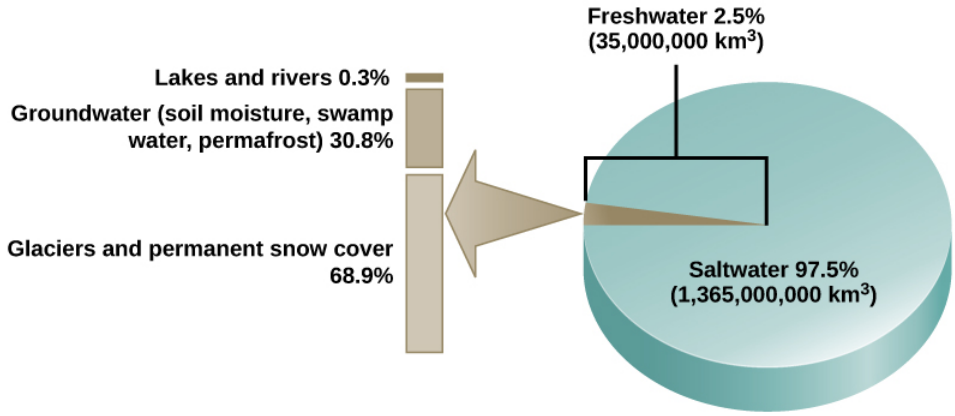


Figure 4.4.5.1: Only 2.5 percent of water on Earth is fresh water, and less than 1% of fresh water is easily accessible to living things.

Water cycling is extremely important to ecosystem dynamics. Water has a major influence on climate and, thus, on the environments of ecosystems, some located on distant parts of the Earth. Most of the water on Earth is stored for long periods in the oceans, underground, and as ice. Figure 4.4.5.2 illustrates the average time that an individual water molecule may spend in the Earth's major water reservoirs. **Residence time** is a measure of the average time an individual molecule stays in a particular reservoir. A large amount of the Earth's water is locked in place in these reservoirs as ice, beneath the ground, and in the ocean, and, thus, is unavailable for short-term cycling (only surface water can evaporate).

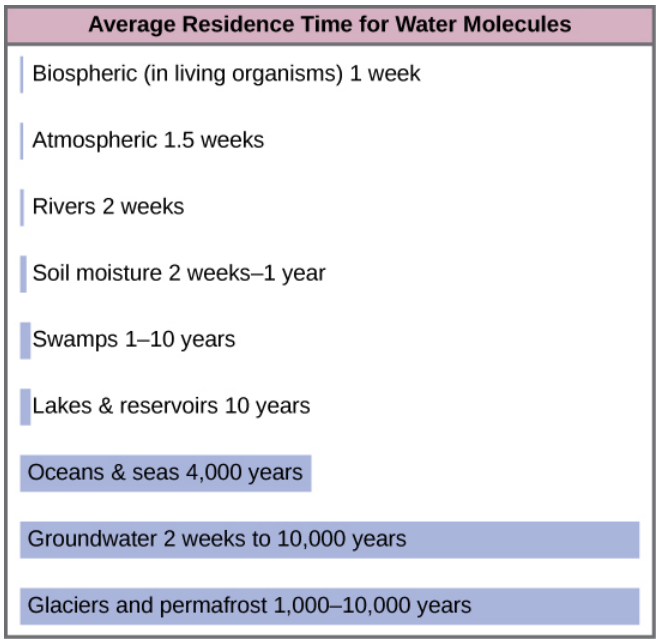


Figure **4.4.5.2**: This graph shows the average residence time for water molecules in the Earth's water reservoirs.

There are various processes that occur during the cycling of water, shown in Figure **4.4.5.3**. These processes include the following:

- evaporation/sublimation
- condensation/precipitation
- subsurface water flow
- surface runoff/snowmelt
- streamflow

The water cycle is driven by the Sun's energy as it warms the oceans and other surface waters. This leads to the **evaporation** (water to water vapor) of liquid surface water and the **sublimation** (ice to water vapor) of frozen water, which deposits large amounts of water vapor into the atmosphere. Over time, this water vapor condenses into clouds as liquid or frozen droplets and is eventually followed by **precipitation** (rain or snow), which returns water to the Earth's surface. Rain eventually **infiltrates** into the ground, where it may evaporate again if it is near the surface, flow beneath the surface, or be stored for long periods. More easily observed is surface **runoff**: the flow of fresh water either from rain or melting ice. Runoff can then make its way through streams and lakes to the oceans or flow directly to the oceans themselves.

Rain and surface runoff are major ways in which minerals, including carbon, nitrogen, phosphorus, and sulfur, are cycled from land to water. The environmental effects of runoff will be discussed later as these cycles are described.

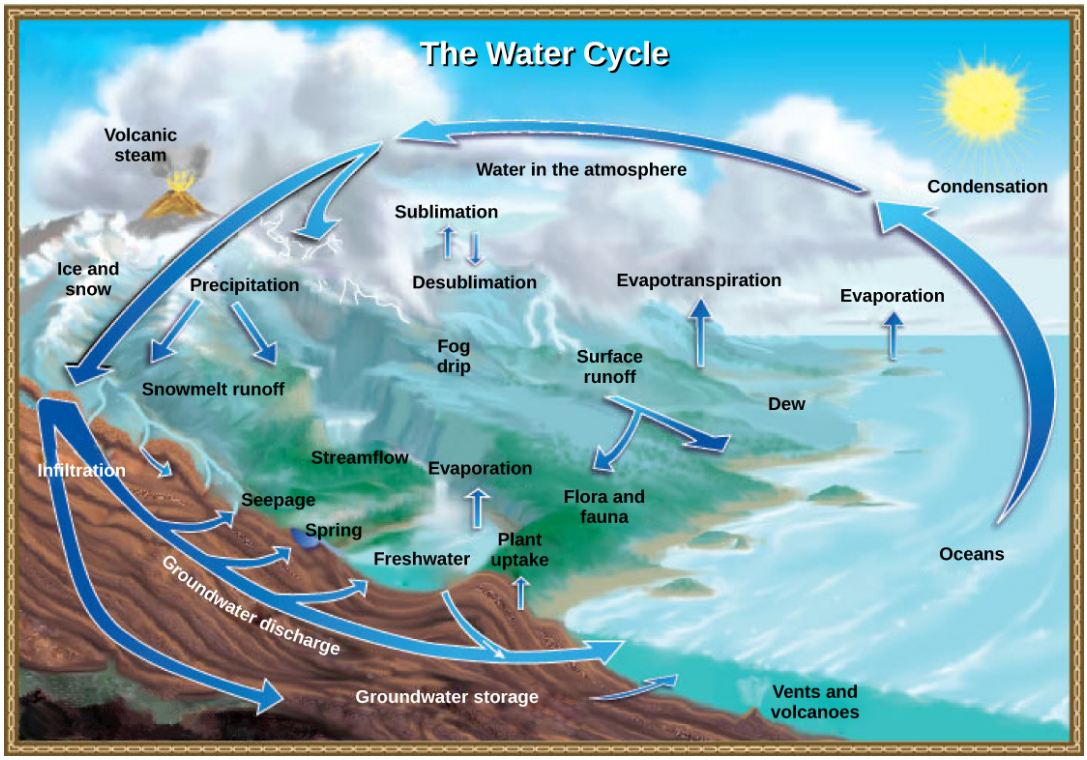


Figure **4.4.5.3**: Water from the land and oceans enters the atmosphere by evaporation or sublimation, where it condenses into clouds and falls as rain or snow. Precipitated water may enter freshwater bodies or infiltrate the soil. The cycle is complete when surface or groundwater reenters the ocean. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

The Carbon Cycle

Carbon is the second most abundant element in living organisms. Carbon is present in all organic molecules, and its role in the structure of macromolecules is of primary importance to living organisms. Carbon compounds contain especially high energy, particularly those derived from fossilized organisms, mainly plants, which humans use as fuel. Since the 1800s, the number of countries using massive amounts of fossil fuels has increased. Since the beginning of the Industrial Revolution, global demand for the Earth's limited fossil fuel supplies has risen; therefore, the amount of carbon dioxide in our atmosphere has increased. This increase in carbon dioxide has been associated with climate change and other disturbances of the Earth's ecosystems and is a major environmental concern worldwide. Thus, a **carbon footprint** is based on how much carbon dioxide is produced by an individual or per capita and how much fossil fuel countries consume.

The carbon cycle is most easily studied as two interconnected sub-cycles: one dealing with rapid carbon exchange among living organisms and the other dealing with the long-term cycling of carbon through geologic processes. The entire carbon cycle is shown in Figure **4.4.5.4**.

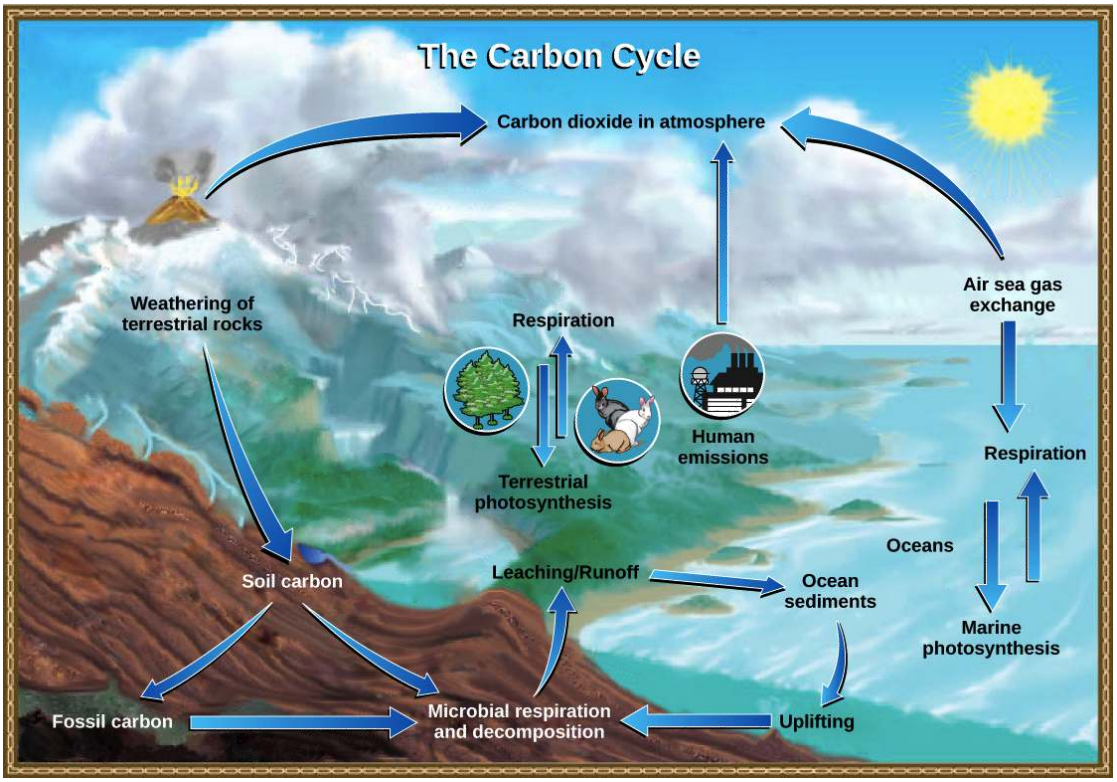


Figure **4.4.5.4**: Carbon dioxide gas exists in the atmosphere and is dissolved in water. Photosynthesis converts carbon dioxide gas to organic carbon, and respiration cycles the organic carbon back into carbon dioxide gas. Long-term storage of organic carbon occurs when matter from living organisms is buried deep underground and becomes fossilized. Volcanic activity and, more recently, human emissions, bring this stored carbon back into the carbon cycle. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

The Biological Carbon Cycle

Living organisms are connected in many ways, even between ecosystems. A good example of this connection is the exchange of carbon between autotrophs and heterotrophs within and between ecosystems by way of atmospheric carbon dioxide. Carbon dioxide is the basic building block that most autotrophs use to build multi-carbon, high-energy compounds, such as glucose. The energy harnessed from the Sun is used by these organisms to form the covalent bonds that link carbon atoms together. These chemical bonds thereby store this energy for later use in the process of respiration. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (carbonic acid, $H_2CO_3^-$). However carbon dioxide is acquired, a by-product of the process is oxygen. Photosynthetic organisms are responsible for depositing approximately 21% of the atmosphere's oxygen content that we observe today.

Heterotrophs and autotrophs are partners in biological carbon exchange (especially the primary consumers, largely herbivores). Heterotrophs acquire the high-energy carbon compounds from the autotrophs by consuming them and breaking them down by respiration to obtain cellular energy, such as ATP. The most efficient type of respiration, aerobic respiration, requires oxygen obtained from the atmosphere or dissolved in water and releases carbon dioxide as a by-product (this is a source). Thus, there is a constant exchange of oxygen and carbon dioxide between the autotrophs (which need the carbon) and the heterotrophs (which need the oxygen). Gas exchange through the atmosphere and water is one way that the carbon cycle connects all living organisms on Earth.

The Biogeochemical Carbon Cycle

The movement of carbon through the land, water, and air is complex, and in many cases, it occurs much more slowly geologically than as seen between living organisms. Carbon is stored for long periods in what are known as carbon reservoirs, or sinks, which include the atmosphere, bodies of liquid water (mostly oceans), ocean sediment, soil, land sediments (including fossil fuels), and the Earth’s interior.

As stated, the atmosphere is a major reservoir of carbon in the form of carbon dioxide and is essential to the process of photosynthesis. The level of carbon dioxide in the atmosphere is greatly influenced by the reservoir of carbon in the oceans. The exchange of carbon between the atmosphere and water reservoirs influences how much carbon is found in each location, and each one affects the other reciprocally. Carbon dioxide (CO_2) from the atmosphere dissolves in water and combines with water molecules to form carbonic acid, and then it ionizes to carbonate and bicarbonate ions.

More than 90 percent of the carbon in the ocean is found as bicarbonate ions. Some of these ions combine with seawater calcium to form calcium carbonate ($CaCO_3$), a major component of marine organism shells. These organisms eventually form sediments on the ocean floor. Over geologic time, the calcium carbonate forms limestone, which comprises the largest carbon reservoir on Earth.

On land, carbon is stored in soil as a result of the decomposition of living organisms (by decomposers) or from weathering of terrestrial rock and minerals. This carbon can be leached into the water reservoirs by surface runoff. Deeper underground, on land and at sea, are fossil fuels: the anaerobically decomposed remains of plants that take millions of years to form. Fossil fuels are considered a **non-renewable resource** because their use far exceeds their rate of formation. A non-renewable resource, such as fossil fuel, is either regenerated very slowly or not at all. Another way for carbon to enter the atmosphere is from land (including land beneath the surface of the ocean) by the eruption of volcanoes and other geothermal systems. Carbon sediments from the ocean floor are taken deep within the Earth by the process of subduction: the movement of one tectonic plate beneath another. Carbon is released as carbon dioxide when a volcano erupts or from volcanic hydrothermal vents.

Carbon dioxide is also added to the atmosphere by the animal husbandry practices of humans. The large numbers of land animals raised to feed the Earth's growing population results in increased carbon dioxide levels in the atmosphere due to farming practices and animal respiration and methane production. This is another example of how human activity indirectly affects biogeochemical cycles in a significant way. Although much of the debate about the future effects of increasing atmospheric carbon on climate change focuses on fossils fuels, scientists take natural processes, such as volcanoes and respiration, into account as they model and predict the future impact of this increase.

? Optional Activity 4.4.5.1

Carbon is present in the atmosphere as

a. carbon dioxide
b. carbonate ion
c. carbon dust
d. carbon monoxide

Answer

a. carbon dioxide

The Nitrogen Cycle

Getting nitrogen into the living world is difficult. Plants and phytoplankton are not equipped to incorporate nitrogen from the atmosphere due to its chemistry, even though this molecule comprises approximately 78 percent of the atmosphere. Nitrogen enters the living world via free-living and symbiotic bacteria, which incorporate nitrogen into their macromolecules through nitrogen fixation (conversion of N_2 into organic molecules) (see Unit 3.4.2). Cyanobacteria live in most aquatic ecosystems where sunlight is present; they play a key role in nitrogen fixation. Cyanobacteria are able to use inorganic sources of nitrogen to "fix" nitrogen. *Rhizobium* bacteria live symbiotically in the root nodules of legumes (such as peas, beans, and peanuts) and provide them with the organic nitrogen they need. Free-living bacteria, such as *Azotobacter*, are also important nitrogen fixers.

Organic nitrogen is especially important to the study of ecosystem dynamics since many ecosystem processes, such as primary production and decomposition, are limited by the available supply of nitrogen. As shown in Figure **4.4.5.5**, the nitrogen that enters living systems by nitrogen fixation is successively converted from organic nitrogen back into nitrogen gas by bacteria. This process occurs in three steps in terrestrial systems: ammonification, nitrification, and denitrification. First, the ammonification process converts nitrogenous waste from living animals or from the remains of dead animals into ammonium (NH_4^+) by certain bacteria and fungi. Second, the ammonium is converted to nitrites (NO_2^-) by bacteria, such as *Nitrosomonas*, through nitrification.

Subsequently, nitrites are converted to nitrates (NO_3^-) by similar organisms. Third, the process of denitrification occurs, whereby bacteria, such as *Pseudomonas* and *Clostridium*, convert the nitrates into nitrogen gas, allowing it to re-enter the atmosphere.

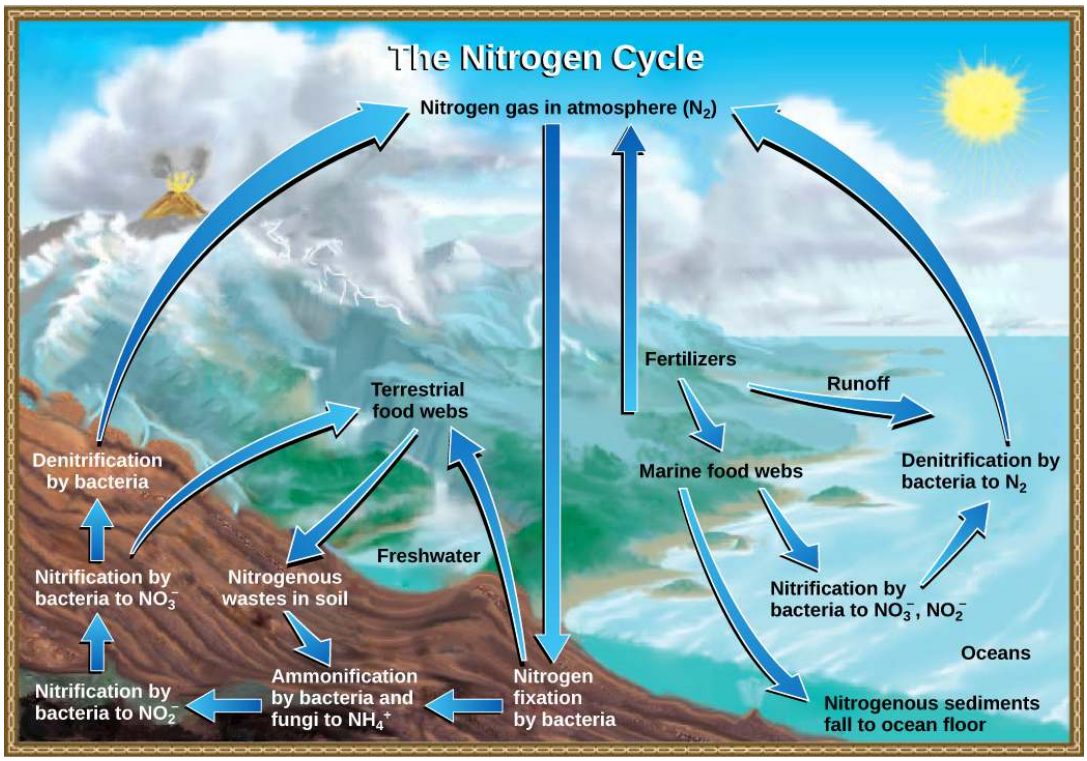


Figure **4.4.5.5**: Nitrogen enters the living world from the atmosphere via nitrogen-fixing bacteria. This nitrogen and nitrogenous waste from animals is then processed back into gaseous nitrogen by soil bacteria, which also supply terrestrial food webs with the organic nitrogen they need. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

? Optional Activity 4.4.5.2

Which of the following statements about the nitrogen cycle is false?

A. Ammonification converts organic nitrogenous matter from living organisms into ammonium (NH_4^+).
B. Denitrification by bacteria converts nitrates (NO_3^-) to nitrogen gas (N_2).
C. Nitrification by bacteria converts nitrates (NO_3^-) to nitrites (NO_2^-).
D. Nitrogen fixing bacteria convert nitrogen gas (N_2) into organic compounds.

Answer

C. Nitrification by bacteria converts nitrates (NO_3^-) to nitrites (NO_2^-).

Human activity can release nitrogen into the environment by two primary means: the combustion of fossil fuels, which releases different nitrogen oxides, and by the use of artificial fertilizers in agriculture, which are then washed into lakes, streams, and rivers by surface runoff. Atmospheric nitrogen is associated with several effects on Earth's ecosystems including the production of acid rain (as nitric acid, HNO_3) and greenhouse gas (as nitrous oxide, N_2O) potentially causing climate change. A major effect from fertilizer runoff is saltwater and freshwater eutrophication, a process whereby nutrient runoff causes the excess growth of microorganisms, depleting dissolved oxygen levels and killing ecosystem fauna.

A similar process occurs in the marine nitrogen cycle, where the ammonification, nitrification, and denitrification processes are performed by marine bacteria. Some of this nitrogen falls to the ocean floor as sediment, which can then be moved to land in geologic time by uplift of the Earth's surface and thereby incorporated into terrestrial rock. Although the movement of nitrogen from rock directly into living systems has been traditionally seen as insignificant compared with nitrogen fixed from the

atmosphere, a recent study showed that this process may indeed be significant and should be included in any study of the global nitrogen cycle.[1]

The Phosphorus Cycle

Phosphorus is an essential nutrient for living processes; it is a major component of nucleic acid and phospholipids, and, as calcium phosphate, makes up the supportive components of our bones. Phosphorus is often the limiting nutrient (necessary for growth) in aquatic ecosystems (Figure **4.4.5.6**).

Phosphorus occurs in nature as the phosphate ion (PO_4^{3-}). In addition to phosphate runoff as a result of human activity, natural surface runoff occurs when it is leached, or chemically pulled, from phosphate-containing rock by weathering, thus sending phosphates into rivers, lakes, and the ocean. This rock has its origins in the ocean. Phosphate-containing ocean sediments form primarily from the bodies of ocean organisms and from their excretions. However, in remote regions, volcanic ash, aerosols, and mineral dust may also be significant phosphate sources. This sediment then is moved to land over geologic time by the uplifting of areas of the Earth's surface.

Phosphorus is also reciprocally exchanged between phosphate dissolved in the ocean and marine ecosystems. The movement of phosphate from the ocean to the land and through the soil is extremely slow, with the average phosphate ion having an oceanic residence time between 20,000 and 100,000 years.

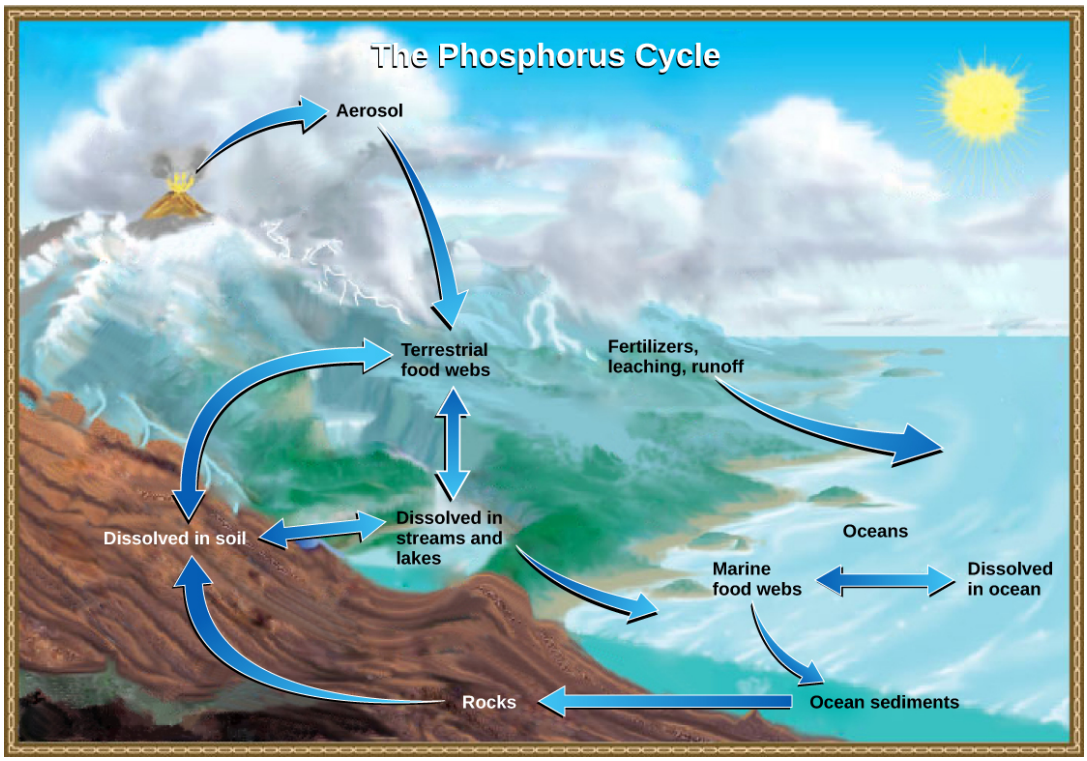


Figure **4.4.5.6**: In nature, phosphorus exists as the phosphate ion (PO_4^{3-}). Weathering of rocks and volcanic activity releases phosphate into the soil, water, and air, where it becomes available to terrestrial food webs. Phosphate enters the oceans via surface runoff, groundwater flow, and river flow. Phosphate dissolved in ocean water cycles into marine food webs. Some phosphate from the marine food webs falls to the ocean floor, where it forms sediment. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

Excess phosphorus and nitrogen that enters these ecosystems from fertilizer runoff and from sewage causes excessive growth of microorganisms and depletes the dissolved oxygen, which leads to the death of many ecosystem fauna, such as shellfish and finfish. This process is responsible for dead zones in lakes and at the mouths of many major rivers (Figure **4.4.5.7**).

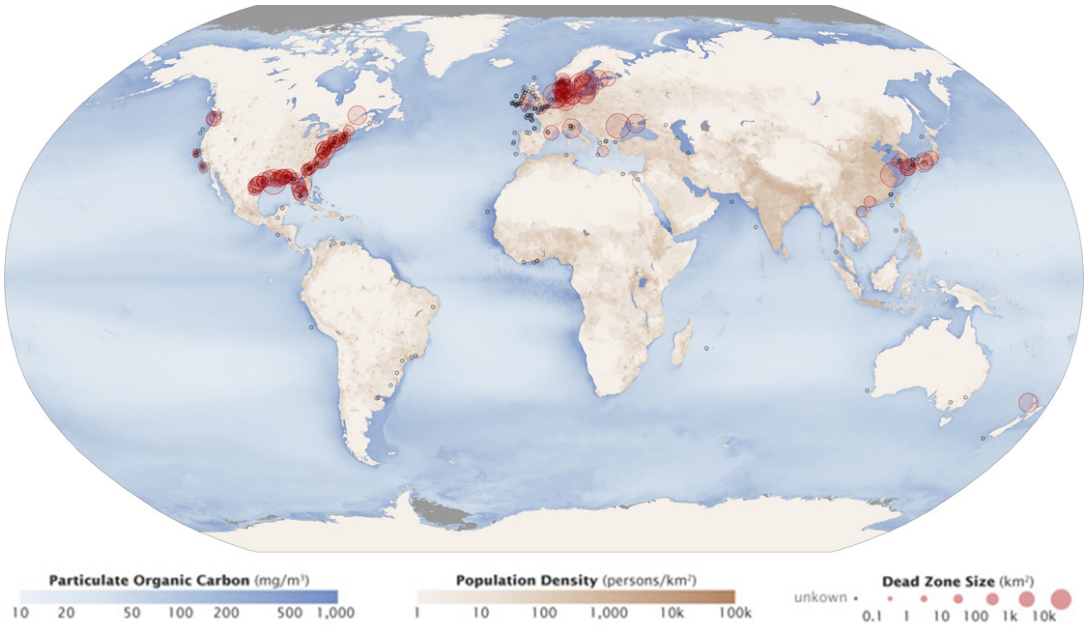
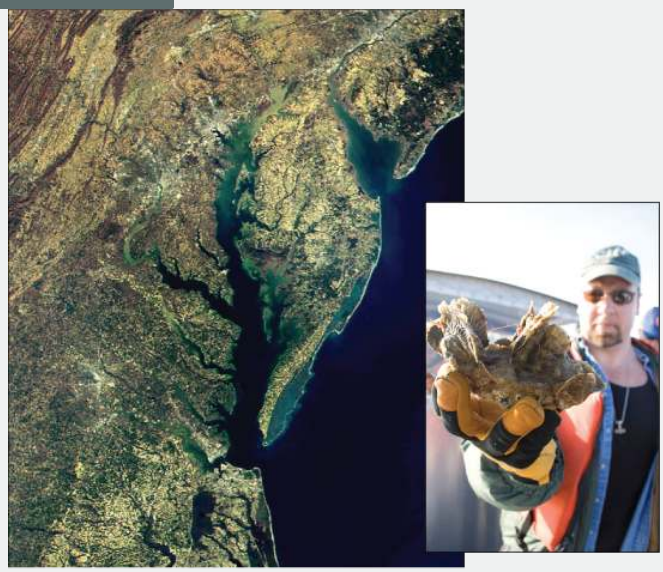


Figure 4.4.5.7: Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. Worldwide, large dead zones are found in coastal areas of high population density. (credit: NASA Earth Observatory)

A **dead zone** is an area within a freshwater or marine ecosystem where large areas are depleted of their normal flora and fauna; these zones can be caused by eutrophication, oil spills, dumping of toxic chemicals, and other human activities. The number of dead zones has been increasing for several years, and more than 400 of these zones were present as of 2008. One of the worst dead zones is off the coast of the United States in the Gulf of Mexico, where fertilizer runoff from the Mississippi River basin has created a dead zone of over 21,919 km^2. Phosphate and nitrate runoff from fertilizers also negatively affect several lake and bay ecosystems including the Chesapeake Bay in the eastern United States (Figure 4.4.5.8).

Everyday Connection: Chesapeake Bay



(a) (b)

Figure 4.4.5.8: This (a) satellite image shows the Chesapeake Bay, an ecosystem affected by phosphate and nitrate runoff. A (b) member of the Army Corps of Engineers holds a clump of oysters being used as a part of the oyster restoration effort in the bay. (credit a: modification of work by NASA/MODIS; credit b: modification of work by U.S. Army)

The Chesapeake Bay has long been valued as one of the most scenic areas in the United States; it is now in distress and is recognized as a declining ecosystem. In the 1970s, the Chesapeake Bay was one of the first ecosystems to have identified dead zones, which continue to kill many fish and bottom-dwelling species, such as clams, oysters, and worms. Several species have declined in the Chesapeake Bay due to surface water runoff containing excess nutrients from artificial fertilizer used on land. The source of the fertilizers (with high nitrogen and phosphate content) is not limited to agricultural practices. There are many nearby urban areas and more than 150 rivers and streams empty into the bay that are carrying fertilizer runoff from lawns and gardens. Thus, the decline of the Chesapeake Bay is a complex issue and requires the cooperation of industry, agriculture, and everyday homeowners.

Of particular interest to conservationists is the oyster population; it is estimated that more than 80,937 hectares of oyster reefs existed in the bay in the 1700s, but that number has now declined to only 14,569 hectares. Oyster harvesting was once a major industry for Chesapeake Bay, but it declined 88 percent between 1982 and 2007. This decline was due not only to fertilizer runoff and dead zones but also to overharvesting. Oysters require a certain minimum population density because they must be in close proximity to reproduce. Human activity has altered the oyster population and locations, greatly disrupting the ecosystem.

The restoration of the oyster population in the Chesapeake Bay has been ongoing for several years with mixed success. Not only do many people find oysters good to eat, but they also clean up the bay. Oysters are filter feeders, and as they eat, they clean the water around them. In the 1700s, it was estimated that it took only a few days for the oyster population to filter the entire volume of the bay. Today, with changed water conditions, it is estimated that the present population would take nearly a year to do the same job.

Restoration efforts have been ongoing for several years by non-profit organizations, such as the Chesapeake Bay Foundation. The restoration goal is to find a way to increase population density so the oysters can reproduce more efficiently. Many disease-resistant varieties (developed at the Virginia Institute of Marine Science for the College of William and Mary) are now available and have been used in the construction of experimental oyster reefs. Efforts to clean and restore the bay by Virginia and Delaware have been hampered because much of the pollution entering the bay comes from other states, which stresses the need for inter-state cooperation to gain successful restoration.

The new, hearty oyster strains have also spawned a new and economically viable industry—oyster aquaculture—which not only supplies oysters for food and profit, but also has the added benefit of cleaning the bay.

Learn about the ecology of *natural* dead zones in the Saanich Inlet in British Columbia here: https://www.uvic.ca/science/home/news/archive/saanich%20inlet%20project.php

The Sulfur Cycle

Sulfur is an essential element for the macromolecules of living things. As a part of the amino acid cysteine, it is involved in the formation of disulfide bonds within proteins, which help to determine their 3-D folding patterns, and hence their functions. As shown in Figure **4.4.5.9**, sulfur cycles between the oceans, land, and atmosphere. Atmospheric sulfur is found in the form of sulfur dioxide (SO_2) and enters the atmosphere in three ways: from the decomposition of organic molecules, from volcanic activity and geothermal vents, and from the burning of fossil fuels by humans.

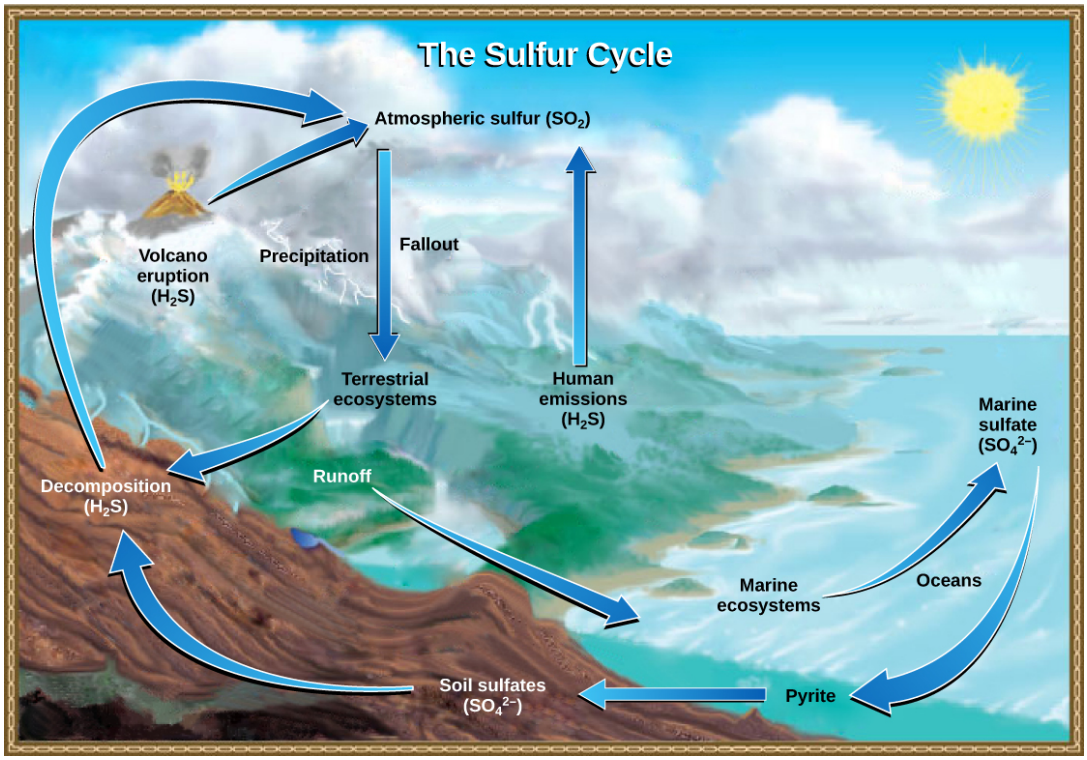


Figure **4.4.5.9**: Sulfur dioxide from the atmosphere becomes available to terrestrial and marine ecosystems when it is dissolved in precipitation as weak sulfuric acid or when it falls directly to the Earth as fallout. Weathering of rocks also makes sulfates available to terrestrial ecosystems. Decomposition of living organisms returns sulfates to the ocean, soil and atmosphere. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

On land, sulfur is deposited in four major ways: precipitation, direct fallout from the atmosphere, rock weathering, and geothermal vents (Figure **4.4.5.10**). Atmospheric sulfur is found in the form of sulfur dioxide (SO_2), and as rain falls through the atmosphere, sulfur is dissolved in the form of weak sulfuric acid (H_2SO_4). Sulfur can also fall directly from the atmosphere in a process called **fallout**.

Also, the weathering of sulfur-containing rocks releases sulfur into the soil. These rocks originate from ocean sediments that are moved to land by the geologic uplifting of ocean sediments. Terrestrial ecosystems can then make use of these soil sulfates (SO_4^{2-}), and upon the death and decomposition of these organisms, release the sulfur back into the atmosphere as hydrogen sulfide (H_2S) gas. Sulfur enters the ocean via runoff from land, from atmospheric fallout, and from underwater geothermal vents. Some ecosystems rely on chemoautotrophs using sulfur as a biological energy source. This sulfur then supports marine ecosystems in the form of sulfates.



Figure 4.4.5.10: At this sulfur vent in Lassen Volcanic National Park in northeastern California, the yellowish sulfur deposits are visible near the mouth of the vent.

Human activities have played a major role in altering the balance of the global sulfur cycle. The burning of large quantities of fossil fuels, especially coal, releases larger amounts of hydrogen sulfide gas into the atmosphere. As rain falls through this gas, it creates the phenomenon known as acid rain. **Acid rain** is corrosive rain caused by rainwater falling to the ground through sulfur dioxide gas, turning it into weak sulfuric acid, which causes damage to aquatic ecosystems. Acid rain damages the natural environment by lowering the pH of lakes, which kills many of the resident fauna; it also affects the man-made environment through the chemical degradation of buildings. For example, many marble monuments, such as the Lincoln Memorial in Washington, DC, have suffered significant damage from acid rain over the years. These examples show the wide-ranging effects of human activities on our environment and the challenges that remain for our future.

? Optional Activity 4.4.5.3

The average time a molecule spends in its reservoir is known as _____.

a. residence time
b. restriction time
c. resilience time
d. storage time

Answer

a. residence time

? Optional Activity 4.4.5.4

The process whereby nitrogen is brought into organic molecules is called _____.

a. ammonification
b. denitrification
c. nitrogen fixation
d. nitrogen cycling

Answer

c. nitrogen fixation

Footnotes

1. 1 Scott L. Morford, Benjamin Z. Houlton, and Randy A. Dahlgren, “Increased Forest Ecosystem Carbon and Nitrogen Storage from Nitrogen Rich Bedrock,” *Nature* 477, no. 7362 (2011): 78–81.

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Unit 4.4.6 - Biogeography

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 30 minutes.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to the Unit Glossary and Summary, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Define biogeography
- List and describe abiotic factors that affect the global distribution of plant and animal species
- Compare the impact of abiotic forces on aquatic and terrestrial environments
- Summarize the effects of abiotic factors on net primary productivity

Introduction

As noted in Unit 2, **biogeography** is the study of the geographic distribution of living things and the abiotic factors that affect their distribution. Abiotic factors such as temperature and rainfall vary based mainly on latitude and elevation. As these abiotic factors change, the composition of plant and animal communities also changes. For example, if you were to begin a journey at the equator and walk north, you would notice gradual changes in plant communities. At the beginning of your journey, you would see tropical wet forests with broad-leaved evergreen trees, which are characteristic of plant communities found near the equator. As you continued to travel north, you would see these broad-leaved evergreen plants eventually give rise to seasonally dry forests with scattered trees. You would also begin to notice changes in temperature and moisture. At about 30 degrees north, these forests would give way to deserts, which are characterized by low precipitation.

Moving farther north, you would see that deserts are replaced by grasslands or prairies. Eventually, grasslands are replaced by deciduous temperate forests. These deciduous forests give way to the boreal forests found in the subarctic, the area south of the Arctic Circle. Finally, you would reach the Arctic tundra, which is found at the most northern latitudes. This trek north reveals gradual changes in both climate and the types of organisms that have adapted to environmental factors associated with ecosystems found at different latitudes. However, different ecosystems exist at the same latitude due in part to abiotic factors such as jet streams, the Gulf Stream, and ocean currents. If you were to hike up a mountain, the changes you would see in the vegetation would parallel those as you move to higher latitudes.

Ecologists who study biogeography examine patterns of species distribution. No species exists everywhere; for example, the Venus flytrap is endemic to a small area in North and South Carolina. An **endemic** species is one that is naturally found only in a specific geographic area that is usually restricted in size. Other species are generalists: species that live in a wide variety of geographic areas; the raccoon, for example, is native to most of North and Central America.

Species distribution patterns are based on biotic and abiotic factors and their influences during the very long periods of time required for species evolution; therefore, early studies of biogeography were closely linked to the emergence of evolutionary thinking in the eighteenth century. Some of the most distinctive assemblages of plants and animals occur in regions that have been physically separated for millions of years by geographic barriers. Biologists estimate that Australia, for example, has between 600,000 and 700,000 species of plants and animals. Approximately 3/4 of living plant and mammal species are endemic species found solely in Australia (Figure **4.4.6.1**).



(a) (b)

Figure **4.4.6.1**: Australia is home to many endemic species. The (a) wallaby (*Wallabia bicolor*), a medium-sized member of the kangaroo family, is a pouched mammal, or marsupial. The (b) echidna (*Tachyglossus aculeatus*) is an egg-laying mammal. (credit a: modification of work by Derrick Coetzee; credit b: modification of work by Allan Whittome)

Sometimes ecologists discover unique patterns of species distribution by determining where species are *not* found. Hawaii, for example, has no native land species of reptiles or amphibians, and has only one native terrestrial mammal, the hoary bat. Most of New Guinea, as another example, lacks placental mammals.

Plants can be endemic or generalists: endemic plants are found only in specific regions of the Earth, while generalists are found in many regions. Isolated land masses—such as Australia, Hawaii, and Madagascar—often have large numbers of endemic plant species. Some of these plants are endangered due to human activity. The forest gardenia (*Gardenia brighamii*), for instance, is endemic to Hawaii; only an estimated 15–20 trees are thought to exist (Figure **4.4.6.2**).



Figure **4.4.6.2**: Listed as federally endangered, the forest gardenia (*Gardenia brighamii*) is a small tree with distinctive flowers. It is found only in five of the Hawaiian Islands in small populations consisting of a few individual specimens. (credit: Forest & Kim Starr)

Energy Sources

Energy from the sun is captured by plants, algae, cyanobacteria, and photosynthetic protists. These organisms convert solar energy into the chemical energy needed by all living things. Light availability can be an important force directly affecting the evolution of adaptations in photoautotrophs. For instance, plants in the understory of a temperate forest are shaded when the trees above them in the canopy completely leaf out in the late spring. Not surprisingly, understory plants have adaptations to successfully capture available light. One such adaptation is the rapid growth of spring ephemeral plants such as the springbeauty (*Claytonia virginica*) (Figure **4.4.6.3**). These spring flowers achieve much of their growth and finish their life cycle (reproduce) early in the season before the trees in the canopy develop leaves.



Figure **4.4.6.3**: The springbeauty (*Claytonia virginica*) is an ephemeral spring plant that flowers early in the spring to avoid competing with larger forest trees for sunlight. (credit: John Beetham)

In aquatic ecosystems, the availability of light may be limited because sunlight is absorbed by water, plants, suspended particles, and resident microorganisms. Toward the bottom of a lake, pond, or ocean, there is a zone that light cannot reach. Photosynthesis cannot take place there and, as a result, a number of adaptations have evolved that enable living things to survive without light. For instance, aquatic plants have photosynthetic tissue near the surface of the water; for example, think of the broad, floating leaves of a water lily—water lilies cannot survive without light. In environments such as hydrothermal vents, some bacteria extract energy from inorganic chemicals because there is no light for photosynthesis.

The availability of nutrients in aquatic systems is also an important aspect of energy or photosynthesis. Many organisms sink to the bottom of the ocean when they die in the open water; when this occurs, the energy found in that living organism is sequestered for some time unless ocean upwelling occurs. **Ocean upwelling** is the rising of deep ocean waters that occurs when prevailing winds blow along surface waters near a coastline (Figure **4.4.6.4**). As the wind pushes ocean waters offshore, water from the bottom of the ocean moves up to replace this water. As a result, the nutrients once contained in dead organisms become available for reuse by other living organisms.

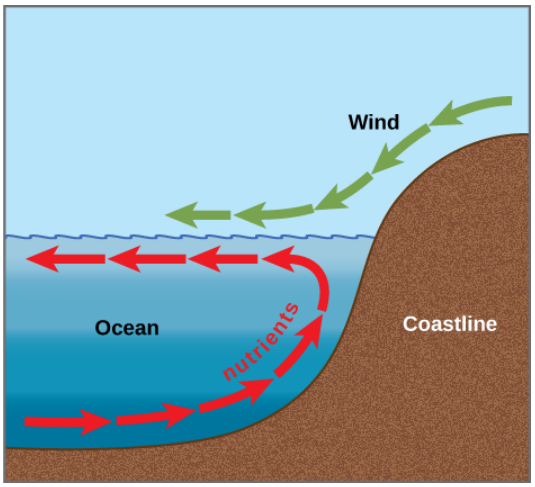


Figure **4.4.6.4**: Ocean upwelling is an important process that recycles nutrients and energy in the ocean. As wind (green arrows) pushes offshore, it causes water from the ocean bottom (red arrows) to move to the surface, bringing up nutrients from the ocean depths. It is prevalent on the west coasts of continents, like in BC, and important to those ocean ecosystems and the maintenance of its biodiversity.

In freshwater systems, the recycling of nutrients occurs in response to air temperature changes. The nutrients at the bottom of lakes are recycled twice each year: in the spring and fall turnover. Spring and fall **turnovers** are seasonal processes that recycle nutrients and oxygen from the bottom of a freshwater ecosystem to the top of a body of water (Figure **4.4.6.5**). These turnovers are caused by the formation of a **thermocline**: a layer of water with a temperature that is significantly different from that of the surrounding layers. In wintertime, the surface of lakes found in many northern regions is frozen. However, the water under the ice is slightly

warmer, and the water at the bottom of the lake is warmer yet at 4°C to 5°C. Water is densest at 4°C; therefore, the deepest water is also the densest. The deepest water is oxygen-poor because the decomposition of organic material at the bottom of the lake uses up available oxygen that cannot be replaced by means of oxygen diffusion into the water due to the surface ice layer.

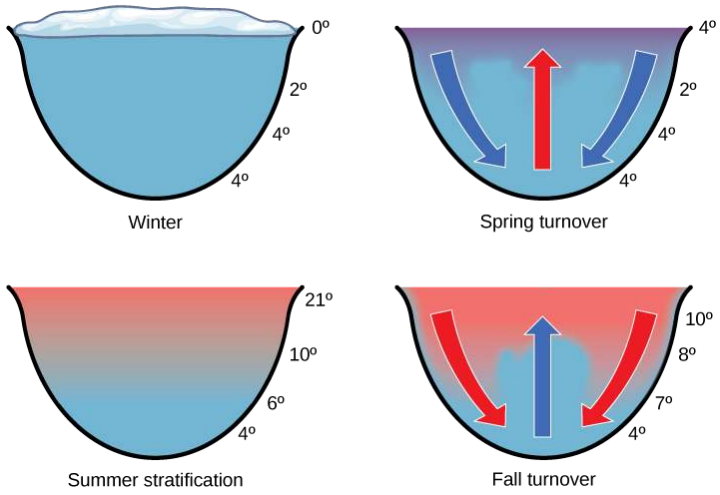


Figure **4.4.6.5**: The spring and fall turnovers are important processes in freshwater lakes that act to move the nutrients and oxygen at the bottom of deep lakes to the top. Turnover occurs because water has a maximum density at 4 °C. Surface water temperature changes as the seasons progress, and denser water sinks.

In springtime, air temperatures increase and surface ice melts. When the temperature of the surface water begins to reach 4°C, the water becomes heavier and sinks to the bottom. The water at the bottom of the lake is then displaced by the heavier surface water and, thus, rises to the top. As that water rises to the top, the sediments and nutrients from the lake bottom are brought along with it. During the summer months, the lake water stratifies, or forms layers, with the warmest water at the lake surface.

As air temperatures drop in the fall, the temperature of the lake water cools to 4°C; therefore, this causes fall turnover as the heavy cold water sinks and displaces the water at the bottom. The oxygen-rich water at the surface of the lake then moves to the bottom of the lake, while the nutrients at the bottom of the lake rise to the surface (Figure **4.4.6.5**). During the winter, the oxygen at the bottom of the lake is used by decomposers and other organisms requiring oxygen, such as fish.

? Optional Activity 4.4.6.1

Figure **4.4.6.5**: How might turnover in tropical lakes differ from turnover in lakes that exist in temperate regions?

Answer

Tropical lakes don’t freeze, so they don’t undergo spring turnover in the same way temperate lakes do. However, stratification does occur, as well as seasonal turnover.

Temperature

Temperature affects the physiology of living things as well as the density and state of water. Temperature exerts an important influence on organisms because few living things can survive at temperatures below 0°C due to metabolic constraints. It is also rare for living things to survive at temperatures exceeding 45°C; this is a reflection of evolutionary response to typical temperatures. Enzymes are most efficient within a narrow and specific range of temperatures; below that chemical reactions happen too slowly to support most life and biomolecules become rigid, above that enzyme degradation can occur. Therefore, organisms either must maintain an internal temperature or they must inhabit an environment that will keep the body within a temperature range that supports metabolism. Some animals have adapted to enable their bodies to survive significant temperature fluctuations, such as seen in hibernation or reptilian torpor. Similarly, some bacteria are extremophiles, living in extremely hot temperatures such as geysers.

Temperature can limit the distribution of living things. Animals faced with temperature fluctuations may respond with adaptations, such as migration, in order to survive. **Migration**, the movement from one place to another, is an adaptation found in many

animals, including many that inhabit seasonally cold climates. Migration solves problems related to temperature, locating food, and finding a mate. In migration, for instance, the Arctic tern (*Sterna paradisaea*) makes a 40,000 km round trip flight each year between its feeding grounds in the southern hemisphere and its breeding grounds in the Arctic Ocean. Monarch butterflies (*Danaus plexippus*) live in the eastern United States in the warmer months and migrate to Mexico and southeastern Canada in the wintertime. Some species of mammals also make migratory forays. Reindeer (*Rangifer tarandus*) travel about 5,000 km each year to find food. Amphibians and reptiles are more limited in their distribution because they lack migratory ability. Not all animals that can migrate do so: migration carries risk and comes at a high energy cost.

Some animals hibernate or estivate to survive hostile temperatures. Hibernation enables animals to survive cold conditions, and estivation allows animals to survive the hostile conditions of a hot, dry climate. Animals that hibernate or estivate enter a state known as torpor: a condition in which their metabolic rate is significantly lowered. This enables the animal to wait until its environment better supports its survival. Some amphibians, such as the wood frog (*Rana sylvatica*), have an antifreeze-like chemical in their cells, which retains the cells' integrity and prevents them from bursting when temperatures fall below 0°C.

Water

Water is required by all living things because it is critical for cellular processes. Since terrestrial organisms lose water to the environment by simple diffusion, they have evolved many adaptations to retain water.

- Plants have a number of interesting features on their leaves, such as leaf hairs and a waxy cuticle, that serve to decrease the rate of water loss via transpiration.
- Freshwater organisms are surrounded by water and are constantly in danger of having water rush into their cells because of osmosis. Many adaptations of organisms living in freshwater environments have evolved to ensure that solute concentrations in their bodies remain within appropriate levels. One such adaptation is the excretion of dilute urine.
- Marine organisms are surrounded by water with a higher solute concentration than the organism and, thus, are in danger of losing water to the environment because of osmosis. These organisms have morphological and physiological adaptations to retain water and release solutes into the environment. For example, marine iguanas (*Amblyrhynchus cristatus*), sneeze out water vapor that is high in salt in order to maintain solute concentrations within an acceptable range while swimming in the ocean and eating marine plants.

Inorganic Nutrients and Soil

Inorganic nutrients, such as nitrogen and phosphorus, are important in the distribution and abundance of living things. Plants obtain these inorganic nutrients from the soil when water moves into the plant through the roots. Therefore, soil structure (particle size of soil components), soil pH, and soil nutrient content play an important role in the distribution of plants. Aquatic autotrophs such as algae, aquatic plants, and cyanobacteria absorb nutrients directly from the water.

Heterotrophs such as many protists, animals, and fungi obtain inorganic nutrients from the organisms they consume. Therefore, heterotroph distributions are related to the distribution of what they eat. In some cases, heterotrophs will follow their food resource as it moves through the environment.

Other Abiotic Factors

Some abiotic factors, such as gasses like oxygen and carbon dioxide, are important in aquatic ecosystems as well as terrestrial environments. Terrestrial organisms obtain needed gasses directly from the air. Gas availability can be an issue for organisms living at very high elevations where there are fewer molecules of oxygen in the air.

Aquatic organisms obtain necessary gasses from those dissolved in the water. In aquatic systems, the concentration of dissolved gasses is related to water temperature and the speed at which the water moves. Cold water has more dissolved gasses than warmer water. In addition, salinity, currents, and tides can be important abiotic factors in aquatic ecosystems.

For terrestrial systems, wind can be an important abiotic factor because it influences the rate of evaporation and transpiration. The physical force of wind is also important because it can move soil, water, or other abiotic factors, as well as an ecosystem's organisms.

Fire is another terrestrial factor that can be an important agent of disturbance in terrestrial ecosystems. Some organisms are adapted to fire and, thus, require the high heat associated with fire to complete a part of their life cycle. For example, the jack pine (*Pinus banksiana*), a coniferous tree, requires heat from fire for its seed cones to open (Figure **4.4.6.6**). Through the burning of pine needles, fire adds nitrogen to the soil and limits competition by destroying undergrowth.



Figure **4.4.6.6**: The mature cones of the jack pine (*Pinus banksiana*) open only when exposed to high temperatures, such as during a forest fire. Fire is likely to kill most vegetation, so a seedling that germinates after a fire is more likely to receive ample sunlight than one that germinates under normal conditions. (credit: USDA)

Abiotic Factors Influencing Plant Growth

Temperature and moisture are important influences on plant production (primary productivity) and the amount of organic matter available as food (net primary productivity). Net primary productivity is an important variable when considering differences in biomes. Very productive biomes have a high level of aboveground biomass. Aboveground biomass produces several important resources for other living things, including habitat and food.

Annual biomass production is directly related to the abiotic components of the environment. Environments with the greatest amount of biomass have conditions in which photosynthesis, plant growth, and the resulting net primary productivity are optimized. The climate of these areas is warm and wet. Photosynthesis can proceed at a high rate, enzymes work efficiently, and stomata can remain open without the risk of excessive transpiration; together, these factors lead to the maximal amount of carbon dioxide (CO_2) moving into the plant, resulting in high biomass production. Conversely, dry and/or cold environments have lower photosynthetic rates and therefore less biomass. Heterotrophs living in these environments will then be affected by the decrease in available food.

? Optional Activity 4.4.6.2

Which of the following is a biotic factor?

a. disease-causing microbe
b. temperature
c. soil particle size
d. wind

Answer

a. disease-causing microbe

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4.G: Unit 4 - Glossary

Unit 4.2

abiotic
nonliving components of the environment

age structure
proportion of population members at specific age ranges

allelopathy
a type of chemical competition performed by plants in the soil

biotic
living components of the environment

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

camera traps
useful for studying rare and/or nocturnal animals to estimate density

carrying capacity (*K*)
number of individuals of a species that can be supported by the limited resources of a habitat

clumped distribution
individuals are clustered together due to behavior, resources, or limited dispersion of offspring from the parent

community
the different species within an area, typically a three-dimensional space, and the interactions within and among these species

complete census
counting each individual present within the population

conspecifics
organisms that are all members of the same species

constraints
limits can be physical, developmental, or historical, and they are imposed by the existing traits of the organism

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

dispersal
long-range movement between populations

ecological footprint
combined impact of resource utilization and waste generation of an individual

ecology
study of interactions between living things and their environment

ecosystem
community of living organisms and their interactions with their abiotic environment

ecosystem ecology
studies how nutrients and energy are stored and how they move among organisms and the surrounding atmosphere, soil, and water

energy budget
allocation of energy resources for body maintenance, reproduction, and parental care

exponential growth
accelerating growth pattern seen in species under conditions where resources are not limiting

fecundity
potential reproductive capacity of an individual

fundamental geographic range
the area a species occupies in which environmental conditions are favorable, without restriction from barriers to disperse or colonize

generalists
species that can thrive in a wide variety of environmental conditions

heterospecifics
individuals that are members of different species

home range
an area utilized and perhaps defended by a single organism

instantaneous growth rate
instant-specific measurement of growth based on calculus

intraspecific competition
competition between members of the same species

intrinsic rate of increase
difference between birth and death rates; potential for reproduction

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

life cycle
specific sequence in the development of the life of an individual as defined by its species

life expectancy
the length of time individuals remain in the population

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

line or point transect
distance sampling methods to estimate density or abundance; frequently used for animals

logistic growth
leveling off of exponential growth due to limiting resources

mark and recapture
technique used to determine population size in mobile organisms

mortality rate
proportion of the population surviving to the beginning of an age interval that dies during the age interval

niche
how an organism or population responds to the distribution of environmental resources (abiotic components of the environment) and predators, pathogens, and competitors (biotic components of the environment)

occupancy
whether a given species or member of a population occurs in a habitat patch, fragment, or area

ontogeny
timing and pattern of life cycle events of a species

optimality
a life history strategy that allows the highest level of fitness possible

organismal ecology
studies adaptations that enable individuals to live in specific habitats

population
a group of interbreeding organisms that are members of the same species living in the same area at the same time

population density
number of population members divided by the area or volume being measured

population distribution
geographic area where a particular population of a species occurs

population dynamics
changes in population size over time and the processes that cause them to occur

population ecology
studies the number of individuals in an area and how and why population size changes over time

population growth rate
number of organisms added in each reproductive generation

population index
data that correlates with abundance of individuals

population size (*N*)
number of population members in a habitat at the same time

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

random distribution
individuals are neither uniform nor clumped but rather are randomly dispersed with respect to one another

realized geographic range
a more narrow subset of its larger fundamental geographic range due to limitations from abiotic or biotic interactions

relative abundance
individuals in a given area of space per the total number of all individuals of all species

reproductive effort
energy towards producing offspring

restricted range
a species in which the range is so small, there is basically a single population; the species' population distribution and geographic range are essentially the same

S-shaped growth curve
shape of a logistic growth curve

semelparity
life history strategy characterized by a single reproductive event followed by death

somatic effort
energy towards growth and maintenance of the body

specialists
species that can thrive in a specialized subset of environmental conditions

species
a group of organisms capable of interbreeding

species dispersion pattern

(also, species distribution pattern) spatial location of individuals of a given species within a habitat at a particular point in time compared to one another

species distribution pattern

(also, species dispersion pattern) spatial location of individuals of a given species within a habitat at a particular point in time compared to one another

survivorship curve

graph of the number of surviving population members versus the relative age of the member

Type I survivorship curve

high percentage of offspring survive their early and middle years—death occurs predominantly in older individuals

Type II survivorship curve

individuals die more or less equally at each age

Type III survivorship curve

very few of these organisms survive their younger years; however, those that make it to old age are more likely to survive for a relatively long period of time

uniform distribution

individuals are equidistant from each other, due to competition or territorialism

zero population growth

steady population size where birth rates and death rates are equal

Unit 4.3

alternative stable states

various stable end-points for secondary succession

ambush predation

predators sit and wait for prey

aposematic coloration

coloration as a way of warning predators that they are not good to eat

Batesian mimicry

a harmless species imitates the warning coloration of a harmful one

biodiversity

describes a community’s biological complexity

browsing

90% of an herbivore's diet is tree leaves and twigs

camouflage

defense strategy of avoiding detection by blending in with the background

chain of infection

the chain of events involves several steps including the infectious agent, reservoir, entering a susceptible host, exit, and transmission to new hosts

chemical defense
discourage animal predation and herbivory by generating toxins or unpalatable chemicals

climax community
final stage of succession, where a stable community is formed by a characteristic assortment of plant and animal species

commensalism
relationship between species wherein one species benefits from the close, prolonged interaction, while the other species neither benefits nor is harmed

community dynamics
how communities change over time

community structure
the types and numbers of species present in a community

competitive exclusion principle
no two species within a habitat can coexist when they compete for the same resources at the same place and time

disturbance
changes to environmental conditions due to abiotic or biotic factors

equilibrium
steady state of an ecosystem where all organisms are in balance with their environment and each other

evolutionary arms race
a cycle of adaptations and counter-adaptations between predators and prey

foundation species
species which often forms the major structural portion of the habitat

grazing
90% of an herbivore's diet is grass

herbivory
a form of consumption in which an organism principally eats autotrophs such as plants, algae and photosynthesizing bacteria

host
organism a parasite lives on

infection
the invasion of an organism's body tissues by pathogens

infectious disease (also, transmissible or communicable disease)
an illness resulting from an infection

interspecific competition
competition between individuals of different species

intermediate disturbance hypothesis (IDH)
local species diversity is maximized when ecological disturbances are neither too rare nor too frequent

invasive speces
non-native organisms that, when introduced to an area out of their native range, threaten the ecosystem balance of that habitat

island biogeography
study of life on island chains and how their geography interacts with the diversity of species found there

keystone species
species whose presence is key to maintaining biodiversity in an ecosystem and to upholding an ecological community's structure

mechanical defense
discourage animal predation and herbivory by causing physical pain to the predator/herbivore or by physically preventing the predator/herbivore from being able to eat the prey

mimicry
one species imitates the adaptations of another

mixed-feeding
a combination of browsing and grazing by herbivores

Müllerian mimicry
multiple species share the same warning coloration and all of them have defenses

mutualism
symbiotic relationship between two species where both species benefit

parasite
organism that uses resources from another species, the host

parasitism
symtbiotic relationship between two species where one species benefits and the other species has significant costs

parasitoid
an organism whose feeding leads to the death of its host; defined as different than predator due to only one prey over its lifetime

pathogens
disease-causing agents

pioneer (early successional) species
first species to appear in primary and secondary succession

predation
where one organism (predator) kills and eats another (prey)

predator
animal species that hunt and are carnivores or "flesh eaters"; a predator has many prey over its lifetime

primary consumer
trophic level that obtains its energy from the primary producers of an ecosystem

primary succession
succession on newly exposed substrate or soil with no life currently present

pursuit predation
predators actively search for and/or pursue prey

secondary succession

succession in response to environmental disturbances that move a community away from its equilibrium

species diversity
the number of species occupying the same habitat and their relative abundance

species interactions
an effect that a pair of organisms living together in a community have on each other

species richness
number of different species in a community

succession
the process of change in the species structure of an ecological community over time

Unit 4.4

aboveground biomass
total mass of aboveground living plants per area

abyssal zone
deepest part of the ocean at depths of 4000 m or greater

acid rain
corrosive rain caused by rainwater falling to the ground through sulfur dioxide gas, turning it into weak sulfuric acid; can damage structures and ecosystems

algal bloom
rapid increase of algae in an aquatic system

analytical model
ecosystem model that is created with mathematical formulas to predict the effects of environmental disturbances on ecosystem structure and dynamics

apex consumer
organism at the top of the food chain

aphotic zone
part of the ocean where no light penetrates

Arctic tundra
very cold, long winters and extremely short, cold summers with very low precipitation; vegetation dominated by small, low-growing shrubs, lichens, and mo

sses.

assimilation

biomass consumed and assimilated from the previous trophic level after accounting for the energy lost due to incomplete ingestion of food, energy used for respiration, and energy lost as waste

benthic realm
(also, benthic zone) part of the ocean that extends along the ocean bottom from the shoreline to the deepest parts of the ocean floor

bioaccumulate

the ability of a substance to remain within an organism and not be metabolized

biogeochemical cycle
cycling of mineral nutrients through ecosystems

biogeography
study of the geographic distribution of living things and the abiotic factors that affect their distribution

biomagnification
increasing concentrations of persistent, toxic substances in organisms at each trophic level, from the primary producers to the apex consumers

biomass
total weight, at the time of measurement, of living or previously living organisms in a unit area within a trophic level

biome
ecological community of organisms that is adapted to a characteristic set of environmental conditions

bleaching
when coral reefs expel their symbiotic, food-producing algae due to stressors, usually leading to the death of the reef

bog
wetlands that develop in depressions where water flow is low or nonexistent

boreal forest (taiga)
biome with cold, dry winters and short, cool, wet summers; dominated by coniferous trees

brackish
the dilute seawater associated with estuaries

canopy
branches and foliage of trees that form a layer of overhead coverage in a forest

carbon footprint
how much carbon dioxide is produced by an individual or per capita

channel
width of a river or stream from one bank to the other bank

chapparal
a warm-to-hot biome with a dry/wet cycle; dominated by shrubs well adapted to periodic fires and dormancy

chemoautotroph
organism capable of synthesizing its own food using energy from inorganic molecules

conceptual model
(also, compartment models) ecosystem model that consists of flow charts that show the interactions of different compartments of the living and non-living components of the ecosystem

coral reef
ocean ridges formed by marine invertebrates living in warm, shallow waters within the photic zone

cryptofauna
invertebrates found within the calcium carbonate substrate of coral reefs

dead zone

area within an ecosystem in lakes and near the mouths of rivers where large areas of ecosystems are depleted of their normal flora and fauna; these zones can be caused by eutrophication, oil spills, dumping of toxic chemicals, and other human activities

detrital food web

type of food web in which the primary consumers consist of decomposers; these are often associated with grazing food webs within the same ecosystem

ecological pyramid

(also, Eltonian pyramid) graphical representation of different trophic levels in an ecosystem based of organism numbers, biomass, or energy content

ecosystem

community of living organisms and their interactions with their abiotic environment

ecosystem dynamics

study of the changes in ecosystem structure caused by changes in the environment or internal forces

ectotherm

organisms whose internal temperature is externally regulated

emergent vegetation

wetland plants that are rooted in the soil but have portions of leaves, stems, and flowers extending above the water's surface

endemic

species found only in a specific geographic area that is usually restricted in size

endotherm

organisms whose internal temperature is internally regulated

epiphyte

plants that grow commensally or mutualistically on other plants

equilibrium

the steady state of an ecosystem where all organisms are in balance with their environment and with each other

estuary

biomes where a source of fresh water, such as a river, meets the ocean

eutrophication

process whereby nutrient runoff causes the excess growth of microorganisms, depleting dissolved oxygen levels and killing ecosystem fauna

evaporation

transition from water to water vapor

fallout

direct deposit of solid minerals on land or in the ocean from the atmosphere

food chain

linear representation of a chain of primary producers, primary consumers, and higher-level consumers used to describe ecosystem structure and dynamics; not as useful for ecologists

food web

graphic representation of a holistic, non-linear web of primary producers, primary consumers, and higher-level consumers used to describe ecosystem structure and dynamics

forbs
herbaceous flowering plants

gross primary productivity
rate at which photosynthetic primary producers incorporate energy from the sun

grazing food web
type of food web in which the primary producers are either plants on land or phytoplankton in the water; often associated with a detrital food web within the same ecosystem

halophyte
plants that tolerate salty conditions

holistic ecosystem model
study that attempts to quantify the composition, interactions, and dynamics of entire ecosystems; often limited by economic and logistical difficulties, depending on the ecosystem

humus
rich organic matter in soil

hydrologic cycle
cycle of water molecules through the geosphere, hydrosphere, and atmosphere

hydrosphere
area of the Earth where water movement and storage occurs

incomplete ingestion
some consumers eat only a part of their food, leaving some calories unused

infiltrates
precipitation that soaks into the ground

intertidal zone
part of the ocean that is closest to land; parts extend above the water at low tide

lakes and ponds
standing water that is stratified in the summer; spring and fall mixing bring oxygen and nutrients to the upper layers

leach
chemical removal of a particular element from the lithosphere

marshes and swamps
characterized by slow and steady water flow

mesocosm
portion of a natural ecosystem to be used for experiments

microcosm
re-creation of natural ecosystems entirely in a laboratory environment to be used for experiments

migration

the movement of an organism from one place to another

net consumer productivity
energy content available to the organisms of the next trophic level

neritic zone
part of the ocean that extends from low tide to the edge of the continental shelf

net primary productivity
energy that remains in the primary producers after accounting for the organisms' respiration and heat loss

net production efficiency (NPE)
measure of the ability of a trophic level to convert the energy it receives from the previous trophic level into biomass

nocturnal
organisms that are active at night; common in arid ecosystems

non-renewable resource
resource, such as fossil fuel, that is either regenerated very slowly or not at all

ocean upwelling
rising of deep ocean waters that occurs when prevailing winds blow along surface waters near a coastline

oceanic zone
part of the ocean that begins offshore where the water measures 200 m deep or deeper

pelagic realm
(also, pelagic zone) open ocean waters that are not close to the bottom or near the shore

percolation
movement of water through the pores in the soil or rocks

permafrost
perennially frozen portion of the Arctic tundra soil

photic zone
portion of the ocean that light can penetrate

photoautotroph
photosynthetic autotrophs

planktivore
animal species that eats plankton

precipitation
rain or snow

productivity
the percentage of energy entering the ecosystem incorporated into biomass in a particular trophic level

primary producer
trophic level that obtains its energy from sunlight, inorganic chemicals, or dead and/or decaying organic material

pyramid of biomass

measures the amount of energy converted into living tissue at the different trophic levels

pyramid of energy
indicates energy flow through the trophic levels

pyramid of numbers
measures the relative amount of individuals across trophic levels

residence time
measure of the average time an individual water molecule stays in a particular reservoir

resilience (ecological)
speed at which an ecosystem recovers equilibrium after being disturbed

resistance (ecological)
ability of an ecosystem to remain at equilibrium in spite of disturbances

rivers and streams
continuously moving bodies of water that carry large amounts of water from the source, or headwater, to a lake or ocean

runoff
the flow of fresh water either from rain or melting ice

savanna
hot grassland with extensive dry season; dominated by grasses and forbs

second law of thermodynamics
states whenever energy is converted from one form to another, there is a tendency toward disorder (entropy) in the system

secondary consumer
usually a carnivore that eat primary consumers

simulation model
ecosystem model that is created with computer programs to holistically model ecosystems and to predict the effects of environmental disturbances on ecosystem structure and dynamics

source water
point of origin of a river or stream

stratification
the separation of water into layers, often by temperature or salt content

subduction
movement of one tectonic plate beneath another

sublimation
transition of ice to water vapor

subtropical desert
hot, very dry biome dominated by perennial vegetation well adapted to the biome

temperate forest
biome with warm summers, cold winters, and fairly constant precipitation year-round; dominated by deciduous trees

temperate grassland (prairie)

biome with hot summers and cold winters; summer rains allow plant growth but winter is a time of dormancy; dominated by dense grasses

tertiary consumer

carnivore that eat other carnivores

thermocline

layer of water with a temperature that is significantly different from that of the surrounding layers

trophic level

position of a species or group of species in a food chain or a food web

trophic level transfer efficiency (TLTE)

energy transfer efficiency between two successive trophic levels

tropical wet (rain) forest

terrestrial biome found in equatorial regions characterized by stable hot temperatures, high annual rainfall, and plants with broad evergreen leaves

turnover (fall and spring)

seasonal process that recycles nutrients and oxygen from the bottom of a freshwater ecosystem to the top

understory

short shrubby foliage under the canopy of a forest

wetland

environments in which the soil is either permanently or periodically saturated with water

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4.S: Unit 4 - Summary

Unit 4.2

Ecology is the study of the interactions of living things with their environment. Ecologists ask questions across four levels of biological organization—organismal, population, community, and ecosystem. At the organismal level, ecologists study individual organisms and how they interact with their environments. At the population and community levels, ecologists explore, respectively, how a population of organisms changes over time and the ways in which that population interacts with other species in the community. Ecologists studying an ecosystem examine the living species (the biotic components) of the ecosystem as well as the nonliving portions (the abiotic components), such as air, water, and soil of the environment.

Populations are individuals of a species that live in a particular habitat. Ecologists measure the characteristics of populations: size, density, dispersion pattern, age structure, and sex ratio. Life tables are useful to calculate the life expectancies of individual population members. Survivorship curves show the number of individuals surviving at each age interval plotted versus time.

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.

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. 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.

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.

Unit 4.3

Populations of species do not exist in isolation – they exist in the context of coevolved ecological communities. Species interactions can harm both species involved (competition), benefit both involved (mutualism), or benefit one and harm the other (Predation, Parasitism, Herbivory). These interactions play a key role in evolution (e.g., prey evolve to avoid detection by predators) and in structuring ecological communities (e.g., loss of top predators can lead to drastic reductions in biodiversity). While some of these interactions involved trophic relationships, others, such as habitat-formation by foundation species, do not.

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.

Unit 4.4

Ecosystems exist on land, at sea, in the air, and underground. Different ways of modeling ecosystems are necessary to understand how environmental disturbances will affect ecosystem structure and dynamics. Conceptual models are useful to show the general relationships between organisms and the flow of materials or energy between them. Analytical models are used to describe linear food chains, and simulation models work best with holistic food webs.

Organisms in an ecosystem acquire energy in a variety of ways, which is transferred between trophic levels as the energy flows from the bottom to the top of the food web, with energy being lost at each transfer. The efficiency of these transfers is important for

understanding the different behaviors and eating habits of warm-blooded versus cold-blooded animals. Modeling of ecosystem energy is best done with ecological pyramids of energy, although other ecological pyramids provide other vital information about ecosystem structure.

The Earth has terrestrial biomes and aquatic biomes. Aquatic biomes include both freshwater and marine environments. There are eight major terrestrial biomes: tropical wet forests, savannas, subtropical deserts, chaparral, temperate grasslands, temperate forests, boreal forests, and Arctic tundra. The same biome can occur in different geographic locations with similar climates. Temperature and precipitation, and variations in both, are key abiotic factors that shape the composition of animal and plant communities in terrestrial biomes. Some biomes, such as temperate grasslands and temperate forests, have distinct seasons, with cold weather and hot weather alternating throughout the year. In warm, moist biomes, such as the tropical wet forest, net primary productivity is high, as warm temperatures, abundant water, and a year-round growing season fuel plant growth. Other biomes, such as deserts and tundra, have low primary productivity due to extreme temperatures and a shortage of available water.

Aquatic ecosystems include both saltwater and freshwater biomes. The abiotic factors important for the structuring of aquatic ecosystems can be different than those seen in terrestrial systems. Sunlight is a driving force behind the structure of forests and also is an important factor in bodies of water, especially those that are very deep, because of the role of photosynthesis in sustaining certain organisms. Density and temperature shape the structure of aquatic systems. Oceans may be thought of as consisting of different zones based on water depth and distance from the shoreline and light penetrance. Different kinds of organisms are adapted to the conditions found in each zone. Coral reefs are unique marine ecosystems that are home to a wide variety of species. Estuaries are found where rivers meet the ocean; their shallow waters provide nourishment and shelter for young crustaceans, mollusks, fishes, and many other species. Freshwater biomes include lakes, ponds, rivers, streams, and wetlands. Bogs are an interesting type of wetland characterized by standing water, lower pH, and a lack of nitrogen.

Mineral nutrients are cycled through ecosystems and their environment. Of particular importance are water, carbon, nitrogen, phosphorus, and sulfur. All of these cycles have major impacts on ecosystem structure and function. As human activities have caused major disturbances to these cycles, their study and modeling is especially important. A variety of human activities, such as pollution, oil spills, and other events have damaged ecosystems, potentially causing global climate change. The health of Earth depends on understanding these cycles and how to protect the environment from irreversible damage.

Biogeography is the study of the geographic distribution of living things and the abiotic factors that affect their distribution. Endemic species are species that are naturally found only in a specific geographic area. The distribution of living things is influenced by several environmental factors that are, in part, controlled by the latitude or elevation at which an organism is found. Ocean upwelling and spring and fall turnovers are important processes regulating the distribution of nutrients and other abiotic factors important in aquatic ecosystems. Energy sources, temperature, water, inorganic nutrients, and soil are factors limiting the distribution of living things in terrestrial systems. Net primary productivity is a measure of the amount of biomass produced by a biome.

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CHAPTER OVERVIEW

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5.2: Biodiversity and HIPPPOC

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5.2.2: Importance of Biodiversity

5.2.3: The Biodiversity Crisis - HIPPPOC

5.2.4: Preserving Biodiversity

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5.4.4: Sustainability and the Future

5.G: Unit 5 - Glossary

5.S: Unit 5 - Summary

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5.1: Unit 5 Introduction

Unit 5 Introduction

This unit introduces biodiversity, climate change, and sustainability.

Vignettes on Indigenous Science and the ecology of British Columbia are included.

Unit 5 Learning Outcomes

By the end of this Unit, you will be able to:

- Critically discuss the role of humans as a force of change in the biosphere.
- Understand and articulate the principles and processes of scientific inquiry.
- Think critically about the principles of biology studied and communicate your thinking clearly and concisely in speaking and in writing.

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Unit 5 Assessments

If you are a TRU student using this resource, all of your assessed learning activities and assignments are in your course Moodle site.

This unit introduces learners to the scale and scope of humanity's impact on the Earth and its inhabitants, as well as possible solutions to those impacts.

Please click on the blue arrow on the right to start Unit 5: Chapter 5.2. If you are on a mobile device, use the navigation links at the bottom of this page.

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- **Unit I: The Chemistry of Life** by OpenStax is licensed CC BY 4.0.

SECTION OVERVIEW

5.2: Biodiversity and HIPPPOC

Conservation biology is the management of nature and of Earth's biodiversity with the aim of protecting species, their habitats, and ecosystems from excessive rates of extinction and the erosion of biotic interactions. It is an interdisciplinary subject drawing on natural and social sciences and the practice of natural resource management.

Video



This 3-minute video summarizes Unit 5.2.
Question after watching: What areas from the video are you already familiar with? What topics are you unfamiliar with?

5.2.1: Introduction to Biodiversity

5.2.2: Importance of Biodiversity

5.2.3: The Biodiversity Crisis - HIPPPOC

5.2.4: Preserving Biodiversity

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Unit 5.2.1 - Introduction to Biodiversity

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to the Unit 5.2.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Define biodiversity
- Explain what is meant by the 'biodiversity crisis'
- Provide examples of anthropogenic extinctions

Introduction

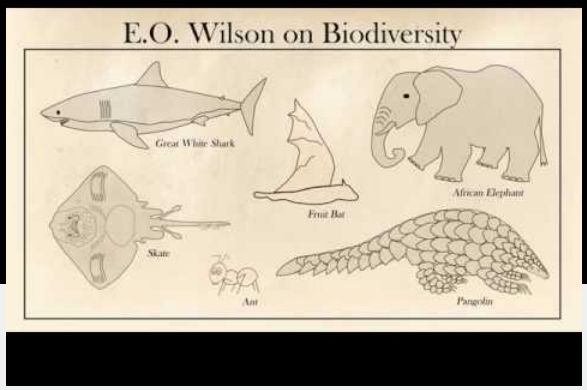
In the 1980s, biologists working in Lake Victoria in Africa discovered one of the most extraordinary products of evolution on the planet. Located in the Great Rift Valley, Lake Victoria (Figure **5.2.1.1**) is a large lake about 68,900 km^2 in area (larger than Lake Huron, the second largest of North America's Great Lakes). Biologists were studying species of a family of fish called cichlids. They found that as they sampled for fish in different locations of the lake, they never stopped finding new species, and they identified nearly 500 evolved types of cichlids. But while studying these variations, they quickly discovered that the invasive Nile Perch was destroying the lake's cichlid population, bringing hundreds of cichlid species to extinction with devastating rapidity.



Figure **5.2.1.1**: Cichlids are some of the most biodiverse fish on the planet but are also a casualty of devastating biodiversity loss. (credit: modification of work by Rishabh Tatiraju, using NASA World Wind software)

Video





Watch a 1-minute presentation by biologist E.O. Wilson (1929-2021) on the importance of biodiversity.

What is Biodiversity?

Biodiversity is a broad term for biological variety, and it can be measured at a number of organizational levels. Traditionally, ecologists have measured biodiversity by taking into account both the number of species and the number of individuals of each species (known as **relative abundance**). However, biologists are using different measures of biodiversity, including genetic diversity, to help focus efforts to preserve the biologically and technologically important elements of biodiversity.

Species Diversity

Scientists accept that the term biodiversity generally describes the number and kinds of species in a location or on the planet. This is known as **species diversity**. Species can be difficult to define, but most biologists still feel comfortable with the concept and are able to identify and count eukaryotic species in most contexts.

For example, the American Ornithologists' Union lists 2078 species of birds in North and Central America. This is one measure of the bird biodiversity on the continent. More sophisticated measures of diversity take into account the relative abundances of species. An ecologist analyzing a forest with 10 equally common species of trees would note that this first forest is more diverse than a forest that has the same 10 species of trees but where just one of those species makes up 95 percent of the trees.

In addition to these measures of species diversity, biologists have identified alternate measures of biodiversity, some of which are important in planning how to preserve biodiversity.

Genetic Diversity

One alternate concept of biodiversity, **genetic diversity**, is the raw material for evolutionary adaptation in a species and is represented by the variety of genes present within a population. A species' potential to adapt to changing environments or new diseases depends on this genetic diversity. The same is true for higher taxonomic categories. A genus with very different types of species will have more genetic diversity than a genus with species that look alike and have similar ecologies. If there were a choice between one of these genera of species being preserved, the one with the greatest potential for subsequent evolution is the most genetically diverse one. It would be ideal not to have to make such choices, but increasingly this may be the norm.

Beyond ecological importance, genetic diversity has potential benefits for humans as sources of pharmaceuticals, so it provides one way to measure diversity that is important to human health and welfare. Humans have also generated diversity through domestic animals, plants, and fungi. This diversity is suffering losses because of migration, market forces, and increasing globalism in agriculture, especially in heavily populated regions such as China, India, and Indonesia. The human population directly depends on this diversity as a stable food source, and its decline is troubling biologists and agricultural scientists.

Ecosystem Diversity

It is also useful to define **ecosystem diversity**, meaning the number of different ecosystems on the planet or in a given geographic area (Figure 5.2.1.2). Whole ecosystems can disappear even if some of the species might survive by adapting to other ecosystems. The loss of an ecosystem means the loss of interactions between species, the loss of unique features of coadaptation, and the loss of

biological productivity that an ecosystem is able to create. An example of a large, nearly extinct ecosystem in North America are the prairies (Figure 5.2.1.2*b*). Prairies once spanned central North America from the boreal forest in northern Canada down into Mexico. They are now all but gone, replaced by crop fields, pasture lands, and suburban sprawl. Many of the individual species survive but the hugely productive ecosystem as a whole has fallen apart. As a consequence, the most productive agricultural soils on the planet are disappearing or must be maintained at greater expense.

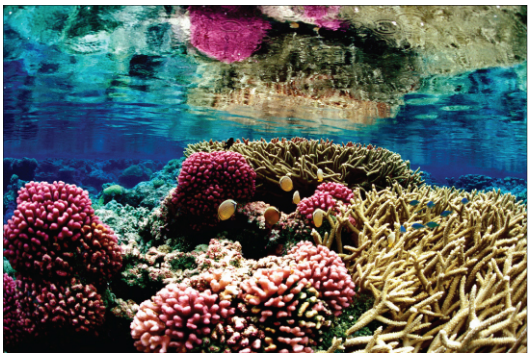
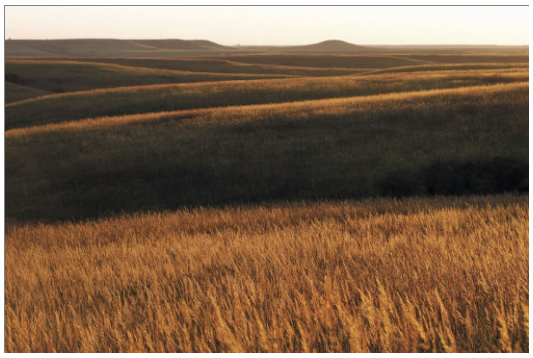



Figure 5.2.1.2: The variety of ecosystems on Earth—from (a) coral reef to (b) prairie—enables a great diversity of species to exist. (credit a: modification of work by Jim Maragos, USFWS; credit b: modification of work by Jim Minnerath, USFWS)

How Many Species?

As of August 2022, taxonomists have described nearly 2.3 million species that share this planet with us. While this total may seem impressive, available evidence suggests that this estimate vastly underestimates the true extent of Earth's biodiversity. In fact, even now, after all the exploration in years gone by, several thousand new species are described each year. Many new discoveries are made by skilled researchers recognizing new species by discerning variation in morphological characters; that includes the discoveries of a new small forest antelope from West Africa and a new species of shark off the coast of Mozambique. New genetic technologies have highlighted that there are many thousands of species yet to be described. Both traditional and genetic techniques rely heavily on the availability of specimens in Natural History Museums collections to help identify and describe new species. A lack of taxonomists and natural history collections in many of the world's most biodiverse countries means there is still a great deal of work to do.

The most exciting and newsworthy discoveries of new species generally involve higher-level taxa, especially living fossils. For example, in 1938, biologists across the world were stunned by the report of a strange fish caught in the Indian Ocean off South Africa. This fish, subsequently named *Latimeria chalumnae*, belongs to a group of marine fishes known as coelacanths that were common in ancient seas but were thought to have gone extinct 65 million years ago. Coelacanths are of interest to evolutionary biologists because they show certain features of muscles and bones in their fins that are comparable to the limbs of the first vertebrates that crawled onto land. Following the initial discovery, coelacanths have been found along Africa's Indian Ocean coast from South Africa to the Comoros and through to Kenya. Unfortunately, the entire coelacanth population, estimated at fewer than 500 individuals, is currently highly threatened because of ongoing fishing pressures.

Although field surveys have proven to be of great importance for discovering new species and populations, perhaps the greatest taxonomic progress has come from advances in genetic analyses which help to separate cryptic species previously lumped under more widespread species. For example, advances in genetic research recently highlighted that the African clawed frog *Xenopus laevis*—a popular model organism in biomedical research—consists of seven distinct species.

Molecular genetics and data processing and storage technologies are maturing to the point where cataloging the planet's species in an accessible way is close to feasible. DNA barcoding is one molecular genetic method, which takes advantage of rapid evolution in a mitochondrial gene present in eukaryotes, except the plants, to identify species using the sequence of portions of the gene. Plants are barcoded using a combination of chloroplast genes. Rapid mass sequencing machines make the molecular genetics portion of the work relatively inexpensive and quick. Computer resources store and make available large volumes of data. Projects are currently underway to use DNA barcoding to catalog museum specimens, which have already been named and studied, as well as testing the method on less studied groups. As of mid-2020, close to 750,000 named species had been barcoded. Early studies suggest there are significant numbers of undescribed species that looked too much like sibling species to previously be recognized as different. These now can be identified with DNA barcoding.

Numerous computer databases now provide information about named species and a framework for adding new species. However, at the present rate of description of new species, it would still take close to 500 years before the complete catalog of life is known. Many, perhaps most, species on the planet do not have that much time given the **anthropogenic**, or human-caused, pressures on species around the world (Unit 5.2.3).

The presence of so many undiscovered species and communities makes precise estimates of species diversity incredibly difficult. Biologists' most recent estimates, combining genetic analysis of well-known groups with mathematical patterns, suggests there are between 1–6 billion distinct species on Earth, of which there are only about 163 million animals and 340 thousand plants. This is obviously much greater than the current catalog of around 2.3 million species.

Anthropogenic Extinctions

A review of the previous five mass extinctions can be found in Unit 3.3. The sixth, or Holocene, mass extinction appears to have begun earlier than previously believed and has mostly to do with the activities of *Homo sapiens*. Since the beginning of the Holocene period, there are numerous recent extinctions of individual species that are recorded in human writings. Most of these are coincident with the expansion of the European colonies since the 1500s.

Recent Extinctions

One of the earlier and popularly known examples is the dodo bird. The dodo bird lived in the forests of Mauritius, an island in the Indian Ocean. The dodo bird became extinct around 1662. It was hunted for its meat by sailors and was easy prey because the dodo, which did not evolve with humans, would approach people without fear. Introduced pigs, rats, and dogs brought to the island by European ships also killed dodo young and eggs (Figure **5.2.1.3**).



Figure **5.2.1.3**. The dodo bird was hunted to extinction around 1662. (credit: Ed Uthman, taken in Natural History Museum, London, England)

Steller's sea cow became extinct in 1768; it was related to the manatee and probably once lived along the northwest coast of North America. Steller's sea cow was first discovered by Europeans in 1741 and was hunted for meat and oil. The last sea cow was killed in 1768. That amounts to 27 years between the sea cow’s first contact with Europeans and extinction of the species.

In 1914, the last living passenger pigeon died in a zoo in Cincinnati, Ohio. This species had once darkened the skies of North America during its migrations, but it was hunted and suffered from habitat loss through the clearing of forests for farmland. In 1918, the last living Carolina parakeet died in captivity. This species was once common in the eastern United States, but it suffered from habitat loss. The species was also hunted because it ate orchard fruit when its native foods were destroyed to make way for farmland. The Japanese sea lion, which inhabited a broad area around Japan and the coast of Korea, became extinct in the 1950s due to fishermen. The Caribbean monk seal was distributed throughout the Caribbean Sea but was driven to extinction via hunting by 1952.

These are only a few of the recorded extinctions in the past 500 years.

The Red List

There is also the problem of understanding which species known to science are currently threatened and to what degree they are threatened. The International Union for Conservation of Nature (IUCN), an international non-profit, keeps a list of extinct and endangered species called the Red List, supported by scientific research. The list is not complete, but it describes 380 species of vertebrates that went extinct after 1500 AD, 86 of which were driven extinct by overhunting or overfishing. In 2011, the list contained 61,000 species. It is categorized by taxonomy, type of threat, and other criteria (Figure **5.2.1.4**).

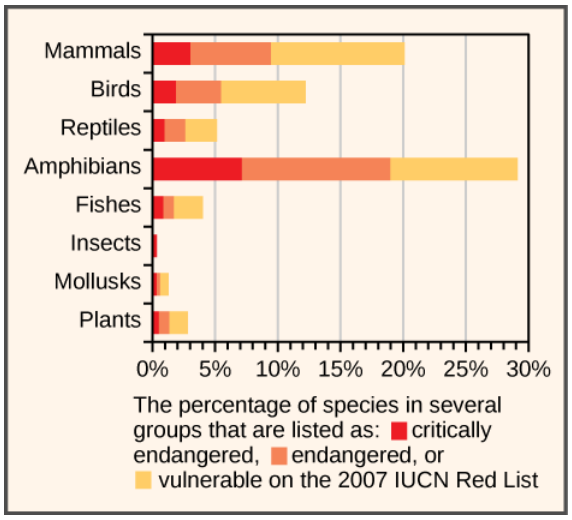


Figure **5.2.1.4**: This chart shows the percentage of various animal species, by group, on the IUCN Red List as of 2007.

? Optional Activity 5.2.1.1

Which of the following statements is NOT supported by Figure **5.2.1.4**?

A. There are more vulnerable fishes than critically endangered and endangered fishes combined.
B. There are more critically endangered amphibians than vulnerable, endangered, and critically endangered reptiles combined.
C. Within each group, there are more critically endangered species than vulnerable species.
D. A greater percentage of bird species are critically endangered than mollusk species.

Answer

C. Within each group, there are more critically endangered species than vulnerable species.

Evolution Connection: Lake Victoria cichlids

The Lake Victoria cichlids provide an example through which we can begin to understand biodiversity. The biologists studying cichlids in the 1980s discovered hundreds of cichlid species representing a variety of specializations to particular habitat types and specific feeding strategies: eating plankton floating in the water, scraping and then eating algae from rocks, eating insect larvae from the bottom, and eating the eggs of other species of cichlid. The cichlids of Lake Victoria are the product of adaptive radiation. Adaptive radiation is a rapid (less than three million years in the case of the Lake Victoria cichlids) branching through speciation of a phylogenetic tree into many closely related species; typically, the species “radiate” into different habitats and niches. The Galápagos finches are an example of a modest adaptive radiation with 15 species. The cichlids of Lake Victoria are an example of a spectacular adaptive radiation that includes about 500 species.

At the time biologists were making this discovery, some species began to quickly disappear. A culprit in these declines was a species of large fish that was introduced to Lake Victoria by fisheries to feed the people living around the lake. The Nile perch was introduced in 1963, but lay low until the 1980s when its populations began to surge. The Nile perch population grew by consuming cichlids, driving species after species to the point of extinction (the disappearance of a species). In fact, there were several factors that played a role in the extinction of perhaps 200 cichlid species in Lake Victoria: the Nile perch, declining lake water quality due to agriculture and land clearing on the shores of Lake Victoria, and increased fishing pressure. Scientists had not even cataloged all of the species present—so many were lost that were never named. The diversity is now a shadow of what it once was.

The cichlids of Lake Victoria are a thumbnail sketch of contemporary rapid species loss that occurs all over Earth and is caused by human activity. Extinction is a natural process of macroevolution that occurs at the rate of about one out of 1 million species becoming extinct per year. The fossil record reveals that there have been five periods of mass extinction in history with much higher rates of species loss, and the rate of species loss today is comparable to those periods of mass extinction. However, there

is a major difference between the previous mass extinctions and the current extinction we are experiencing: human activity. Specifically, three human activities have a major impact: the destruction of habitat, introduction of exotic species, and over-harvesting. Predictions of species loss within the next century, a tiny amount of time on geological timescales, range from 10 percent to 50 percent. Extinctions on this scale have only happened five other times in the history of the planet, and they have been caused by cataclysmic events that changed the course of the history of life in each instance. Earth is now in one of those times.

Estimates of Present-day Extinction Rates

Estimates of extinction rates are hampered by the fact that most extinctions are probably happening without being observed. The extinction of a bird or mammal is often noticed by humans, especially if it has been hunted or used in some other way. But there are many organisms that are less noticeable to humans (not necessarily of less value) and many that are undescribed.

The **background extinction rate** is estimated to be about 1 per million species years (E/MSY). One "species year" is one species in existence for one year. One million species years could be one species persisting for one million years, or a million species persisting for one year. If it is the latter, then one extinction per million species years would be one of those million species becoming extinct in that year. For example, if there are 10 million species in existence, then we would expect 10 of those species to become extinct in a year. This is the background rate.

One contemporary extinction-rate estimate uses the extinctions in the written record since the year 1500. For birds alone, this method yields an estimate of 26 E/MSY, almost three times the background rate. However, this value may be underestimated for three reasons. First, many existing species would not have been described until much later in the time period and so their loss would have gone unnoticed. Second, biologists know the number is higher than the written record suggests because now extinct species are being described from skeletal remains that were never mentioned in written history. And third, some species are probably already extinct even though conservationists are reluctant to name them as such. Taking these factors into account raises the estimated extinction rate to nearer 100 E/MSY. The predicted rate by the end of the century is 1500 E/MSY.

A second approach to estimating present-time extinction rates is to correlate species loss with habitat loss, and it is based on measuring forest-area loss and understanding species–area relationships. The species-area relationship is the rate at which new species are seen when the area surveyed is increased (Figure 5.2.1.5). Likewise, if the habitat area is reduced, the number of species seen will also decline. This kind of relationship is also seen in the relationship between an island's area and the number of species present on the island: as one increases, so does the other, though not in a straight line.

Estimates of extinction rates based on habitat loss and species–area relationships have suggested that with about 90 percent of habitat loss an expected 50 percent of species would become extinct. Reducing forest area from 100 km^2 to 10 km^2, a decline of 90 percent, reduces the number of species by about 50 percent (Figure 5.2.1.5). Species–area estimates have led to estimates of present-day species extinction rates of about 1000 E/MSY and higher.

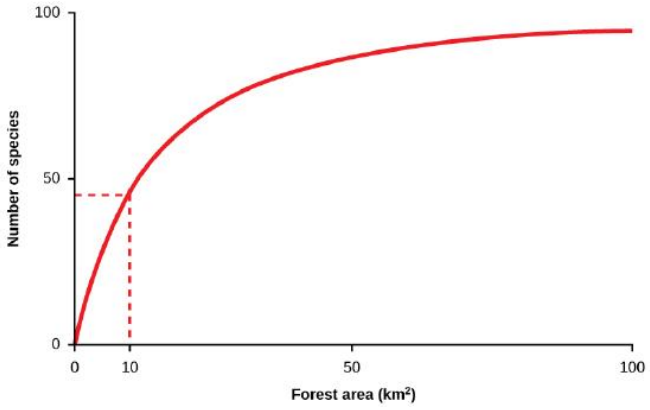


Figure 5.2.1.5. A typical species-area curve shows the cumulative number of species found as more and more area is sampled. The curve has also been interpreted to show the effect on species numbers of destroying habitat; a reduction in habitat of 90 percent from 100 km^2 to 10 km^2 reduces the number of species supported by about 50 percent.

Video



In this 9-minute video, discover why the current impacts of humans are as devastating to biodiversity as a large meteor. Question after watching: What is lost when a species goes extinct? Consider all of the things that are lost, not just the biological ones.

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Unit 5.2.2 - Importance of Biodiversity

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.2.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Summarize the benefits of biodiversity

Introduction

It may not be clear why biologists are concerned about biodiversity loss. When biodiversity loss is thought of as the extinction of the passenger pigeon, the dodo bird, and even the woolly mammoth, the loss may appear to be an emotional one. However, is the loss practically important for the welfare of the human species? The loss of a keystone species can lead to ecological disaster and the extinction of many other species. But, from the perspective of evolution and ecology, the loss of one or two individual species may be relatively unimportant. Extinction is a normal part of macroevolution. Humans have accelerated the extinction rate, though, leading to losses of tens of thousands of species within our lifetimes. These losses are likely to have dramatic effects on human welfare through the collapse of ecosystems and added costs to maintain food production, clean air and water, and human health. There are strategies to avoid some of these losses and the field of study to preserve biodiversity is known as **conservation biology**.

Video



Watch this 4-minute video for an understanding of the importance of biodiversity.
Question after watching: Humans have cut and frayed the woven tapestry of Earth's biodiversity. List and describe three ways.

The Biodiversity Crisis

Biologists estimate that species extinctions are currently 500–1,000 times the normal, or **background**, rate seen previously in Earth's history. The current high rates will cause a precipitous decline in the biodiversity of the planet in the next century or two. The loss of biodiversity will include many species we know today. Although it is sometimes difficult to predict which species will become extinct, many are listed as **endangered** (at great risk of extinction). However, many extinctions will affect species that biologists have not yet discovered.

Most of these “invisible” species that will become extinct currently live in tropical rainforests like those of the Amazon basin or on coral reefs. Rainforests are the most diverse terrestrial ecosystems on the planet and are being destroyed rapidly by deforestation (Figure 5.2.2.1). Between 1970 and 2011, almost 20 percent of the Amazon rainforest was lost. Coral reefs are being lost to overharvesting, warming oceans, and pollution.



Figure 5.2.2.1. This tropical lowland rainforest in Madagascar is an example of a high biodiversity habitat. This particular location is protected within a national forest, yet only 10 percent of the original coastal lowland forest remains, and research suggests half the original biodiversity has been lost. (credit: Frank Vassen)

Biodiversity loss refers to the reduction of biodiversity due to displacement or extinction of species. The loss of a particular individual species may seem unimportant to some, especially if it is not a **charismatic species** like the Bengal tiger or the bottlenose dolphin. However, the current accelerated extinction rate means the loss of tens of thousands of species within our lifetimes. Much of this loss is occurring in tropical rainforests as mentioned above, which are very high in biodiversity but are being cleared for timber and agriculture. This is likely to have dramatic effects on human welfare through the collapse of ecosystems.

Biologists recognize that human populations are embedded in ecosystems and are dependent on them, just as is every other species on the planet. Agriculture began after early hunter-gatherer societies first settled in one place and heavily modified their immediate environment. This cultural transition has made it difficult for many modern humans to recognize their dependence on living things other than crops and domesticated animals on the planet. Today our technology smooths out the harshness of existence and allows many of us to live longer, more comfortable lives, but ultimately the human species cannot exist without its surrounding ecosystems. Our ecosystems provide us with food, medicine, clean air and water, recreation, and spiritual and aesthetical inspiration.

Current Species Diversity

Despite considerable effort, knowledge of the species that inhabit the planet is limited. A recent estimate suggests that only 13% of eukaryotic species have been named (Table 1). Estimates of numbers of prokaryotic species are largely guesses, but biologists agree that science has only just begun to catalog their diversity. Some scientists estimate that there may be over 100 million species of prokaryotes alone. Given that Earth is losing species at an accelerating pace, science knows little about what is being lost.

Table 1. This table shows the estimated number of species by taxonomic group—including both described (named and studied) and predicted (yet to be named) species.

Estimated Numbers of Described and Predicted species						
	Source: Mora et al 2011		Source: Chapman 2009		Source: Groombridge and Jenkins 2002	
	Described	Predicted	Described	Predicted	Described	Predicted
Animals	1,124,516	9,920,000	1,424,153	6,836,330	1,225,500	10,820,000
Photosynthetic protists	17,892	34,900	25,044	200,500	—	—
Fungi	44,368	616,320	98,998	1,500,000	72,000	1,500,000
Plants	224,244	314,600	310,129	390,800	270,000	320,000
Non-photosynthetic protists	16,236	72,800	28,871	1,000,000	80,000	600,000
Prokaryotes	—	—	10,307	1,000,000	10,175	—
Total	1,438,769	10,960,000	1,897,502	10,897,630	1,657,675	13,240,000

There are various initiatives to catalog described species in accessible and more organized ways, and the internet is facilitating that effort. Nevertheless, at the current rate of species description, which according to the State of Observed Species reports is 17,000–20,000 new species a year, it would take close to 500 years to describe all of the species currently in existence. The task, however, is becoming increasingly impossible over time as extinction removes species from Earth faster than they can be described.

Naming and counting species may seem an unimportant pursuit given the other needs of humanity, but it is not simply an accounting. Describing species is a complex process by which biologists determine an organism's unique characteristics and whether or not that organism belongs to any other described species. It allows biologists to find and recognize the species after the initial discovery to follow up on questions about its biology. That subsequent research will produce the discoveries that make the species valuable to humans and to our ecosystems. Without a name and description, a species cannot be studied in depth and in a coordinated way by multiple scientists.

Patterns of Biodiversity

Biodiversity is not evenly distributed on the planet. Lake Victoria contained almost 500 species of cichlids (just one family of fishes that are present in the lake) before the introduction of an exotic species in the 1980s and 1990s caused a mass extinction. All of these species were found only in Lake Victoria, which is to say they were endemic. Endemic species with highly restricted distributions, like the ciclids, are particularly vulnerable to extinction.

Lake Huron contains about 79 species of fish, all of which are found in many other lakes in North America. What accounts for the difference in diversity between Lake Victoria and Lake Huron? Lake Victoria is a tropical lake, while Lake Huron is a temperate lake. Lake Huron in its present form is only about 7,000 years old, while Lake Victoria in its present form is about 15,000 years old. These two factors, latitude and age, are two of several hypotheses biogeographers have suggested to explain biodiversity patterns on Earth.

Biogeography is the study of the distribution of the world's species both in the past and in the present (Unit 4.4.5). The work of biogeographers is critical to understanding our physical environment, how the environment affects species, and how changes in environment impact the distribution of a species.

There are three main fields of study under the heading of biogeography: ecological biogeography, historical biogeography (called paleobiogeography), and conservation biogeography. Ecological biogeography studies the current factors affecting the distribution of plants and animals. Historical biogeography, as the name implies, studies the past distribution of species. Conservation biogeography, on the other hand, is focused on the protection and restoration of species based upon the known historical and current ecological information.

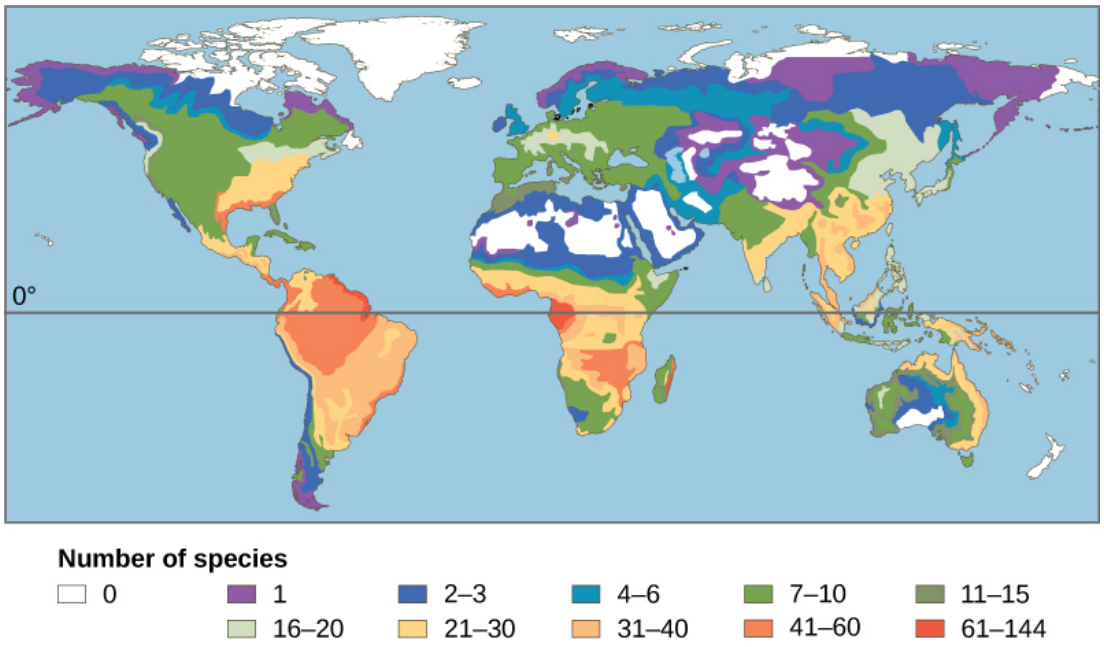


Figure **5.2.2.3**. This map illustrates the number of amphibian species across the globe and shows the trend toward higher biodiversity at lower latitudes. A similar pattern is observed for most taxonomic groups.

One of the oldest observed patterns in ecology is that biodiversity typically increases as latitude decreases. In other words, biodiversity increases closer to the equator (Figure **5.2.2.3**).

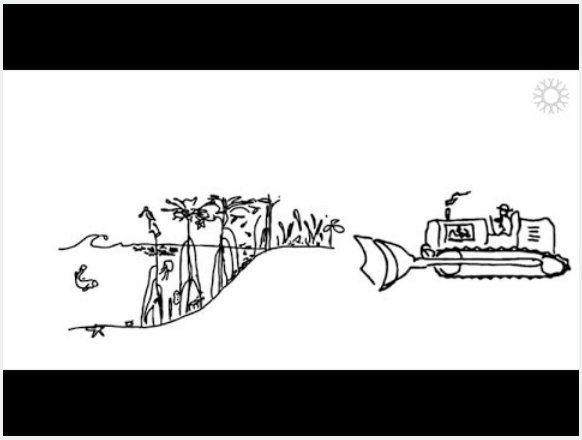
It is not yet clear why biodiversity increases closer to the equator, but hypotheses include the greater age of the ecosystems in the tropics versus temperate regions, which were largely devoid of life or drastically impoverished during the last ice age. The greater age provides more time for speciation, the evolutionary process of creating new species. Another possible explanation is the greater energy the tropics receive from the sun. But scientists have not been able to explain how greater energy input could translate into more species. The complexity of tropical ecosystems may promote speciation by increasing the habitat complexity, thus providing more ecological niches. Lastly, the tropics have been perceived as being more stable than temperate regions, which have a pronounced climate and day-length seasonality. The stability of tropical ecosystems might promote speciation. Regardless of the mechanisms, it is certainly true that biodiversity is greatest in the tropics. There are also high numbers of endemic species.

Importance of Biodiversity

Loss of biodiversity may have reverberating consequences on ecosystems because of the complex interrelations among species. For example, the extinction of one species may cause the extinction of another. Biodiversity is important to the survival and welfare of human populations because it has impacts on our health and our ability to feed ourselves through agriculture and harvesting populations of wild animals. Much of the importance of biodiversity comes from what is known as **ecosystem services** (Unit 5.2.3).

Video





In this 9-minute video by the California Academy of Sciences, the many ecosystem services that biodiversity provides are described.

Question after watching: Describe three different services and several examples of how biodiversity is important to humans.

Health

Many medications are derived from natural chemicals made by a diverse group of organisms. For example, many plants produce compounds meant to protect the plant from insects and other animals that eat them. Some of these compounds also work as human medicines. Contemporary societies that live close to the land often have a broad knowledge of the medicinal uses of plants growing in their area. For centuries in Europe, older knowledge about the medical uses of plants was compiled in herbals—books that identified the plants and their uses. Humans are not the only animals to use plants for medicinal reasons. The other great apes, orangutans, chimpanzees, bonobos, and gorillas as well as many other organisms such as elephants, bees, lizards, and canids have all been observed self-medicating with plants.

Modern pharmaceutical science also recognizes the importance of these plant compounds. Examples of significant medicines derived from plant compounds include aspirin (from the white willow, *Salix alba*), codeine (from the poppy, *Papaver somniferum*), digoxin (from the genus *Digitalis)*, atropine (from the belladonna, *Atropa belladonna)*, and vincristine (Figure **5.2.2.4**). Many medications were once derived from plant extracts but are now synthesized. It is estimated that, at one time, 25 percent of modern drugs contained at least one plant extract. That number has probably decreased to about 10 percent as natural plant ingredients are

replaced by synthetic versions of the plant compounds. Antibiotics, which are responsible for extraordinary improvements in health and lifespans in developed countries, are compounds largely derived from fungi and bacteria.



Figure **5.2.2.4**. *Catharanthus roseus*, the Madagascar periwinkle, has various medicinal properties. Among other uses, it is a source of vincristine, a drug used in the treatment of lymphomas. (credit: Forest and Kim Starr)

In recent years, animal venoms and poisons have excited intense research for their medicinal potential. By 2007, the FDA had approved five drugs based on animal toxins to treat diseases such as hypertension, chronic pain, and diabetes. Another five drugs are undergoing clinical trials and at least six drugs are being used in other countries. Other toxins under investigation come from mammals, snakes, lizards, various amphibians, fish, snails, octopuses, and scorpions.

Aside from representing billions of dollars in profits, these medications improve people's lives. Pharmaceutical companies are actively looking for new natural compounds that can function as medicines. It is estimated that more than 30% of pharmaceutical research and development is spent on natural compounds and that about 35% of new drugs brought to market between 1981 and 2002 were from natural compounds.

Agriculture

Since the beginning of human agriculture more than 10,000 years ago, human groups have been breeding and selecting crop varieties. This crop diversity matched the cultural diversity of highly subdivided populations of humans. For example, potatoes were domesticated beginning around 7,000 years ago in the central Andes of Peru and Bolivia. The potatoes grown in that region belong to seven species and the number of varieties likely is in the thousands. Each variety has been bred to thrive at particular elevations and soil and climate conditions. The diversity is driven by the diverse demands of the topography, the limited movement of people, and the demands created by crop rotation for different varieties that will do well in different fields.

Potatoes are only one example of human-generated diversity. Every plant, animal, and fungus that has been cultivated by humans has been bred from original wild ancestor species into diverse varieties arising from the demands for food value, adaptation to growing conditions, and resistance to pests. The potato demonstrates a well-known example of the risks of low crop diversity: the tragic Irish potato famine when the single variety grown in Ireland became susceptible to potato blight, wiping out the crop. The loss of the crop led to famine, death, and mass emigration. Resistance to disease is a chief benefit to maintaining crop biodiversity, and the lack of diversity in contemporary crop species carries similar risks. Seed companies, which are the source of most crop varieties in developed countries, must continually breed new varieties to keep up with evolving pest organisms. These same seed companies, however, have participated in the decline of the number of varieties available as they focus on selling fewer varieties in more areas of the world.

The ability to create new crop varieties relies on the diversity of varieties available and the accessibility of wild forms related to the crop plant. These wild forms are often the source of new gene variants that can be bred with existing varieties to create varieties with new attributes. Loss of wild species related to a crop will mean the loss of potential in crop improvement. Maintaining the genetic diversity of wild species related to domesticated species ensures our continued food supply.

Since the 1920s, government agriculture departments have maintained seed banks of crop varieties as a way to maintain crop diversity. This system has flaws because, over time, seed banks are lost through accidents, and there is no way to replace them. In 2008, the Svalbard Global Seed Vault (Figure **5.2.2.5**) began storing seeds from around the world as a backup system to the regional seed banks. If a regional seed bank stores varieties in Svalbard, losses can be replaced from Svalbard. The seed vault is located

deep into the rock of an arctic island. Conditions within the vault are maintained at ideal temperature and humidity for seed survival, but the deep underground location of the vault in the arctic means that failure of the vault's systems will not compromise the climatic conditions inside the vault.



Figure 5.2.2.5. The Svalbard Global Seed Vault is a storage facility for seeds of Earth's diverse crops. (credit: Mari Tefre, Svalbard Global Seed Vault)

? Optional Activity 5.2.2.1

Figure 5.2.2.5: The Svalbard Global Seed Vault is located on Spitsbergen island in Norway, which has an arctic climate. Why might an arctic climate be good for seed storage?

Answer

The ground is permanently frozen so the seeds will keep even if the electricity fails.

Crop success is largely dependent on the quality of the soil. Although some agricultural soils are rendered sterile using controversial cultivation and chemical treatments, most contain a huge diversity of organisms that maintain nutrient cycles—breaking down organic matter into nutrient compounds that crops need for growth. These organisms also maintain soil texture that affects water and oxygen dynamics in the soil that are necessary for plant growth. If farmers had to maintain arable soil using alternate means, the cost of food would be much higher than it is now. These kinds of processes are called ecosystem services. They occur within ecosystems, such as soil ecosystems, as a result of the diverse metabolic activities of the organisms living there, but they provide benefits to human food production, drinking water availability, and breathable air.

Other key ecosystem services related to food production are plant pollination and crop pest control. Over 150 crops in the United States require pollination to produce. One estimate of the benefit of honeybee pollination within the United States is $1.6 billion per year; other pollinators contribute up to $6.7 billion more.

Many honeybee populations are managed by apiarists who rent out their hives' services to farmers. Honeybee populations in North America have been suffering large losses caused by a syndrome known as colony collapse disorder, whose cause is unclear. Other pollinators include a diverse array of other bee species and various insects and birds. Loss of these species would make growing crops requiring pollination impossible, increasing dependence on other crops.

Finally, humans compete for their food with crop pests, most of which are insects. Pesticides control these competitors; however, pesticides are costly and lose their effectiveness over time as pest populations adapt. They also lead to collateral damage by killing non-pest species and risking the health of consumers and agricultural workers. Ecologists believe that the bulk of the work in removing pests is actually done by predators and parasites of those pests, but the impact has not been well studied. A review found that in 74 percent of studies that looked for an effect of landscape complexity on natural enemies of pests, the greater the complexity, the greater the effect of pest-suppressing organisms. An experimental study found that introducing multiple enemies of pea aphids (an important alfalfa pest) increased the yield of alfalfa significantly. This study shows the importance of landscape diversity via the question of whether a diversity of pests is more effective at control than one single pest; the results showed this to be the case. Loss of diversity in pest enemies will inevitably make it more difficult and costly to grow food.

Optional Activity 5.2.2.2

Which of the following agricultural crops is most likely to survive a catastrophic event?

A. a monoculture of a crop on a large surface
B. diverse varieties of a crop surrounded by a diverse ecosystem
C. a single crop surrounded by a diverse ecosystem
D. diverse varieties of a crop in a simple ecosystem

Answer

B. diverse varieties of a crop surrounded by a diverse ecosystem.

Video



In this short 1.5-minute video, learn how biodiversity for food and agriculture is indispensable to food security, sustainable development, and the supply of many vital ecosystem services.
Question after watching: In what ways could you diversify your own diet and support local food growers?

Wild Food Sources

In addition to growing crops and raising food animals, humans obtain food resources from wild populations, primarily wild fish populations. For about one billion people, aquatic resources provide the main source of animal protein. But since 1990, production from global fisheries has declined. Despite considerable effort, few fisheries on Earth are managed sustainability.

Fishery extinctions rarely lead to complete extinction of the harvested species, but rather to a radical restructuring of the marine ecosystem in which a dominant species is so over-harvested that it becomes a minor player, ecologically. In addition to humans losing a food source, these alterations affect many other species in ways that are difficult or impossible to predict. The collapse of fisheries has dramatic and long-lasting effects on local human populations that work in the fishery. In addition, the loss of an inexpensive protein source to populations that cannot afford to replace it will increase the cost of living and limit societies in other ways. In general, the fish taken from fisheries have shifted to smaller species and the larger species are overfished. The ultimate outcome could clearly be the loss of aquatic systems as food sources.

Psychological and Moral Value

Finally, it has been argued that humans benefit psychologically from living in a biodiverse world. The chief proponent of this idea was famed entomologist E. O. Wilson. He argued that human evolutionary history has adapted us to living in a natural environment and that built environments generate stresses that affect human health and well-being. There is considerable research into the psychologically regenerative benefits of natural landscapes that suggest the hypothesis may hold some truth. In addition, there is a moral argument that humans have a responsibility to inflict as little harm as possible on other species.

Video



This 5.5-minute video from the EU's Science for Environment Policy summarizes many of the ecosystem services and benefits discussed above.

Question after watching: What is your opinion of using monetary values for nature to convince people to preserve or restore natural systems?

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Unit 5.2.3 - The Biodiversity Crisis - HIPPPOC

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1.5 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.2.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Identify and explain the major causes of anthropogenic global change and their impacts on biodiversity.

Introduction

The core threat to biodiversity on the planet, and therefore a threat to human welfare, is the combination of human population growth and the resources used by that population. The human population requires resources to survive and grow, and many of those resources are being removed unsustainably from the environment. The three greatest proximate threats to biodiversity are habitat loss, overexploitation (also known as overharvesting), pollution, predator losses, and introduction of invasive species. These are a direct result of human population growth, resource use, increased mobility, and trade (Unit 4.2.6). One of the major causes of extinction, **anthropogenic climate change**, is covered in more depth in the next section (Unit 5.3).

Together, these threats are known as **HIPPPOC**: **h**abitat loss, **i**nvasive species, **p**ollution, **p**opulation (human), **p**redator loss, **o**verexploitation, and **c**limate change.

Habitat Loss

Humans rely on technology to modify their environment and make it habitable. Other species cannot do this. Elimination of their habitat—whether it is a forest, coral reef, grassland, or flowing river—will kill the individuals in the species. Remove the entire habitat and the species will become extinct, unless they are among the few species that do well in human-built environments. Human destruction of habitats accelerated in the latter half of the twentieth century.

Consider the exceptional biodiversity of Sumatra: it is home to one species of orangutan, a species of critically endangered elephant, and the Sumatran tiger, but half of Sumatra's forest is now gone. The neighboring island of Borneo, home to the other species of orangutan, has lost a similar area of forest. Forest loss continues in protected areas of Borneo. The orangutan in Borneo is listed as endangered by the International Union for Conservation of Nature (IUCN), but it is simply the most visible of thousands of species that will not survive the disappearance of the forests of Borneo. The forests are removed for timber and to plant palm oil plantations (Figure **5.2.3.1**). Palm oil is used in many products including food products, cosmetics, and biodiesel in Europe. A 5-year estimate of global forest cover loss for the years from 2000 to 2005 was 3.1%. Much loss (2.4%) occurred in the tropics where forest loss is primarily from timber extraction. These losses certainly also represent the extinction of species unique to those areas.



(a) (b)



(c)



(d) (e)

Figure 5.2.3.1: (a) One species of orangutan, *Pongo pygmaeus*, is found only in the rainforests of Borneo, and the other species of orangutan (*Pongo abelii*) is found only in the rainforests of Sumatra. These animals are examples of the exceptional biodiversity of (c) the islands of Sumatra and Borneo. Other species include the (b) Sumatran tiger (*Panthera tigris sumatrae*) and the (d) Sumatran elephant (*Elephas maximus sumatranus*), both critically endangered species. Rainforest habitat is being removed to make way for (e) oil palm plantations such as this one in Borneo's Sabah Province. (credit a: modification of work by Thorsten Bachner; credit b: modification of work by Dick Mudde; credit c: modification of work by U.S. CIA World Factbook; credit d: modification of work by "Nonprofit Organizations"/Flickr; credit e: modification of work by Dr. Lian Pin Koh)

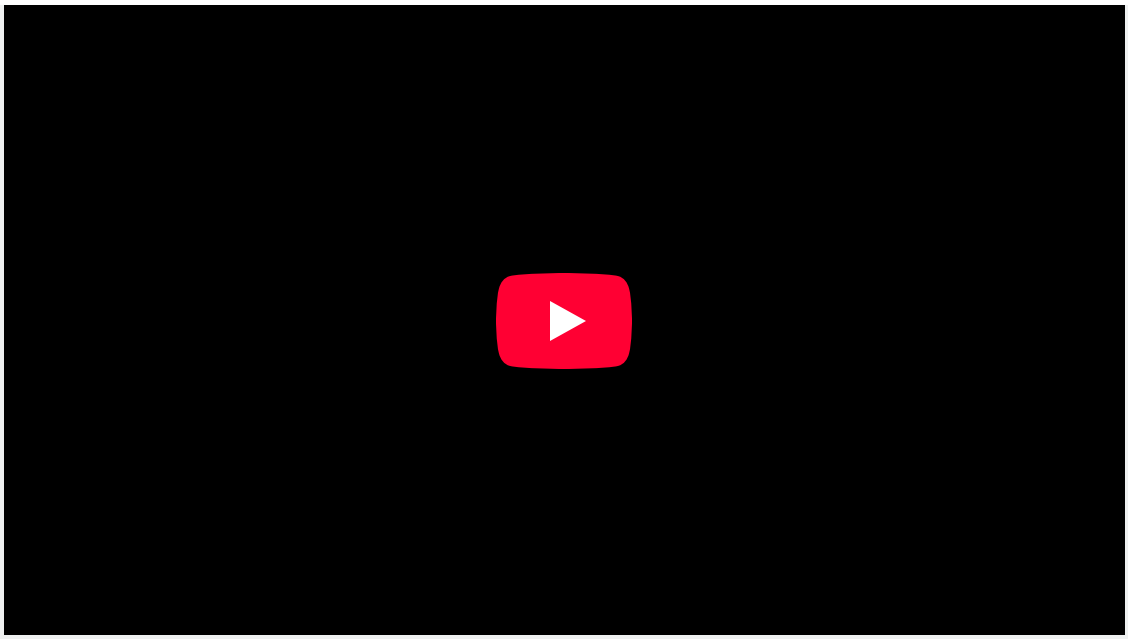
Preventing Habitat Destruction with Wise Wood Choices

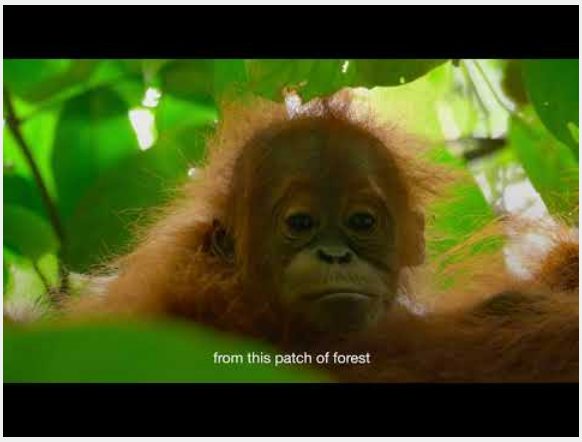
Most consumers do not imagine that the home improvement products they buy might be contributing to habitat loss and species extinctions. Yet the market for illegally harvested tropical timber is huge, and the wood products often find themselves in building supply stores. How is it possible to determine if a wood product, such as flooring, was harvested sustainably or even legally?

Various certifications can identify sustainably harvested forest products. Looking for certifications on flooring and other hardwood products is one way to ensure that the wood has not been taken illegally from a tropical forest. Some of these certifications are run by timber companies, however, thus creating a conflict of interest. Another approach is to buy domestic wood species. While it would be great if there was a list of legal versus illegal woods, it is not that simple. Logging and forest management laws vary from country to country; what is illegal in one country may be legal in another. Where and how a product is harvested and whether the forest from which it comes is being sustainably maintained all factor into whether a wood product will be certified. It is always a good idea to ask questions about where a wood product came from and how the supplier knows that it was harvested legally.

Habitat destruction can affect ecosystems other than forests. Rivers and streams are important ecosystems and are frequently the target of habitat modification. Damming of rivers affects flow and access to habitat. Altering a flow regime can reduce or eliminate populations that are adapted to seasonal changes in flow. Many fish species, including salmon, have seen declines caused by river damming and habitat loss.

Research has confirmed that species of amphibians that must carry out parts of their life cycles in both aquatic and terrestrial habitats are at greater risk of population declines and extinction because of the increased likelihood that one of their habitats or access between them will be lost. This is of particular concern because amphibians have been declining in numbers and going extinct more rapidly than many other groups for a variety of possible reasons.





Foresters identify strategies to manage forest habitats sustainably by mimicking natural processes in this 3.5-minute video from the World Wildlife Fund.
Question after watching: What are benefits to sustainable logging as described in the video?

Invasive Species

Non-native species are those that have been intentionally or unintentionally introduced by humans into an ecosystem in which they did not evolve. Human transportation of people and goods, including the intentional transport of organisms for trade, has dramatically increased the introduction of species into new ecosystems. These new introductions are often at distances that are well beyond the capacity of the species to ever travel on its own, and outside the range of the species' natural predators.

Most non-native species introductions probably fail because of the low number of individuals introduced or poor adaptation to the ecosystem they enter. Some species, however, have characteristics that can make them especially successful in a new ecosystem. These non-native species may undergo dramatic population increases in their new habitat and reset the ecological conditions in the new environment, threatening the native species that already exist there. When this happens, the non-native species is termed an **invasive species**. Invasive species can threaten other species through competition for resources, increased predation, or by causing new diseases.

Many invasive species are well suited evolutionarily to exploiting human transportation as a means to migrate, whether by air, sea, or land. The accidental introduction of the brown tree snake via aircraft (Figure 5.2.3.2) from the Solomon Islands to Guam in 1950 led to the extinction of three species of birds and three to five species of reptiles endemic to the island. Several other species are

still threatened. Islands do not make up a large area of land on the globe, but they do contain a disproportionate number of endemic species because of their isolation from mainland ancestors.

Lakes and islands are particularly vulnerable to extinction threats from non-native species. In Lake Victoria, the intentional introduction of the Nile perch was largely responsible for the extinction of about 200 species of cichlids. Many introductions of aquatic species, both marine and freshwater, have occurred when ships have dumped ballast water taken on at a port of origin into waters at a destination port. Water from the port of origin is pumped into tanks on a ship empty of cargo to increase stability. The water is drawn from the ocean or estuary of the port and typically contains living organisms such as plant parts, microorganisms, eggs, larvae, or aquatic animals. The water is then pumped out before the ship takes on cargo at the destination port, which may be on a different continent.

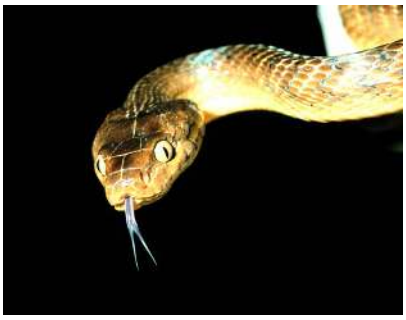


Figure **5.2.3.2**. The brown tree snake, *Boiga irregularis*, is an exotic species that has caused numerous extinctions on the island of Guam since its accidental introduction in 1950. (credit: NPS)

Invading exotic species can also be disease organisms. It now appears that the global decline in amphibian species recognized in the 1990s is, in some part, caused by the fungus *Batrachochytrium dendrobatidis*, which causes the disease chytridiomycosis (Figure **5.2.3.3**). There is evidence that the fungus is native to Africa and may have been spread throughout the world by transport of a commonly used laboratory and pet species: the African clawed frog, *Xenopus laevis*. It may well be that biologists themselves are responsible for spreading this disease worldwide. The North American bullfrog, *Rana catesbeiana*, which has also been widely introduced as a food animal but which easily escapes captivity, survives most infections of *B. dendrobatidis* and can act as a reservoir for the disease.



Figure **5.2.3.3**. This Limosa harlequin frog (*Atelopus limosus*), an endangered species from Panama, died from a fungal disease called chytridiomycosis. The red lesions are symptomatic of the disease. (credit: Brian Gratwicke)

Video



In this 5-minute video, discover the devastating impact that invasive species can have on ecosystems.
Question after watching: Do some research to find out what invasive species are a problem in your area? What is being done to combat them?

Optional Activity 5.2.3.1

Invasive predator species are especially threatening to what kind of ecosystem?

A. deserts
B. marine ecosystems
C. islands
D. tropical forests

Answer

C. islands

Pollution

Air Pollution

Air pollution occurs in many forms but can generally be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**.

Outdoor air pollution involves exposures that take place outside of the built environment. Examples include fine particles produced by the burning of coal, noxious gases such as sulfur dioxide, nitrogen oxides and carbon monoxide; ground-level ozone and tobacco smoke. **Indoor air pollution** involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. Examples include household products and chemicals, out-gassing of building materials, allergens (cockroach and mouse dropping, mold, pollen), and tobacco smoke.

A **point source** of air pollution refers to an emission source that does not move including factories, power plants, and dry cleaners. The term **non-point sources** is used to describe many sources of air pollution located together whose individual emissions may be below thresholds of concern, but whose collective emissions can be significant. Non-point sources include the construction of housing developments, runoff from asphalt, and landfills. In crop production, the misapplication of fertilizers, herbicides, and pesticides can potentially result in aerial drift of these materials and harm may be caused.

Video



In this 4-minute video from National Geographic, learn how greenhouse gasses, smog, and toxic pollutants affect climate change and human health.

Question after watching: What strategies beyond those discussed in the video do you think will help to reduce air pollution?

Unlike the above-mentioned sources of air pollution, air pollution caused by **natural sources** is not caused by people or their activities. An erupting volcano emits particulate matter and gases, forest and prairie fires can emit large quantities of pollutants, dust storms can create large amounts of particulate matter, and plants and trees naturally emit volatile organic compounds which can form aerosols that can cause a natural blue haze.

Water Pollution

Water pollution is the contamination of water by an excess amount of a substance that can cause harm to human beings and/or the ecosystem. The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water. Pollutants are derived from biological, chemical, or physical processes. Although natural processes such as volcanic eruptions or evaporation sometimes can cause water pollution, most pollution is derived from human, land-based activities (Figure **5.2.3.4**).



Figure 5.2.3.4. Water Pollution. Obvious water pollution in the form of floating debris, largely plastics; microscopic and chemical water pollutants are often much more harmful than visible ones. Source: Stephen Codrington at Wikimedia Commons

Water pollutants can move through different water reservoirs, as the water carrying them progresses through stages of the water cycle (Figure 5.2.3.5). **Water residence time** (the average time that a water molecule spends in a water reservoir) is very important to pollution problems because it affects pollution potential. Water in rivers has a relatively short residence time, so pollution usually is there only briefly. Of course, pollution in rivers may simply move to another reservoir, such as the ocean, where it can cause further problems. Groundwater is typically characterized by slow flow and longer residence time, which can make groundwater pollution particularly problematic. Finally, **pollution residence time** can be much greater than the water residence time because a pollutant may be taken up for a long time within the ecosystem or absorbed onto sediment.

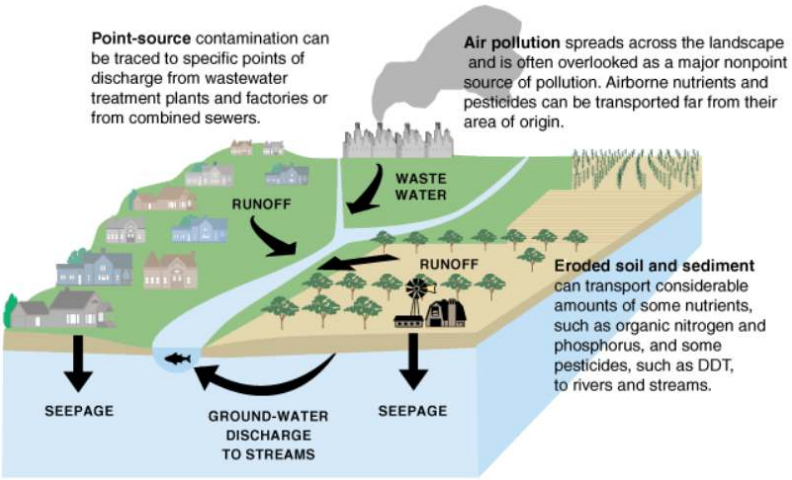


Figure 5.2.3.5. Sources of Water Contamination. Sources of some water pollutants and movement of pollutants into different water reservoirs of the water cycle. Source: U.S. Geological Survey

Like air pollution, water pollutants may enter the water cycle from point sources, which include identifiable and (generally) relatively small locations, or nonpoint sources, which include large and more diffuse areas. Point sources of pollution include animal factory farms (Figure 5.2.3.6) that raise a large number and high density of livestock such as cows, pigs, and chickens.



Figure 5.2.3.6. Large animal farms are often referred to as concentrated feeding operations (CFOs). These farms are considered potential point sources of pollution because untreated animal waste may enter nearby waterbodies as untreated sewage. Credit: ehp.gov

Included in point sources are pipes from factories or sewage treatment plants. Combined sewer systems that have a single set of underground pipes to collect both sewage and stormwater runoff from streets for wastewater treatment can be major point sources of pollutants. During heavy rain, stormwater runoff may exceed sewer capacity, causing it to back up and spilling untreated sewage directly into surface waters (Figure 5.2.3.7).

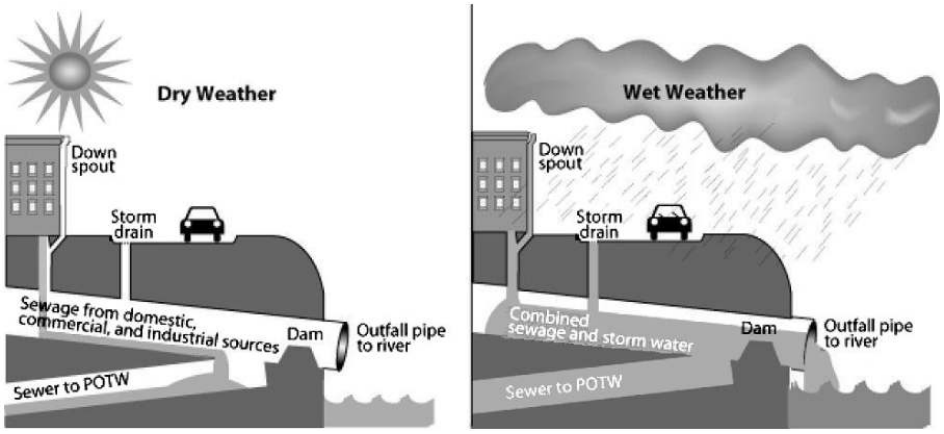


Figure 5.2.3.7. Combined Sewer System A combined sewer system is a possible major point source of water pollution during heavy rain due to overflow of untreated sewage. During dry weather (and small storms), all flows are handled by the publicly-owned treatment works. During large storms, the relief structure allows some of the combined stormwater and sewage to be discharged untreated to an adjacent water body. Source: U.S. Environmental Protection Agency at Wikimedia Commons

Non-point sources of pollution include agricultural fields, cities, and abandoned mines. Rainfall runs over the land and through the ground, picking up pollutants such as herbicides, pesticides, and fertilizer from agricultural fields and lawns; oil, antifreeze, animal waste, and road salt from urban areas; and acid and toxic elements from abandoned mines. Then, this pollution is carried into surface water bodies and groundwater. Non-point source pollution, which is the leading cause of water pollution, is usually much more difficult and expensive to control than point source pollution because of its low concentration, multiple sources, and much greater volume of water.

Video



In this 9-minute video, discover how the plastic we dump into the ocean might be hiding in plain sight.
Question after watching: What is the ultimate solution to plastic waste in the ocean? What part can individuals play in this solution? What part can corporations play?

Population

Humans, while subject to the same ecological constraints as any other species (a need for nutrients, water, etc.), have some features as individuals and some as a population that make them a unique species. Unlike most other organisms, humans have the capacity to alter their number of offspring, level of resource consumption and distribution. While most women around the world could potentially have the same number of children during their lives, the number they actually have is affected by many factors. Depending upon technological, cultural, economic and educational factors, people around the world have families of different sizes. Additionally, unlike other organisms, humans invent and alter technology, which allows them to change their environment. This ability makes it difficult to determine the human carrying capacity (Figure **5.2.3.8**).

For example, families in developing nations are often larger, but less resource-intensive (e.g., they use fewer resources per person) than those in more developed nations. However, increasingly, human populations wish to have a "western" standard of living. An increase in the world's average standard of living significantly lowers the potential human carrying capacity of the earth. Therefore, in order to reduce their impact as a species, humans must not only reduce the resources they use per person, they must also reduce their average family size.

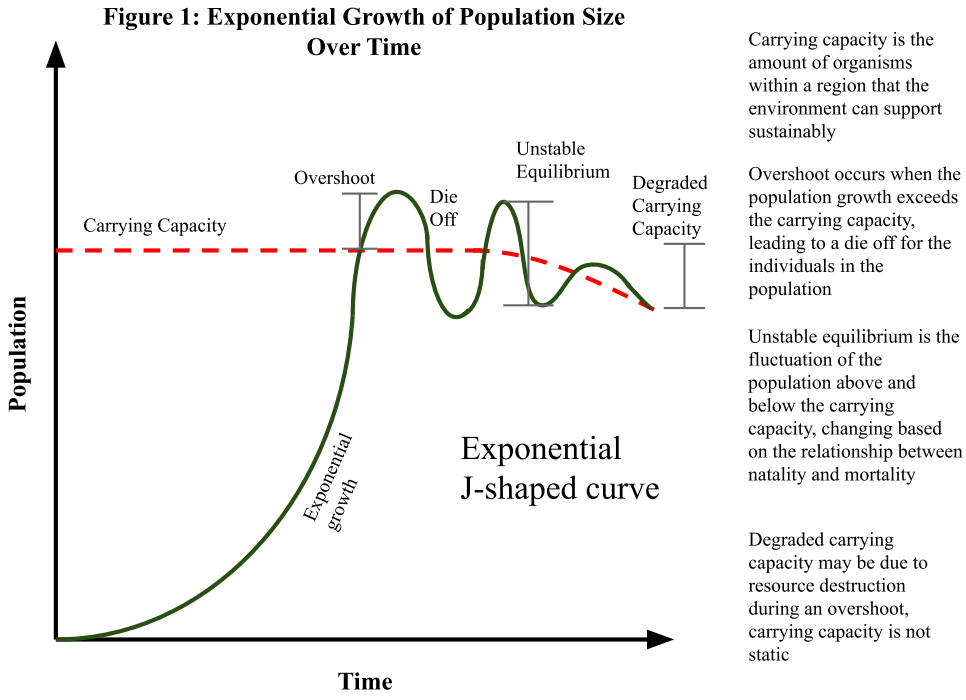


Figure **5.2.3.8**: Reaching carrying capacity through exponential growth, followed by die-off and carrying capacity degradation (Copyright; Nchisick CC BY-SA 4.0)

Human Resource Utilization

Humans have always made an impact on the environment through their use of resources. For example, early humans were primarily hunter-gatherers who used tools to survive. They fashioned wood and stone tools for hunting and food preparation, and used fire for cooking. Early humans developed methods for changing habitats to suit their needs and herding wild animals. As time passed, humans developed more tools and techniques and came to rely on that technology in their daily lives. Although the tools of early humans were primitive by today's standards, they significantly affected the environment and probably hastened the extinction of some large Ice Age mammals.

Over the last 10,000 years, land clearing for agriculture has destroyed and degraded the habitats of many species of plants and animals. Today, growing populations in less developed countries are rapidly clearing tropical forests and savannas for agricultural use. These tropical rainforests and savannas provide habitat for most of the earth's species. It has become clear that modern agricultural practices are not sustainable. Once-fertile areas are becoming infertile because of overgrazing, erosion and nutrient depletion. Furthermore, modern agriculture requires large inputs of energy and fertilizers, usually produced from nonrenewable fossil fuels.

Advanced industrialization leads to many changes in human society, and some of those changes negatively affect the supply of natural resources and result in environmental degradation. These changes include: increased production and consumption of goods by humans, dependence on non-renewable resources such as oil and coal, production of synthetic materials (which may be toxic or non-biodegradable), and consumption of large amounts of energy at home and work. For example, if everyone on the planet lived as the average Canadian, humanity would need the equivalent of 5.1 Earths to support everyone.

Other changes may have positive benefits. These include: creation and mass production of useful and affordable products, significant increases in the average **gross national product** per person, large increases in agricultural productivity, sharp rises in average life expectancy and a gradual decline in population growth rates. The information age was born with the invention of miniaturized electronics such as integrated circuits and computer central processing units. This stage in human development has changed and continues to change society as we know it. By making good use of information technologies, less developed countries may be able to reduce potential environmental problems as their economies expand in the future. With so much information easily

available, developing countries may not repeat the environmental mistakes that more developed countries made as they became industrialized.

Predator Losses

"The loss of apex consumers is arguably humankind's most pervasive influence on the natural world. This is true in part because it has occurred globally and in part because extinctions are by their very nature perpetual, whereas most other environmental impacts are potentially reversible on decadal to millenial time scales. Recent research suggests that the disappearance of these animals reverberates further than previously anticipated, with far-reaching effects on processes as diverse as the dynamics of disease; fire; carbon sequestration; invasive species; and biogeochemical exchanges among Earth's soil, water, and atmosphere."[1] The loss of these predators leads to what is known as **trophic cascades**.

"Predation is ubiquitous in nature and can be an important component of both ecological and evolutionary interactions. One of the most striking features of predators is how often they cause evolutionary diversification in natural systems. Predators are effective agents of natural selection because they possess key traits that allow them to capture and consume their prey; they adopt different strategies to do so, and they are common, but not too common, such that they can drive prey evolution without driving prey species to extinction."[2]

"Classic ecological studies that viewed predators as static entities that interact with prey in fixed ways resulting in predictable population dynamics are likely too simplistic. Today it is recognized that both predator and prey populations evolve—and that this evolution can happen very rapidly, even on ecological time scales, often with more than two species involved."[2]

"Ecosystems may be shaped by the loss of consumers. The loss of a single predator species may reverberate through the community. The loss of apex consumers reduces food chain length, thus altering the intensity of herbivory and the abundance and composition of plants in largely predictable ways. The transitions in ecosystems that characterize such changes are often abrupt, are sometimes difficult to reverse, and commonly lead to radically different patterns and pathways of energy and [matter]."[2]

Video



Scientists have discovered that reintroducing apex predators has led to successful recovery of previously damaged ecosystems, profiled in this 6-minute video from the IUCN.

Question after watching: Why do apex predators play such a crucial role in ecosystems and how can we effectively preserve them?

? Optional Activity 5.2.3.2

Wolves are a keystone species in Yellowstone National Park, Wyoming, USA. Predict what would happen if they were hunted to extinction.

A. Many species would increase and the elk population would disappear.
B. Many species would disappear and the elk population would initially increase.
C. Many species along with elk population would increase.
D. Many species, along with the elk population, would disappear.

Answer

B. Many species would disappear and the elk population would initially increase.

Overharvesting

Overharvesting is a serious threat to many species, but particularly to aquatic species. There are many examples of regulated fisheries (including hunting of marine mammals and harvesting of crustaceans and other species) monitored by fisheries scientists that have nevertheless collapsed. The western Atlantic cod fishery is the most spectacular recent collapse. While it was a hugely productive fishery for 400 years, the introduction of modern factory trawlers in the 1980s and the pressure on the fishery led to it becoming unsustainable. The causes of fishery collapse are both economic and political in nature.

Most fisheries are managed as a common resource, available to anyone willing to fish, even when the fishing territory lies within a country's territorial waters. Common resources are subject to an economic pressure known as the tragedy of the commons, in which fishers have little motivation to exercise restraint in harvesting a fishery when they do not own the fishery. The general outcome of harvests of resources held in common is their overexploitation. While large fisheries are regulated to attempt to avoid this pressure, it still exists in the background. This overexploitation is exacerbated when access to the fishery is open and unregulated and when technology gives fishers the ability to overfish. In a few fisheries, the biological growth of the resource is less than the potential growth of the profits made from fishing if that time and money were invested elsewhere. In these cases—whales are an example—economic forces will drive toward fishing the population to extinction.

Video



Learn about overfishing and its effects on ecosystems, food security, jobs, economies, and coastal cultures in this 4.5-minute video.
Question after watching: What can communities do to ensure their local waters are fished sustainably?

Coral reefs are extremely diverse marine ecosystems that face peril from several processes. Reefs are home to 1/3 of the world's marine fish species—about 4,000 species—despite making up only one percent of marine habitat. Most home marine aquaria house coral reef species that are wild-caught organisms—not cultured organisms. Although no marine species is known to have been driven extinct by the pet trade, there are studies showing that populations of some species have declined in response to harvesting,

indicating that the harvest is not sustainable at those levels. There are also concerns about the effect of the pet trade on some terrestrial species such as turtles, amphibians, birds, plants, and even the orangutans Figure **5.2.3.9**.



Figure **5.2.3.9**. Harvesting of pangolins for their scales and meat, and as curiosities, has led to a drastic decline in population size for this fascinating creature. *This work by David Brossard is licensed under CC BY 4.0*

Many around the world eat wild animals for food. Hunting is practiced throughout the world, but hunting practices, particularly in equatorial Africa and parts of Asia, are believed to threaten several species with extinction. Traditionally, wild meat in Africa was hunted to feed families directly. However, recent commercialization of the practice now has wild meat available in grocery stores, which has increased harvest rates to the level of unsustainability. Additionally, human population growth has increased the need for protein foods that are not being met from agriculture. Species threatened by the wild meat trade are mostly mammals including many monkeys and the great apes living in the Congo basin.

Climate Change

Climate change, and specifically the anthropogenic (meaning, caused by humans) warming trend presently underway, is recognized as a major extinction threat, particularly when combined with other threats such as habitat loss. Extinction rate estimates range from 15 percent to 40 percent of species committed to extinction by 2050 due to climate change. Climate change will alter regional climates, including rainfall and snowfall patterns, making habitats less hospitable to the species living in them. The warming trend will shift colder climates toward the north and south poles, forcing species to move with their adapted climate norms while facing habitat gaps along the way.

The shifting ranges will impose new competitive regimes on species as they find themselves in contact with other species not present in their historic range. One such unexpected species contact is between polar bears and grizzly bears (Figure **5.2.3.10**). Previously, these two species had separate ranges. Now, their ranges are overlapping and there are documented cases of these two species mating and producing viable offspring. Changing climates also throw off species' delicate timing adaptations to seasonal food resources and breeding times. Many contemporary mismatches to shifts in resource availability and timing have already been documented.



Figure 5.2.3.10: Since 2008, grizzly bears (*Ursus arctos horribilis*) have been spotted farther north than their historic range, a possible consequence of climate change. As a result, grizzly bear habitat now overlaps polar bear (*Ursus maritimus*) habitat. The two kinds of bears, which are capable of mating and producing viable offspring, are considered separate species as historically they lived in different habitats and never met. However, in 2006 a hunter shot a wild grizzly-polar bear hybrid known as a grolar bear, the first wild hybrid ever found.

Range shifts are already being observed: for example, some European bird species ranges have moved 91 km northward. The same study suggested that the optimal shift based on warming trends was double that distance, suggesting that the populations are not moving quickly enough. Range shifts have also been observed in plants, butterflies, other insects, freshwater fishes, reptiles, and mammals.

Climate gradients will also move up mountains, eventually crowding species higher in altitude and eliminating the habitat for those species adapted to the highest elevations. Some climates will completely disappear. The rate of warming appears to be accelerated in the arctic, which is recognized as a serious threat to polar bear populations that require sea ice to hunt seals during the winter months: seals are the only source of protein available to polar bears. A trend to decreasing sea ice coverage has occurred since observations began in the mid-twentieth century. The rate of decline observed in recent years is far greater than previously predicted by climate models.

Finally, climate change will raise ocean levels due to meltwater from glaciers and the greater volume of warmer water. Shorelines will be inundated, reducing island size, which will have an effect on some species, and a number of islands will disappear entirely. Additionally, the gradual melting and subsequent refreezing of the poles, glaciers, and higher-elevation mountains—a cycle that has provided freshwater to environments for centuries—will also be jeopardized. This could result in an overabundance of salt water and a shortage of fresh water.

More on climate change follows in Unit 5.3.

Video



This 6-minute video from PBS discusses that as the world figures out how to live with a rapidly changing climate, traditional knowledge from Indigenous cultures could help Western Science understand just how things are transforming.
Question after watching: In what ways is Indigenous Science dynamic regarding climate change? In what areas are Indigenous people facing discrimination in science?

Optional Activity 5.2.3.3

Converting a prairie to a farm field is an example of _____.

A. overharvesting
B. habitat loss
C. exotic species
D. climate change

Answer

B. habitat loss

Optional Activity 5.2.3.4

Loss of biodiversity and acceleration of extinction rates have several causes. Which of the following situations causes direct loss of biodiversity owing to overexploitation?

A. fishing cod at a rate that is greater than natural replacement
B. building a housing subdivision in place of second-growth forest
C. introduction of an invasive ornamental plant in a new ecosystem
D. emission of greenhouse gases increasing the average temperatures of an area

Answer

A. fishing cod at a rate that is greater than natural replacement

Video



In this 3.5-minute video, learn of a 2019 United Nations report that says humans are transforming the planet's natural habitat at an unprecedented rate.

Question after watching: Are you optimistic or pessimistic of humans' capability to change and reduce their collective ecological footprint?

Footnotes:

1. Estes, J.A. et al. 2011. Trophic Downgrading of Planet Earth. *Science.* 333(6040): 301-306: https://doi.org/10.1126/science.1205106

2. Johnson, J.B. and M.C. Belk. 2020. Predators as Agents of Selection and Diversification. *Diversity.* 12(11): 415; https://doi.org/10.3390/d12110415

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Unit 5.2.4 - Preserving Biodiversity

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.



Introduction

Preserving biodiversity is an extraordinary challenge that must be met by a greater understanding of biodiversity itself, changes in human behavior and beliefs, and various preservation strategies. The threats to biodiversity have been recognized for some time. Today, the main efforts to preserve biodiversity involve legislative approaches to regulate human and corporate behavior, setting aside protected areas, and habitat restoration. A lofty goal is to protect 50% of the Earth's natural spaces for wildlife known as the Half-Earth Project, as described by the late Dr. E.O. Wilson below. Others, such as David Attenborough and Dr. Sylvia Earle, weigh in on the issue as well.

Videos



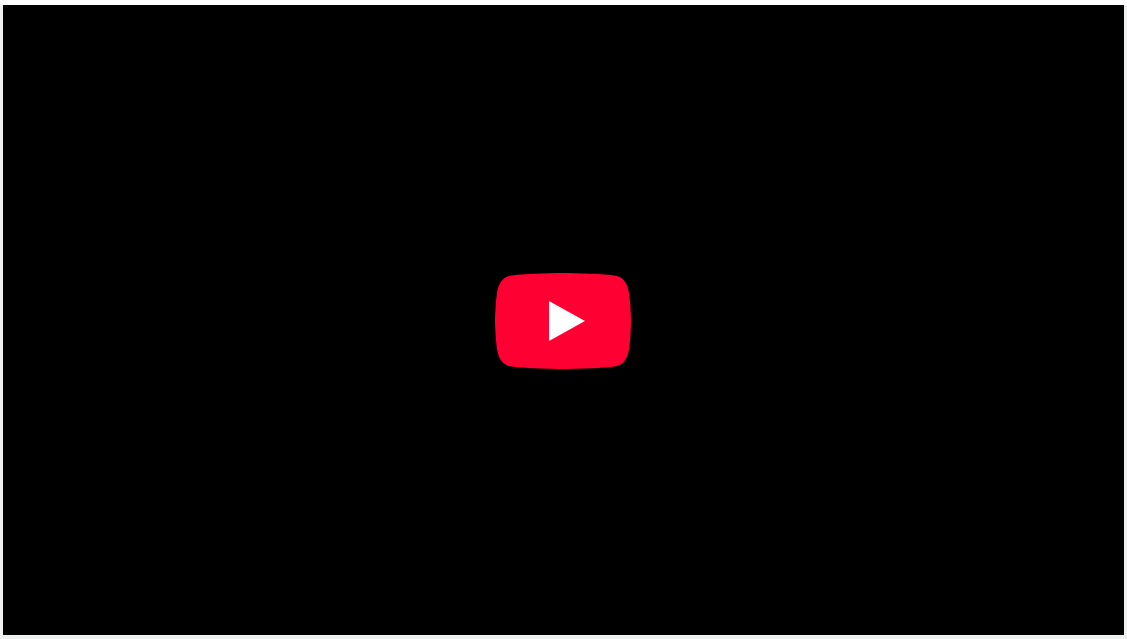


6-minute video with famed conservationist David Attenborough





6-minute video with famed biologist E.O. Wilson





3-minute video with famed marine biologist Sylvia Earle

Question after watching: What common themes do you find in the messages of these conservation ambassadors?

Changing Human Behavior

Ultimately, human behavior will change when human values change. At present, the growing urbanization of the human population is a force that poses challenges to the valuing of biodiversity. Legal avenues can help to protect biodiversity in the meantime.

International Legislation

Legislation throughout the world has been enacted to protect species. The legislation includes international treaties as well as national and provincial laws. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (**CITES**) agreement came into force in 1975. The agreement, and the national legislation that supports it in Canada and most other countries, provides a legal framework for preventing approximately 33,000 listed species from being transported across national borders, thus protecting them from being caught or killed when international trade is involved. The treaty is limited in its reach because it only deals with the international movement of organisms or their parts. It is also limited by some countries' ability or willingness to enforce the treaty and supporting legislation. The illegal trade in organisms and their parts is probably a market in the hundreds of millions of dollars. Illegal wildlife trade is monitored by a non-profit: Trade Records Analysis of Flora and Fauna in Commerce (**TRAFFIC**).

The **Convention on Biological Diversity** is now the leading international treaty to advance the conservation of biodiversity, within the context of a comprehensive agenda for sustainable development. The three key goals of the Convention are the conservation of biodiversity, the sustainable use of its components, and the equitable sharing of benefits from the use of genetic resources. The 194 ratified parties to the Convention are engaged in a multitude of cooperative initiatives and information and technology sharing, and are committed to identify and conserve their biodiversity.

A key action is to periodically undertake science assessments of the status of global biodiversity. Broadly speaking, the most recent assessment found that the prospects of biodiversity were rapidly worsening in many parts of the world, although considerable progress was being made in cooperative planning and in the designation of protected areas and other conservation measures in many countries. It is too soon to tell whether these international actions will be successful because the programs began only in the late 1970s (as an earlier program called the World Conservation Strategy). However, it is encouraging to know that this sort of comprehensive international effort exists and that almost all of Earth's nations are participating, including countries in all stages of economic development.

? Optional Activity 5.2.4.1

The Convention on International Trade in Endangered Species (CITES) passed a resolution to protect rhinoceroses in the wild. Rhinoceroses have been hunted to the brink of extinction because their horns, which are made of the protein keratin, the same as humans' fingernails and hair, are considered an aphrodisiac and a powerful drug in some cultures. Why does the protection of rhinoceroses require an international agreement?

A. The rhinoceroses are hunted in their native countries, but the trade crosses borders.
B. The use of rhinoceros' horns as an aphrodisiac has showed negative effects internationally.
C. The hunters from different countries travel to the native country to hunt for rhinoceroses.
D. Their demand is greater in foreign countries as compared to their native countries.

Answer

A. The rhinoceroses are hunted in their native countries, but the trade crosses borders.

Canadian Legislation

In Canada, the conservation status of the 80,000 confirmed species is assessed by the Committee on the Status of Endangered Wildlife in Canada (**COSEWIC**). COSEWIC is a consultative body with expert representatives from governments (federal, provincial, territorial, and Indigenous), universities, and non-governmental organizations. It makes recommendations to the federal, provincial, and territorial governments, whose responsibility it is to designate conservation status.

Once a species is listed as endangered or threatened in Canada, a parallel body known as RENEW (REcovery of Nationally Endangered Wildlife) is mandated to prepare a plan that would ensure the recovery of its population to a safer level. However, because of a lack of funding, as of 2014 only about 40 recovery plans had been completed, although many others are in various stages of development.

COSEWIC recognizes five categories of risk, each of which has a specific meaning in terms of imminent threats to the future survival of the species (COSEWIC, 2015).

- **Extinct** refers to any species of wildlife that was formerly indigenous to Canada but no longer exists anywhere in the world. Canadian examples of extinct species are the great auk (*Pinguinus impennis*), passenger pigeon (*Ectopistes migratorius*), Labrador duck (*Camptorhynchus labradorium*), sea mink (*Mustela macrodon*), deepwater cisco (*Coregonus johannae*), longjaw cisco (*Coregonus alpenae*), and eelgrass limpet (*Lottia alveus*). Extinct subspecies are the Queen Charlotte caribou (*Rangifer tarandus dawsoni*), blue pike (*Stizostedion vitreum glaucum*), and Banff longnose dace (*Rhinichthys cataractae smithi*). As of 2020, 15 Canadian taxa (species, subspecies, or distinct populations) were extinct.
- **Extirpated** refers to any species or subspecies that was formerly indigenous to Canada but now only survives in the wild or elsewhere, usually in the neighboring United States. Examples include the black-footed ferret (*Mustela nigripes*), Atlantic grey whale (*Eschrichtius robustus*), Northwest Atlantic walrus (*Odobenus rosmarus*), greater prairie chicken (*Tympanuchus cupido*),

pygmy short-horned lizard (*Phrynosoma douglassi*), paddlefish (*Polyodon spathula*), and blue-eyed Mary (*Collinsia verna*). As of 2020, 135 taxa were extirpated in Canada, most of which are plants and beetles.

- **Critically imperiled** refers to indigenous species that are faced with imminent extinction or extirpation throughout all or a significant portion of their Canadian range. As of 2020, 824 taxa were considered to be critically imperiled. Examples include the Vancouver Island marmot (*Marmota vancouverensis*), bowhead whale (*Balaena mysticetus*), right whale (*Balaena glacialis*), whooping crane (*Grus americana*), Eskimo curlew (*Numenius borealis*), burrowing owl (*Speotyto cunicularia*), piping plover (*Charadrius melodus*), Blanchard's cricket frog (*Acris crepitans blanchardi*), blue racer snake (*Coluber constrictor foxii*), eastern prickly pear cactus (*Opuntia humifusa*), small white ladyslipper (*Cypripedium candidum*), thread-leaved sundew (*Drosera filiformis*), and seaside centipede lichen (*Heterodermia sitchensis*)
- **Imperiled** refers to any indigenous taxon that is likely to become critically imperiled unless factors affecting its status are reversed. As of 2020, 1,245 taxa were considered imperiled in Canada. Examples include the wood bison (*Bison bison athabascae*), sea otter (*Enhydra lutris*), Pacific humpback whale (*Megaptera novaeangliae*), marbled murrelet (*Brachyramphus marmoratus*), massasauga rattlesnake (*Sistrurus catenatus*), and American chestnut (*Castanea dentata*).
- **Vulnerable** refers to any indigenous species that is not currently imperiled but is at risk of becoming so because of small or declining numbers, occurrence at the fringe of its range or in restricted areas, habitat fragmentation, or some other reason. As of 2020, 2,765 taxa or populations were considered to be vulnerable. Examples include the grizzly bear (*Ursus arctos horribilis*), polar bear (*Thalarctos maritimus*), blacktail prairie dog (*Cynomys ludovicianus*), long-billed curlew (*Numenius americanus*), ivory gull (*Pagophila eburnea*), spotted turtle (*Clemmys guttata*), and eastern prairie fringed orchid (*Platanthera leucophaea*).

It must be recognized that the designation of species at risk is a continuing and always incomplete process. For instance, because the conservation status of only a few species of invertebrates has been investigated, critically imperiled species in this group are enormously under-represented in the COSEWIC list. Unfortunately, more rapid progress is constrained by a shortage of funding for research and monitoring of endangered species, and by a lack of specialists with the necessary taxonomic and ecological skills and knowledge.

Of course, it is not sufficient merely to designate species as being at risk of extirpation or extinction. If their status is to be improved, the species and their habitats must also be protected. Remarkably, the Canadian federal government have not yet enacted effective legislation to protect endangered species and their habitat across the whole of the country. However, this situation is starting to change. In 2002, the Government of Canada passed the Species at Risk Act (SARA), which provides some protection for species occurring on crown lands and otherwise within federal jurisdiction.

However, the federal legislation has little direct influence on the status of the many species-at-risk that are living on provincial, territorial, Indigenous, or private land. Most importantly, the Act does not fully address the protection of habitat of critically imperiled species off federal land. To some degree, this deficiency is covered by legislation that has been enacted by provinces and territories. However, their legislations are also not very effective, because they, too, do not protect the habitat of species at risk, especially on private land. Such a piecemeal approach results in uneven levels of protection for species-at-risk, which is unacceptable from the conservation viewpoint.

The lack of effective protection of species-at-risk in Canada is raising controversy. Governments feel the need to demonstrate that they are making rapid progress toward sustainability, an important component of which involves the protection of native species and their habitats. Unfortunately, the progress to date has been lacking and is not yet effective in protecting our biodiversity most at-risk. Hopefully, the lobbying efforts of Canadian non-governmental organizations (NGOs) will result in appropriate changes to the currently weak legislation of all levels of government. Key national organizations in this regard are Nature Canada, Canadian Parks and Wilderness Society (CPAWS), Ecojustice, and World Wildlife Fund-Canada (WWF).

Some of the natural ecosystems of Canada now exist only as small remnants of their former extent. Because of this, they are as endangered as the species they support. The most endangered of our natural ecosystems are:

- the tall-grass prairie of southwestern Ontario and southeastern Manitoba
- Carolinian forest of southern Ontario
- dry coastal Douglas fir and Garry oak forest types of southwestern British Columbia
- semi-desert of southeastern British Columbia
- various kinds of old-growth forest in all parts of Canada, but particularly in the east
- and many kinds of freshwater wetlands

Some of these ecosystems, particularly the tall-grass prairie and Carolinian forest, are also rich in endangered species. It is imperative that the remaining areas of these endangered ecosystems become preserved in parks and other kinds of protected areas.

Video



Discover the importance of habitat conservation in Canada and the threats to Pacific salmon in this 5-minute video. Question after watching: What are the most pressing threats to Pacific salmon? How can Pacific salmon be preserved?

Non-Profit Impacts

Governments throughout Canada have created many protected areas, but their actions are almost exclusively on Crown land. However, many of the properties with the greatest conservation value are privately owned by individuals or corporations. The private non-profit sector plays a large role in the conservation effort both in North America and around the world (more in Unit 5.4.4). The approaches range from species-specific organizations to the broadly focused IUCN and TRAFFIC.

This is particularly the case in southern regions of Canada, where most species-at-risk and endangered ecosystems occur. Because of a lack of money and other priorities, governmental agencies are often reluctant to secure ecologically important habitat on privately owned lands. For this reason, conservation charities known as land trusts have formed for the purpose of raising funds to acquire private property in order to establish protected areas.

At the national level, the largest of these organizations is the Nature Conservancy of Canada (NCC). The focus of NCC is on acquiring private property of high conservation value, which it does by purchasing or accepting donations of real estate, as well as rights of land-use. The latter involves a kind of private property called a conservation easement (or in Quebec, a servitude). If owned by NCC, a conservation easement can prevent current and future owners of the real estate from converting its natural habitat into residential lots or cultivated agriculture, or from engaging in other proscribed activities that might threaten the natural values of the property. There are many other land trusts that operate at local and provincial scales that also acquire private conservation lands and easements. However, NCC is the only national organization, and it is by far the biggest.

Since its origin in 1962, NCC has contributed to the protection of 1.1-million hectares of natural habitat throughout Canada. In 2020-2021, NCC secured an additional 20,000 hectares over 53 individual properties. In partnership with the Natural Heritage Conservation Program, aiming to preserve 30% of Canadian land and water by 2030, they secured an additional 28,907 hectares with $25 million of federal investment and $60 million from other sources. In 2021, it exceeded the goals of its Landmark fund-raising campaign, which raised more than $750 million from more than 110,000 individual donors.

The conservation actions of NCC are being guided by “ecoregional plans”, also known as “conservation blueprints”, which help to identify the most important places where private action can make the greatest difference in protecting native species and natural ecosystems. These plans are developed in close partnership with governments, the U.S. Nature Conservancy, Ducks Unlimited Canada, provincial and local land trusts, industrial interests, and academic scientists. Successful conservation action requires more than just acquiring properties – each project must also be properly stewarded to maintain or enhance its natural values. Stewardship actions range from posting signs at property boundaries, to innovative, science-based management actions that are needed to sustain particular species or ecological communities.

For example, NCC routinely subjects its tall-grass prairie reserves in southeastern Manitoba to prescribed burns, which prevents the endangered grassland from being degraded by incursions of shrubs and trees. At NCC reserves that protect imperiled Garry oak forests on southern Vancouver Island, stewardship volunteers spend many hours pulling alien weeds that threaten rare plants. One last example involves a protected area of rare Carolinian forest at Clear Creek in southern Ontario, where NCC is converting adjacent cornfields into natural forest in order to increase the size and enhance the viability of the conserved ecosystem. These kinds of stewardship activities must be advised by leading-edge scientific knowledge, which NCC develops by hiring ecologists and by working in partnership with other organizations.

The Nature Conservancy of Canada is only one example of the many highly motivated and effective non-governmental conservation organizations in Canada. Their work is crucial to sustaining the biodiversity-at-risk of our country. Of course, being charities, private organizations like NCC can only spend money that they can manage to raise, which is a good reason for all sectors of our society to support their important work of protecting natural habitats.

Video



In this 3 min video, you will be introduced to the argument that biodiversity loss results in economic loss in diverse ways, therefore natural resource management practices need to be applied.
Question after watching: Do you agree that biodiversity loss should be treated with natural resource management practices? What are the advantages and disadvantages of doing this?

Indigenous Connections: Preserving Salmon Fisheries

According to the research of Reid et al. (2022):

> Pacific salmon—fish known by a host of Indigenous names throughout their vast geographic range (genus *Oncorhynchus*)—have been in a state of decline in British Columbia (BC), Canada for several decades (Price et al., 2017) such that a growing number of wild salmon populations have been assessed as "at risk"' (from Special Concern (n = 5 populations) to Threatened (n = 3) to Endangered (n = 10)) by the Committee on the Status of Endangered Wildlife in Canada (Fisheries and Oceans Canada, 2020). As both ecological and cultural keystone species, without the continued existence of salmon, ecosystems and societies alike would be entirely transformed (Willson & Halupka, 1995; Garibaldi & Turner, 2004).
>
> For the Nisga'a Nation, which sits on the BC–Alaska border (and to which the lead author belongs), salmon are vital. They shape *ayuukhl* (code of law) and *adaawak* (oral histories), they figure centrally in *yukw* (feasts, known externally as "potlatches"), and they are a focal point of the Nisga'a Final Agreement Act (Government of British Columbia, 2000) that defines Nisga'a rights tied specifically to salmon. As Nisga'a and indeed many Indigenous nations identify as "Salmon People" (Columbia River Inter-Tribal Fish Commission, 2020; Earth Economics, 2021), there is serious concern about what will become of salmon-linked cultures, economies, knowledges, languages, laws, well-being, and worldviews as the annual return of these anadromous fish to rivers across the Pacific Northwest become increasingly unpredictable and, in many systems, Indigenous fisheries for wild salmon become a shadow of their former selves (Jacob

et al., 2010; Atlas et al., 2021). Decolonial research strategies that respect Indigenous intellectual traditions and affirm Indigenous control over Indigenous knowledge are critical to the maintenance and recovery of salmon-based knowledge systems and salmon populations (Simpson, 2004; Bingham et al., 2021).

> *Not only would it behoove fisheries scientists to use all and the best tools and knowledge available at this time of [social-ecological] crisis, irrespective of their origin and the perceived objectivity and superiority of Western scientific approaches (TallBear, 2014), but this would importantly serve decolonial and reconciliatory efforts that help rectify uneven power relations, knowledge inequalities, and other racially linked and unjust dynamics in fisheries (Latulippe, 2015; Held, 2019). (Reid, 2020)*

The research of Gies (2022) supports this:

> Indigenous peoples have been managing landscapes more or less sustainably for thousands of years. Indigenous peoples' successes stem, in part, from the fact that many Indigenous worldviews recognize that species do not exist in isolation; they are part of a natural system.

Traditional Ecological Knowledge (TEK) provides invaluable time-tested resource management practices that can be used alongside Western Science (WS) to develop more workable and effective approaches to current resource management strategies than either could accomplish alone. In fact, it has become a policy requirement in Canada, and in particular Northern Canada, that TEK be incorporated into environmental assessments affecting wildlife management including: migratory birds, species at risk, forest practices, and fisheries management (Usher, 2000).

The Nisga'a Nation's understanding of, and work with, Pacific salmon is an excellent example of the role that Indigenous Science plays in understanding biodiversity and how to protect species and habitat in a sustainable manner.

According to the research of Reid et al. (2022):

> Through partnerships with 18 communities of "Salmon People" and semi-structured interviews with 48 knowledge holders (i.e., Elders), we learned that, on average, Elders spent more than half of a century actively engaged in salmon fishing and processing. Modern salmon catches are reported to be approximately one-sixth of what they were estimated to be five to seven decades ago, and the top five threats to salmon identified by Elders included (i) aquaculture, (ii) climate change, (iii) contaminants, (iv) industrial development, and (v) infectious diseases. Threat priorities varied regionally, reflecting distinct lived experiences and regional variation in the prevalence and impact of different threats. Elders perceived threats to salmon equally as threats to aquatic health and human well-being, with evidence that the relationships between people and water, and salmon and people, are being profoundly transformed.

The Nisga'a people of northern British Columbia live in the Nass Valley near Alaska. Every spring, members of some Nisga'a families still walk their salmon streams to ensure that spawning channels are clear of debris and that salmon are not obstructed in their ascent to spawning grounds. Concerned with the multiple perils faced by their Nass River salmon, the Nisga'a have themselves implemented a salmon protection project that uses both the ancient technology and wisdom practices, as well as modern statistical methods of data analysis to provide more reliable fish counts than electronic tracking systems (Figure **5.2.4.1**). The Nisga'a project, which earned a Department of Fisheries and Oceans Canada award, is described in the following account by Corsiglia and Snively (1997):

> *Observing that electronic fish counters can be inaccurate, the Nisga'a have instituted an ingenious fish counting system in the Nass River that combines ancient fish wheel technology with modern statistical methods. The ancient fish wheel was made of cedar wood and nettle fibre mesh, and the elongated axle of the fish wheel was fitted with three parallel vanes constructed in the form of large, flattened dip nets. The swift moving downstream current turned the wheel by exerting force against the submerged*

> *vanes, and as the companion vanes rose in turn, they gently caught and uplifted the fish as they swam upriver. As each vane rose from the horizontal, the fish slid toward wooden baffles that guided them out of the side of the fish wheel and into submerged holding baskets. This technology provided the Nisga'a with an effortless fishing technique as well as a ready supply of fresh salmon. (p. 19)*

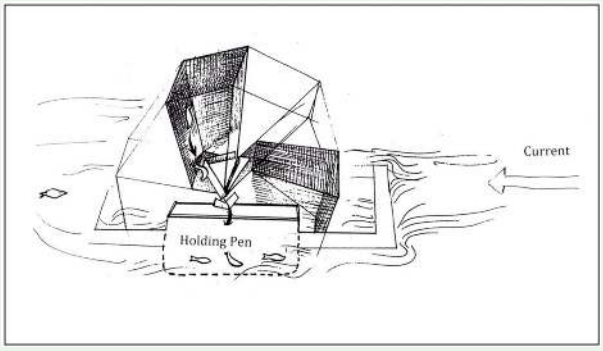


Figure 5.2.4.1. *Nisga'a fish wheel showing holding pen. Illustration by Laura Corsiglia (1997).*

Modern Nisga'a fishing wheels are made of aircraft aluminum and nylon mesh. Like their predecessors, these fish wheels allow fish to be captured live and held in holding tanks. This enables the Nisga'a to tag and count the fish by means of statistical analysis. Returning salmon are first caught using a fish wheel at a lower river station where fish are tagged. Fish are also caught at an upper fish station where the proportion of tagged fish is used to calculate returns. Reportedly, "this system provides more accurate and reliable data than that collected by electronic tracking systems alone" (Chief Harry Nyce, personal communication to John Corsiglia, 1986).

In a similar context, the Wuikinuxv of central British Columbia identify the season's quotas for salmon not only with humans in mind but also with bears. They recognize that not only are the bears an important part of their ecosystem and culture but, if the bears are well-fed with salmon, they are less likely to seek out food in areas where humans live (Gies, 2022). The forest and other inhabitants that the Wuikinuxv rely on are nourished in one way or another by the remains of the salmon.

The conservation research of Gies (2022) explains this concept further:

> The Wuikinuxv calculate fishing quotas based on salmon availability and existing bear density, assuming that, as salmon populations recover, the bear population will grow until it is limited by some other factor. Salmon and bear numbers are then balanced against the benefits of salmon to human fishers. Spawning targets aim to balance the costs felt by humans and bears, the latter of which encompasses the needs of other beings in the ecosystem. In contrast, Canada manages salmon at the federal level, while bears are managed provincially, making holistic management difficult. The smaller, more intimate scale of Indigenous management efforts, in contrast, allows closer observation of the landscape [...] and demonstrates how local knowledge is often undervalued.
>
> In a decolonized approach to conservation, the observations of people living in the area would be given proper respect, and systems would be in place to incorporate those observations into models. Another step toward decolonizing conservation [...] is for settler governments to work with Indigenous communities as equals rather than as just one of many stakeholders. Resource stewardship should be inseparable from Indigenous sovereignty, assert the study's authors.

Source: Adapted from Snively and Corsiglia (2016).

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In this 2.5-minute video, you will meet Kasey Stirling, a Nlaka'pamux, Mi'kmaq, and Acadienne researcher who is a master's student in the Centre for Indigenous Fisheries at the Institute for the Oceans and Fisheries. Stirling works in partnership with the First Nations Fisheries Legacy Fund, a collective of six Lower Fraser First Nations (Katzie, Kwantlen, Kwikwetlem, Musqueam, Tsleil-Waututh, and Tsawwassen), to co-develop a more culturally relevant framework for watershed health assessment, which directly impacts salmon populations.

Question after watching: What might be gained from scientists working in partnership with Indigenous communities to preserve diversity? What type of knowledge and perspective can each group bring to the partnership?

Adapting to and Mitigating Climate Change

More on climate change is discussed in Unit 5.3, but it should be clear to anyone that climate change has the potential to greatly restructure the world's ecosystems, ecosystem services, and national economies. Many coastal areas will experience rising sea levels and increased flooding, while inland areas may experience desertification and less favorable growing conditions for crops. Poorer countries and communities will suffer the consequences disproportionately because of their limited mobility, high dependence on ecosystem services, and general lack of disaster management infrastructure.

If we are to mitigate the far-reaching impacts of climate change, we must carefully monitor and study changes in biological communities and ecosystem functioning, and how they relate to changes in climate and other stressors. While we may lose some species in a warmer world, we can also prevent many extinctions with proactive wildlife management. It is likely that many existing protected areas will no longer preserve some of the rare and threatened species that currently live in them, necessitating careful planning when establishing new protected areas. Even if climate change is not as severe as predicted, the steps we take now to safeguard biodiversity can only help in the future.

The widespread and dramatic impacts of climate change rightfully deserve much attention. But it is also important to remember that we continue to destroy habitats at a massive scale and increasing pace and this loss of habitat is currently the main cause of species extinctions. The highest priorities for conservation must continue to be the preservation of healthy, intact, and connected ecosystems, and the restoration of degraded ecosystems. These actions will simultaneously reduce the impacts of climate change, by reducing carbon emissions, increasing carbon sequestration, and giving wildlife more opportunities to adjust their ranges, in their own time, as the world's climate changes.

Videos

https://bio.libretexts.org/@go/page/108112



Indigenous communities in British Columbia are preparing for climate change, as detailed in this 5-minute video.
Question after watching: How are Indigenous communities reconnecting to the land in a changing climate? What other strategies are they utilizing internally and sharing with non-Indigenous communities?

Conservation in Preserves

Video



This 10-minute video by Hank Green provides an overview of both conservation science and restoration efforts, described in further detail below.
Question after watching: What conserved spaces are nearest to you? Do you visit them? Do you know of any restoration efforts near where you live?

The establishment of wildlife and ecosystem **preserves** is one of the key tools in conservation efforts (Figure **5.2.4.2**). A preserve is an area of land set aside with varying degrees of protection for the organisms that exist within the boundaries of the preserve. Preserves can be effective in the short term for protecting both species and ecosystems, but they face challenges that scientists are still exploring to strengthen their viability as long-term solutions. Human behavior can still be problematic in these areas as well. For example, the public's misbehavior at national parks has become an increasing problem for governments in many countries.



Figure 5.2.4.2: National parks, such as Kootenay National Park in British Columbia, help conserve biodiversity. (Parks Canada)

Video



This 3-minute video from the National Resources Defense Council profiles the importance of Canada's boreal forest and current threats to this ecosystem.
Question after watching: What strategies might be used to preserve these habitats?

Canadian Preservation

National parks, provincial parks, and similar places are the largest and most important protected areas in Canada. Canada currently has the most preserved area of any nation. However, the nationally protected area of about 10% is still smaller than recommended by many conservation scientists, whose ideal estimates range from 15-40% of the landmass.

In addition to their primary goal of conserving biodiversity, most parks serve additional purposes, including the support of economically important outdoor recreation and tourism. To some degree, the use of parks for these purposes is a challenge to their ability to function as ecological reserves. For example, strictly interpreted, the ecological values of national parks are not compatible with consumptive uses of their natural resources (such as sport fishing) or with the development of infrastructure to support recreation and tourism (such as campgrounds, golf courses, hotels, roads, ski facilities, and even interpretation facilities).

The ecological-reserve function of many protected areas is also threatened by land-use and management activities that are occurring in their surrounding area. Usually, the most important of the “external” stressors are associated with agriculture, forestry, mining, tourism, or hydroelectric development. In fact, all of the national parks in more southern regions of Canada are significantly threatened in this way.

Banff National Park in southwestern Alberta was the first national park to be established in Canada, in 1885. The original intent was to protect extremely scenic views and hot springs and to develop the area in support of the economic benefits of tourism. It was not until several decades later that the philosophical underpinning of national parks shifted toward the protection of natural values. In any event, the early development of Banff featured the enthusiastic construction of large hotels, golf courses, skiing facilities, major highways, a transcontinental railroad, several villages, and other structures. This pattern continues today with much ongoing

construction, coupled with rapid development of the area east of the park for tourism, residential neighborhoods, forestry, and other uses. These facilities severely threaten the long-term viability of the natural values of Banff.

Provincial and territorial governments also have a responsibility to protect natural values within their jurisdiction. These governments have designated many ecological reserves and wilderness areas, supplemented by natural areas that are protected in provincial parks and conservation areas, which are also well-used for recreation. Some municipalities also have natural-area parks that provide habitat for native species. An outstanding example is the city of Windsor, Ontario, which is protecting important remnants of tall-grass prairie and Carolinian forest, and their many species-at-risk.

How Much Area to Preserve?

Due to the way protected lands are allocated (they tend to contain less economically valuable resources rather than being set aside specifically for the species or ecosystems at risk) and the way biodiversity is distributed, determining a target percentage of land or marine habitat that should be protected to maintain biodiversity levels is challenging. The IUCN World Parks Congress estimated that 11.5% of Earth's land surface was covered by preserves of various kinds in 2003. This area is greater than previous goals; however, it only represents 9 out of 14 recognized major biomes. Research has shown that 12% of all species live only outside preserves; these percentages are much higher when only threatened species and high-quality preserves are considered. For example, high-quality preserves include only about 50% of threatened amphibian species. The conclusion must be that either the percentage of area protected must increase, the percentage of high-quality preserves must increase, or preserves must be targeted with greater attention to biodiversity protection. Researchers argue that more attention to the latter solution is required.

A **biodiversity hotspot** is a conservation concept developed by Norman Myers in 1988. Hotspots are geographical areas that contain high numbers of endemic species. The purpose of the concept was to identify important locations on the planet for conservation efforts, a kind of conservation triage. Protecting hotspots would be able to protect a larger number of species. The original criteria for a hotspot included the presence of 1,500 or more species of endemic plants and 70 percent of the area disturbed by human activity. While many have still not been conserved, there are now 34 identified global biodiversity hotspots (Figure **5.2.4.3**) that contain large numbers of endemic species, which include half of Earth's endemic plants. In addition to natural spaces, there are numerous human cultural sites preserved in the **UNESCO World Heritage Sites** list: https://whc.unesco.org/en/list/

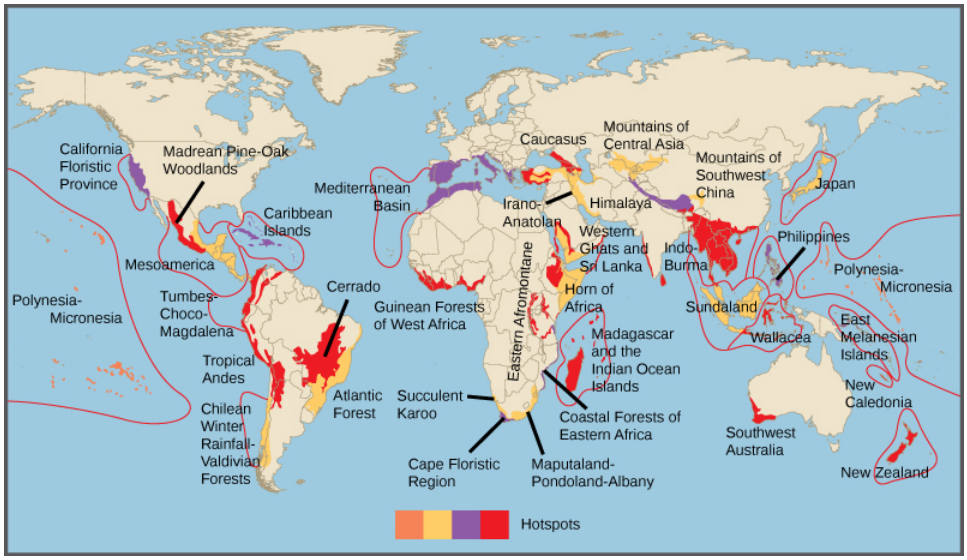


Figure **5.2.4.3**. Conservation International has identified 34 biodiversity hotspots. Although these cover only 2.3 percent of the Earth's surface, 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants are endemic to those hotspots.

? Optional Activity 5.2.4.2

Scientists are evaluating an island ecosystem for consideration as a biodiversity hotspot. What information should they collect and evaluate as part of their fieldwork to produce their final assessment?

a. the total number of endemic species in an ecosystem
b. the total number of organisms in an ecosystem

c. the total number of species divided by the area of the ecosystem
d. the total number of endangered species in an ecosystem

Answer

A. the total number of endemic species in an ecosystem.

Preserve Design

There has been extensive research into optimal preserve designs for maintaining biodiversity. The fundamental principle behind much of the research has been the seminal theoretical work of Robert H. MacArthur and Edward O. Wilson published in 1967 on island biogeography.[1] This work sought to understand the factors affecting biodiversity on islands. The fundamental conclusion was that biodiversity on an island was a function of the origin of species through migration, speciation, and extinction on that island. Islands farther from the mainland are harder to get to, so migration is lower and the equilibrium number of species is lower. Within island populations, evidence suggests that the number of species gradually increases to a level similar to the numbers on the mainland from which the species is suspected to have migrated. In addition, smaller islands are harder to find, so their immigration rates for new species are lower. Smaller islands are also less geographically diverse so there are fewer niches to promote speciation. And finally, smaller islands support smaller populations, so the probability of extinction is higher.

As islands get larger, the number of species accelerates, although the effect of island area on species numbers is not a direct correlation. Conservation preserves can be seen as “islands” of habitat within “an ocean” of non-habitat. For a species to persist in a preserve, the preserve must be large enough. The critical size depends, in part, on the home range that is characteristic of the species. A preserve for wolves, which ranges hundreds of kilometers, must be much larger than a preserve for butterflies, which might range within ten kilometers during its lifetime. But larger preserves have more core area of optimal habitat for individual species, they have more niches to support more species, and they attract more species because they can be found and reached more easily.

Preserves perform better when there are buffer zones around them of suboptimal habitat. The buffer allows organisms to exit the boundaries of the preserve without immediate negative consequences from predation or lack of resources. One large preserve is better than the same area of several smaller preserves because there is more core habitat unaffected by edges. For this same reason, preserves in the shape of a square or circle will be better than a preserve with many thin “arms.” If preserves must be smaller, then providing wildlife corridors between them so that individuals and their genes can move between the preserves, for example along rivers and streams, will make the smaller preserves behave more like one large one. All of these factors are taken into consideration when planning the nature of a preserve before the land is set aside.

In addition to the physical, biological, and ecological specifications of a preserve, there are a variety of policy, legislative, and enforcement specifications related to the uses of the preserve for functions other than the protection of species. These can include anything from timber extraction, mineral extraction, regulated hunting, human habitation, and non-destructive human recreation. Many of these policy decisions are made based on political pressures rather than conservation considerations. In some cases, wildlife protection policies have been so strict that subsistence-living Indigenous populations have been forced from ancestral lands that fell within a preserve. In other cases, even if a preserve is designed to protect wildlife, if the protections are not or cannot be enforced, the preserve status will have little meaning in the face of illegal poaching and timber extraction. This is a widespread problem with preserves in areas of the tropics.

? Optional Activity 5.2.4.3

A preserve design is proposed for a densely populated suburban area. Which overall design plan would be best for preservation of local ecosystems?

A. Set up many, small, unconnected, protected areas.
B. Select one, small area that is isolated from residences.
C. Plan buffer zones around all backyard spaces.
D. Set up several, connected, larger areas to be set aside for natural ecosystems.

Answer

D. Set up several, connected, larger areas to be set aside for natural ecosystems.

Limitations on Preserves

Some of the limitations of preserves as conservation tools are evident from the discussion of preserve design. Political and economic pressures typically make preserves smaller, never larger, so setting aside areas that are large enough is difficult. If the area set aside is sufficiently large, there may not be sufficient area to create a buffer around the preserve. In this case, an area on the outer edges of the preserve inevitably becomes a riskier suboptimal habitat for the species in the preserve. Enforcement of protections is also a significant issue in countries without the resources or political will to prevent poaching and illegal resource extraction.

Climate change will create inevitable problems with the location of preserves. The species within them will migrate to higher latitudes as the habitat of the preserve becomes less favorable. Scientists are planning for the effects of global warming on future preserves and striving to predict the need for new preserves to accommodate anticipated changes to habitats; however, the end effectiveness is tenuous since these efforts are prediction-based.

Finally, an argument can be made that conservation preserves reinforce the cultural perception that humans are separate from nature, can exist outside of it, and can only operate in ways that do damage to biodiversity. Creating preserves reduces the pressure on human activities outside the preserves to be sustainable and non-damaging to biodiversity. Ultimately, the political, economic, and human demographic pressures will degrade and reduce the size of conservation preserves if the activities outside them are not altered to be less damaging to biodiversity.

Habitat Restoration

Habitat restoration holds considerable promise as a mechanism for restoring and maintaining biodiversity. Of course, once a species has become extinct, its restoration is impossible. However, **restoration** can improve the biodiversity of degraded ecosystems. Reintroducing wolves, a top predator, to Yellowstone National Park in 1995 led to dramatic changes in the ecosystem that increased biodiversity (Figure 5.2.4.4).

The wolves, a keystone species, function to suppress elk and coyote populations and provide more abundant resources to the guild of carrion eaters. Reducing elk populations has allowed the revegetation of riparian areas, which has increased the diversity of species in that habitat. Decreasing the coyote population has increased the populations of species that were previously suppressed by this predator. The number of species of carrion eaters has increased because of the predatory activities of the wolves.

The results from the Yellowstone experiment suggest that restoring a keystone species can have the effect of restoring biodiversity in the community. Ecologists have argued for the identification of keystone species where possible and for focusing protection efforts on those species; likewise, it also makes sense to attempt to return them to their ecosystem if they have been removed.

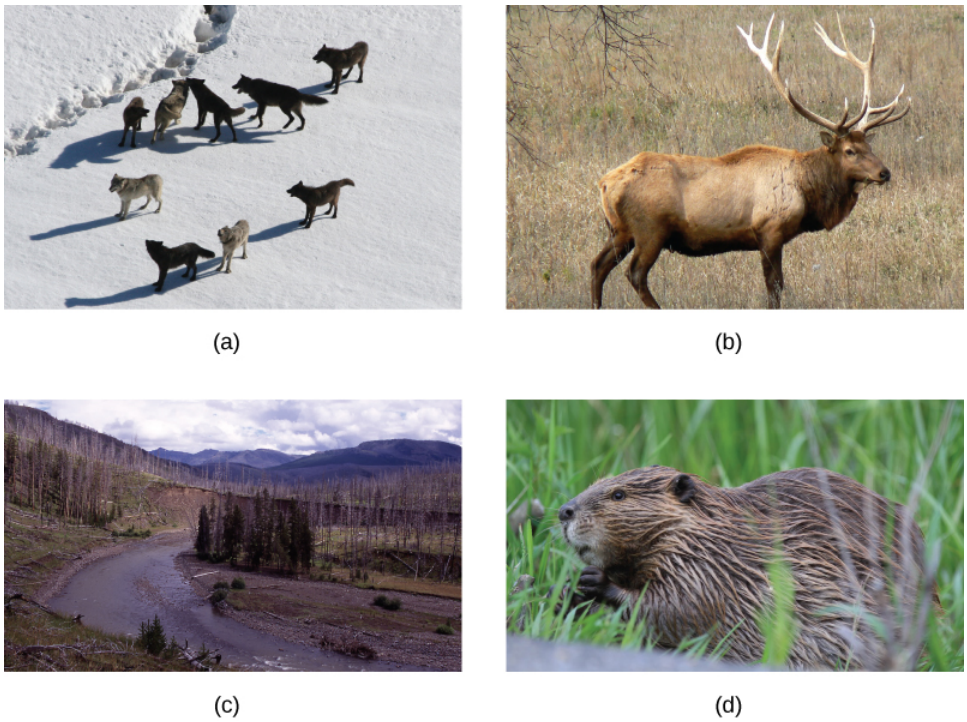


Figure **5.2.4.4**: (a) The Gibbon wolf pack in Yellowstone National Park, March 1, 2007, represents a keystone species. The reintroduction of wolves into Yellowstone National Park in 1995 led to a change in the grazing behavior of (b) elk. To avoid predation, the elk no longer grazed exposed stream and riverbeds, such as (c) the Lamar Riverbed in Yellowstone. This allowed willow and cottonwood seedlings to grow. The seedlings decreased erosion and provided shading to the creek, which improved fish habitat. A new colony of (d) beaver may also have benefited from the habitat change. (credit a: modification of work by Doug Smith, NPS; credit c: modification of work by Jim Peaco, NPS; credit d: modification of work by "Shiny Things"/Flickr)

Other large-scale restoration experiments underway involve dam removal. Since the mid-1980s, many aging dams are being considered for removal rather than replacement because of shifting beliefs about the ecological value of free-flowing rivers and because many dams no longer provide the benefit and functions that they did when they were first built. The measured benefits of dam removal include restoration of naturally fluctuating water levels (the purpose of dams is frequently to reduce variation in river flows), which leads to increased fish diversity and improved water quality.

On the Pacific coast, dam removal projects are expected to increase populations of salmon, which is considered a keystone species because it transports key nutrients to inland ecosystems during its annual spawning migrations. In other regions such as the Atlantic coast, dam removal has allowed the return of other spawning anadromous fish species (species that are born in freshwater, live most of their lives in salt water, and return to freshwater to spawn). Some of the largest dam removal projects have yet to occur or have happened too recently for the consequences to be measured. The large-scale ecological experiments that these removal projects constitute will provide valuable data for other dam projects slated either for removal or construction.

Video

https://bio.libretexts.org/@go/page/108112

SECTION OVERVIEW

5.3: Climate Change

Learning Objectives

- Describe the major causes of anthropogenic global climate change
- Identify impacts of global climate change on living systems and human civilization
- Suggest personal and systemic adaption and mitigation measures to address global climate change

5.3.1: Introduction to Climate Change

5.3.2: Anthropogenic Climate Change

5.3.3: Current and Future Climate Change Impacts

5.3.4: Climate Strategies

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Unit 5.3.1 - Introduction to Climate Change

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.3.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Define global climate change
- Summarize the effects of the Industrial Revolution on global atmospheric carbon dioxide concentration
- Describe three natural factors affecting long-term global climate
- List two or more greenhouse gases and describe their role in the greenhouse effect

Introduction

All biomes are universally affected by global conditions, such as climate, that ultimately shape each biome's environment. Scientists who study climate have noted a series of marked changes that have become increasingly evident during the last sixty years. **Climate change** refers to the complete set of climate characteristics—temperature; precipitation; pressure systems; wind patterns; and oceanic currents—that are changing locally, regionally, and globally due to human influences. It is closely related to **global warming**, also called global heating, which describes the general trend of increasing global temperatures we see under climate change. However, *climate change* is more inclusive of the totality of abiotic effects of a warming planet.

Climate and Weather

A common misconception about global climate change is that a specific weather event occurring in a particular region (for example, a very cool week in June in central Saskatchewan) is evidence of global climate change. However, a cold week in June is a weather-related event and not a climate-related one. These misconceptions often arise because of confusion over the terms climate and weather.

Video



Discover the real reason we confuse weather and climate in this 5-minute video from Hot Mess (US PBS).
Question after watching: How does our personal experience of weather have an effect on how we view climate change?

Climate refers to the long-term, predictable atmospheric conditions of a specific area. The climate of a biome is characterized by having consistent temperature and annual rainfall ranges. Climate does not address the amount of rain that fell on one particular day in a biome or the colder-than-average temperatures that occurred one season. In contrast, **weather** refers to the conditions of the atmosphere during a short period of time. Weather forecasts are usually made for 48-hour cycles. Long-range weather forecasts are available but can be unreliable.

To better understand the difference between climate and weather, imagine that you are planning an outdoor event in Kamloops, BC. You would be thinking about *climate* when you plan the event in the summer rather than the winter because you have long-term knowledge that any Saturday in May through August would be a better choice for an outdoor event in Kamloops than a Saturday in January. However, you cannot determine the specific day on which that event should be held because it is difficult to accurately predict the weather. Climate can be considered "average" weather.

? Optional Activity 5.3.1.1

Which of the following is an example of climate?

A. An intense thunderstorm in Houston.
B. The average temperature in Chicago over the past 50 years.
C. An unusually hot fall in Boston.
D. A foggy day in San Francisco.

Answer

B. The average temperature in Chicago over the past 50 years.

Global Climate Change

Climate change can be understood by approaching three areas of study:

- current and past global climate change
- causes of past and present-day global climate change
- ancient and current results of climate change

It is helpful to keep these three different aspects of climate change clearly separated when consuming media reports about global climate change. It is common for reports and discussions about global climate change to confuse the data showing that Earth's climate is changing with the factors that drive this climate change.

Evidence for Past and Current Global Climate Change

Since scientists cannot go back in time to directly measure climatic variables, such as average temperature and precipitation, they must instead indirectly measure temperature. To do this, scientists rely on historical evidence of Earth's past climate.

Antarctic ice cores are a key example of such evidence. These **ice cores** are samples of polar ice obtained by means of drills that reach thousands of meters into ice sheets or high mountain glaciers. Viewing the ice cores is like traveling backwards through time; the deeper the sample, the earlier the time period. Trapped within the ice are bubbles of air and other biological evidence that can reveal temperature and carbon dioxide data. Antarctic ice cores have been collected and analyzed to indirectly estimate the temperature of the Earth over the past 400,000 years (Figure 5.3.1.1a). The 0°C on this graph refers to the long-term, modern-day average. Temperatures that are greater than 0°C exceed Earth's long-term average temperature. Conversely, temperatures that are less than 0°C are less than Earth's average temperature. This figure shows that there have been periodic cycles of increasing and decreasing temperature.

Before the late 1800s, the Earth was as much as 9°C cooler and as much as 3°C warmer. Most of the past 400,000 years have been colder than today. Most of the past warming and cooling periods happened over long enough time scales that the majority of organisms were able to adapt and evolve with the changing climate.

The graph in Figure 5.3.1.1b shows that the atmospheric concentration of carbon dioxide has also risen and fallen in periodic cycles. Note the relationship between carbon dioxide concentration and temperature. Figure 5.3.1.1b shows that carbon dioxide levels in the

atmosphere have historically cycled between 180 and 300 parts per million (ppm) by volume.

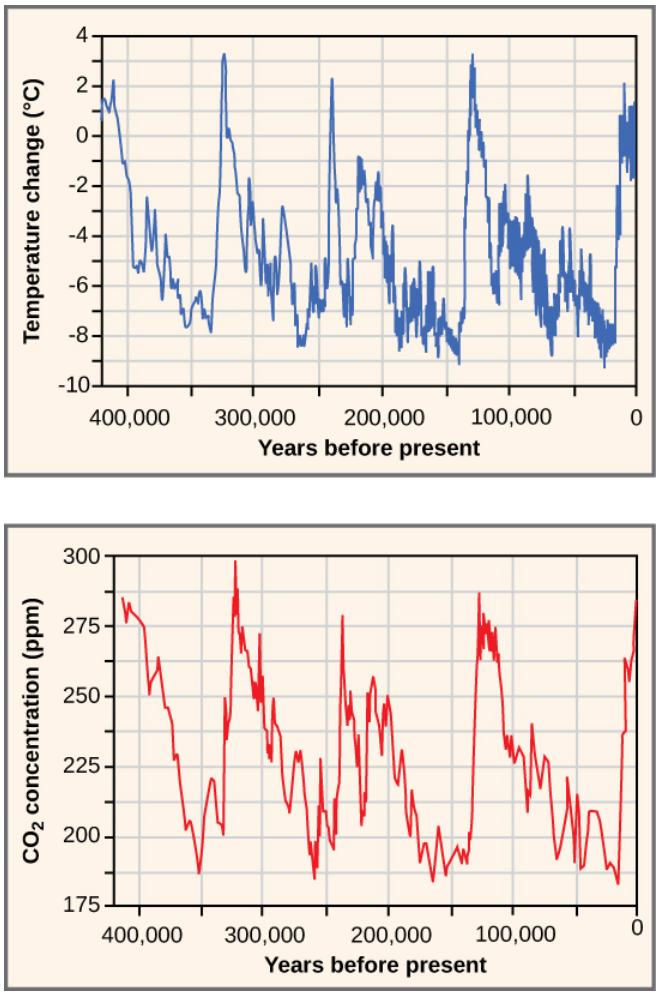


Figure **5.3.1.1:** Ice at the Russian Vostok station in East Antarctica was laid down over the course of 420,000 years and reached a depth of over 3,000 m. By measuring the amount of CO_2 trapped in the ice, scientists have determined past atmospheric CO_2 concentrations. Temperatures relative to modern-day were determined from the amount of deuterium (an isotope of hydrogen) present.

Figure **5.3.1.1** does not show the last 2,000 years with enough detail to compare the changes in Earth's temperature during the last 400,000 years with the temperature change that has occurred in the more recent past. Three significant temperature anomalies, or irregularities, have occurred in the last 2000 years. The first two are the Medieval Climate Anomaly (or the Medieval Warm Period) and the Little Ice Age. A third temperature anomaly aligns with the Industrial Era.

The **Medieval Climate Anomaly** occurred between 900 and 1300 AD. During this time period, many climate scientists think that slightly warmer weather conditions prevailed in many parts of the world; the higher-than-average temperature changes varied between 0.10 °C and 0.20 °C above the norm. Although 0.10 °C does not seem large enough to produce any noticeable change, it did free seas of ice. Remember, the temperatures stated here are global averages. Some areas became much warmer, especially at higher latitudes, and some areas remained at their same averages. Because of the warming in the higher latitudes, the Vikings were able to colonize Greenland.

The **Little Ice Age** was a cold period that occurred between 1550 AD and 1850 AD. During this time, a slight cooling of a little less than 1°C was observed in North America, Europe, and possibly other areas of the Earth. This 1°C change in global temperature is a seemingly small deviation in temperature (as was observed during the Medieval Climate Anomaly); however, it also resulted in noticeable changes. Historical accounts reveal a time of exceptionally harsh winters with much snow and frost.

The **Industrial Revolution**, which began around 1750, was characterized by changes in much of human society. Advances in agriculture increased the food supply, which improved the standard of living for people in Europe and North America. New

technologies were invented and provided jobs and cheaper goods. These new technologies were powered using fossil fuels, especially coal. The Industrial Revolution starting in the early nineteenth century ushered in the beginning of the Industrial Era. When a **fossil fuel** (coal, oil, or natural gas) is burned, carbon dioxide is released. With the beginning of the Industrial Era, atmospheric carbon dioxide began to rise (Figure **5.3.1.2**).

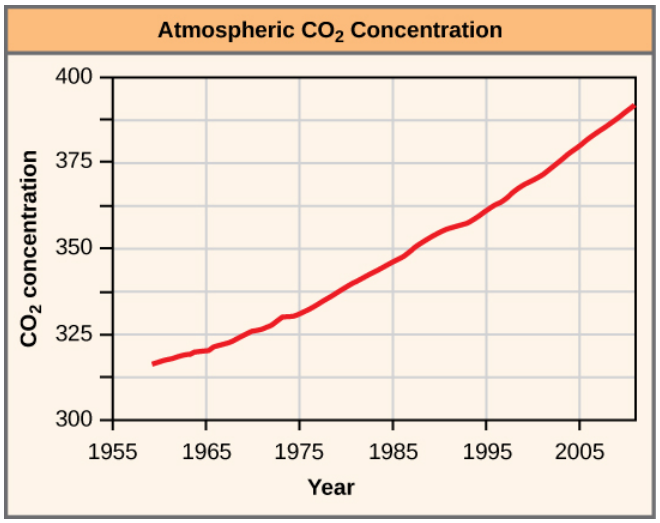


Figure **5.3.1.2**: The atmospheric concentration of CO_2 has risen steadily since the beginning of industrialization, which began in 1750. Modern isotopic measurements of atmospheric CO_2 began in the late 1950s, which is reflected in this graph.

Causes of Past Climate Change

Since it is not possible to go back in time to directly observe and measure climate, scientists use indirect evidence to determine the **drivers**, or causes, that may be responsible for climate change. The indirect evidence includes data collected using ice cores, boreholes (a narrow shaft bored into the ground), tree rings, glacier lengths, pollen remains, and ocean sediments. The data shows a correlation between the timing of temperature changes and drivers of climate change: before the Industrial Era (pre-1780), there were three drivers of climate change that were not related to human activity or atmospheric gases.

The first of these is the **Milankovitch cycles**. The Milankovitch cycles describe the effects of slight changes in the Earth's orbit on Earth's climate. The length of the Milankovitch cycles ranges between 19,000 and 100,000 years. In other words, one could expect to see some predictable changes in the Earth's climate associated with changes in the Earth's orbit at a minimum of every 19,000 years and maximum every 100,000 years.

The variation in the sun's intensity is the second natural factor responsible for climate change. **Solar intensity** is the amount of solar power or energy the sun emits in a given amount of time. There is a direct relationship between solar intensity and temperature. As solar intensity increases (or decreases), the Earth's temperature correspondingly increases (or decreases). Changes in solar intensity have been proposed as one of several possible explanations for the Little Ice Age.

Finally, volcanic eruptions are a third natural driver of climate change. Volcanic eruptions can last a few days, but the solids and gases released during an eruption can influence the climate over a period of a few years, causing short-term climate changes. The gases and solids released by volcanic eruptions can include carbon dioxide, water vapor, sulfur dioxide, hydrogen sulfide, hydrogen, and carbon monoxide. Generally, volcanic eruptions cool the climate. This occurred in 1783 when volcanoes in Iceland erupted and caused the release of large volumes of sulfuric oxide. This led to **haze-effect cooling**, a global phenomenon that occurs when dust, ash, or other suspended particles block out sunlight and trigger lower global temperatures as a result; haze-effect cooling usually extends for one or more years. In Europe and North America, haze-effect cooling produced some of the lowest average winter temperatures on record in 1783 and 1784.

However, today, greenhouse gases are probably the most significant drivers of the climate. When heat energy from the sun strikes the Earth, gases known as **greenhouse gases** trap the heat in the atmosphere, just as the glass panes of a greenhouse keep heat from escaping. The greenhouse gases that affect Earth include carbon dioxide, methane, water vapor, nitrous oxide, and chlorofluorocarbons (CFCs). Approximately half of the radiation from the sun passes through these gases in the atmosphere and strikes the Earth. This radiation is converted into thermal radiation on the Earth's surface, and then a portion of that energy is re-

radiated back into the atmosphere. Greenhouse gases, however, reflect much of the thermal energy back to the Earth's surface. The more greenhouse gases there are in the atmosphere, the more thermal energy is reflected back to the Earth's surface. Greenhouse gases absorb and emit radiation and are an important factor in the greenhouse effect: the warming of Earth due to carbon dioxide and other greenhouse gases in the atmosphere.

Video



Discover the intricacies of Earth's greenhouse effect in this 3-minute video.
Question after watching: How do the so-called greenhouse gases act to insulate the Earth? Why do more greenhouse gases lead to a warmer planet?

Optional Activity 5.3.1.2

What is the greenhouse effect?

A. Certain gases in the atmosphere trap heat and warm the Earth
B. Life on Earth 'exhales' gas that warms up the atmosphere
C. The tilt of the Earth changes the amount of solar energy the Earth receives
D. The Sun is putting out more radiant energy over time

Answer

A. Certain gases in the atmosphere trap heat and warm the Earth.

Results of Past Climate Change

Climate change is not a new phenomenon. Scientists have geological evidence of the consequences of long-ago climate change. Increased global temperatures and greenhouse gases have been associated with at least one planet-wide extinction event during the geological past. The Permian extinction event occurred about 251 million years ago toward the end of the roughly 50-million-year-long geological time span known as the Permian period. This geologic time period was one of the three warmest periods in Earth's geologic history. Scientists estimate that more than 90 percent of all life became extinct near the end of the Permian period. Organisms that had adapted to wet and warm climatic conditions, such as annual rainfall of 300–400 cm and 20 °C–30 °C in the tropical wet forest, may not have been able to survive the Permian climate change.

During the past 2 million years, there have been at least 10 cycles of natural warming and cooling on a planetary scale. When the polar ice caps melted during warming periods, sea levels rose to well above their earlier levels, and a larger portion of Earth experienced tropical climates. During cooling periods, the polar ice caps expanded, sea levels dropped, and tropical species' ranges contracted. Sometimes these changes occurred gradually, which enabled the affected species to adapt. But the onset of some climate change periods was abrupt, causing major ecosystem disruptions and global mass extinction events. Yet, nature recovered every time; many of the species we see today are survivors of previous climate change events. It is thus fair to ask why today's climate change is of such concern to us.

Video



A look at the history of climate change on Earth can give us some much-needed perspective on our current climate dilemma because, the surprising truth is, what we are experiencing now is different than anything this planet has encountered before. This 11-minute video gives an overview of Earth's prior climates.

Question after watching: In what way is the current climate change different than historical climate changes?

Climate Change's Impact on Humans (Past and Present)

History provides us with many lessons to illustrate the impact of climate change on human societies. These lessons start with the earliest well-documented example of a societal collapse—that of the Middle East's Natufian communities roughly 10,000 years ago—which has been attributed to climatic changes. Since then, climate change has regularly contributed to the collapse of complex human societies across the world. Notable examples of such collapses include the Akkadian Empire (the world's first empire) of the Middle East, Egypt's Old Kingdom (the builders of the pyramids), Central America's Classic Mayan civilization, the first English colony in America, several Chinese dynasties, and the Late Bronze Age societies along the Mediterranean Sea. Also, in Southern Africa, the fall of the Mapungubwe Kingdom has been attributed to crop failures and declining grazing lands due to regional droughts and warming cycles.

Similar patterns hold true today, only on a global scale. Because of humans' collective lack of response in addressing the drivers of climate change, more people will suffer the consequences than will not. Prominently, many parts of the world are already seeing higher temperatures and longer droughts. These conditions are compromising our quality of life by leading to more intense wildfires, increased incidences of vector-borne disease, increased crop failures, and increased competition for water. Many coastal areas are also seeing storms increasing in intensity and frequency, exposing people living near large rivers, deltas, and estuaries to more frequent flooding and storm surges. For example, the impacts from Cyclone Idai, one of the worst storms on record to have hit Africa, led to the deaths of more than 1,000 people (Figure **5.3.1.3**). While no single flooding event can be attributed to climate change, it is undeniable that warmer oceans create conditions for hurricanes and cyclones to be stronger, bigger, and more frequent. Sea level rise is expected to leave many low-lying oceanic islands uninhabitable within a few decades. With all these impacts expected to increase the competition for space under an increasing human population, it would be wise for the world's governments to start preparing for millions of climate refugees that need to be relocated soon.

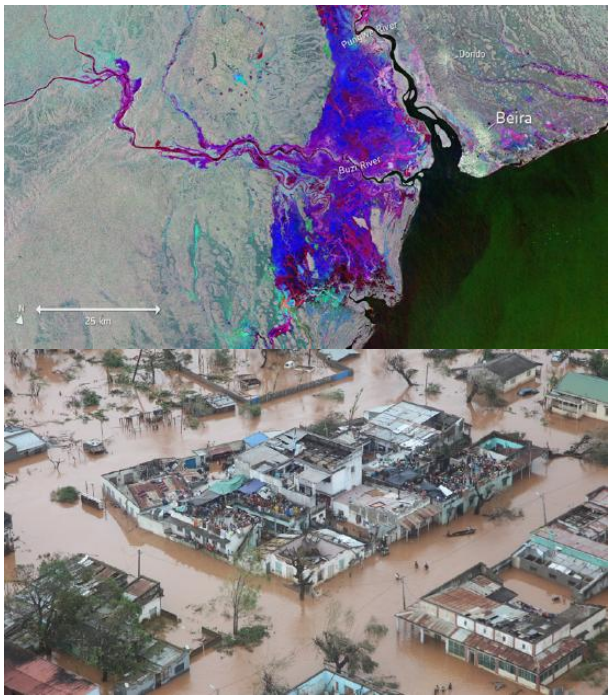


Figure **5.3.1.3**: (Top) A Copernicus Sentinel-1 satellite image showing the extent of flooding (areas shown in blue) in central Mozambique after Cyclone Idai made landfall on 15 March, 2019. Photograph by European Space Agency, https://www.flickr.com/photos/europeanspaceagency/47477652401, CC BY-SA 2.0. (Bottom) People in Beira, Mozambique, taking refuge on rooftops to escape flooding brought by Cyclone Idai. Photograph by World Vision, https://www.flickr.com/photos/dfid/46570320385, CC BY 2.0.

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Unit 5.3.2 - Anthropogenic Climate Change

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.3.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Identify the historical beginnings of anthropogenic climate change
- Explain how current climate change is measured
- Describe the scientific consensus on anthropogenic climate change
- Identify human impacts on specific greenhouse gases

Introduction

Evidence supports the relationship between atmospheric concentrations of carbon dioxide and temperature: as carbon dioxide rises global temperature rises. Since 1950, the concentration of atmospheric carbon dioxide has increased from about 280 ppm to 382 ppm in 2006. In 2021, the atmospheric carbon dioxide concentration was 415 ppm.

Video



This 2.5-minute video shows how atmospheric CO_2 has varied recently and also over the last 800,000 years as determined by many CO_2 monitoring stations (shown on the insert map). It is also instructive to watch the CO_2 variation of the video by latitude. This shows that most of the sources of CO_2 are in the Northern Hemisphere where humans reside.
Question after watching: What general trends do you notice over the last 800,000 years? How is the current climate breaking those trends?

Scientists look at patterns in data and try to explain differences or deviations from these patterns. The atmospheric carbon dioxide data reveal a geologic pattern of carbon dioxide increasing and decreasing, cycling between a low of 180 ppm and a high of 300 ppm before decreasing again, generally over 100,000 year Malankovich cycles (see Unit 5.3.1). Scientists have concluded that it took around 50,000 years for the atmospheric carbon dioxide level to increase from its traditionally low minimum concentration at the height of the last ice age to its higher maximum concentration. However, starting recently, atmospheric carbon dioxide concentrations have increased beyond the historical maximum of 300 ppm. The current increases in atmospheric carbon dioxide

have happened very quickly—in a matter of hundreds of years rather than thousands of years. What is the reason for this difference in the rate of change and the amount of increase in carbon dioxide and other greenhouse gases (GHGs)?

Anthropogenic Climate Change

Anthropogenic climate change refers to the impacts of humans on the climate system. Scientists generally look to the Industrial Era as the beginning of anthropogenic climate change, which is the advent of the use of fossil fuels, beginning with coal, to power machinery in the middle of the 1700s. Some climate scientists argue that anthropogenic climate change actually begins much earlier than the Industrial Era and that humans began impacting the climate through deforestation and land clearing to grow food. This would include farming grains in Europe and the Middle East during the first Agricultural Revolution around 8,000 years BCE and developing artificial wetlands for rice cultivation in Asia around 5,000 years BCE. Clearing vegetation for crops is a type of **climate-forcing**, meaning greenhouse gases (in this case, carbon dioxide) are being released into the atmosphere. The carbon dioxide storage capacity of crops is generally lower than that of the forests originally there. Creating wetlands is also a carbon source due to the bacterial decay of organic matter within wetlands that produces methane.

In fact, whether anthropogenic climate change started with the Agricultural Revolution or the Industrial Revolution is not important, because the really significant climate changes did not start until the early part of the 20th century. Human activities and population size are intertwined. As more and more of the world's population adopts a resource-intensive lifestyle, the climate problem becomes worse. These lifestyles currently require fossil fuels, which provide relatively cheap and abundant energy and are used for everything from transportation and heating and cooling to industry and food production.

This escalating level of industrialization and mechanization of our lives has driven the anthropogenic climate change of the past century. The trend of mean global temperatures since 1880 is shown in Figure 5.3.2.1. For approximately the past 55 years, the temperature has increased at a relatively steady and rapid rate, especially compared to past changes. The average temperature now is approximately 1.0°C higher than before industrialization, and two-thirds of this warming has occurred since 1975. Since 1880, average global surface temperatures have trended upward and most of that warming has occurred since 1970. Since the ocean is absorbing a lot of the additional trapped heat, surface temperatures include both land surface and ocean temperatures.

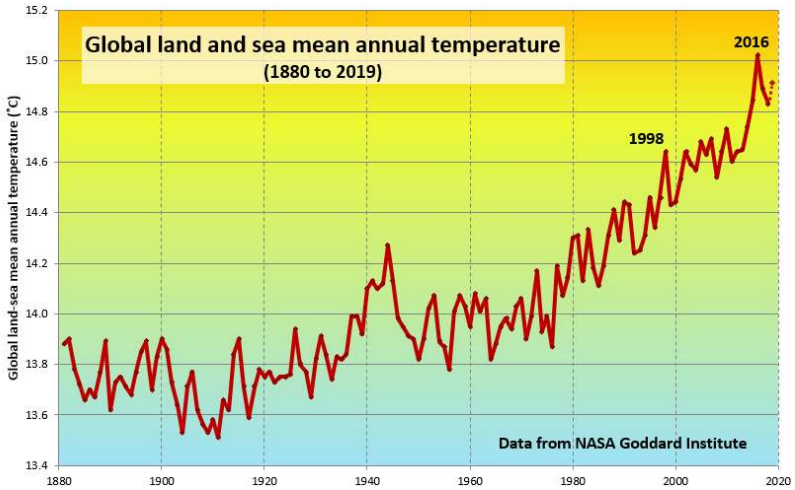


Figure 5.3.2.1: Global mean annual temperatures for the period from 1880 to 2019. The value for 2019 is projected, based on only 6 months of data. 1998 and 2016 were strong El Niño years. © Steven Earle. CC BY. Based on data from NASA.

Video



This 60-second animation from two of the world's leading science academies brings you the science behind climate change. Question after watching: Of the graphs shown, which had you seen before (similar or the same)? Which ones were new to you? What does this make you think about?

Optional Activity 5.3.2.1

How has the global average temperature changed since the Industrial Revolution?

A. Cooler by 0.1°C
B. The temperature has gone up and down, but remains overall the same
C. Warmer by more than 1°C
D. Warmer by almost 2°C

Answer

C. Warmer by more than 1°C

How Do We Know? Measuring Current Climate Change

Changes in land surface or ocean surface temperatures can be expressed as temperature **anomalies**. A temperature anomaly is a difference in average temperature measurement from a predetermined datum (or baseline). This datum is the average temperature of a particular date range, for example, 1951 to 1980. Another common datum is the last century (1900-2000). Therefore, an anomaly of 1.25 ℃ for 2015 (last century datum) means that the average temperature for 2015 was 1.25 ℃ greater than the 1900-2000 average. In 1950, the temperature anomaly was -0.28 ℃, so this is -0.28 ℃ lower than the 1900-2000 average [3]. These temperatures are annual average surface temperatures. Figure **5.3.2.2** shows the global mean temperature estimates for the period of 1880 to 2020 using the datum of the 1951-1980 average temperature.

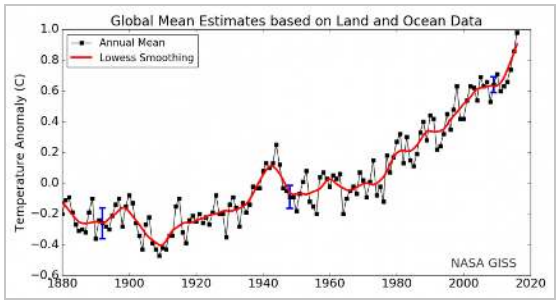


Figure **5.3.2.2**: Land-ocean temperature index, 1880 to present, with a base time 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth curve. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling.
[From https://opengeology.org/textbook/15-...limate-change/ Adapted from *Source: National Climate Data Center*]

Other valuable insights have been obtained by running sophisticated mathematical global **climate models** on high-powered supercomputers. These "virtual experiments" examine the potential climatic responses to increases in atmospheric CO_2. These computer simulations are known as three-dimensional general circulation models (GCMs). The models simulate the complex movements of energy and mass in the global circulation of the atmosphere. They also examine the interactions of these processes with physical variables that are important aspects of climate, such as temperature and precipitation. A strong tendency that emerges from these virtual experiments is that global warming and associated climate changes are a likely consequence of the well-documented increases of CO_2 and other GHGs in the atmosphere.

Many such simulation experiments have examined the scenario of a doubling of CO_2 concentration to 800 ppm from its recent concentration of just over 400 ppm. These experiments suggest that such a doubling would result in an increase of 1°C to 4°C in the average temperature of the surface atmosphere. The intensity of warming is predicted to be greatest in high-latitude regions, where the temperature increases might be two to three times greater than in the tropics.

Warming of the lower atmosphere will be one likely change that will be caused by an increased intensity of the greenhouse effect. However, there could also be important effects that occur indirectly due to increased temperatures. The most important of these would include large-scale shifts in the patterns of atmospheric circulation. Such shifts would likely result in changes in the amounts, distribution, and seasonality of precipitation. Changes in precipitation regimes would influence soil moisture, which would greatly affect the distribution and productivity of vegetation, both natural and managed. These changes in precipitation regime would likely have much greater effects on agricultural and wild ecosystems than would any direct influence of a warmed atmosphere.

Indigenous Connections: Monitoring Climate Change

As described in the *Indigenous Climate Monitoring Toolkit* (First Peoples Group, n.d.):

> Indigenous research methodologies are "as old as our ceremonies and our nations. They are with us and have always been with us" (Cardinel, 2001). The methodologies for Indigenous-led research are varied across and within First Nation, Inuit, and Métis communities across Canada reflecting the diversity of worldviews and ways of knowing.
>
> Many Indigenous climate monitoring projects co-apply Indigenous Knowledge Systems with science bringing together the strengths of both knowledge systems. This has been described as two-eyed seeing (*Etuaptmumk* in Mi'kmaw), which involves "learning to see from one eye with the strengths of Indigenous Knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all" (Reid et al., 2020).
>
> Indicators are used by many Indigenous Peoples to understand and communicate about ecological change. They are the signs and signals that have guided understanding and decisions within Indigenous communities for hundreds if not thousands of years. Climate indicators can relate to:
>
> - radiation (solar radiation or sunlight; surface temperature and thermal radiation)
> - the atmosphere (e.g., temperature, precipitation, wind, humidity);
> - the land (e.g., changes in permafrost, soil moisture, soil temperature, water-table depth)
> - water quantity (e.g., flow, water depth) or quality (e.g., pH, dissolved oxygen, nitrate, phosphates, water temperature)
> - ice and snow (e.g., timing of ice formation and breakup, thickness, quality; snow depth)
> - plants and animals (e.g., timing of arrival of species, species population and distribution, health and body condition, taste and yield of berries, spectroscopy)" (First Peoples Group, 2022).
>
> Elders and Knowledge keepers hold invaluable knowledge about the changes to the land and the environment as a whole. Going out on the land with Knowledge holders can provide a natural space for intergenerational knowledge transfer and Indigenous Knowledge sharing. Participatory video is a newer method of documenting community climate observations and stories through mobilizing stories and collectively-held knowledge with diverse audiences to inform climate adaptation.
>
> Many Indigenous climate monitoring projects also follow scientific methods for collecting data. Many monitoring projects incorporate sensors and automated instrumentation which remain in the field such as weather stations,

hydrological sensors, trail cameras, soil temperature sensors, etc. Some community-based monitoring projects are even using observations from space-based remote sensors (e.g., Landsat 8, LIDAR).

In 2022, the federal government announced $800 million towards Indigenous-led conservation efforts (Prime Minister of Canada, 2022), including those that help to mitigate climate change, like the BC Northern Shelf Bioregion.

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This beautifully illustrated animation video explains what climate change means for Tsay Keh Dene, the changes that Elders have observed in their territories of British Columbia, and how these changes will impact local cultures and traditional practices. It describes the Tsay Keh Dene and Carcross Tagish Community-Based Climate Monitoring project funded by Crown-Indigenous Relations and Northern Affairs Canada.

Scientific Consensus: Global Anthropogenic Climate Change is Real

The **Intergovernmental Panel on Climate Change** (IPCC)—established by the United Nations Environment Programme and the World Meteorological Organization in 1988—is responsible for reviewing the scientific literature on climate change and issuing periodic reports on several topics, including the scientific basis for understanding climate change, our vulnerability to observed and predicted climate changes, and what we can do to limit climate change and minimize its impacts. The IPCC uses this information to evaluate current impacts and future risks, in addition to providing policymakers with assessments. These assessments are released about once every six years. The Panel is on their most recent Synthesis Report, the 6th Assessment Report. Working group reports were released in 2021-2022. Hundreds of leading scientists from around the world are chosen to author these reports. Over the history of the IPCC, these scientists have reviewed thousands of peer-reviewed, publicly available studies. The scientific consensus according to the last IPCC assessment is clear: global climate change is real and humans are very likely the cause for this change.

Additionally, the major scientific agencies of Canada and the Canadian government also agree that climate change is occurring and that humans are driving it. From the Environment and Climate Change Canada: “Human activity is the main cause of climate change. Carbon dioxide is the main cause of human-induced climate change.” Many independent scientific organizations have released similar statements, both in Canada and abroad. This does not necessarily mean that every scientist agrees on the strength of each component of the climate change system, but nearly universal agreement exists that climate change is happening and is primarily caused by excess greenhouse gases from human activities.

Video



This 14-minute video from the IPCC summarizes much of the 6th Assessment Report on Impacts, Adaptation, and Vulnerability with a global focus.
Question after watching:

Climate varies naturally over a wide range of time scales. In general, climate changes prior to the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas (GHG) concentrations. Recent changes in climate**,** however, cannot be explained by natural causes alone. Research indicates that natural causes are very unlikely to explain most observed warming, especially warming since the mid-20th century. Rather, human activities, especially our combustion of fossil fuels, explains the current warming (Figure **5.3.2.3**). The scientific consensus is clear: through alterations of the carbon cycle, humans are changing the global climate by increasing the effects of something known as the greenhouse effect.

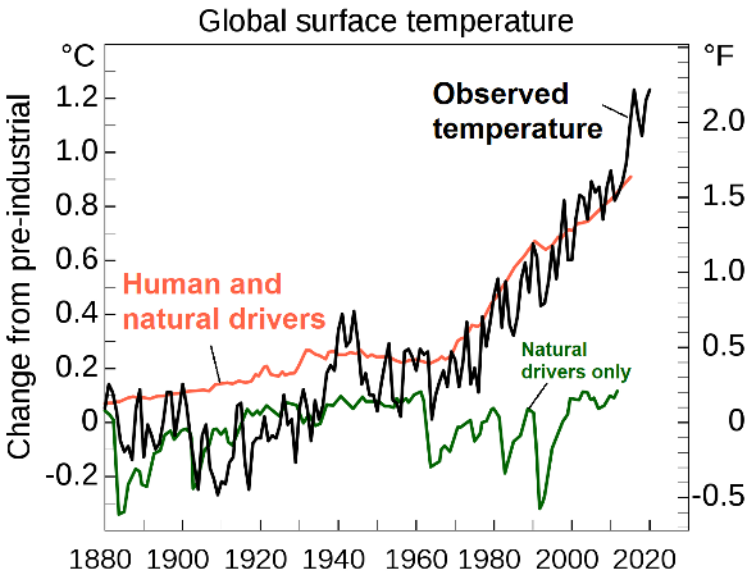


Figure **5.3.2.3**: This graph shows the predicted temperatures from two climate models and observed temperatures from 1880 to 2020. The first model considered only natural factors that could influence temperature and is represented by the green line (bottom). It shows some fluctuations in temperature by no overall increase or decrease. The second model considered both human and natural factors and is represented by the orange line (top). It shows an overall increase in temperature. Actual observations (black, jagged line; middle) more closely match the second model. Overall, temperature has increased about 1.2°C since pre-industrial times. Image relabeled from Efbrazil CC-BY-SA.

Climate change forecasting is famously complex, with a great amount of uncertainty attached to the task. The general models used for climate change forecasting need to account for a great number of highly variable components, each affecting one another across the only planet we can adequately measure or examine (we have no other planet where we can test predictions). Among thousands of considerations, **climatologists**, scientists who study climate, need to account for how human activities might change over time, and how these activities will change the atmosphere's composition. They also need to account for how much CO_2 the world's oceans and plants will absorb, and how wind and fire might influence these processes. Combining all the component parts, climatologists then need to estimate how increased temperatures will affect the polar ice caps, how the melting ice will affect oceanic conditions and currents which, in turn, will affect terrestrial conditions and weather patterns. Uncertainty also exists over interactive effects of some drivers. For example, higher temperatures increase evaporation and cloud cover which, in turn, will have a moderate cooling effect. Because of the complexity of these and other variables going into climate models, a great number of research groups are encouraged to develop their own climate forecasts, each using a range of different scenarios on how human activity might change in the future.

By regularly doing extensive reviews of all the evidence and climate science literature, the IPCC has found that, despite the complexity of climate models, results of all the models taken together exhibited significant agreement with changes already observed. Climate change models have also proven reliable in predicting responses of biodiversity to climate change. While climatologists continue to improve on the finer details of their models, conservation biologists can and should confidently use the climate forecasts available for general conservation planning purposes.

Specific Human Impacts on Greenhouse Gases

Recall that GHGs are probably the most significant drivers of current climate change. The GHGs that affect Earth include carbon dioxide, methane, water vapor, nitrous oxide, and ozone. Water vapor is the most abundant greenhouse gas and also the most important in terms of its contribution to the natural greenhouse effect, despite having a short atmospheric lifetime. Some human activities can influence local water vapor levels. However, on a global scale, the concentration of water vapor is controlled by temperature, which influences overall rates of evaporation and precipitation. Therefore, the global concentration of water vapor is not substantially affected by direct human emissions.



Figure 5.3.2.6: The burning of fossil fuels in industry and by vehicles releases carbon dioxide and other greenhouse gases into the atmosphere. (CC-BY-SA 4.0 “Pöllö”/Wikimedia Commons)

Sinks and Sources

Places in the ecosystem that store GHGs are reservoirs. Places that supply and remove are **sources** and **sinks**, respectively. If more GHGs are released than stored, the place is a source. If more GHGs are absorbed than emitted, the reservoir is a sink. A reservoir can change from a sink to a source and vice versa. For example, a forest is a sink for carbon, but when the forest burns it becomes a carbon source.

Carbon Dioxide

Carbon dioxide (CO_2) is the primary greenhouse gas that is contributing to recent global climate change. Healthy living forests and the oceans act as carbon sinks. The mantle is a natural source of carbon from volcanic gases. The link between human-induced climate change and atmospheric CO_2 concentrations was first highlighted in the late 19th century by Arrhenius. However, it was not until the mid-1950s that scientists started to raise concerns about increasing CO_2 concentrations in the atmosphere. By the 1980s, as global annual mean temperatures started to rise, consensus about climate change linked to CO_2 began to spread among the broader public. Yet concrete steps to curb CO_2 emissions have only been initiated recently.

In the meantime, CO_2 emissions continue to accelerate: more than 37 billion tonnes of carbon, a new record, were released into the atmosphere in 2018. CO_2 is a natural component of the carbon cycle, involved in such activities as photosynthesis, respiration, volcanic eruptions, and ocean-atmosphere exchange. Human activities, primarily the burning of fossil fuels, deforestation, and changes in land use, release very large amounts of CO_2 to the atmosphere, causing its concentration in the atmosphere to rise, where each molecule may remain for more than 200 years. Cement manufacture, animal agriculture, the clearing of land, and the burning of forests are other human activities that release carbon dioxide.

Scientists look at patterns in data and try to explain differences or deviations from these patterns. As stated in Unit 5.3.1, the atmospheric carbon dioxide data reveal a historical pattern of carbon dioxide increasing and decreasing, cycling between a low of 180 ppm and a high of 300 ppm (Figure 5.3.2.4). Scientists have concluded that it took around 50,000 years for the atmospheric carbon dioxide level to increase from its low minimum concentration to its higher maximum concentration. However, starting recently, atmospheric carbon dioxide concentrations have increased beyond the historical maximum of 300 ppm. Atmospheric CO_2 concentrations have increased by 45% since pre-industrial times, from approximately 280 parts per million (ppm) in the 18th century to 415 ppm in 2021. What is the reason for this difference in the rate of change and the amount of increase in carbon dioxide? A key factor that must be recognized when comparing the historical data and the current data is the presence of modern human society; no other driver of climate change has yielded changes in atmospheric carbon dioxide levels at this rate or to this magnitude.

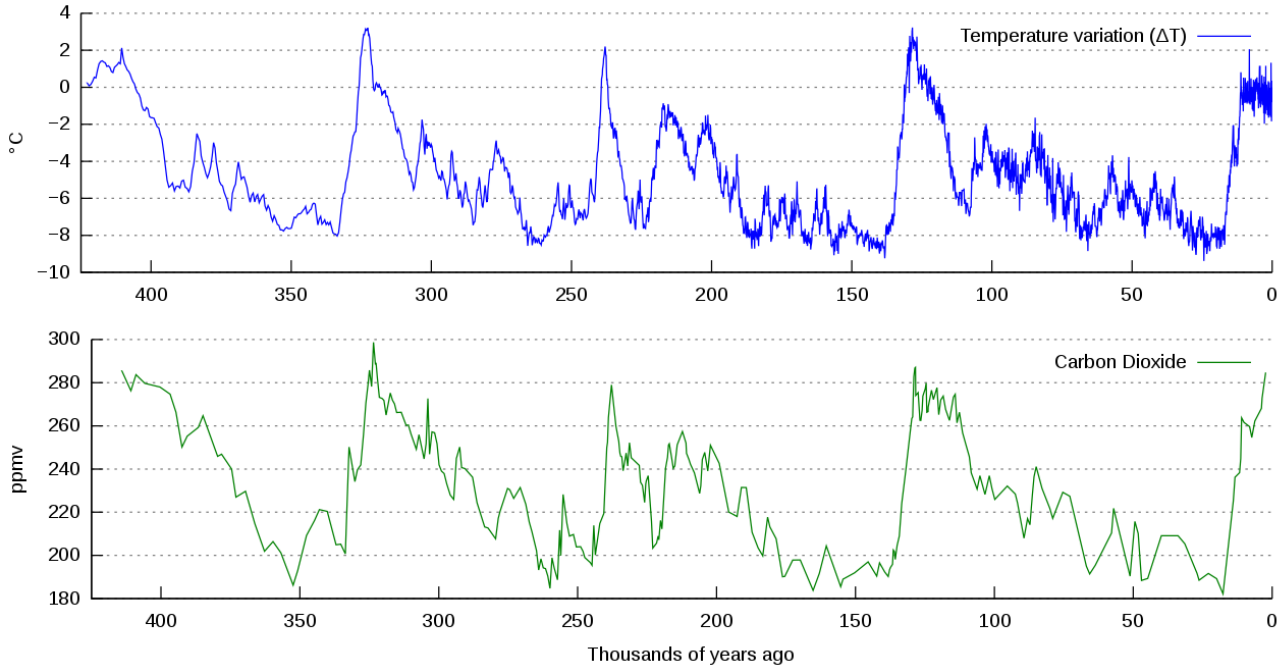


Figure **5.3.2.4**: Graph of change in temperature in degrees Celsius (top, blue line) and carbon dioxide concentration in parts per million by volume (bottom, green line) measured from the Vostok, Antarctica ice core. These have been associated for over 400,000 years. As carbon dioxide concentration increased, so did temperature. As carbon dioxide concentration decreased, so did temperature. These data were collected in 1999. Since then, carbon dioxide concentrations have stabilized to over 410 ppm. Image and caption (modified) by NOAA/Autopilot (CC-BY-SA)

Video



This 4-minute animation describes the natural carbon cycle and how humans are disrupting that cycle.
Question after watching: Which of the technologies to remove carbon from the atmosphere have you heard of before? Which have you not? What do these technologies do?

Optional Activity 5.3.2.2

How long does a molecule of CO_2 remain in the atmosphere?

A. CO_2 washes out of the atmosphere seasonally.
B. CO_2 remains in the atmosphere for 5-10 years.
C. CO_2 remains in the atmosphere for up to 200 years, or more.

Answer

C. CO_2 remains in the atmosphere for up to 200 years, or more.

Optional Activity 5.3.2.3

What is the primary cause of the overall rising trend in CO_2 in the atmosphere?

A. The increase in CO_2 is caused by burning of fossil fuels.
B. CO_2 is increasing because we are coming out of an ice age.
C. As human population grows, people exhale more CO_2.
D. CO_2 is released by the oceans as they warm.

Answer

A. The increase in CO_2 is caused by burning of fossil fuels.

Methane

Although this concentration is far less than that of CO_2, **methane** (CH_4) is 28 times as potent a greenhouse gas. Methane is produced when bacteria break down organic matter under anaerobic conditions and can be released due to natural or anthropogenic processes. Anaerobic conditions can happen when organic matter is trapped underwater (such as in rice paddies) or in the intestines of herbivores. Anthropogenic causes now account for 60% of total methane release. Examples include agriculture, fossil fuel extraction and transport, mining, landfill use, and burning of forests. Methane can also be released from natural gas fields and the decomposition that occurs in landfills. Specifically, raising cattle releases methane due to fermentation in their rumens producing methane that is expelled from their GI tract. Methane is more abundant in Earth's atmosphere now than at any time in at least the past 650,000 years, and CH_4 concentrations increased sharply during most of the 20th century. They are now more than 2.5 times pre-industrial levels and increasing rapidly.

Another source of methane is the melting of clathrates (methane hydrate). **Clathrates** are frozen chunks of methane hydrate found at the bottom of the ocean. When water warms these chunks of ice melt and methane is released. As the ocean's water temperature increases, the rate at which clathrates melt is increasing, releasing even more methane. This leads to increased levels of methane in the atmosphere, which further accelerates the rate of global warming. This is an example of the positive feedback loop that is leading to the rapid rate of increase in global temperatures. There is strong evidence that warming during the Quaternary period 55 million years ago was caused, at least in part, by a massive release of clathrates.

Video



This 2-minute, 3D volumetric visualization shows the emission and transport of atmospheric methane around the globe between December 9, 2017 and December 1, 2018. (NASA)

Question after watching: What patterns do you notice based on the narrator's descriptions and the visualization?

Other Greenhouse Gases

Nitrous oxide (N_2O) is produced through natural and human activities, mainly through agricultural activities and natural biological processes. Fuel-burning and some other processes also create N_2O. Concentrations of N_2O have risen approximately 18% since the start of the Industrial Revolution, with a relatively rapid increase towards the end of the 20th century. [3] In contrast, the atmospheric concentration of N_2O varied only slightly for a period of 11,500 years before the onset of the industrial period, as shown by ice core samples.

Ground-level ozone (O_3), which also has a short atmospheric lifetime, is a potent greenhouse gas. Chemical reactions create ozone from emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight. In addition to trapping heat, ozone is a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6), together called **F-gases**, are often used in coolants, foaming agents, fire extinguishers, solvents, pesticides, and aerosol propellants. Unlike water vapor and ozone, these F-gases have a long atmospheric lifetime, and some of these emissions will affect the climate for many decades or centuries.

Human-Induced Changes in Albedo and Aerosols

When sunlight energy reaches Earth it can be reflected or absorbed. The amount that is reflected or absorbed depends on Earth's surface and atmosphere. Light-colored objects and surfaces, like snow and clouds, tend to reflect most sunlight, while darker objects and surfaces, like the ocean and forests, tend to absorb more sunlight. The term **albedo** refers to the amount of solar radiation reflected from an object or surface, often expressed as a percentage. Earth as a whole has an albedo of about 30%, meaning that 70% of the sunlight that reaches the planet is absorbed. Sunlight that is absorbed warms Earth's land, water, and atmosphere.

Albedo is also affected by aerosols. **Aerosols** are small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight. Unlike greenhouse gases (GHGs), the climate effects of aerosols vary depending on what they are made of and where they are emitted. Those aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect. In addition, human activities have generally increased the number of aerosol particles in the atmosphere. Overall, human-generated aerosols have a net cooling effect offsetting about one-third of the total warming effect associated with human greenhouse gas emissions. Reductions in overall aerosol emissions can therefore lead to more warming. However, targeted reductions in black carbon emissions can reduce warming.

Human changes in land use and land cover have changed Earth's albedo. Processes such as deforestation, reforestation, desertification, and urbanization often contribute to changes in climate in the places they occur. These effects may be significant regionally but are smaller when averaged over the entire globe.

Video



This 2-minute video visualizes albedo.
Question after watching: What are some human activities that change albedo as visualized in the video?

Climate Feedbacks

When sea ice melts, as it has done in the Arctic Ocean at a disturbing rate over the past decade, the albedo of the area affected changes dramatically, from around 80% down to less than 10%. This is a positive feedback (see a review of feedback loops in Unit 4.4.1) because much more solar energy is absorbed by the water than by the pre-existing ice, and the temperature increase is amplified. The same applies to ice and snow on land, but the difference in albedo is not as great.

When ice and snow on land melt, sea level rises. Sea level is also rising because the oceans are warming and that increases their volume. A higher sea level means a larger proportion of the planet is covered with water, and since water has a lower albedo than land, more heat is absorbed and the temperature goes up a little more. Since the last glaciation, sea-level rise has been about 125m; a huge area that used to be land is now flooded by heat-absorbent seawater. During the current period of anthropogenic climate change, sea level has risen only about 20 cm, and although that does not make a big change to albedo, sea-level rise is accelerating.

Video



A warming Arctic can catapult the world into drastic climate impacts through feedback loops as seen in this 3.5-minute video.
Question after watching: Why should we be concerned with permafrost melting as well as ice in the Arctic?



Figure 5.3.2.10: A degrading permafrost site on the north coast of Alaska.

Most of northern Canada has a layer of permafrost that ranges from a few centimeters to hundreds of meters in thickness; the same applies in Alaska, Russia, and Scandinavia. Permafrost is a mixture of soil and ice (Figure 5.3.2.10), and it also contains a significant amount of trapped organic carbon that is released as CO_2 and CH_4 when the permafrost breaks down. Because the

amount of carbon stored in permafrost is in the same order of magnitude as the amount released by burning fossil fuels, this is a feedback mechanism that has the potential to equal or surpass the forcing that has unleashed it. In some polar regions, including northern Canada, permafrost also includes methane hydrate. Breakdown of permafrost releases this form of methane.

There is about 45 times as much carbon in the ocean (as dissolved bicarbonate) as there is in the atmosphere (as CO_2), and there is a steady exchange of carbon between the two reservoirs. But the ability of CO_2 to dissolve in water (its **solubility**) decreases as the temperature goes up. In other words, the warmer it gets, the more oceanic bicarbonate gets released to the atmosphere as CO_2. That makes CO_2 solubility another positive feedback mechanism.

Vegetation growth responds positively to both increased temperatures and elevated CO_2 levels, and so in general, it represents negative feedback to climate change because the more the vegetation grows, the more CO_2 is taken from the atmosphere. However, trees grow bigger and more vigorously so forests have lower albedo so they absorb more heat. In addition, climate change is not just more CO2, it may mean more or less rain, extreme weather events, or drastic seasonal changes that interfere with forest health. Furthermore, climate warming isn't necessarily good for vegetation growth; some areas have become too hot, too dry, or even too wet to support the plant community that was growing there, and it might take centuries for something to replace it successfully.

All of these positive (and negative) feedbacks work both ways. For example, during climate cooling, growth of glaciers leads to higher albedos, and formation of permafrost results in storage of carbon that would otherwise have returned quickly to the atmosphere.

Video



This 3.5-minute video describes climate tipping points.
Question after watching: What is meant by a "tipping point" for climate? What types of systemic changes are studied in terms of climate tipping points? Are these positive feedbacks or negative feedbacks?

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Unit 5.3.3 - Current and Future Climate Change Impacts

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.3.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Identify current global climate impacts and their confidence level
- Explain several projected abiotic climate impacts and their effects on living organisms

Introduction

Climate change has the potential to render Earth unrecognizable from what any human has ever experienced. These changes will have an immense impact on ecosystem services, global economies, and our own quality of life. Yet, while there is much talk about these risks, there is still too little action addressing its main causes.

Current Climate Change Impacts

Some of the lack of action may be attributed to “climate change” and “future” often being used in the same sentence, giving politicians and industries a false impression that we can deal with climate change once we achieved sufficient economic growth. The reality could however not be further from the truth, as we already see signs of the changes to come here today (Table **5.3.3.1**), including near-annual crop failures, record-high temperatures, and record-strength coastal storms.

Table **5.3.3.1**: Some examples illustrating how climate change is already impacting our planet (IPCC, 2022).

Impact	Evidence
Increased extreme weather	The rise in weather and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt. (high confidence). Widespread, pervasive impacts to ecosystems, people, settlements, and infrastructure have resulted from observed increases in the frequency and intensity of climate and weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, drought, and fire weather (high confidence).
Widespread flood and droughts	Flood and drought-related acute food insecurity and malnutrition have increased in Africa (high confidence) and Central and South America (high confidence).
Rising sea levels	Continued and accelerating sea level rise will encroach on coastal settlements and infrastructure (high confidence) and commit low-lying coastal ecosystems to submergence and loss (medium confidence).
Earlier spring activity	Widespread deterioration of ecosystem structure and function, resilience, and natural adaptive capacity, as well as shifts in seasonal timing have occurred due to climate change (high confidence), with adverse socioeconomic consequences (high confidence).
Disease spread	The occurrence of climate-related food-borne and water-borne diseases has increased (very high confidence). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (high confidence). Animal and human diseases, including zoonoses, are emerging in new areas (high confidence).
Shifts in species ranges	Approximately half of the species assessed globally have shifted polewards and to higher elevations on land (very high confidence).
Wildlife population declines	Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater and coastal and open ocean marine ecosystems (high confidence). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (high confidence). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (high confidence), as well as mass mortality events on land and in the ocean (very high confidence) and loss of kelp forests (high confidence). Some losses are already irreversible, such as the first species extinctions driven by climate change (medium confidence).

Terms from Table 5.3.3.1

Risk: provides a framework for understanding the increasingly severe, interconnected, and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors, and communities; and how to best reduce adverse consequences for current and future generations.

Adaptation: in human systems, the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate

and its effects; human intervention may facilitate this.

Resilience: the capacity of social, economic, and ecosystems to cope with a hazardous event, trend, or disturbance, responding, or reorganizing in ways that maintain their essential function, identity, and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning, and transformation.

Mitigation: reducing emissions, and stabilizing the levels, of heat-trapping greenhouse gases in the atmosphere.

Confidence: each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high.

Between June 25 and July 1, 2021, British Columbia experienced a massive heat dome with temperatures reaching 49.6^{o}C in some areas. Scientists have stated that climate change was a contributing factor. More than 500 deaths were attributed to the heat. Glaciers throughout British Columbia are in retreat, with losses ranging from 6% to 34% from 1985-2005, and their melting is increasing. See more from the British Columbia Provincial Government: Change in Size of B.C. Glaciers.

A summary of the impacts of climate change on natural disasters is given in Figure **5.3.3.1**. The major types of disasters related to climate are floods and storms, but the health implications of extreme temperatures are also becoming a great concern. In the decade 1971 to 1980, extreme temperatures were the fifth most common natural disasters; by 2001 to 2010, they were the third most common.

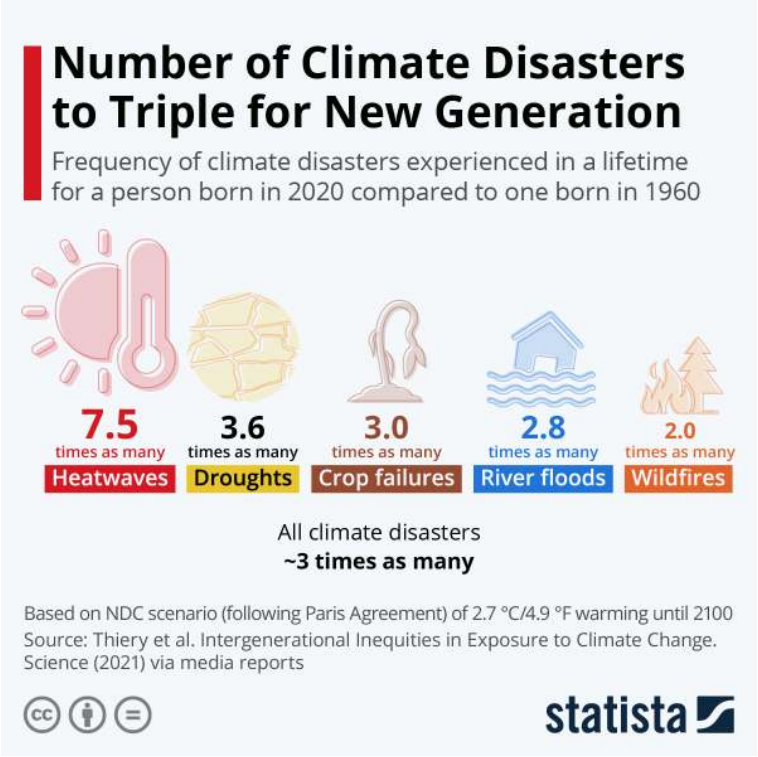
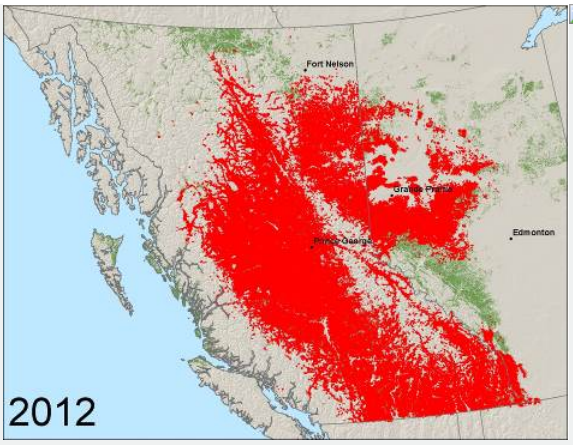


Figure **5.3.3.1**: Predicted future climate disasters for someone born in 2020 versus someone born in 1960.

Canadian Perspective - The Mountain Pine Beetle

"The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is native to western North America, from northern Mexico to northern British Columbia. It is also present in an isolated population of pine that is surrounded by prairie in the Cypress Hills area of southwestern Saskatchewan, which was likely infested in the early 1980s. In the 2000s, the beetle significantly expanded its range in Canada, invading new habitat east of the Rocky Mountains in northeastern British Columbia and northern Alberta (Figure **5.3.3.2** left)."[1]



Reddened pine, caused by pine beetle attack, in central British Columbia.

Figure **5.3.3.2**: Left: Observed presence of mountain pine beetle from 1999 to 2012 (Government of Canada). Right: Large area of damaged forest (Government of British Columbia)

"Most species of pine that grow in the beetle's range are readily attacked, with the exception of Jeffrey pine. In Canada, these hosts include ponderosa, western white, whitebark, limber pines, and, very recently, jack pine in the expanded range. Lodgepole pine is the most common host in the mountain pine beetle's range in British Columbia."[1]

"This small beetle attacks and kills mature trees by boring through the bark and mining the phloem (living tissue in vascular plants that carries organic nutrients). Its eggs hatch into larvae that consume the phloem, killing the tree. The beetles are killed by very cold winter weather, which historically has kept their numbers in check."[2]

"Trees will attempt to repel the beetles by releasing quantities of resin, which mixes with the boring dust and forms a soft, white or reddish pitch tube around each borehole. These pitch tubes usually appear from the duff line to a top diameter of 15cm. Infected trees' foliage turns yellow and then red by the spring of the year following the initial beetle attack. Most of the needles drop from the tree after two years, leaving a dead grey snag."[2]

"In British Columbia, the northern limit of the beetle's range has been limited by cold winter temperatures (−40°C) and cool summers. Outbreaks have been linked to favorable weather in both summer and winter. Warm, dry summers are good for beetle development and dispersal, and drought stress reduces tree defenses. In the late 1990s, after several relatively warm winters, a massive outbreak resulted in the loss of millions of hectares of pine forest in British Columbia over the next 15 years."[1,2]

Resources:

1. Government of Canada. 2021. *Mountain pine beetle (factsheet)*. Natural Resources Canada [Online]. Available from: https://www.nrcan.gc.ca/forests/fire-insects-disturbances/top-insects/13397

2. Government of British Columbia. 2022. *Mountain pine beetle*. Forest Health [Online]. Available from: https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-health/forest-pests/bark-beetles/mountain-pine-beetle

Future Climate Change

Many greenhouse gases stay in the atmosphere for long periods of time. As a result, even if emissions stopped increasing, atmospheric greenhouse gas concentrations would continue to remain elevated for hundreds of years. Moreover, if we stabilized concentrations and the composition of today's atmosphere remained steady (which would require a dramatic reduction in current greenhouse gas emissions), surface air temperatures would continue to warm (Figure **5.3.3.3**). This is because the oceans, which store heat, take many decades to fully respond to higher greenhouse gas concentrations. The ocean's response to higher greenhouse gas concentrations and higher temperatures will continue to impact climate over the next several decades to hundreds of years. Thus, past and present GHG emissions will affect climate far into the future.

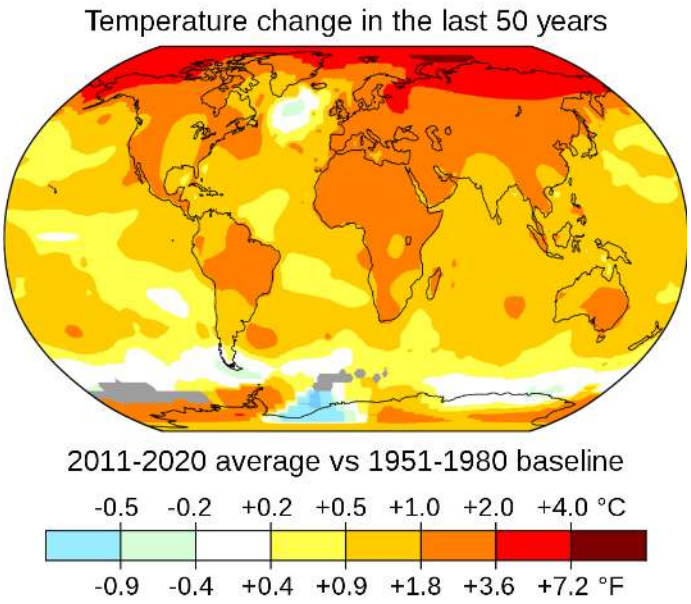


Figure **5.3.3.3**: Temperature increases have been most pronounced in northern latitudes and over land masses. The colors represent the temperature difference between the 2011-2020 average and the 1951-1980 baseline, with warmer colors (yellow, orange, red) representing increases, and cool colors (green, blue) representing decreases. The image uses longer term averages of at least a decade to smooth out climate variability due to factors such as El Niño. Grey areas in the image have insufficient data for rendering. Image and caption (modified) from NASA's Scientific Visualization Studio/Eric Fisk (public domain).

Temperature Changes

Climate models project the following key temperature-related changes:

- Average global temperatures are expected to increase by 1.1°C to 6.4°C by 2100, depending on the level of future greenhouse gas emissions, and the outcomes from various climate models.
- By 2100, global average temperature is expected to warm at least twice as much as it has during the last 100 years.
- Ground-level air temperatures are expected to continue to warm more rapidly over land than oceans.
- Some parts of the world are projected to see larger temperature increases than the global average.

These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health. The magnitude and rate of future climate change will primarily depend on the following factors:

- The rate at which levels of greenhouse gas concentrations in our atmosphere continue to increase, often known as "climate scenarios" (Figure **5.3.3.4**);
- How strongly features of the climate (e.g., temperature, precipitation, and sea level) respond to the expected increase in greenhouse gas concentrations; and
- Natural influences on climate (e.g., from volcanic activity and changes in the sun's intensity) and natural processes within the climate system (e.g., changes in ocean circulation patterns).

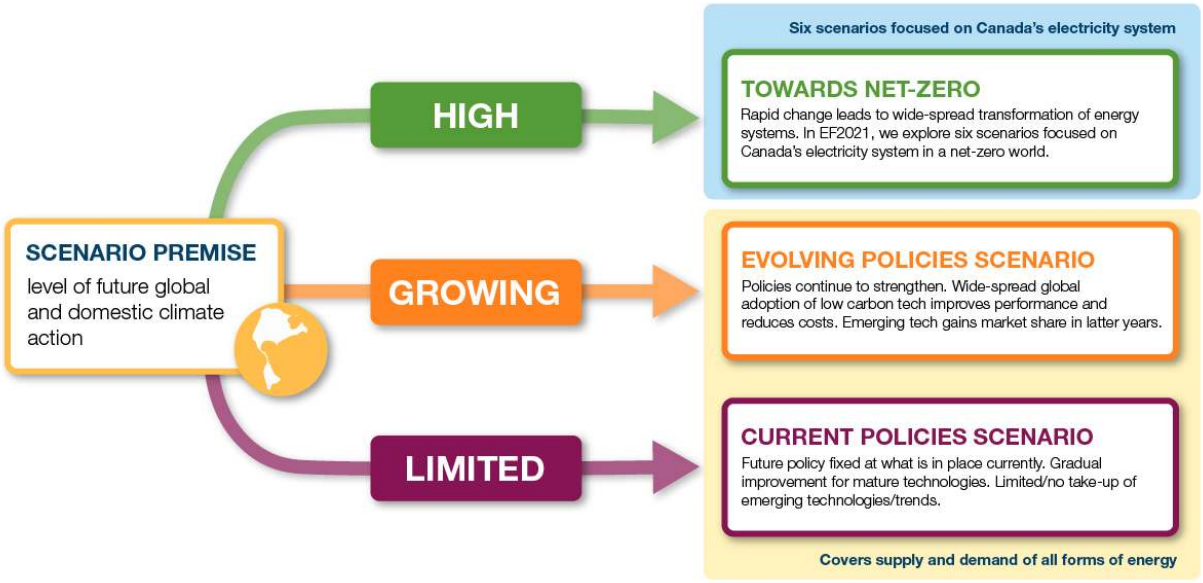


Figure **5.3.3.4**: Conceptual illustration of Canada's energy and climate scenarios, 2021. The first main scenario is the Evolving Policies Scenario. The premise of this scenario is that there is *growing* action to reduce the GHG emissions from our energy system at a pace similar to recent history, in both Canada and the world. Relative to a scenario with less action to reduce GHG emissions, this projection implies less global demand for fossil fuels, and greater use of low-carbon technologies. The second main scenario is the Current Policies Scenario, which assumes *limited* action to reduce GHGs beyond policies already in place today. The third main set of scenarios explores a net-zero future with a *high* level of global and domestic climate action. Specifically, the set of scenarios in the Net-Zero premise explore what Canada's electricity grid might look like in a net-zero world under six different sets of assumptions about future technologies, climate policies, and electricity use. (Government of Canada - Canada Energy Regulator)

Species that are highly mobile are not entirely spared from the negative impacts of climate change. Consider that migratory species rely on environmental cues, such as day length and temperature, to determine when to start moving from one area to the next. But because different species rely on different environmental cues to time their life cycles (e.g. breeding), not all species will adjust to climate change at the same rate. There is consequently a high likelihood that climate change will disrupt these synchronous movements that the animals in particular have developed over thousands to millions of years. This disruption of timed aspects of a species' life cycle, such as migration and breeding, is called **phenological mismatch**. Researchers have already seen signs of phenological mismatch: some migratory birds that overwinter in the tropics have started to migrate to their breeding grounds at earlier dates than before. If these trends hold, they may soon start breeding before peak food availability, which could lead to lower fitness of offspring.

Resident species are also vulnerable to phenological mismatch. While these species might not be known for large-scale movements around the globe, they may still have to adjust their ranges to keep track of their climatic niches. Considering the improbability that different species will all adapt at the same pace, there is thus a danger that important mutualistic relationships might be pulled apart during these range adaptations. This is of concern for species with specialized feeding niches, as seen in some pollinators. Extinctions arising from this decoupling of mutualistic relationships are referred to as **coextinction**.

Freshwater ecosystems will generally experience temperature increases under climate change. Like their terrestrial counterparts, many freshwater species are sensitive to temperature shifts as warmer water also holds less dissolved oxygen. In addition, longer growing seasons and higher water temperatures will lead to increased nutrient loads, algae blooms, and eutrophication. All these factors will force many freshwater species—even those not sensitive to temperature shifts—to adjust their ranges to keep track of suitable conditions. For some freshwater species, the impediments to adjusting their ranges as necessary may be insurmountable.

Not all species will be impacted negatively. A variety of species are expected to benefit from climate change. These include generalist species currently limited by interactions with localized specialists that are—at least at present—better competitors for limiting resources. Some tropical species may thrive as their habitats become hotter and wetter. Species with high genetic diversity that reproduce quickly (allowing for rapid adaption to environmental changes) are also likely to benefit. Unfortunately, many species that exhibit these traits carry diseases and/or are agricultural pests. For example, populations of the coffee berry borer (*Hypothenemus hampei*)—Africa's most notorious coffee pest—are expected to greatly increase in a warmer world. This growing

threat is particularly worrying given that higher temperatures have already reduced coffee harvests in countries such as Tanzania by as much as 50%.

The range of disease-carrying insects and the viruses and pathogenic parasites they harbor will increase. This spread has already been documented in North America with several different diseases including West Nile and Lyme disease. Colder temperatures typically limit the distribution of certain species, such as the mosquitoes that transmit malaria, because freezing temperatures destroy their eggs. Not only will the range of some disease-causing insects expand, but increasing temperatures will also accelerate the host lifecycles, allowing them to breed and multiply more quickly. They may even evolve pesticide resistance faster. In addition to those listed above, other diseases such as dengue fever, malaria, yellow fever, zika virus, and chikungunya are expected to spread to new regions as the global climate warms.

Climate change does not only increase the spread of diseases in humans. Rising temperatures are associated with greater amphibian mortality due to chytridiomycosis (see Unit 5.2.3). Similarly, warmer temperatures have exacerbated bark beetle infestations of coniferous trees, such as pine and spruce.

? Optional Activity 5.3.3.1

How do climate factors (temperature, precipitation, & humidity) relate to vector-borne disease?

A. Heavy rain increases the risk of animals transmitting pathogens.
B. Milder winters increase the vector density & risk of disease
C. Dry summers & drought increase the risk of vectors expanding their range
D. More intense snowstorms Snow increase vector density & risk of disease

Answer

B. Milder winters increase the vector density & risk of disease.

Precipitation and Storm Events

Patterns of precipitation and storm events, including both rain and snowfall are likely to change. However, some of these changes are less certain than the changes associated with temperature. Because warm air is able to hold more water than cold air, the general global trend over the past century has been one of increasing precipitation (Figure 5.3.3.5).

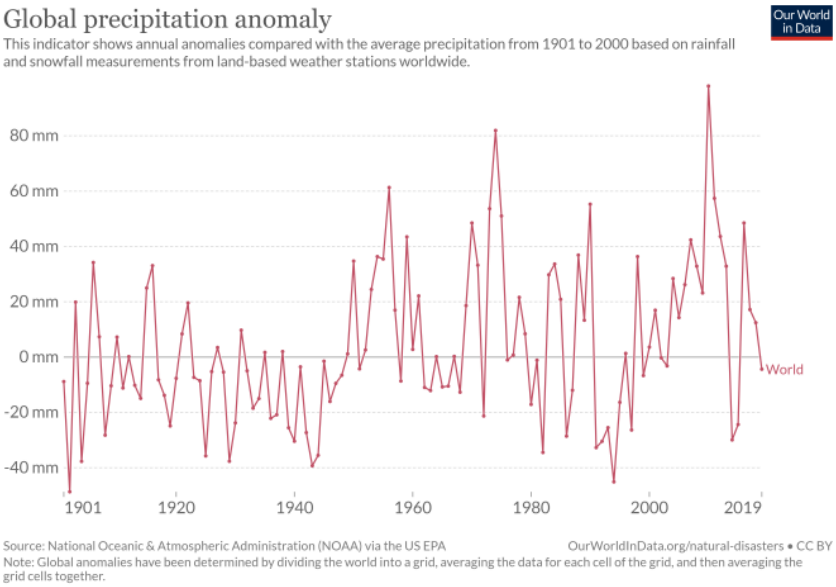


Figure **5.3.3.5**: Data shows global precipitation patterns, based on rainfall and snowfall measurements from land-based weather stations worldwide. This indicator shows annual anomalies, or differences, compared with the average precipitation from 1901 to 2000. CC-BY United States Environmental Protection Agency (EPA)

Projections show that future precipitation and storm changes will vary by season and region. Some regions may have less precipitation, some may have more precipitation, and some may have little or no change. The amount of rain falling in heavy precipitation events is likely to increase in most regions, while storm tracks are projected to shift toward the poles. Climate models project the following precipitation and storm changes:

- Global average annual precipitation through the end of the century is expected to increase, although changes in the amount and intensity of precipitation will vary by region.
- The intensity of precipitation events will likely increase on average. This will be particularly pronounced in tropical and high-latitude regions, which are also expected to experience overall increases in precipitation.
- The strength of the winds associated with tropical storms is likely to increase. The amount of precipitation falling in tropical storms is also likely to increase.
- Annual average precipitation is projected to increase in some areas and decrease in others.

One of the other risks for coastal populations, besides sea-level rise, is that climate warming is also associated with an increase in the intensity of coastal storms (e.g., atmospheric rivers, hurricanes, cyclones, or typhoons), which almost always bring serious flooding from intense rain and storm surges. Some recent examples are the Vancouver floods of 2021 and the impact of Hurricane Fiona on Nova Scotia in 2022 (Figure **5.3.3.6**).

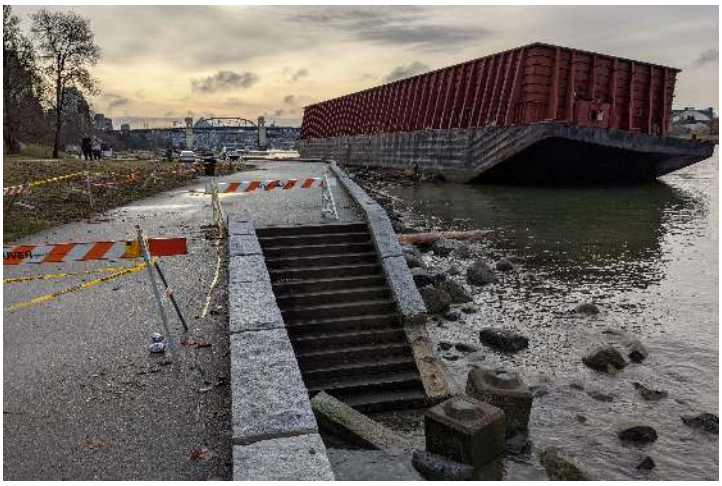


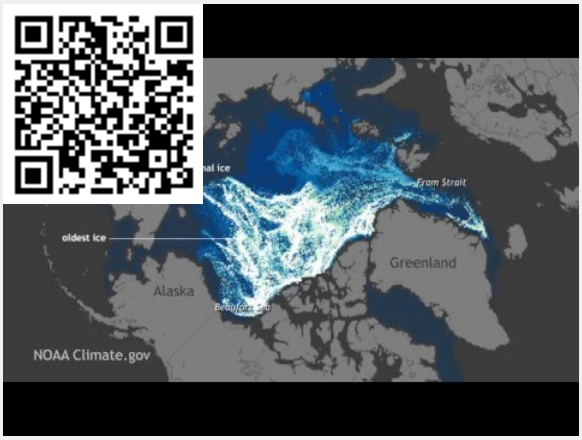
Figure **5.3.3.6**: Grounded barge along Vancouver's Seawall in English Bay. November 2021. CC-BY-SA 4.0 Northwest

Changing precipitation levels will have several impacts on freshwater ecosystems, particularly as it relates to changes in their flow regimes. For example, areas that are undergoing decreased precipitation will experience decreased runoff and increased drying of wetlands and small streams, while areas with increased precipitation will experience increased storm surges and flushing. Given these multiple stressors, there is a reasonable expectation that many freshwater species will go extinct or face significant population declines and range shifts over the next decades. These changes are of major concern in countries that are currently majority subsistence, where so many people depend on fish and related natural resources for their livelihoods. Many communities around the world are already finding it more difficult to meet their nutritional needs due to climate-induced freshwater fish declines. Also, at some large lakes, which may supply 20–40% of the surrounding countries' dietary protein—fish yields have decreased by 30% in recent years, also attributed to climate change.

Ice Melt and Sea Level Rise

Arctic sea ice is already declining. Sea ice is ice floating in the ocean (not on land like a glacier). Most sea ice is in the Arctic Ocean and the extent of sea ice is shrinking. Below, the NOAA animation shows how perennial sea ice has declined from 1990 to 2015. The oldest ice is white and the youngest (seasonal) ice is dark blue. The amount of old ice has declined from 20% in 1985 to 3% in 2015. For every 1°C of warming, models project about a 15% decrease in the extent of annually averaged sea ice (the total ice extent and concentration averaged over a year) and a 25% decrease in September Arctic sea ice.

Video



This 2-minute video from the US's National Oceanic and Atmospheric Association illustrates the loss of Arctic sea ice from 1990-2015.

Question after watching: What seasonal patterns do you notice? What do you notice regarding the oldest ice over the 25 years portrayed in the video?

The land-based, coastal sections of the Greenland and Antarctic ice sheets have been melting significantly and are expected to continue to do so (Figure **5.3.3.7**). If the rate of this ice melting increases in the 21st century, these ice sheets could add significantly to global sea level rise and disrupt global ocean currents. Before anthropogenic warming, glacial activity was variable with some retreating and some advancing. Now, nearly all glaciers globally a retreating and expected to continue to melt, leading to freshwater shortages globally.

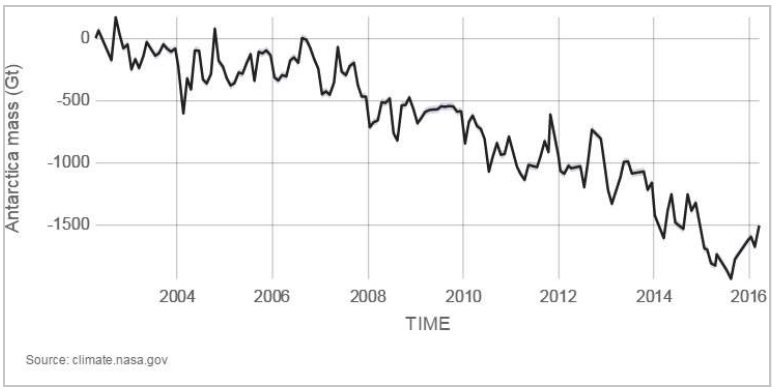


Figure **5.3.3.7**: Decline of Antarctic ice mass from 2002 to 2016. (NASA)

On average, the sea is rising at a rate of 1.8 mm per year. However, between 1993 and 2010 the rate of sea level increase ranged between 2.9 and 3.4 mm per year (Figure **5.3.3.8**). This is thought largely to be from both the melting of glaciers and thermal expansion. Thermal expansion means that as objects such as solids, liquids, and gases heat up, they expand in volume. Since 1970, the melting of glaciers and thermal expansion account for 75% of the sea-level rise (scientists are still researching the other 25%). As the oceans creep further inland, the extent of low-lying coastal ecosystems such as rocky shores or sandy beaches will shrink, and so also the sizes of the wildlife populations living in those areas.

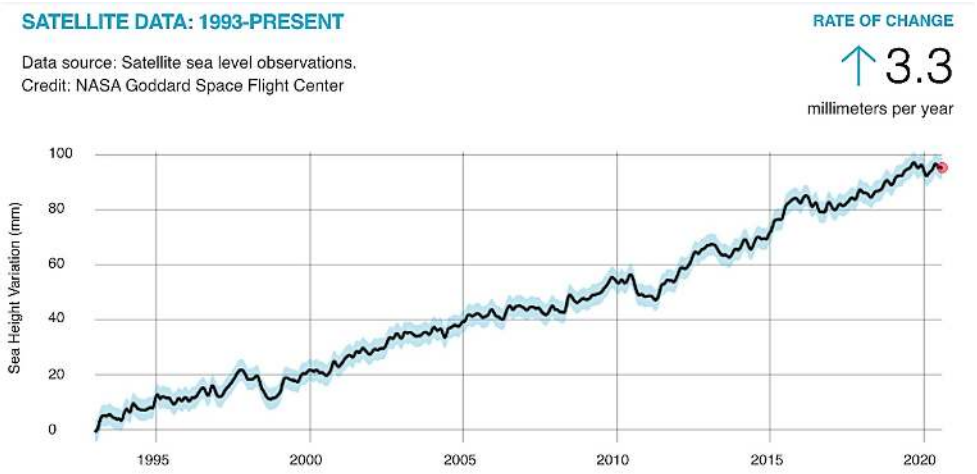


Figure **5.3.3.8**: Sea height variation (mm) over time. Sea height has increased about 3.3 millimeters per year on average since 1993. Data is from satellite sea level observations by the NASA Goddard Space Flight Center. Image by NASA (public domain)

Projections for sea level rise to the end of this century vary widely. This is in large part because we do not know which of the above climate change scenarios (Figure **5.3.3.3**) we will most closely follow, but many are in the range from 0.5 m to 2.0 m. One of the problems in predicting sea level rise is that we do not have a strong understanding of how large ice sheets, such as Greenland and Antarctica, will respond to future warming. Another issue is that the oceans do not respond immediately to warming. For example, with the current amount of warming, we are already committed to a future sea level rise of between 1.3 m and 1.9 m, even if we could stop climate change today.

? Optional Activity 5.3.3.2

What are the major causes of sea level rise?

A. Melting sea ice
B. Melting glaciers and ice sheets
C. Seawater expanding as it gets warmer
D. A and B
E. B and C

Answer

B and C. Melting glaciers and ice sheets and seawater expanding as it gets warmer.

Ocean Acidification and Deoxygenation

Since 1750, the ocean has absorbed about 30% of all anthropogenic carbon dioxide sources. When carbon dioxide gets absorbed in the ocean, it creates carbonic acid which makes the ocean more acidic. **Ocean acidification** is the process of ocean waters' decreasing pH (lower values are more acidic on the pH scale). The pH level of the oceans has decreased by approximately 0.1 pH units since pre-industrial times, which is equivalent to a 25% increase in acidity. The pH level of the oceans is projected to decrease even more by the end of the century as CO_2 concentrations are expected to increase for the foreseeable future.

Ocean acidification adversely affects many marine species, including plankton, mollusks, shellfish, and corals. As ocean acidification increases, the availability of calcium carbonate will decline. Calcium carbonate is a key building block for the shells and skeletons of many marine organisms. Most tropical oceans have experienced extensive coral bleaching events in recent years due to increased sea surface temperatures and ocean acidification. Ocean acidification also disturbs predator-prey dynamics by impairing the senses of prey species and compromising the ability of marine creatures to communicate with those within their same species.

Marine fish and invertebrates rely on dissolved oxygen that enters the water either through the atmosphere or by photosynthetic plankton. But because warmer water absorbs less oxygen, scientists predict that some areas of the ocean will see a 3–6% drop in dissolved oxygen concentrations under climate change. This process, known as **ocean deoxygenation**, will leave parts of the ocean unsuitable for marine fishes and invertebrates, leading to dead zones. The impact of ocean deoxygenation will also be felt by economically important fisheries where climate change is predicted to lead to fisheries-related economic losses upwards of $415 million each year.

Acidification combined with warmer temperatures and lower oxygen levels is expected to have severe impacts on marine ecosystems, especially coral reefs, and associated fisheries possibly affecting our ocean-derived food sources.

? Optional Activity 5.3.3.3

What causes ocean acidification?

A. Deoxygenated ocean water.
B. Ocean pollution.
C. Warm freshwater from land.
D. CO_2 dissolved in ocean water.

Answer

D. CO_2 dissolved in ocean water.

Climate Change Affects Everyone

We have all experienced the effects of climate change over the past decade. However, it is not straightforward for climatologists to make the connection between a warming climate and specific weather events, and most are justifiably reluctant to ascribe any specific event to climate change. In this respect, the best measures of climate change are those that we can detect over several decades, such as the temperature changes shown in Figure **5.3.3.2**, or the sea level rise shown in Figure **5.3.3.7**.

Our lives are connected to the climate**.** Human societies have adapted to the relatively stable climate we have enjoyed since the last ice age which ended several thousand years ago. A warming climate will bring changes that can affect our water supplies, agriculture, power and transportation systems, the natural environment, and even our own health and safety. Carbon dioxide can stay in the atmosphere for nearly a century, on average, so Earth will continue to warm in the coming decades. The warmer it gets, the greater the risk for more severe changes to the climate and Earth's system. Although it is difficult to predict the exact impacts of climate change, what is clear is that the climate we are accustomed to is no longer a reliable guide for what to expect in the future.

Indigenous Connections: Climate Change Vulnerabilities

In 2019, the Tsleil-Waututh Nation published *Understanding Our Community's Climate Change Vulnerabilities: Community Climate Change Resilience Planning | PHASE 1 Summary*. As noted in the report, "Climate change has the potential to profoundly impact the Tsleil-Waututh Nation (TWN) and many key aspects of community life. It influences the ability of our community to harvest some wild foods and medicinal plants, how we access the shoreline and marine waters, and how we connect with Nature. It poses community health risks, influence our ability to practice spiritual and cultural ceremonies, and share cultural teachings. This report serves to build an understanding of community vulnerability to climate change and begins to explore potential climate adaptation actions" (Tsleil-Waututh Nation, 2019).

The project focused on "climate change impacts to Sleil-Waututh, also known as Burrard Inlet IR#3, which is the current village site for the Nation. In the future, TWN hopes to expand the assessment to consider the vulnerability of other areas within its traditional territory" (Tsleil-Waututh Nation, 2019).

Below is a summary of some of what this report details as possible impacts of climate change on the Tsleil-Waututh Nation:

- Coastal flood hazard modeling results showed that most waterfront properties may experience flooding during an extreme flood under a 2 m sea level rise scenario.
- Coastal erosion may affect waterfront properties and natural habitats, and threaten buildings, archeological, and other cultural sites.
- Ocean acidification from climate change poses an acute threat to species (particularly shellfish) along the mudflats and beaches of Burrard Inlet IR#3.
- [Loss of intertidal areas] will have significant impacts on species that live in the intertidal zone (e.g., shellfish) or that forage for food in these areas (e.g., marine birds and salmon). Many of these species are critically important as sources of food for TWN community and cultural health and serve as important opportunities to share traditional teachings (Figure **5.3.3.9**).
- The waters of Burrard Inlet will be increasingly vulnerable to harmful algal blooms as water temperatures rise and summer precipitation decreases.
- Climate change has the potential to make local waters more habitable for invasive non-native species, particularly those from warmer waters.
- Extended periods of extreme heat can cause heat exhaustion or heat stroke, particularly among vulnerable groups.
- Community member health and the opportunity for recreation, cultural practices, and job productivity is also impacted by poor air quality and smoke from wildfires across BC.
- Ongoing changes to air temperatures and precipitation patterns from climate change could increase the success and abundance of some invasive species.



Figure **5.3.3.9**: A keystone species, the ochre sea star (*Pisaster ochraceus*) taken at Ganges Harbour, Salt Spring Island, British Columbia (D. Gordon E. Robertson; CC-BY-SA)

References

Tsleil-Waututh Nation. (2019). *Understanding our community's climate change vulnerabilities: Community climate change resilience planning | Phase 1 summary*. https://twnation.ca/wp-content/uploa...e-Jan-2020.pdf

Video



Learn how climate change will transform British Columbia by 2050 in this 3.5-minute video by CBC's Johanna Wagstaffe. Question after watching: Which of the changes will affect you directly? Which of the changes will affect you indirectly?

Suggested Supplementary Reading

Intergovernmental Panel on Climate Change. 2021. 6th Assessment: Summary for Policymakers.

NASA. 2022. Global Climate Change: Vital Signs of the Planet. This website by NASA provides a multi-media smorgasbord of engaging content. Learn about climate change using data collected by NASA satellites and more.

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- **6.3: The Impact of Climate Change** by John W. Wilson & Richard B. Primack is licensed CC BY 4.0. Original source: https://doi.org/10.11647/OBP.0177.

Unit 5.3.4 - Climate Strategies

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Explain the global efforts to communicate about, and combat, climate change
- Describe the differences between adaptation and mitigation strategies

Introduction

With the increase in understanding that our activities are creating a global crisis of epic proportions, the impacts of climate change are now being actively debated in the corridors of governments and major corporations. Politicians, the media, and others are also increasingly replacing “climate change” with more vivid language, like “climate crisis” and “climate emergency.” This will hopefully encourage even more governments and industries to come to the table and cooperate like never before to address the fundamental drivers of climate change. Solving this global crisis requires an international multi-pronged approach that should include ecosystem protection, restoration, and direct species management, reduction of carbon emissions, sustainable planning, and legislative action.

International Agreements

On the international front, key initiatives related to research and planning are being led by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), which in 1988 established the Intergovernmental Panel on Climate Change (IPCC). The IPCC undertakes comprehensive reviews of the science of global warming, with a focus on likely scenarios of climatic, ecological, and economic consequences. The IPCC also does research on ways to slow or prevent the increases in GHGs and on how economic and ecological systems might adapt to predicted climate change. At the international level, the IPCC is the most credible source of information about climate change.

Because of concerns about the potentially disastrous consequences of global warming, in 1990 the IPCC and other groups of climate specialists recommended that the United Nations (UN) mobilize global leadership to negotiate an international agreement to reduce emissions of GHGs. The UN then established an Intergovernmental Negotiating Committee to draft the terms of a **UN Framework Convention on Climate Change (UNFCCC)**. After a series of difficult international negotiations, the UNFCCC was drafted and then adopted in 1992 at the UN Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil.

The objective of the UNFCCC is to stabilize atmospheric GHGs at concentrations that would prevent a dangerous intensification of the planetary greenhouse effect. Signatory nations to the UNFCCC, known as “parties to the convention,” have agreed to undertake certain actions to compile information on emissions of GHGs, develop policies to decrease emissions, prepare strategies to adapt to anticipated effects of climate change, and provide financial and scientific support to developing countries. Moreover, the 140 countries that signed the UNFCCC in Rio agreed to discuss its implementation at a global forum, which was held in Berlin in 1995. At that meeting, it was agreed that global emissions of GHGs should be reduced and a further series of international negotiations was needed to reach consensus on an implementation strategy. Those negotiations were completed at another meeting, held in Kyoto, Japan, in 1997. The outcome of that key meeting was the **Kyoto Protocol**.

Most years, since 1992, the world's countries have come together to renegotiate and discuss climate change at an UN-organized **Conference of the Parties** (Parties meaning those who signed to the UNFCCC), also known as "COP". As of 2022, COP27 was

held in Egypt celebrating the 30th Anniversary of the ratification of the UNFCCC where attendees from 197 countries met to discuss solutions, financing, and collaboration.

National and Local Action

When Canada ratified the Kyoto Protocol in 2002, it committed to reduce its emissions of CO_2 by 6% below the levels in 1990, and to achieve that goal by 2008-2012. To accomplish such a large reduction was, however, a formidable challenge. In fact, by the target date, Canadian emissions of CO_2 had increased by about 33% since 1990. That had occurred mostly because of rapid economic developments in Alberta, especially great increases in the amount of mining and processing of oil-sands.

Even today, like most other developed countries, Canada has not produced an effective strategy for meeting its legal obligations under the Protocol, largely because of the intense political and economic controversies associated with the actions that would be necessary. Moreover, the governments of Canada and some other jurisdictions, notably Alberta, are focusing on intensity-based targets, which encourage improved technological efficiencies but do not necessarily reduce the aggregate emissions of GHGs. Such tactics do little to reduce the rapid increase of emissions from new fossil-fuel enterprises, such as the aggressively growing oil-sands industry.

To combat climate change, the leadership of many provinces, and cities have started to enact laws to reduce greenhouse gas emissions and habitat destruction. Many industries are also hard at work developing “greener” technologies to enable us to live more sustainably. Communities are coming together to implement solutions that are a best-fit for local environments and economies. Conservation biologists also play a crucial role in mitigating the negative impacts of climate change. In addition to highlighting the plight of the natural world to society at large, we could work towards reducing the loss of ecosystem services and preventing species extinctions. To accomplish this task, we need to identify which species and ecosystems are most sensitive to climate change and develop strategies that will ensure the continued persistence of as many sensitive species and their habitats as possible.

While the situation surrounding global climate change is in serious need of our attention, it is important to realize that many scientists, leaders, and concerned citizens are making solutions to climate change part of their life’s work (Figure **5.3.4.1**). The two solutions to the problems caused by climate change are mitigation and adaptation, and we will likely need a combination of both in order to prosper in the future.



Figure **5.3.4.1**: Young people demand action to protect their futures at the 2021 UN Climate Change Conference, also known as COP26, held in Glasgow, Scotland. Photograph by UNFCCC, https://ukcop26.org/young-people-dem...ures-at-cop26/, Open Government Licence(OGL).

Video

The UN's Sustainable Development Goals (SDGs) outline issues and strategies for the future of humans and natural systems. This 8.5-minute video describes SDG 13, which is focused on Climate Action.
Question after watching: Which of the strategies have you heard of before? Which strategies are new to you? What barriers to change resonate with you? What actions can you take to make change happen?

Climate Mitigation Strategies

In general, a strategy to mitigate climate change is one that reduces the amount of greenhouse gases in the atmosphere or prevents additional emissions. Mitigation strategies attempt to “fix” the problems caused by climate change.

Greenhouse Gas Reduction

There are many options for reducing the adverse impacts to society from CO_2 and other greenhouse gas emissions, such as switching to sources of electricity that do not contribute to the CO_2 problem, trying to generate fossil-based electricity by not releasing the CO_2 into the atmosphere, or exploring ways to reduce the demand for products that produce greenhouse gas emissions. Governmental regulations regarding the fuel efficiency of vehicles is one example of an institutionalized mitigation strategy already in place in many countries around the world.

Putting a price on carbon is the method many economists favor for reducing or controlling greenhouse gas emissions. Pricing carbon provides producers and consumers with a monetary incentive to reduce greenhouse gas emissions by placing a value on each unit of carbon dioxide or carbon dioxide equivalent that is emitted into the atmosphere. In Canada, there are **carbon taxes,** or charges for burning fossil fuels. This is known as the "carbon pollution pricing system" and has been in place since 2019. The federal pricing system has two parts: a regulatory charge on fossil fuels like gasoline and natural gas, known as the **Fuel Charge**, and a performance-based system for industries, known as the **Output-Based Pricing System**. Each province or territory can design its own pricing structure or the region will default to the Canadian government's minimum national stringency standards (known as the Federal Backstop) (Figure 5.3.4.2). Currently, this pricing mechanism is in place for the burning of fossil fuels such as gasoline or natural gas and for industries.

"Proceeds from the federal carbon pricing system remain in the jurisdiction where they were collected. Provinces and territories that requested the federal system receive these proceeds directly and can use them as they see fit. In other jurisdictions, the federal government delivers all proceeds to individuals, families, and businesses through payments and climate action programs. This helps make carbon pricing affordable, and enables households to make investments to increase energy efficiency and further reduce emissions" (Government of Canada, 2022). This type of governmental mitigation strategy has been shown to be effective in many other countries including India, Japan, France, Costa Rica, Canada, and the United Kingdom.



Figure 5.3.4.2: The provinces and territories on the map of Canada are one of three colors depending on whether the federal backstop applies in full, in part or not at all. CC-BY-SA Government of Canada

Carbon Capture and Sequestration

In addition to government measures and incentives, technology can also be harnessed to mitigate climate change. One strategy for this is the use of **carbon capture and sequestration** (CCS). Through CCS, 80-90% of the CO_2 that would have been emitted to the atmosphere from sources such as a coal-fired power plant is instead captured and then stored deep beneath the Earth's surface. The CO_2 is often injected and sequestered hundreds of miles underground into porous rock formations sealed below an impermeable layer, where it is stored permanently.

Scientists are also looking into the use of soils and vegetation for carbon storage potential. Proper management of soil and forest ecosystems has been shown to create additional carbon sinks for atmospheric carbon, reducing the overall atmospheric CO_2 burden. Increasing soil carbon further benefits communities by providing better-quality soil for agriculture and cultivation.

Technologies related to alternative energy sources mitigate climate change by providing people with energy not derived from the combustion of fossil fuels. Finally, simple activities such as energy conservation, choosing to walk or bike instead of driving, and disposing of waste properly are activities that, when done by large numbers of people, actively mitigate climate change by preventing carbon emissions.

Video



This 2-minute video describes using natural and artificial carbon sinks to help mitigate climate change but notes that these do not solve it.

Question after watching: What is the ultimate solution to mitigating climate change?

Optional Activity 5.3.4.1

Why are forests important for mitigating climate change?

A. Forests serve as a sink in the carbon cycle.
B. Trees provide building materials.
C. Trees are an important food source.
D. Leaves of trees reflect all sunlight away from the Earth.

Answer

A. Forests serve as a sink in the carbon cycle.

Climate Adaptation Strategies

Beyond mitigation, we know that climate change is already occurring as we can see and feel its effects. For this reason, it is essential to also adapt to our changing environment. This means that we must change our behaviors in response to the changing environment around us. Adaptation strategies will vary greatly by region, depending on the largest specific impacts in that area. For example, in the city of Delhi, India, a dramatic decrease in rainfall is projected over the next century. This city will likely need to

implement policies and practices relating to the conservation of water like rainwater harvesting, water re-use, and increased irrigation efficiency. Rain-limited cities near oceans, such as Los Angeles, California may choose to use desalination to provide drinking water to their citizens. **Desalination** involves taking the salt out of seawater to make it potable. Cities with low elevations near oceans may need to implement adaptation strategies to rising sea levels, from seawalls and levees to relocation of citizens. One adaptation strategy gaining use is the creation or conservation of wetlands, which provide natural protection against storm surges and flooding.

The IPCC 6th Assessment Report (2022) outlines just some of the following global strategies for adaptation to climate change:

- Sustainable land use and urban planning
- Water use efficiency and water resource management
- Integrated coastal zone management
- Resilient power systems
- Health and health systems adaptation
- Planned relocation and resettlement
- Disaster risk management
- Climate services, including Early Warning Systems

Want to know more? Visit this site for short courses on Climate Change Adaptation Fundamentals: https://pcs.royalroads.ca/climate-change-adaptation-fundamentals-online

Indigenous Connections: Climate Action

As stated by the British Columbia Assembly of First Nations (n.d.):

> First Nations are seriously threatened by the climate emergency but are also essential drivers of effective climate change action. Indigenous ecological knowledge, authority, and deep responsibilities to traditional lands and waters are critical to achieving world targets for greenhouse gas emission reductions and developing effective climate adaptation strategies.
>
> The BC Assembly of First Nations (BCAFN), as part of the First Nations Leadership Council (FNLC), strongly advocates for First Nations in BC to be true partners with the Provincial and Federal Governments to tackle the climate emergency. This approach is consistent with the *UN Declaration on the Rights of Indigenous Peoples* and respectful of First Nations' inherent Aboriginal Title, Rights, and Treaty Rights.
>
> In recognition of the climate emergency, the Union of BC Indian Chiefs (UBCIC) Chiefs Council and the BCAFN Chiefs-in-Assembly have passed resolutions mandating that the FNLC take action to respond to climate change. In addition to previous resolutions, the UBCIC passed Resolution no. 2019-02, known as the *Climate Emergency and BC First Nations Climate Emergency Plan* (Union of British Columbia Indian Chiefs, 2019), and the BCAFN passed Resolution no. 04/2019, known as the *Climate Emergency and Support for the Development of a BC First Nations Climate Change Strategy* (British Columbia Assembly of First Nations, 2019).
>
> Since 2019, the FNLC has worked with First Nations in BC to develop the *BC First Nations Climate Strategy and Action Plan* (First Nations Leadership Council, 2022a), endorsed by Chiefs in February and March of 2022.
>
> The Strategy is designed to be a living and flexible document for use and implementation in different contexts. It is a means for collective advocacy on climate change while respecting the autonomy and self-determination of each Nation to address climate change on their own terms and through their own processes.

Below are just some of the adaptation measures included in the *BC First Nations Climate Strategy and Action Plan* (First Nations Leadership Council, 2022a):

- Ensuring long-term and stable climate funding for First Nations communities. Specifically, by establishing a BC First Nations Climate Fund.
- Implementing effective climate data governance and management systems within and between Indigenous communities broadly.

- Ensuring mechanisms are in place to restore the lands, waters, and ecosystems that have been impacted by human activity and climate change. This involves strengthening First Nation-led conservation efforts and implementing accountability measures for environmentally impactful human actions.
- Effectively responding to climate-related emergencies and associated risks and impacts by strengthening First Nation-led emergency management and preparedness mechanisms and increasing collaboration between relevant entities.
- Assessing impacts of climate change on First Nations health and wellness and developing appropriate responses to ensure long-term resiliency. As an immediate action, this involves ensuring that all First Nations have long-term and reliable access to safe and clean food and water sources.

The Executive Summary of the plan (First Nations Leadership Council, 2022b) is also available for a succinct overview.

References

British Columbia Assembly of First Nations. (n.d.). *Climate emergency*. https://www.bcafn.ca/priority-areas/...mate-emergency

British Columbia Assembly of First Nations. (2019, March). *Special chiefs assembly: Resolution 04/2019*. https://www.bcafn.ca/sites/default/f...geStrategy.pdf

First Nations Leadership Council. (2022a). *BC First Nations climate strategy and action plan*. https://fnlcclimatestrategy.ca/wp-co...NCSAP_2022.pdf

First Nations Leadership Council. (2022b). *BC First Nations climate strategy and action plan: Executive summary (excerpt)*. https://www.bcafn.ca/sites/default/f...mmary%20v2.pdf

Union of British Columbia Indian Chiefs. (2019, February). *Chiefs council: Final resolutions*. https://assets.nationbuilder.com/ubc...pdf?1552433595



BC's climate is changing, and Indigenous peoples are taking action to help their communities prepare and adapt to these impacts. In this 5-minute video, some actions are highlighted, such as helping the Klinse-Za caribou thrive in a new environment, adapting traditional food systems at T'eqt''aqutn'mux, and Fort Nelson First Nation returning to fish camp. Question after watching: Which of the adaptation measures listed above did you see in the video?

If we are to mitigate and adapt to the far-reaching impacts of climate change, we must carefully monitor and study changes in biological communities and ecosystem functioning, and how they relate to changes in climate and other stressors. While we may lose some species in a warmer world, we can also prevent many extinctions with proactive wildlife management (Unit 5.2.4). It is likely that many existing protected areas will no longer preserve some of the rare and threatened species that currently live in them, necessitating careful planning when establishing new protected areas. Even if climate change is not as severe as predicted, the steps we take now to safeguard biodiversity and our own future can only help.

Read these additional articles:

- Individual actions (via EPA)
- UN's 2022 Conference of the Parties 27th Annual Meeting (COP 27)
- 10 Solutions to Climate Change (Scientific American)

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SECTION OVERVIEW

5.4: Sustainability

Learning Objectives

- Define sustainability and the sustainability paradigm
- Describe the historical development of the sustainability paradigm
- Describe how ethics and moral extensionism connect to sustainability
- Understand that true sustainability promotes environmental equity and justice, thus eliminating environmental racism
- Describe the evolution of ethics leading to the modern environmental ethic
- Understand how environmental policy has changed based on movements and need
- Describe how sustainable lifestyle choices influence sustainability

Video



In this 7-minute animated video, a simple definition of sustainability is presented based on science and natural cycles, in addition to the four root causes of un-sustainability (the 4 things we need to stop doing in order to become sustainable). Question after watching: Which of these concepts are review from the previous 5 Units? Which are new?

5.4.1: Introduction to Sustainability

5.4.2: Sustainability Ethics and Environmental Justice

5.4.3: Environmental Policy, Monitoring, and Impact Assessments

5.4.4: Sustainability and the Future

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Unit 5.4.1 - Introduction to Sustainability

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.4.2, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Define sustainability and the sustainability paradigm
- Describe the historic events that lead to the sustainability paradigm
- Explain the three pillars of sustainability
- Identify trade-offs in traditional economic development
- Describe the importance of the seventeen Sustainable Development Goals from the UN

Introduction

Of all the different forms of life that have inhabited the Earth in its three to four-billion-year history, 99.9% are now extinct. Against this backdrop, humans, with our roughly 200,000-year history, barely merit attention. But while modern humans (*Homo sapiens*) might be insignificant in geologic time, we are by no means insignificant in terms of our recent planetary impact. A 1986 study estimated that 40% of the product of terrestrial plant photosynthesis — the basis of the food chain for most life — was being appropriated by humans for their use. More recent studies estimate that 25% of photosynthesis on continental shelves (coastal areas) is ultimately being used to satisfy human demand. Human appropriation of such natural resources is having a profound impact on the wide diversity of other species that also depend on them (Unit 5.2 and Unit 5.3).

In the past, evolution has resulted in new lifeforms at a faster rate than the extinction of other species, resulting in strong biological diversity (Unit 2 and Unit 3.4). However, scientists have evidence that, for the first *observable* time in evolutionary history, another species — *Homo sapiens* — has upset this balance to the degree that the rate of species extinction is now estimated at 10,000 times the background extinction rate, on par with other mass extinction events of the past. Human beings, just one species among millions, are crowding out most species. Evidence of human interference with the natural world is visible in every ecosystem from the presence of pollutants in the stratosphere to the artificially changed courses of the majority of river systems on the planet. All organisms impact their environment to a degree but the rate, scale, and nature of human-induced global change — particularly in the post-industrial period — is unprecedented in the history of life on Earth.

Review of Human-Induced Global Change

1. Mechanization of both industry and agriculture in the last three hundred years has resulted in vastly improved productivity, which led to an explosion in the amount and types of goods and services. Scientific advances and technological innovations, powered by ever-increasing inputs of fossil fuels and their by-products, have revolutionized every industry and created many new ones. The development of resource-intensive consumer cultures and disposable-centric lifestyles has generated waste at an unprecedented scale. Humans are now responsible for moving more matter across the planet than all natural occurrences (earthquakes, storms, etc.) put together.
2. While the rate of human population growth has been plateauing, the human population is still increasing: every year humans add nearly 100 million people to the planet. The environmental impact varies significantly between countries (and within them). However, the exponential growth of humans, coupled with the ideas in the first point, bring the issue of distribution to prominence. Global inequalities in resource consumption and purchasing power mark the clearest dividing line between the rich and the poor. Present patterns of production and consumption are unsustainable for a global population projected to reach 11

billion by the year 2050. If ecological crises and rising social conflict are to be countered, present rates of over-consumption by a rich minority, and under-consumption by a large majority, need to be brought into balance.

3. It is not only the rate and the scale of change but the nature of that change that is unprecedented. Humans have introduced chemicals and materials into the environment that do not occur naturally OR do not occur in the ratios in which we have introduced them. Persistent pollutants are believed to be causing alterations in the environment, the effects of which are only slowly manifesting themselves, and the full scale of which is currently beyond calculation. Chlorofluorocarbons (CFCs) and polychlorinated biphenyls (PCBs) are two examples of the approximately 100,000 human-derived chemicals currently in global circulation (between 500 and 1,000 new chemicals are being added to this list annually). Most of these chemicals have not been tested for their toxicity on humans and/or natural systems, let alone tested for their effects in combination with other chemicals. These issues are now the subject of special UN and other intergovernmental working groups.

Video



In this 5.5-minute Ted-Ed, discover how human impacts have become so pervasive, profound, and permanent that some geologists believe we merit our own epoch.
Question after watching: Explain how, to some degree, humans have created a homogenous world.

Sustainability as a Concept

Our Common Future (1987), also known as the Brundtland Report, by the UN's World Commission on Environment and Development, is widely credited with having popularized the concept of **sustainability.** Sustainability is derived from two Latin words: *sus* which means up, and *tenere* which means to hold. Thus, sustainability is about maintaining human existence by meeting the needs of the present without compromising the ability of future generations to meet their needs. Sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the orientation of technological development, and institutional change are made consistent with future, as well as present, needs.

The concept of sustainability, however, can be traced back much further to the oral histories of Indigenous cultures. For a species that at present is only 6,000 generations old and whose current political decision-makers operate on time scales of months or a few years, the thought that other human cultures have based their decision-making systems on time scales of many decades seems wise.

Video



This 7-minute video profiles how Indigenous peoples are reviving traditional stewardship in the temperate rainforests of Clayoquot Sound, BC.

Question after watching: How do the Guardian programs help to maintain the health of the ecosystems and humans in the region?

It is not uncommon to think of sustainability as being a recent interpretation of environmental policy, one that was given credence by the Brundtland Report. However, sustainability did not suddenly come into being at a single moment in time. Most environmental historians who have studied policy have discerned at least three distinct periods of the modern era during which new concepts and ideas, scientific understandings, technological advances, political institutions, and laws and regulations came or were brought into being in order to understand and manage human impacts on the environment.

History of Environmental Movements

1. **The conservation movement:** This 19th-century movement's main objective was the conservation of land and resources and it grew out of opposite philosophies. On one side, those like Gifford Pinchot (first head of the USA's National Forest Service) were very pragmatic about their desire for conservation. For example, conservationists observed that policies for harvesting some resources (like lumber) were not sustainable, so they began sustainability research and new policies so the resources would not run out in the foreseeable future. On the other side were people like John Muir and Theodore Roosevelt that saw land/habitats/wildlife as intrinsic entities, meaning that they had value in their own right, separate from economic value.
2. **Environmental scientists became alarmed by the extent and degree of damage that was being documented:** The publication of *Silent Spring* in 1962 by Rachel Carson (1907-1964), about the impact of the widespread and indiscriminate use of pesticides, was a watershed moment, bringing environmental concerns to the forefront of policy discussions. Carson collected evidence on the effects of pesticides, particularly dichlorodiphenyltrichloroethane (DDT), heptachlor, and dieldrin, on humans, mammals, and birds, and the systemic disruption they caused to ecosystems. *Silent Spring* is credited with bringing about a ban on the use of DDT in many countries. It also set in motion a chain of events that would ultimately result in the transformation of environmental public policy from one based on the problems and attitudes based in 19th-century conservation, to one based on the management of risks from chemical toxins.
3. **The rise of environmental risk management as a basis for policy:** The beginnings of environmental risk management can be traced to the spread of disease, a particularly troublesome problem as the country continued to urbanize in the latter decades of the 19th-century and beginning of the 20th.
4. **The integration of social and economic factors into the sustainability paradigm:** Eventually, humanity realized that in order to solve environmental issues, human social and economic factors had to be accounted for. This is what defines the sustainability paradigm: environmental, social, and economic disciplines. Only superficial solutions can be applied if we only take a one-minded approach.

Video



This 4-minute video explores how, through a change in perspective, we can re-design the way our economy works: designing products that can be 'made to be made again' and powering the system with renewable energy.
Question after watching: This process is known as a 'circular economy'. Why do you think it is named this?

Indigenous Connections: UNDRIP

As noted by the United Nations Human Rights Office (n.d.):

> The High Commissioner for Human Rights welcomed the adoption of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) by the General Assembly on 13 September 2007, as a triumph for justice and human dignity following more than two decades of negotiations between governments and Indigenous peoples' representatives.
>
> It was adopted with 144 votes in favour, 11 abstentions, and four States against (Australia, Canada, New Zealand, and the United States of America). Since then, a number of States have changed their position, including the four which voted against but have now endorsed the Declaration.
>
> The Declaration is the most comprehensive instrument detailing the rights of Indigenous peoples in international law and policy, containing minimum standards for the recognition, protection and promotion of these rights. It establishes a universal framework of minimum standards for the survival, dignity, wellbeing and rights of the world's Indigenous peoples.
>
> The Declaration addresses both individual and collective rights; cultural rights and identity; rights to education, health, employment, language, and others. It outlaws discrimination against Indigenous peoples and promotes their full and effective participation in all matters that concern them. It also ensures their right to remain distinct and to pursue their own priorities in economic, social and cultural development. The Declaration explicitly encourages harmonious and cooperative relations between States and Indigenous peoples.

Included in the Declaration by the Office of the United Nations High Commissioner for Human Rights (2008) are articles expressing the rights of Indigenous peoples to practice sustainability as they see fit:

- Article 25:
  - Indigenous peoples have the right to maintain and strengthen their distinctive spiritual relationship with their traditionally owned or otherwise occupied and used lands, territories, waters and coastal seas and other resources and to uphold their responsibilities to future generations in this regard.
- Article 29:
  - Indigenous peoples have the right to the conservation and protection of the environment and the productive capacity of their lands or territories and resources. States shall establish and implement assistance programmes for Indigenous peoples for such conservation and protection, without discrimination.

- States shall take effective measures to ensure that no storage or disposal of hazardous materials shall take place in the lands or territories of Indigenous peoples without their free, prior and informed consent.
- States shall also take effective measures to ensure, as needed, that programmes for monitoring, maintaining and restoring the health of Indigenous peoples, as developed and implemented by the peoples affected by such materials, are duly implemented.

- Article 31:
  - Indigenous peoples have the right to maintain, control, protect and develop their cultural heritage, traditional knowledge and traditional cultural expressions, as well as the manifestations of their sciences, technologies and cultures, including human and genetic resources, seeds, medicines, knowledge of the properties of fauna and flora, oral traditions, literatures, designs, sports and traditional games and visual and performing arts. They also have the right to maintain, control, protect and develop their intellectual property over such cultural heritage, traditional knowledge, and traditional cultural expressions.
  - In conjunction with Indigenous peoples, States shall take effective measures to recognize and protect the exercise of these rights.
- Article 32:
  - Indigenous peoples have the right to determine and develop priorities and strategies for the development or use of their lands or territories and other resources.
  - States shall consult and cooperate in good faith with the Indigenous peoples concerned through their own representative institutions in order to obtain their free and informed consent prior to the approval of any project affecting their lands or territories and other resources, particularly in connection with the development, utilization or exploitation of mineral, water or other resources.
  - States shall provide effective mechanisms for just and fair redress for any such activities, and appropriate measures shall be taken to mitigate adverse environmental, economic, social, cultural or spiritual impact.

References

Office of the United Nations High Commissioner for Human Rights. (2008). *United Nations declaration on the rights of Indigenous peoples*. https://www.ohchr.org/sites/default/files/Documents/Publications/Declaration_indigenous_en.pdf

United Nations Human Rights Office. (n.d.). *UN declaration on the rights of Indigenous peoples*. https://www.ohchr.org/en/indigenous-peoples/un-declaration-rights-indigenous-peoples

The Three Pillars of Sustainability

As mentioned above, there are three pillars, or dimensions, that sustainability seeks to integrate: economic, environmental, and social (including sociopolitical).

- *Economic interests* define the framework for making decisions, the flow of money, and the facilitation of commerce, including the knowledge, skills, competencies, and other attributes embodied in individuals that are relevant to economic activity.
- *Environmental aspects* recognize the diversity and interdependence within living systems, the goods and services produced by the world's ecosystems, and the impacts of anthropogenic wastes.
- *Social/Socio-political dimension* refers to interactions between institutions/firms and people, functions expressive of human values, aspirations, well-being, ethical issues, and decision-making that depends upon collective action.

The intersection of social and economic elements can form the basis of social "equitability". In the sense of enlightened management, "viability" is formed through consideration of economic and environmental interests. Between environment and social elements lies "bearability", the recognition that the functioning of societies is dependent on environmental resources and services. At the intersection of all three of these lies sustainability (Figure **5.4.1.1**).



Figure 5.4.1.1: Venn diagram of defining the components of sustainability. Based on “sustainable development” from Wikimedia.org CC-BY.Adapted from United Nations (1987), International Union for Conservation of Nature (IUCN) (2005), Makkar (2013), and Makkar and Ankers (2014).

Trade-Offs

The three main elements of the sustainability Venn diagram above are thought of as equally important. However, tradeoffs occur depending on the local/global objective. For example, it may be deemed necessary to degrade a particular ecosystem in order to facilitate the economy, food production, or housing. In reality, the extent to which tradeoffs can be made before irreversible damage results is not always known. This has led to the notion of '**strong sustainability**', where tradeoffs among natural, human, and social capital are not allowed or are very restricted, and '**weak sustainability**', where tradeoffs are unrestricted or have few limits. Whether or not one follows the strong or weak form of sustainability, it is important to understand that while economic and social systems are human creations, the environment is not. Rather, a functioning environment underpins both society and the economy.

Sustainable development is the progress made toward an economic system that is ultimately based on the wise use of renewable resources. Therefore, a sustainable economy would not deplete its capital of natural resources, and so would not compromise the availability of those necessities for use by future generations of humans. Ecologically-focused sustainable development would allow humans to thrive, but without causing unacceptable damage to other species or natural ecosystems.

By the criteria above, developed economies (such as that of Canada, the United States, countries of Western Europe, Japan, and Australia) are currently unsustainable. There are two major reasons for this conclusion:

1. The continued push of politicians, economists, and other managers of national and international economies for rapid economic growth (both to keep up with an expanding population and to increase the standard of living).
2. The likelihood that the present size of advanced economies is already too large to be sustained for long.

The rationale for these two statements is briefly explained in the following paragraphs.

Economic growth is achieved by pushing both non-renewable and potentially renewable resources through an economy, thereby making the economy larger. Rapid economic growth can be achieved only as long as resources continue to be readily available. However, most non-renewable and potentially renewable resources are rapidly being depleted. Moreover, many scientists and environmentalists believe that the present sizes of advanced economies (such as that of Canada) are already too large to be sustained.

It is common for politicians, corporations, and resource managers to assert that they support sustainability efforts. However, most of them are confusing genuine sustainable development, as it was defined earlier, with “sustainable economic growth.” On a resource-constrained Earth, unlimited economic growth can never be sustained over the long term. Ecologists and environmental economists believe that further growth is undesirable. It is better to limit the economies to a level that can be supported by Earth’s biosphere and resources over the longer term. Fundamental considerations in a sustainable human economy are:

- the number of people that must be supported
- the total intensity of their resource use
- the equitability of standards of living among the world's peoples
- and the environmental damage that is caused

In part, the resolution of resource dilemmas will require a more equitable sharing of wealth among people living in poorer and richer countries. This would moderate the importance of poverty as a key factor in causing environmental degradation.

United Nations' 17 Sustainable Development Goals

A Brief History of the SDGs

"The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests."

- In January 2015, the General Assembly began the negotiation process, culminating in the subsequent adoption of the 2030 Agenda for Sustainable Development, with 17 SDGs at its core, at the UN Sustainable Development Summit in September 2015.
- 2015 was a landmark year for multilateralism and international policy shaping, with the adoption of several major agreements:
  - Sendai Framework for Disaster Risk Reduction (March 2015)
  - Addis Ababa Action Agenda on Financing for Development (July 2015)
  - Transforming our world: the 2030 Agenda for Sustainable Development with its 17 SDGs was adopted at the UN Sustainable Development Summit in New York in September 2015.
  - Paris Agreement on Climate Change (December 2015)
- Now, the annual High-level Political Forum on Sustainable Development serves as the central UN platform for the follow-up and review of the SDGs.

Today, the Division for Sustainable Development Goals (DSDG) in the United Nations Department of Economic and Social Affairs (UNDESA) provides substantive support and capacity-building for the SDGs and their related thematic issues, including water, energy, climate, oceans, urbanization, transport, science and technology, the Global Sustainable Development Report (GSDR), partnerships and Small Island Developing States. DSDG plays a key role in the evaluation of UN systemwide implementation of the 2030 Agenda and on advocacy and outreach activities relating to the SDGs. In order to make the 2030 Agenda a reality, broad ownership of the SDGs must translate into a strong commitment by all stakeholders to implement the global goals. DSDG aims to help facilitate this engagement." (UN, 2022)

Reference: United Nations, 2022. "The 17 Goals: History". New York, New York. Available From: https://sdgs.un.org/goals#history



This 3.5-minute video profiles the seventeen goals that 193 United Nations member states unanimously adopted to achieve by 2030. These are known as the Sustainable Development Goals (SDGs).
Question after watching: Describe ways in which these goals overlap and tie into one another.

Video



In this first 14-minute video from social progress expert Michael Green in 2015, Green invites us to imagine how the UN's Sustainable Development Goals (SDGs) and their vision for a better world can be achieved.
Question after watching: What are some of the trade-offs from progression towards the goals? What were some of the positive signs?

Video



A simple 3.5-minute introduction to sustainable development and the Sustainable Development Goals (SDGs).
Question after watching: Which concepts in this video are review from the textbook? Which are new?

Video



Discover what a sustainable, universally beneficial economy might look like in this 15-minute video.
Question after watching: What ecological limits are taken into account in this model?

Sustainability in Practice

Cities in the 21st century now hold most of the world's population. Sustainable cities are key to balancing a sustainable society, economy, and environment. According to a 2017 report that rated sustainability across 32 indicators, Zurich, Switzerland, was ranked number one. Zurich invests in renewable energies, sustainable public transport, public green space, and public education. One of the most notable ways Zurich is leading global sustainability efforts is its dedication to keeping its carbon dioxide emissions low. Figure **5.4.1.2** below shows the difference in emissions for Canada and Switzerland.

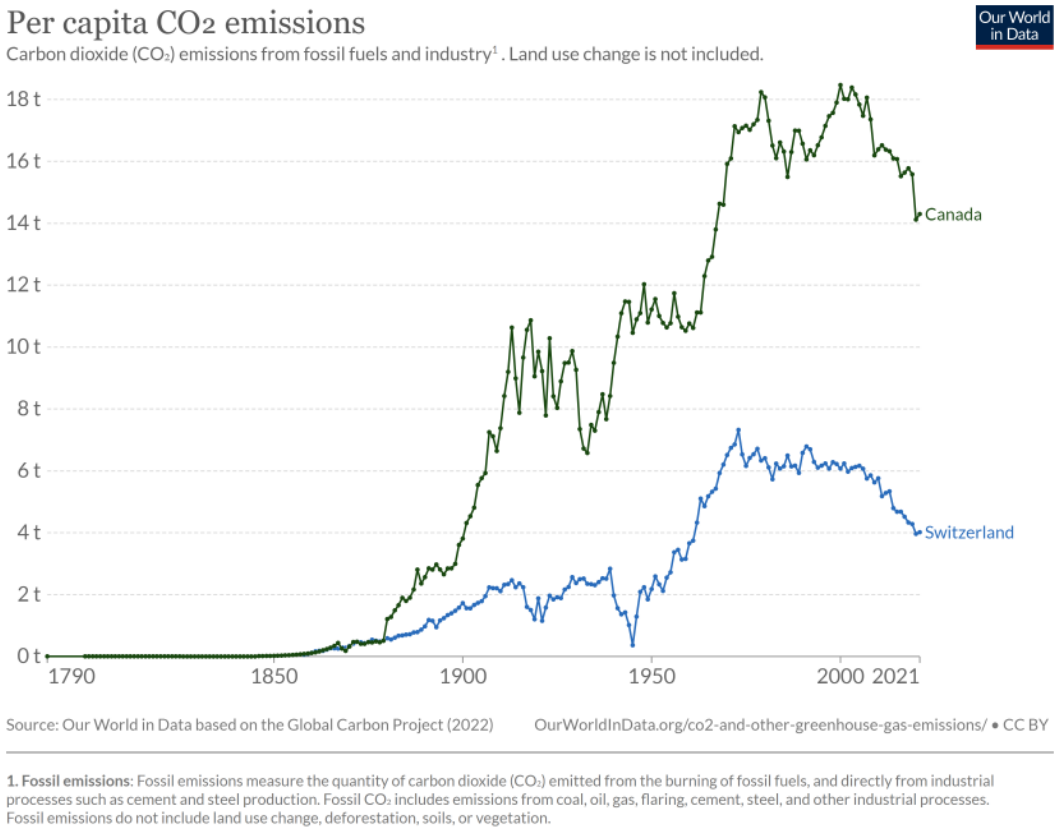


Figure 5.4.1.2: Per capita emissions of carbon dioxide between Canada and Switzerland. Graph by Our World in Data (CC-BY4.0)

Video



More than half of the world's population already lives in cities, and another 2.5 billion people are projected to move to urban areas by 2050. In this 14-minute video, learn how the way we build new cities will be at the heart of so much that matters, from climate change to economic vitality to our very well-being and sense of connectedness.
Question after watching: What are the seven universal principles for sustainable cities?

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Unit 5.4.2 - Sustainability Ethics and Environmental Justice

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.4.3, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe how ethics and moral extensionism connect to sustainability
- Explain how true sustainability promotes environmental equity and justice
- Describe the development of the modern environmental ethic
- Identify some of the historical and current perspectives of Indigenous peoples and sustainability

Introduction

Sustainability can be a difficult concept when applied. It dictates that we are constrained by Earth's resources as to the society and lifestyle we can have. On the other hand, sustainability is also a wonderful, inspiring concept and a quintessentially human idea. The experience of our own limits need not be negative. In fact, sustainability is driven by an ethics of the future. To be sustainable is, by definition, to be attentive to what is to come and so it requires imagination. Sustainability teaches that the environment is not a sideshow or a scenic backdrop to our lives. Our relation to our natural resources is the key to our survival. It is the grounds of possibility for everything else. Unsustainability, conversely, means human possibilities and quality of life are increasingly taken away from us and the generations to come.

Precautionary Principle, Sustainability, and Ethics

The **precautionary principle** is an important concept in environmental sustainability. A 1998 consensus statement characterized the precautionary principle this way: "when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically". For example, if a new pesticide chemical is created, the precautionary principle would dictate that we presume, for the sake of safety, that the chemical may have potentially negative consequences for the environment and/or human health, even if such consequences have not been proven yet. In other words, it is best to proceed cautiously in the face of incomplete knowledge about something's potential harm.

The margins of uncertainty are large across many fields of the biophysical sciences. Simply put, there is a great deal we do not know about the specific impacts of human activities on the natural resources of land, air, and water, and we know even less about combining activities. In general, however, though we might not have known where the breakdown in a given natural system may lie, the vulnerability of ecosystems to human resource extraction is a constant lesson of environmental history (Unit 5.2). The precautionary principle underlying sustainability dictates that in the face of high risk or insufficient data, the priority should lie with ecosystem preservation rather than on economic growth or individual interests.

Environmental Ethics

The concept of **ethics** involves standards of conduct. These standards help to distinguish between behavior that is considered by society to be 'right' and that which is considered 'wrong'. It is not always easy to distinguish between right and wrong, as there is no universal human code of ethics. For example, a poor farmer clears an area of rainforest in order to grow crops. Some would not oppose this action, because the act allows the farmer to provide a livelihood for his family. Others would oppose the action, claiming that deforestation will contribute to soil erosion and climate change. Right and wrong are usually determined by an individual's morals, and to change the ethics of an entire society, it is necessary to change the individual ethics of a majority of the people in that society.

Moral extensionism defines how far a person's values extend outside of themselves. There are many variables that can influence where the limit lies for each individual person. For example, religion, culture, education, and personal interests, among others, all impact how an individual makes moral judgments. Moral extensionism can be applied to the environment in action and intent. The ways in which humans interact with the land and its natural resources are determined by ethical attitudes and behaviors. The following are major ethical perspectives regarding the natural world.

Frontier Ethic

Early European settlers in North America rapidly consumed the natural resources of the land. After they depleted one area, they moved westward to new frontiers. Their attitude towards the land was that of a **frontier ethic**. A frontier ethic assumes that the Earth has an unlimited supply of resources. If resources run out in one area, more can be found elsewhere, or alternatively, human ingenuity will find substitutes. This attitude sees humans as masters who manage the planet. The frontier ethic is completely utilitarian and anthropocentric as only the needs of humans are considered.

Most industrialized societies view population and economic growth through this frontier ethic lens, assuming that infinite resources exist to support continued growth indefinitely. In fact, economic growth is usually considered a measure of how well a society is doing. Now that the human population has passed eight billion and few frontiers are left, many are beginning to question the frontier ethic. Such people are moving toward an **environmental ethic**, which includes humans as part of the natural community rather than managers of it. Such an ethic places limits on human activities (e.g., uncontrolled resource use), that may adversely affect the natural world.

Some still subscribing to the frontier ethic suggest that outer space may be the new frontier: we can simply populate other planets if Earth's resources run out. This seems an unlikely solution, as even the most aggressive colonization plan would be incapable of transferring people to extraterrestrial colonies at a significant rate. Natural population growth on Earth would outpace the colonization effort. A more likely scenario would be that space could provide the resources (e.g. from asteroid mining) that might help to sustain human existence on Earth.

Sustainable Ethic

A **sustainable ethic** is an environmental ethic by which people treat the Earth as if its resources are limited. This ethic assumes that the Earth’s resources are not unlimited and that humans must use and conserve resources in a manner that allows their continued use in the future. A sustainable ethic also assumes that humans are a part of the natural environment and that we suffer when the health of a natural ecosystem is impaired. A sustainable ethic includes the following tenets:

- The Earth has a limited supply of resources.
- Humans must conserve resources.
- Humans share the Earth’s resources with other living things.
- Growth is not sustainable.
- Humans are a part of nature.
- Humans are affected by natural laws.
- Humans succeed best when they maintain the integrity of natural processes and cooperate with nature.

For example, if a fuel shortage occurs, how can the problem be solved in a way that is consistent with a sustainable ethic? The solutions might include finding new ways to conserve oil or developing renewable energy alternatives. A sustainable ethic attitude in the face of such a problem would be that if drilling for oil damages the ecosystem, then that damage will affect the human population as well. This ethic can be either anthropocentric or biocentric (life-centered). An advocate for conserving oil resources may consider all oil resources as the property of humans. Using oil resources wisely so that future generations have access to them is an attitude consistent with an **anthropocentric ethic**. Using resources wisely to prevent ecological damage is in accord with a **biocentric ethic**.

Land Ethic

Aldo Leopold, an American wildlife natural historian and philosopher, advocated a biocentric ethic in his book, *A Sand County Almanac*. He suggested that humans had always considered land as property. He believed that mistreatment of land makes little economic or moral sense. All humans are merely one component of an ethical framework. Leopold suggested that land be included in an ethical framework, calling this the land ethic.

“The **land ethic** simply enlarges the boundary of the community to include soils, waters, plants and animals; or collectively, the land. In short, a land ethic changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of it. It implies respect for his fellow members, and also respect for the community as such.” (Aldo Leopold, 1949)

Leopold divided conservationists into two groups: one group that regards the soil as a commodity and the other that regards the land as biota, with a broad interpretation of its function. If we apply this idea to the field of forestry, the first group of conservationists would grow trees like cabbages, while the second group would strive to maintain a natural ecosystem. Leopold maintained that the conservation movement must be based upon more than just economic necessity. Species with no discernible economic value to humans may be an integral part of a functioning ecosystem. The land ethic respects all parts of the natural world regardless of their utility, and decisions based upon that ethic result in more stable biological communities.

“Anything is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it tends to do otherwise.” (Aldo Leopold, 1949)

Environmental Equity

Environmental equity describes a society and culture in which no single group or community faces disadvantages in dealing with environmental hazards, disasters, or pollution. While much progress is being made to improve resource efficiency, far less progress has been made to improve resource distribution. Currently, 20% of the global population is consuming 80% of the Earth’s resources.

If the poorest 80% of the world's population were to exercise their right to the same standard of living as the richest 20%, it would result in ecological devastation. To date, global income inequalities and lack of purchasing power have prevented developing countries from reaching the standard of living (and also resource consumption/waste emission) of developed countries. However, countries such as China, Brazil, India, Indonesia, and Malaysia are catching up fast.

In such a situation, global consumption of resources and energy needs to be drastically reduced in developed countries to a point where future generations can have access to those same resources. But who is willing to make those changes? The economies of developed countries demand ever-greater consumption-based expansion. Such stalemates have prevented any meaningful progress toward equitable and sustainable resource distribution at the international level. These issues of fairness and distributional justice remain unresolved.

Video



This 2.5-minute video describes SDG 10, which aims to reduce inequality within and among countries by 2030. Question after watching: While each SDG targets specific issues, many of the goals are intertwined. In what ways can achieving other SDGs reduce inequalities?

Environmental Justice

Environmental Justice is defined as the fair treatment and meaningful involvement of all people regardless of race, color, ability, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. It will be achieved when everyone enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment in which to live, learn, and work.

Video



The disproportionate exposure to environmental hazards has long had a larger impact on Indigenous, Black, and other marginalized communities in Canada, as indicated in this 2.5-minute video. A 2021 private members bill is calling for a national strategy to address and track instances of environmental racism.
Question after watching: What would this bill do to help those currently impacted by environmental racism?

In one of the most flagrant cases of environmental injustice in the last decade in a developed country, the city of Flint, Michigan in the United States decided to save money by drawing water for residents from the Flint River in 2014. Soon after, residents complained about the taste, smell, and color of the water. Scientific studies determined that there was a failure to apply corrosion inhibitors to the water, resulting in lead from aging pipes leaching into the water supply, exposing around 100,000 mostly poor residents of color to elevated lead levels. Although the city switched back to its original water source, the damage was already done. Not only did this crisis expose so many to lead, especially concerning for children, but most pipes also needed to be replaced as they were no longer safe to use (Figure **5.4.2.1**). In 2017, a settlement was reached to replace all the pipes totaling $87 million USD. However, in 2021 the project had still not been completed. Citywide lead levels have tested within the safe range for consumption, though many houses considered high risk do continue to show elevated levels.



Figure 5.4.2.1: Flint residents trying to bring awareness of Flint Water Crisis through peaceful demonstration. Image by Shannon Nobles, Wikimedia Commons (CC-BY-SA-4.0).

Environmental Racism

Environmental racism was coined in the 1980s to describe the practice of siting hazardous waste sites in minority neighborhoods. In recent decades it has come to describe more fully the institutional racism that exists for marginalized communities in many developed countries regarding landfills, incinerators, waste sites, and industry in neighborhoods. It also describes the long-standing impacts on Indigenous communities and, on an international level, the extractive nature of relationships of developed countries in developing countries.

In an ideal world, there would be no hazardous waste to plague this planet. Unfortunately, we live in a world with rampant pollution, dumping of hazardous wastes, and people with "living for the now" attitudes. Our industrialized society has necessarily produced waste during the manufacture of products for our basic needs. Until technology can find a way to manage (or eliminate) hazardous waste, disposal facilities will be necessary to protect both humans and the environment. By the same token, this problem must be addressed. Industry and society must keep the health and wellness of all of their community in the selection of future hazardous waste sites. All humans who help produce hazardous wastes must share the burden of dealing with those wastes, not just the historically marginalized.

Indigenous People

Since the end of the 15th century, most of the world's frontiers have been claimed and colonized by nation-states. Invariably, these conquered frontiers were already home to Indigenous peoples. Some were wiped out or assimilated by the invaders, while others survived while trying to maintain their unique cultures and way of life. The United Nations officially classifies Indigenous people as those "having a historical continuity with pre-invasion and pre-colonial societies," and "consider themselves distinct from other sectors of the societies now prevailing in those territories or parts of them." Furthermore, Indigenous people are "determined to preserve, develop and transmit to future generations, their ancestral territories, and their ethnic identity, as the basis of their continued existence as peoples in accordance with their own cultural patterns, social institutions and legal systems."

Many global problems face Indigenous people including the lack of human rights, exploitation of their traditional lands and themselves, and degradation of their culture. In response to the problems faced by these people, the United Nations proclaimed an "International Decade of the World's Indigenous People" beginning in 1994. The main objective of this proclamation, according to the United Nations, was "the strengthening of international cooperation for the solution of problems faced by Indigenous people in such areas as human rights, the environment, development, health, culture and education." Its major goal was to protect the rights of Indigenous people. Such protection would enable them to retain their cultural identity, such as their language and social customs, while participating in the political, economic and social activities of the region in which they reside.

Despite the lofty U.N. goals, the rights and feelings of Indigenous people are often ignored or minimized, even by supposedly culturally sensitive developed countries. The heart of most environmental conflicts faced by governments usually involves what

constitutes proper and sustainable levels of development. For many Indigenous peoples, sustainable development constitutes an integrated wholeness, where no single action is separate from others. While Indigenous peoples are not a monolith, sustainable development requires the maintenance and continuity of life, from generation to generation. Humans are not isolated entities but are part of larger communities, which include the seas, rivers, mountains, trees, fish, animals, and ancestral spirits, constituting a whole (Figure **5.4.2.2**). From the point of view of Indigenous people, sustainable development is a process that must integrate spiritual, cultural, economic, social, political, territorial, and philosophical ideals.



Figure **5.4.2.2**: Bernadette Demietieff speaking in support of protect the Arctic to protect Gwich'in land from oil drilling, Alaska, c. 2019. Deb Haaland CC-BY-SA-4.0.

Video



In this 3-minute video, Indigenous leaders and other participants at the IUCN World Conservation Congress 2016 discuss the value of Indigenous rights, knowledge, and leadership in creating more sustainable ways of life on Earth.
Question after watching: What commonalities do you hear in the message from all of the diverse Indigenous peoples?

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Unit 5.4.3 - Environmental Policy, Monitoring, and Impact Assessments

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 2 hours.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to Unit 5.4.4, use the Contents menu at the top of the page OR the right arrow on the side of the page.
  - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Explain how environmental policy has changed based on movements and needs in Canada
- Identify how environmental monitoring and research provide opportunities for planning and mitigation
- Describe the Environmental Impact Assessment process in Canada and give examples

Introduction

Environmental policies are typically driven by problems of the day, real and perceived, that require systemic solutions. For example:

- Early conservationists were alarmed at the inefficiencies of resource management by humans and the encroachment of humans on unspoiled lands, leading to conservation legislation.
- During the 20th century, many groups (scientists, economists, politicians, and ordinary citizens) became alarmed and fearful of the consequences of toxic pollutant loads to the environment that included localized effects on human health and well-being, leading to clean air and water legislation.
- As society proceeds into the 21st century, an array of complex problems that have the potential to alter substantially the structure and well-being of large segments of humanity, founding calls for renewal and reassessment of our approach to environmental policy.

This has, thus far, proven to be a difficult transition. Many of these complex problems have multiple causes and impacts, affect some groups of people more than others, are economically demanding, and are often not as visibly apparent to casual observers as previous impacts, nor are the benefits perceived to be commensurate with costs. Devising a regulatory strategy for such problems requires an adaptive and flexible approach that current laws do not foster.

Table **5.4.3.1**: Table illustrating historical development of environmental policy.

	1850-1920	1960-1990	1990-Present
Focus	Conservation/sanitation	Media/site/problem specific	Complex regional/ global problems
Outcome	Land preservation/efficiency/control of disease	Manage anthropocentric and ecological risk	Global sustainable development
Principal Activity	Resource management reform/simple contaminant controls	Compliance/remediation/technological emphasis on problem solving	Integration of social, economic, and technological information for holistic problem solving
Economic Focus	Profit maximization/public health	Cost minimization	Strategic investments/long-term societal well-being
Regulatory Activity	Low	Heavy	Adaptive and flexible
Conceptual Model	Expansion vs preservation	Command and control	Systems/life cycle approach
Disciplinary Approach	Disciplinary and insular	Multidisciplinary	Interdisciplinary/integrative

Many activities that could potentially degrade environmental quality are regulated by legislation passed by various levels of government. In addition, Canada has signed a number of international treaties and protocols that deal with important environmental issues.

Canadian Environmental Law

Environmental law in Canada is made extremely complex by jurisdictional overlaps and other factors. One problem is that of harmonization of related pieces of legislation among the provinces/territories and the federal government. In 1998, these governments adopted the Canada-Wide Accord on Environmental Harmonization, which was intended to achieve progress in this direction. However, that action was resisted by certain interest groups, including the Canadian Environmental Law Association (CELA). CELA views the accord as a mechanism for devolving federal environmental roles and responsibilities to the provinces and territories. Canadian environmental law is changing rapidly as new legislation is passed and older laws are modified or more specifically interpreted by the courts.

Indigenous Connections: Environmental Law

In 1999, the Supreme Court's Marshall decision involved a case in which an Indigenous person had been convicted of catching fish out of season, without a license, and for commercial sale. This conviction was overturned on the basis of treaty rights, negotiated in 1760-1761, that guaranteed Mi'kmac and Maliseet Indians the right to commercially harvest natural resources at any time of year within an extensive treaty area in the Maritime Provinces. The Supreme Court interpreted the modern resource-harvesting rights of those Indigenous nations as being sufficient for individuals to earn a "moderate living." The Marshall decision restored to Indigenous peoples a legal right to engage in fish and timber harvests that are not subject to the same seasonal and geographical restrictions as for non-Indigenous people. The Marshall decision resulted in controversy and conflict with government agencies and non-Indigenous fishers.

In 2003, the Supreme Court extended aspects of the Indigenous resource-access rights to Métis in Canada, ruling that those persons could also freely hunt and fish for subsistence purposes. Some key issues were left unresolved, such as the definition of a Métis person as well as restrictions that might be imposed for the purposes of safety and resource conservation. These aspects are being resolved through ongoing negotiations of interest groups with federal, provincial, and territorial governments. The social and economic repercussions of these decisions by the Supreme Court of Canada will take years to work out.

Subsequent decisions of the Supreme Court in 2013 and 2014 have clarified Indigenous rights to land tenure and resource rights in British Columbia. These cases involved proposals to build mines and oil pipelines in areas where First Nations has not signed land-claim agreements with the provincial government and as such had never ceded their rights to property in areas

where large industrial developments were being proposed. In essence, the Supreme Court affirmed those Indigenous rights. Although the implications of that decision are not yet fully appreciated (it is likely that additional legal actions will be needed to accomplish this), it appears that substantial negotiations will be needed to gain Indigenous approval for industrial projects being proposed within their domain.

The settlement of comprehensive land claims with Indigenous nations in Canada (in effect, the modern equivalent of "treaties") includes the formulation of suites of environmental laws. For example, such settlements include provisions that govern many aspects of resource harvesting and management, waste management, and protected areas within the settlement regions.

An important example of the need for effective legislation concerns the protection of species at risk and their habitat. That sort of legislation has existed in the United States since 1973 as the Endangered Species Act (ESA) administered by the Fish and Wildlife Service (2015). As of 2014, 1,330 species of animals and 889 species of plants were listed as endangered or threatened under the ESA (685 of the listed animals occur in the United States and 645 in other countries, while 886 of the plants grow in the United States and three elsewhere). In addition, approved recovery plans were in place for 479 of the listed U.S. animals and 676 of the plants.

In Canada, the conservation status of species is designated by a group of experts from the government, conservation organizations, and academia known as COSEWIC (the Committee on the Status of Endangered Wildlife in Canada). As of 2014, COSEWIC had assigned at-risk status to 721 indigenous species and other taxa (such as subspecies; only native taxa are designated). Moreover, in 2002, a federal **Species at Risk Act (SARA)** became law. SARA has toughened the legal provisions in support of the protection of species listed by COSEWIC. Its provisions are particularly strong with respect to at-risk species and their habitat occurring on lands owned by the federal government or otherwise falling within its jurisdiction.

However, the SARA legislation is much weaker with respect to species and critical habitat on lands beyond direct federal jurisdiction, such as areas owned by provincial, territorial, municipal, Indigenous, or private interests. Although there are provisions in SARA for the federal government to intervene in such cases, and to provide compensation to affected landowners, it is not bound to do so. Many such interventions would inevitably be expensive and controversial, and so far this mechanism has not been used much to protect at-risk species in Canada. Most of the provinces and territories have also passed laws related to the protection of species at risk within their own jurisdictions, or they are preparing such legislation.

Of course, it is not sufficient to simply pass good laws that are intended to regulate actions that might degrade the quality of the environment – it is also necessary to enforce them. Between 2011 and 2015, there were 95 successful prosecutions (that is, with a conviction) under the Canadian Environmental Protection Act (CEPA) or the Fisheries Act. There are, however, a much larger number of cases that can be resolved with softer regulatory actions, such as writing a warning letter to a non-compliant party.

Several non-governmental organizations have taken on the mandate of advocating improvements to environmental law and policy in Canada, while ensuring that the existing laws are rigorously applied. The most prominent of these are the Canadian Environmental Law Association and Ecojustice. These organizations lobby politicians and suggest specific changes to existing or proposed legislation. In some cases, they also take government agencies to court in order to force them to enforce the existing laws or to seek interpretation from a higher court such as the Supreme Court of Canada.

Environmental Monitoring and Research

There are widespread and well-founded concerns about severe damage being caused to the quality of the environment. In response, many nations are implementing programs to monitor changes in environmental quality over time. Most of these programs are intended to document changes that are occurring over large regions or entire countries and to help predict future variations. These efforts are much larger in scale and scope than programs that monitor whether a particular industrial facility is complying with regulations and guidelines. Most large-scale monitoring is conducted by governmental agencies, or in some cases, by non-governmental organizations. The resulting data and knowledge are used to guide decision-making in government, enhance the work of NGOs, and provide material for environmental research and education.

In the sense meant here, environmental monitoring involves repeated measurements of factors that are related to either the inorganic environment, the structure and functioning of ecosystems, and any intersections with human welfare. Because not everything can be monitored, successful monitoring programs depend on the careful choice of a limited number of representative

indicators and on the collection of reliable data. If a monitoring program detects important changes, the possible causes and consequences of those changes are usually researched.

Video



This 2.5-minute video gives a brief explanation of what environmental indicators are, and their role in allowing us to measure the condition of environmental assets (e.g. soils, vegetation, fauna).
Question after watching: What environmental indicators do you think are used in the ecosystems around you?

Suppose that environmental monitoring has detected that precipitation has become acidified in a large region. The cause(s) of the acidification might be understood by determining the concentrations of chemicals in the precipitation and by investigating local emissions of gases and particulates to the atmosphere. Researchers must also understand the consequences of increased deposition of acidifying substances to freshwater and terrestrial ecosystems, as well as the implications for buildings and other urban features. At first, the research would examine the existing knowledge of the causes and ecological effects of acidification in various kinds of habitats. However, that knowledge is always incomplete and, therefore, it must be augmented with new research examining the risks of acidification that are not yet understood. The accumulated information helps society to understand whether the causes of acidification can be controlled and, if so, to assess the potential environmental and economic benefits.

In another example, monitoring might indicate that the ecological character of a region is changing because the natural forest is being extensively converted into plantations through industrial forestry. The ecological consequences would initially be interpreted in the light of existing knowledge of the effects of forestry, supplemented by additional research that investigates poorly understood issues. Specific research questions might address the effects of ecological conversions on biodiversity, forest productivity, watershed hydrology and chemistry, and global environmental change through effects on carbon storage. This information is needed to help decision-makers evaluate whether they should permit further conversions of natural forests into plantations.

Video



Environmental monitoring provides a health assessment of environmental assets such as agricultural soils, rivers, native vegetation, and wildlife, as profiled in this 2.5-minute video.
Question after watching: How do you think the assets are selected?

Environmental Monitoring and Research in Canada

Environmental monitoring and research in Canada are carried out by various agencies. Environment Canada is the most active agency at the federal level. In addition, the Department of Fisheries and Oceans deals with fisheries and oceanic environments, Natural Resources Canada provides data about non-renewable and some renewable resources, the Canadian Forest Service provides information relevant to commercial forests, Parks Canada examines changes in national parks, and Health and Welfare Canada deals with influences of environmental quality on human health. Statistics Canada plays a key role in compiling information and making it available to governments, companies, and the public. All of the provincial and territorial governments of Canada also have comparable agencies that deal with environmental issues within their jurisdiction.

A few non-governmental organizations also undertake a considerable amount of environmental monitoring and research. For instance, the World Wildlife Fund-Canada has programs that fund work on endangered species and ecosystems. The Nature Conservancy of Canada is active in work associated with conservation planning and stewardship. Universities also have considerable technical expertise in environmental issues. University personnel are not necessarily involved in long-term monitoring programs, but many professors and graduate students undertake research into the causes and consequences of environmental changes.

Environmental monitoring programs provide society with crucial information and knowledge. Both are necessary for the implementation of effective programs to prevent further degradation of environmental quality and the health of ecosystems and to repair existing damage. These actions are necessary if society is to conduct its economy in a truly sustainable manner.

Video



This is a 6-minute profile of a day-in-the-life of an environmental technician.
Question after watching: What surprised you about the job and what it entailed? Is this a position you might be interested in pursuing?

Notions of Environmental Quality

Environmental quality, ecosystem health, and ecological integrity are important notions that help us understand the importance of changes in environmental conditions. However, like other notions, these ones cannot be precisely defined, although it is possible to develop a general understanding of what they mean.

Because they integrate changes in many components of ecosystems and environments, these concepts involve complex phenomena. **Environmental quality,** for example, is related to the concentrations of potentially toxic chemicals and other stressors in the environment, to the frequency and intensity of disturbances, and to the effects of these on humans, other

species, ecosystems, and economies. Of particular concern are stressors associated with human activities, because these have become so important in the modern world.

Ecosystem health and ecological integrity are similar to each other and, in many respects, to environmental quality. However, these indicators focus on changes that may be occurring in natural populations and ecosystems, rather than on the effects on people and their economy. All of these notions involve many variables that are related to stressors and socio-economic or ecological responses. As a result, they are sometimes measured using composite indicators, which integrate many possible changes that are thought to be important. Composite indicators are not exact measurements of environmental quality, ecosystem health, or ecological integrity, but they do allow society to determine whether conditions are getting worse or better.

These ideas can be explained by using **ecological integrity** as an example. Obviously, most stressors associated with human activities will enhance some species, ecosystems, and ecological processes, while at the same time damaging others. However, ecological theory suggests that systems with higher values for any or all of the following characteristics will have a greater degree of ecological integrity:

- The ecosystem is resilient and resistant to changes in the intensity of environmental stressors
- The system is rich in indigenous biodiversity values
- The ecosystem is complex in its structure and function
- Large species are present
- Top predators are present
- The ecosystem has controlled nutrient cycling, meaning it is not “leaking” its nutrient capital
- The ecosystem has a “natural” character and is self-maintaining, as opposed to being strongly affected by human influences and management

These sorts of criteria for ecological integrity are of particular relevance to managing protected areas. If ecological integrity is being maintained or enhanced, then a protected area is doing its job of maintaining biodiversity and ecological functions.

Successes

As we noted earlier, programs of monitoring and research should be capable of detecting changes in environmental quality, while also helping to predict future effects. Well-designed programs should deal with the most important known stressors or potential threats to the environment. They should measure or predict the effects on people and on sensitive ecosystems and species, particularly those that are economically or ecologically important.

These are the simple requirements of a sensible program for monitoring and investigating environmental problems. Unfortunately, these criteria are not well met by many existing programs, and as a result, some important environmental problems are not yet well understood. Consequently, they are not being addressed effectively, and they could become worse in the future. To deal properly with these and many other important issues, we must improve our understanding through better monitoring and research. We can illustrate the achievable benefits by examining a few “success stories” in which monitoring, research, and effective actions helped to resolve important environmental problems.

- Eutrophication of fresh water was identified as an important environmental problem during the 1960s and early 1970s. Research discovered that phosphate was the primary cause and that the damage could largely be avoided by constructing sewage-treatment facilities and by using low-phosphorus laundry detergent.
- Acidification (acid rain) was recognized during the late 1970s and the 1980s as an extensive phenomenon causing many ecological damages. Research showed that the problem was largely due to the atmospheric deposition of sulphur and nitrogen compounds. This convinced decision makers to require reductions of industrial emissions, and that action led to some improvements.
- Contamination with persistent chlorinated hydrocarbons, such as DDT, dieldrin, and PCBs, was found to be widespread in the 1960s and 1970s. Research showed that some species, such as predatory birds, were being seriously harmed and that there were possible effects on humans. The toxicological evidence convinced decision makers to ban these chemicals in most countries, to the great benefit of the environment.

Video



In this 5.5-minute video, discover the groundbreaking environmental work of Rachel Carson, whose book Silent Spring explores how human actions threaten the balance of nature.
Question after watching: Why were so many people critical of Carson and Silent Spring? How did she challenge the status quo?

Environmental Impact Assessments

One important interpretive decision of the Supreme Court of Canada affecting environmental impact assessments was the Rafferty decision of 1989, which made it clear that an Environmental Impact Assessment was needed for any undertakings involving the federal government. An **environmental impact assessment (EIA)** is a planning process that is used to help prevent environmental problems. Environmental impact assessments do this by identifying and evaluating the potential consequences that a proposed development may have for environmental quality. Because it can consider ecological, physical-chemical, and other environmental effects, as well as socio-economic consequences, an EIA is a highly multidisciplinary and interdisciplinary activity.

An EIA may be conducted to examine various kinds of activities, or planned developments, that could affect environmental quality, such as the following:

1. an individual project, such as a proposal to construct an airport, dam, highway, incinerator, mine, or power plant
2. an integrated scheme, such as a proposal to develop an industrial park, a pulp or lumber mill with its attendant wood supply and forest-management plans, or other complex developments that involve numerous projects
3. a governmental policy that carries a risk of substantially affecting the environment

The scale of an environmental assessment can vary greatly, from the examination of a relatively small proposal to construct a building near a wetland, to a megaproject associated with natural-resource development.

Canadian EIAs

In Canada, environmental impact assessments for proposals that involve federal funding or jurisdiction are regulated under the **Canadian Environmental Assessment Act (CEAA)**, which was enacted in 1992. The Act is a law that requires federal decision-makers, referred to as “responsible authorities,” to consider the predicted environmental effects of a proposed project before it is allowed to go ahead. If significant adverse effects are predicted, the project is not allowed to proceed until the damages have been addressed by a change in design or through some other mitigation.

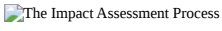


Figure **5.4.3.1**: Impact assessment process overview. Copyright: Government of Canada.

Initially, the CEAA required that EIA studies be done on a wide range of projects involving the jurisdiction of the federal government. However, in 2012 the Act was greatly weakened by requiring that only big projects are considered. Provinces and territories also have legislated requirements for EIA, as do some local levels of government, such as municipalities and First Nations.

EIA is based on the reasonable premise that all proposed projects, programs, and policies carry risks for human welfare and for other species and ecosystems. For example, a proposed project may emit toxic chemicals into the environment. In such a case, it is necessary to determine if the anticipated emissions might exceed the regulated levels. The most stringent standards and guidelines are related to the maximum exposures that humans can tolerate without suffering risks to their health, while criteria to protect other species and ecosystems are less exacting. For example, the guideline for uranium in drinking water is 0.02 mg/L, but that for the protection of aquatic life is 40 mg/L for short-term exposure (<1-4 days) and 5.5 mg/L for long-term exposure.

In addition, a project might cause disturbances to natural habitats during its construction or operation, which could result in ecological damage. These effects should be identified and quantified, and the potential environmental damages evaluated before permission is granted to start the project.

The process of environmental impact assessment is intended to predict these potential damages and to suggest ways of avoiding or mitigating them as much as possible. However, this does not necessarily mean that no damage will be caused by a proposed development. In almost all cases, some damage is inevitable.

Video



Impact assessments help society understand the possible impacts of projects before they start, as detailed in this 2-minute video.
Question after watching: In what ways can individuals or groups give feedback on an EIA in Canada?

Because most developments potentially affect a great variety of species and ecosystems, EIAs are limited to predicting the effects on only a selection of so-called **valued ecosystem components (VECs)**. These components are valued because society perceives them to be important for one or more of the following reasons:

1. They are an economically important resource, such as an agricultural crop, a commercial forest, or a stock of fish, mammals, or birds
2. They are a rare or endangered species or ecological community
3. They are of cultural or aesthetic importance

Cumulative Environmental Effects EIA

The Cumulative Environmental Effects EIA is a planning activity under the Canadian Environmental Assessment Act that includes the need to evaluate cumulative environmental impacts, or those resulting from the effects of a proposed undertaking within some defined area, in addition to those caused by any past, existing, and imminent developments and activities. The concept of cumulative effects recognizes that the environmental effects of separate anthropogenic influences will combine and interact to cause changes that may be different from those occurring separately. Assessment of cumulative impacts requires knowledge of both the likely effects of a proposed development, as well as those of other anthropogenic activities in a study area, plus additional ones that are likely to occur.

There are a number of examples of cumulative environmental effects that are primarily ecological and have occurred in Canada:

- aggregate damage caused to populations of migratory salmon in the Fraser River watershed in British Columbia as a result of commercial fishing in the open Pacific or in the river itself, along with sport and subsistence fishing, plus degradation of freshwater habitat through such influences as the dumping of sewage, agricultural erosion and pesticides, warmer temperatures and woody debris in streams caused by forestry operations, risks of sea-louse infection from aquaculture in coastal waters, and warming oceanic waters caused by climate change
- losses of biodiversity throughout Canada, but particularly in southern regions, caused by deforestation to develop land for urbanized and agricultural uses, fragmentation by roads and transmission corridors, disturbances by forestry and mining, and various kinds of pollution
- ecological damage in a region of boreal forest in northern Alberta in which there are diverse anthropogenic stressors associated with timber harvesting, exploration, and mining for oil and gas, oil-sand extraction and processing, and pipelines and roads to service all of those economic activities
- threats to the ecological integrity of national parks that are associated with the internal development of infrastructure to support tourism, such as campgrounds, interpretation centers, roads and trails, golf courses, and skiing facilities, along with economic activities in the surrounding area such as forestry and agriculture, as well as regional influences such as acid rain and climate change. A requirement that environmental impacts be studied in a cumulative manner acknowledges the complexity of ecosystems and the fact that all aspects of their structure and function are affected by a diverse array of influences.

Much more detail on the full Environmental Impact Assessment process can be found here: https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/impact-assessment-process-overview.html

Planning Options

If, during an EIA, potentially important risks to human welfare or VECs are identified, a number of planning options must be considered. There are three broad choices.

- *Prevent or Avoid*: One option is to avoid the predicted damage by ensuring that there are no significant exposures of people or VECs to damaging stressors related to the project. This can be done by modifying the characteristics of the project, or in cases of severe conflicts with human welfare or ecological values, by choosing to cancel it entirely. Because prevention and avoidance may involve substantial economic costs, this is sometimes considered to be the least desirable option by proponents of development. Politicians and regulators may also dislike this option since it may involve intense controversy. Nevertheless, there is always public and regulatory pressure to take as many precautions as possible before undertaking a proposed development.
- *Mitigation*: Another option is the mitigation of any predicted damages, or to repair or offset them as much as possible. Because any direct damage to people is considered unacceptable (and therefore to be rigorously avoided), mitigation is most relevant to damage inflicted on VECs or to indirect, low-level risks to people. For instance, if the habitat of a valued species is threatened, it may be possible to create or enhance habitat at somewhere else so that the damage is offset. For example, a wetland may be unavoidably destroyed by a proposed development, but the damage may be offset through the creation of a comparable wetland elsewhere (note that this does not help most organisms living in the original wetland). Mitigations are a common way of dealing with potential conflicts between project-related stressors and VECs. However, it is important to understand that mitigations are never complete, often do not address the underlying problem, and there is often residual damage.
- *Accept the Damages*: The third option is for decision-makers to choose to allow a project to cause some or all of the predicted damages to human welfare or VECs. This choice is often considered tolerable by project proponents and by politicians. Their rationale is the perceived socio-economic benefits gained by proceeding with a project are likely to be much greater than the costs of environmental damage. From an environmental perspective, however, this choice might not be viewed as being acceptable, usually because environmental “costs” are grossly undervalued.

Environmental impact assessments generally find that a proposed development carries risks of causing some degree of environmental damage. Usually, the development is allowed to proceed in some form, with the predicted damage being avoided or mitigated to the degree that is considered technologically and economically feasible. As noted previously, however, there are always residual risks that cannot be avoided or mitigated. Any damage that does occur represents some of the environmental costs of development, which are real even if there is financial compensation or other kinds of offsets.

Once a project has begun, compliance monitoring is usually necessary to ensure that regulatory criteria for pollution or health hazards are not being exceeded. It is extremely useful, although not always required, to also monitor the ecological effects of a project. This tests the predictions of the impact assessment and identifies unanticipated effects or “surprises.” Ideally, a monitoring program for ecological effects is begun before a project starts, in order to establish the baseline conditions. The monitoring should then continue for some years after the project is completed until it is determined that important damage is not being caused. If unanticipated damage is shown by the monitoring, it may be prevented, avoided by an adaptive change in the project design, mitigated in some way, or accepted as an ecological “cost” of development.

Examples of Environmental Impact Assessments

EIAs have been conducted in all regions of Canada, examining projects that varied widely in both scale and potential effects. Each of these unique cases is instructive, in the sense of illustrating the environmental implications of development projects and the role played by impact assessment. In the following sections, we briefly examine selected elements of some environmental impact assessments in Canada.

Diamond Mines in the Northwest Territories

This proposal involved the development of mines to extract diamonds from five deposits discovered about 300 km northeast of Yellowknife. A variety of potential environmental damages were identified with this project. First, some of the diamond-bearing rock lies beneath lakes that would have to be drained to develop a mine. These aquatic ecosystems would be destroyed.

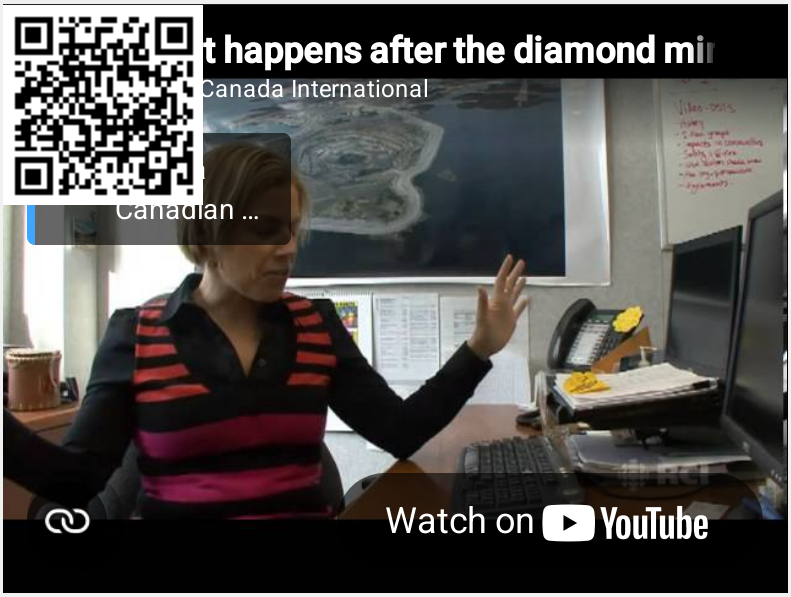
In addition, large amounts of gravel are needed to construct roads and other infrastructure. Much of this material would be obtained from long, sinuous geologic features known as eskers, which are left over from glaciers and provide critical denning habitat for grizzly bear, wolf, and other high-profile species.

Further, large numbers of caribou traverse the region during their seasonal migrations. These are potentially affected by the mine and its network of roads. Substantial damage to the caribou would harm the Indigenous people in the region, who engage in a subsistence hunt for these animals. Those people might also suffer from interference with their commercial harvest of fur-bearing mammals.

Finally, the proposed mines are located in a region that was a huge, roadless wilderness. Conservationists, led by the World Wildlife Fund, objected to the approval of the mine before a system of protected areas was set up in the region for the preservation of natural ecosystems and native species, including large carnivores such as grizzly bear, wolf, and wolverine.

The diamond-mine proposal passed its environmental impact assessment and was allowed to proceed. It was subject to stringent requirements, however, such as the implementation of acceptable methods of disposal of mining and milling wastes and the protection of water bodies and rivers (other than those that must unavoidably be damaged to develop the mines and dispose of tailings). A ban was imposed on local hunting by project personnel. As well, a monitoring program was to be undertaken to ensure that unanticipated damage is not caused to air or water quality or to wildlife. The mine must also meet socio-economic criteria, including several that deal with employment opportunities and other ways of engaging local people (including Indigenous) in the development. As a measure outside the scope of the formal impact assessment, the government of the Northwest Territories committed to establishing protected areas in the larger region, although this has not yet been followed through in its entirety.

Video



This 4-minute video is an interview with the Superintendant for Sustainable Development, Communities, and External Relations at Diavik Diamond Mines Inc. by Radio Canada International in 2013 on plans for the eventual closing of the mine. Question after watching: What environmental, social, and economic considerations are being taken into account during this mine closure plan to make it sustainable?

Destruction of Diseased Bison

Agriculture Canada proposed to slaughter almost all the bison in the southern region of Wood Buffalo National Park and its vicinity. Some of these animals are infected with bovine tuberculosis and brucellosis, and there are concerns over the potential spread of these diseases to herds of cattle to the south and west of the area. The bison targeted for slaughter are hybrids between the indigenous wood bison and plains bison that were introduced to the region during the late 1920s. The proposal did not include the elimination of small populations of genetically "pure" wood bison living farther to the north, and in fact, these were predicted to receive a measure of protection from the potentially harmful effects of interbreeding with hybrid animals.

This proposal was made in support of commercially important livestock interests, but it quickly engendered intense controversy. It was opposed by virtually all conservationists and by local Indigenous people. Although this project successfully passed the impact assessment process, it was later suspended by the federal Minister of the Environment, largely in recognition of the intense opposition from conservation and First Nation interests.



Figure **5.4.3.2**: Plains bison (Wilson Hui; CC BY 2.0.)

The Roberts Bank Terminal 2 Project

The Vancouver Fraser Port Authority is proposing a new three-berth marine-container terminal at Roberts Bank in Delta, B.C. The projected cost of the terminal is approximately $3.5B. The Environmental Impact Assessment was conducted by an independent Review Panel. On March 27, 2020, the Review Panel submitted its report containing its conclusions and recommendations.

In August 2020, after considering the Review Panel's report, the Minister determined that additional information is required from the Port Authority to inform the decision on whether the Project is likely to cause significant adverse environmental effects under the *Canadian Environmental Assessment Act, 2012*. This information request pauses the federal timeline for decision-making. Following receipt of this information from the Port Authority, the Government will have approximately three months to make a final decision on the Project. In the interim, IAAC is coordinating post-panel-Report consultations, including coordinating consultations with the Province of B.C. and Indigenous groups. The responses from the Vancouver Fraser Port Authority were subject to an extended public comment period that closed on March 15, 2022. Comments, including those from expert federal departments, were posted publicly and are being reviewed.



Figure **5.4.3.1**: Roberts Bank, 2013 (Gord McKenna; CC BY-NC-ND 2.0)

Nova Scotia Peat Mine

Peat mined from bogs is used as a horticultural material, and it can also be burned as a source of energy. This proposal would have developed a mine on a bog in Nova Scotia to provide peat as an industrial fuel (Figure **5.4.3.2**). The EIA focused on the fact that the bog in question provides habitat for several rare species, including a carnivorous plant called the thread-leaved sundew (*Drosera filiformis*). This species is endangered in Canada and also in much of the rest of its range in the eastern United States. Because the bog harbors the largest of only four known populations of the sundew in Canada, the provincial Minister of the Environment did not allow a mine to be developed on that site. This was a controversial decision because it canceled a local development initiative in a region in which the economy is chronically depressed.

image28_1a.jpg image28_1b.jpg

Figure **5.4.3.4**: The thread-leaved sundew (Drosera filiformis) and its bog habitat. The largest known population of this carnivorous plant in Canada occurs on a site in southwestern Nova Scotia that was proposed for a peat mine. An environmental impact assessment predicted that the mining would obliterate the most important population of this endangered species, and as a consequence, the Government of Nova Scotia did not allow the mine to proceed. Source: Bill Freedman.

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Unit 5.4.4 - Sustainability and the Future

- Please read and watch the following Learning Resources
- Reading the material for understanding, and taking notes during videos, will take approximately 1 hour.
- Optional Activities are embedded.
- Bolded terms are located at the end of the unit in the Glossary. There is also a Unit Summary at the end of the Unit.
- To navigate to the Unit Glossary and Summary, use the Contents menu at the top of the page OR the right arrow on the side of the page.
    - If on a mobile device, use the Contents menu at the top of the page OR the links at the bottom of the page.

Learning Objectives

- Describe how lifestyle choices influence sustainability
- Recognize important Canadian governmental bodies and international organizations responsible for sustainability
- Explain the importance of environmental citizenship and literacy
- Describe the multi-faceted approach required for sustainability

Introduction

Sustainable development was previously defined as progress made toward an economic system that is ultimately based on the wise use of renewable resources. A sustainable economy would not deplete its capital of natural resources, and so would not compromise the availability of those necessities for use by future generations of humans. We also noted that ecologically sustainable development would allow human activities to continue, but without causing unacceptable damage to other species or natural ecosystems.

This text does not give a falsely optimistic view of the future: sustainability will be a challenge and will take a lot of hard work. All levels of society have a responsibility to protect the quality of our common environment. These obligations are a central aspect of the social contract by which enlightened communities function.

The role of government is an overarching one because it is empowered to regulate the activities of itself, the private sector, non-governmental organizations, and individuals. Of course, many activities of government and the private sector carry risks of causing environmental damage, and there is always an obligation to avoid or mitigate the damage as much as possible.

The role of **environmental non-governmental organizations (ENGOs)** is to lobby government and industry about issues, to raise public awareness, and increasingly (because of shortages of governmental capability), to raise funds that can be used to prevent and repair environmental damage. Finally, all individual citizens have an obligation to live their lives in an environmentally responsible manner.

International Organizations

The **United Nations Environment Programme (UNEP)** is the principal international organization that deals with environmental matters. UNEP is responsible for coordinating global environmental efforts with other agencies of the United Nations, national governments, and non-governmental organizations. UNEP also coordinates the development of multinational treaties and other agreements and periodically hosts global conferences on environmental themes.

Other agencies of the United Nations also have mandates that involve environmental issues. These include the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the United Nations Population Fund (UNPF), the World Health Organization (WHO), and the International Labour Organization (ILO).

A wide range of non-governmental environmental organizations are also active on the international stage:

- ENGOs involved in the international conservation of biodiversity include Conservation International, the Cousteau Society, the International Union for Conservation of Nature and Natural Resources, the Nature Conservancy (U.S.), the Smithsonian Institution, and the World Wildlife Fund.
- Those with general mandates concerning resources and other environmental issues include the Earth Island Institute, the Environmental Policy Institute, Resources for the Future, the Sierra Club, the World Resources Institute, and the Worldwatch Institute.

Video



In this 2-minute video, the Convention on Biological Diversity identifies the Nayoga Protocol as a call to expand the global biodiversity framework to include the full and effective participation of Indigenous peoples and local communities. Question after watching: Why is it important to share natural resources equitably? What are some challenges to achieving this goal?

Canadian Organizations

At the federal level, **Environment and Climate Change Canada** plays a central role in preserving and enhancing environmental quality. Its mandate includes the protection of water, air, and soil quality, renewable resources, and biodiversity. Its institutional objective is to foster a national capacity for sustainable development, in cooperation with international, provincial, territorial, municipal, and Indigenous governments, as well as other departments of the federal government, the private sector, and non-governmental organizations. It is also responsible for informing "Canadians about protecting and conserving our natural heritage, and ensuring a clean, safe and sustainable environment for present and future generations."

Other agencies of the federal government also have important environmental mandates:

- Natural Resources Canada deals with mineral and forest resources, including aspects of the environmental impacts of mining, the use of fossil fuels, and forestry
- Health and Welfare Canada deals with environmental issues related to human health and also has primary jurisdiction over pesticide registrations
- Agriculture and Agri-Food Canada deals with issues involving agricultural practices, including sustainability and pesticide-use registrations
- Fisheries and Oceans Canada is mandated to promote understanding, conservation, and beneficial use of aquatic bio-resources.
- The Canadian Coast Guard helps to protect the marine environment by preventing marine pollution
- Parks Canada manages national parks
- Crown-Indigenous Relations and Northern Affairs Canada is responsible for environmental and resource issues in extensive northern regions
- The Canadian Environmental Assessment Agency conducts environmental assessments of projects involving the federal government
- Statistics Canada compiles environment-related data and makes them available to other agencies and the public

All of the provincial and territorial governments have agencies similar to those listed above for dealing with environmental responsibilities under their jurisdiction. Environmental reporting is one process that is used to communicate information about the environment to the public. Such reporting should involve clear and objective presentations of information about changes in environmental quality, and should also offer unbiased interpretations of the causes and consequences of those changes.

Environmental reporting is delivered to the broader public by various federal agencies, including government departments, educational institutions, non-governmental organizations, and the mass media. Most of the provinces have also released periodic state-of-the-environment reports. Various other federal agencies also make available useful information about the environment available to the public, including Statistics Canada.

Canada also has a wealth of non-governmental organizations that deal with environmental issues. National organizations that focus on the conservation of biodiversity include the Canadian Parks and Wilderness Society, the Canadian Wildlife Federation, Nature Canada, the Nature Conservancy of Canada, and the World Wildlife Fund of Canada (Figure **5.4.4.1**). Organizations with general mandates concerning resources and other environmental issues include the Canadian Arctic Resources Committee, Canadian Ecology Advocates, Ducks Unlimited Canada, Energy Probe Research Foundation, Pollution Probe, the Royal Society of Canada, the Sierra Club (Canada), the Tree Canada Foundation, and Wildlife Habitat Canada. In addition, all of the provinces and territories have non-governmental organizations that deal with environmental issues on a more regional basis.

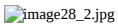


Figure **5.4.4.1**: The Nature Conservancy of Canada is an ENGO whose activities focus on acquiring land or land-use rights for the protection of natural values. This project involved the purchase of property on an island in Nova Scotia that provides habitat for several rare plants, including the best-known locale in Canada of the eastern mountain avens (Geum Peckii). Source: B. Freedman.

Video



Revisiting Tla-o-qui-aht Tribal Parks, the Guardians tend to the Intergenerational Gardens, which include the largest intact ancient coastal rainforest on Vancouver Island, as profiled in this 7-minute video.
Question after watching: What aspects of sustainability are practiced in Tia-o-qui-aht Tribal Parks?

Environmental Citizenship

Although each of us individually has a relatively small effect on the environment, our collective influence is enormous. If all Canadians were to pursue a lifestyle that has gentler environmental effects, there would be great benefits for all of us, for future generations, and for other species.

Environmental citizenship involves actions that are taken by people and families to lessen their impact on the environment. Individual acts of environmentalism involve making lifestyle choices that include having a small family, using less energy and material resources, and causing less damage to the natural world. In addition to the many sustainability actions that people can undertake, they can give moral and financial support to ENGOs that deal with environmental issues at international, national, and regional levels.

Libraries, bookstores, and websites offer many so-called sustainability handbooks and tools. These list hundreds of specific actions that people and families can take to lessen their effect on the environment. The diverse possibilities include shutting off the lights when leaving a room, turning the thermostat down to 15°C or less during the winter (while layering clothing), avoiding wasteful travel habits (such as commuting alone in a car), avoiding the use of pesticides in lawn and garden care, planting native trees to store carbon on one's property and to provide wildlife habitat, becoming a vegetarian, and giving money and volunteer time to environmental charities (Figure **5.4.4.2**).



Figure **5.4.4.2**: Each of us can choose to adopt a lifestyle that is less intensive in terms of its environmental impact. This can involve many appropriate choices, such as commuting by bicycle instead of by automobile. (Paul Krueger; CC-BY-2.0)

However, few individual Canadians will make *all* of the sustainable choices that are possible. To do so would be to voluntarily adopt an austere lifestyle, and most people are unwilling or unable to choose this. Instead, most will undertake some positive actions, perhaps including recycling many household wastes, riding a bicycle to school or work, not worrying about a weedy lawn, and favoring several environmental organizations. This would be selective environmentalism rather than a fully green lifestyle. However, if selective environmentalism is substantial enough, and is adopted by many people, there will be huge benefits. Each of us is responsible for demonstrating our environmental citizenship by making as many green choices as possible and by encouraging relatives, friends, and acquaintances to do the same.

If the citizens of Canada and other countries do not make these sensible, environmentally-conscious choices, the results will eventually be tragic.

Things You Can Do to Be More Sustainable

1. **"Reduce energy use**
   Adopt energy-saving habits. Make it a habit to turn off the lights as you leave a room. Also, replace standard light bulbs with energy-efficient compact fluorescent bulbs. Turn off your computer and unplug electronics when they are not in use.
2. **Change the way you think about transportation**
   Walk or bike whenever possible. Not only will you reduce your carbon footprint, but your overall level of health will improve and you will save money on parking and gasoline.

Take public transit or carpool whenever possible.
When purchasing a vehicle look for one with better mileage. Increase your fuel economy when driving by sticking to posted speed limits and avoiding rapid acceleration and excessive braking. Plan and combine trips and errands. This will save you both time and money as well as reduce wear and tear on your vehicle. When travelling long distances, try to take a train or bus rather than flying or driving.

3. **Insulate your home**
   Insulate yourself and your home. By properly insulating your home, you can ensure that heat stays in or out depending on the season. You can do this by purchasing windows and window coverings that will block out or keep in warmth, and by sealing any existing cracks. In winter, reduce your thermostat by 2 °C to enjoy energy savings and a cozy sweater. In summer, use fans to circulate air, and set air conditioners to make your home a comfortable temperature. Lowering the temperature on your water heater to between 55 and 60 °C and insulating your pipes also makes a difference.
4. **Make every drop count**
   Conserve water by fixing drips and leaks, and by installing low-flow shower heads and toilets. Challenge yourself to a speed shower. Turn off water while brushing teeth or shaving. Treating and transporting water requires energy, while water conservation results in reduced energy requirements and carbon emissions.
5. **Cool wash and hang to dry**
   These are not just washing instructions on a label anymore, but an equation for energy savings. Wash clothing in cold water and hang clothing to dry outside, or indoors on a drying rack. Taking these steps will reduce your electricity bill and also prolong the life of clothing by reducing wear on the fabric caused by dryers.
6. **High efficiency appliances**
   When replacing appliances, look for high efficiency units. Appliances with ENERGY STAR ratings, an international standard for energy-efficient consumer products, typically utilize a minimum of 20 % less energy. This means savings for you and the environment.
7. **Switch to "green power"**
   Research where your power is coming from - wind, water, coal, or solar - and talk to your power provider to determine if a greater percentage could be coming from renewable resources. Encourage power providers to switch to green power and, if possible and/or economically viable, switch to a company offering power from renewable resources.
8. **Recycle**
   Make recycling part of your daily routine. Recycle all packaging and consumer goods that you can. Aim to purchase items with minimal and recyclable packaging. For certain items with large amounts of packaging, ask retailers if they can recycle or re-use it. For electronics, facilities now exist that can dispose of electronics in an environmentally responsible manner.
9. **Repurpose**
   Rather than discarding or recycling clothing and household goods, give them a chance at a second life. Gently used clothing can be donated to charity or exchanged with friends and family. Old T-shirts can be repurposed into rags for cleaning. Household goods can be donated to charity or sold at a garage sale. Through repurposing, the amount of waste being sent to landfill sites is reduced, there is no need to use energy for recycling, and others can benefit from your used items.
10. **Plants, our new best friend**
    When gardening, select plants that are well suited to your climate and require minimal watering and attention. Better yet, plant a tree, and it will provide shade and soak up carbon from the atmosphere."

Find more tips here: https://oceans.ubc.ca/about/sustainability-well-being/sustainability-tips/

Source: Government of Canada. 2015. "Things You Can Do to Help the Environment." [Internet] Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/things-you-can-do-help-environment.html

Environmental Literacy

Environmental literacy refers to a well-informed understanding of environmental issues, and it is an important societal goal. Knowledge about the causes and consequences of environmental damage can influence the decisions and choices made by politicians, regulators, corporations, and individual citizens. If appropriate, those decisions and choices can influence environmental quality in a positive way (Figure **5.4.4.3**). People acquire this knowledge in various ways, the most important of which are through environmental reporting and other forms of education.

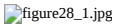


Figure 5.4.4.3: Influences on Environmental Quality. This is a conceptual model of the many influences on environmental quality, including the roles of monitoring, research, regulation, and literacy. Environmental monitoring and research provide an understanding of the causes and consequences of changes in conditions. Ideally, this understanding is based on objective information from monitoring and research programs, interpreted by environmental scientists and other qualified specialists (although their explanations may be conditioned by social and cultural influences). This knowledge is communicated to decision makers in government, who may implement regulations and undertake management activities that affect environmental quality.

Knowledge about environmental and ecological changes is also communicated to the general public, through state-of-the-environment reporting, the educational system, activities of non-governmental organizations, and the mass media. Social attitudes regarding the environment are affected by environmental literacy, and they may result in more appropriate choices of lifestyle and a public influence on the policies and actions of governments and corporations. Environmental literacy has a pervasive influence on the attitudes that people develop. Individuals who are knowledgeable about environmental issues are more likely to make appropriate lifestyle choices and to influence decision-makers to ensure that sensible policies are implemented.

Most people become informed about environmental issues through the mass media, such as the internet, newspapers, and television. These can be effective means of environmental education, but there are drawbacks. Often, media presentations of issues are biased, and sometimes they are inaccurate. The focus is often on controversy, especially when there are unresolved issues that are characterized by scientific uncertainty. This can result in high-profile disputes dominating the environmental agenda, which can detract from efforts to deal with some other important problems whose causation and resolution are better known.

To some degree, this approach can be counterbalanced by providing the broader public with more objective information and by fostering a better understanding of the issues. One means of accomplishing this is to ensure that environmental issues are dealt with, adequately and objectively, in the education system. Ideally, this exposure would occur throughout the system – from primary and high schools, through colleges and universities, to continuing education for the working public.

In contrast, poorly informed public opinion encourages less-appropriate environmental choices, such as rampant consumerism and the wasteful use of natural resources. Environmental illiteracy also fosters the development of controversial “red herrings”, or illogical beliefs that mislead or distract from important issues. An example of an environmental red herring is the common misunderstanding that many people have of the differences between contamination and pollution. Related unhelpful syndromes are known as NIMBY (not in my backyard), LULU (locally unacceptable land use), BANANA (build absolutely nothing anywhere near anybody), and NIMTO (not in my term of office). NIMBY, LULU, and BANANA are common views that many people have about proposed developments that may affect their local environment, while NIMTO is a frequent political response. These attitudes can result, in part, from a lack of credible information about the risks that may be associated with developments in the neighborhood. Alternatively, NIMBY, LULU, and BANANA may result when planners and developers are insensitive to the legitimate concerns of local people.

In addition to affecting the siting of commercial and industrial facilities, NIMBY, LULU, BANANA, and NIMTO cause huge problems for planners who are attempting to build certain kinds of environmental management facilities that society wants and needs. For example, even though all voters recognize that their community needs facilities for the disposal of solid wastes and the treatment of sewage, not many people wish to have such works located in their own neighborhood often leading to environmental injustice.

Sustainable Living

Sustainable living describes a lifestyle that attempts to reduce/eliminate an individual's (or society's) use of resources so as to be as close as possible to "net zero living". As such, an individual (or society) focuses on reducing their footprint (ecologically, carbon, socially, etc) through their choices/methods of:

- Use of resources (energy/food and food waste/transportation/water/etc)
- Support of people/companies (voting/economic/social/etc)
- Practices of reducing, reusing, and recycling
- Consciousness of priority and focus on local concerns/needs versus global concerns/needs
- Sharing knowledge with their community (all ages)

The thought of getting started with sustainable living can be overwhelming. However, it is important to note that although we can acknowledge all the things that need to be accomplished, that the entire burden does not lie with just one individual's control

(Figure 5.4.4.4). In fact, most of the changes will need to take place a higher levels of policy and economic decision-making. Overall, it is a multi-layered approach to action at the individual, societal, and political levels that will lead towards true sustainability and it is still possible that these changes can be made for both humans and nature alike.



Figure 5.4.4.4: Considerations for sustainable living goals. Image by Sustainability Week Switzerland in Wikimedia Commons (CC-BY-SA)

Video



In this 14-minute second video from 2018, Green shares his analysis on the steps each country has (or has not) made toward these Sustainable Development Goals -- and offers new ideas on what needs to change so we can achieve them by 2030. Why does Green use the Social Progress Index to measure the SDGs? What does his data tell us? What is a drawback to his method?

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5.G: Unit 5 - Glossary

Unit 5.2

air pollution
gaseous and particulate contaminants that are present in the Earth’s atmosphere

anthropogenic
human-caused

anthropogenic climate change
climate change due to human activities

background extinction rate
natural rate of extinction without human interference; estimated to be 1 per million species years.

biodiversity
a broad term for biological variety

biodiversity hotspot
geographical areas that contain high numbers of endemic species

biodiversity loss
the reduction of biodiversity due to displacement or extinction of species

charismatic species
species that attract humans' empathy and attention and are therefore deemed more important than others based largely on appearance

CITES
The Convention on International Trade in Endangered Species of Wild Fauna and Flora, an international treaty in force since 1975

climate change
long-term changes to temperature and precipitation patterns

conservation biology
the field of study to preserve biodiversity

Convention on Biological Diversity
the leading international treaty to advance the conservation of biodiversity, within the context of a comprehensive agenda for sustainable development

COSEWIC
Committee on the Status of Endangered Wildlife in Canada; a consultative body with expert representatives from governments (federal, provincial, territorial, and Indigenous), universities, and non-governmental organizations

critically imperiled (Canada)
indigenous species that are faced with imminent extinction or extirpation throughout all or a significant portion of their Canadian range

ecosystem diversity
the number of different ecosystems on the planet or in a given geographic area

ecosystem services
human benefits and services provided by natural ecosystems

endangered
a species at great risk of extinction

ENGO
environmental non-governmental organizations

extinct (Canada)
any species of wildlife that was formerly indigenous to Canada but no longer exists anywhere in the world

extirpated (Canada)
any species or subspecies that was formerly indigenous to Canada but now only survives in the wild or elsewhere, usually in the neighboring United States

genetic diversity
the variety of genes present within a population

gross national product
the total domestic and foreign output claimed by residents of a country

HIPPPOC
threats to biodiversity from **h**abitat loss, **i**nvasive species, **p**ollution, **p**opulation (human), **p**redator loss, **o**verexploitation, and **c**limate change

imperiled (Canada)
any indigenous taxon that is likely to become critically imperiled unless factors affecting its status are reversed

indoor air pollution
exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust

invasive species
when non-native species undergo dramatic population increases in their new habitat and reset the ecological conditions in the new environment, threatening the native species that already exist there

IUCN
International Union on the Conservation of Nature

natural source
pollution not caused by people or their activities

non-native species
those that have been intentionally or unintentionally introduced by humans into an ecosystem in which they did not evolve

non-point source
many sources of air pollution located together whose individual emissions may be below thresholds of concern, but whose collective emissions can be significant

outdoor air pollution
exposures that take place outside of the built environment

overharvesting
the hunting and fishing of a species that is above what the organism can withstand to maintain a healthy population

point source
an emission source that does not move or can be tracked to one specific location

pollutant residence time
time a pollutant spends in a reservoir; a pollutant may be taken up for a long time within the ecosystem or absorbed into lithosphere or hydrosphere

preserve
an area of land set aside with varying degrees of protection for the organisms that exist within the boundaries of the preserve

primary pollutants
chemicals discharged into the air that have a direct impact on the environment

relative species abundance
absolute population size of a particular species relative to the population sizes of other species within the community

residence time
average time that a molecule spends in a reservoir

restoration
a mechanism for restoring and maintaining biodiversity in disturbed habitats

secondary pollutants
the result of primary pollutants reacting with other chemicals in the air

species diversity
the number and kinds of species in a location or on the planet

TRAFFIC
Trade Records Analysis of Flora and Fauna in Commerce - a non-profit that tracks the illegal trade in wildlife

trophic cascade
the consequences to an ecosystem due to the loss of apex predators

UNESCO World Heritage Site
includes 34 identified global biodiversity hotspots as well as important human cultural sites

vulnerable (Canada)
any indigenous species that is not currently imperiled but is at risk of becoming so because of small or declining numbers, occurrence at the fringe of its range or in restricted areas, habitat fragmentation, or some other reason

water pollution
contamination of water by an excess amount of a substance that can cause harm to human beings and/or the ecosystem

Unit 5.3

adaptation (climate)
the process of adjustment to actual climate and its effects

aerosol
small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight

albedo
the amount of solar radiation reflected from an object or surface, often expressed as a percentage

anomaly (temperature)
a difference in average temperature measurement from a predetermined datum

anthropogenic climate change
the impacts of humans on the climate system

carbon capture and sequestration (CCS)
technology that captures and stores carbon deep beneath the Earth's surface

carbon dioxide (CO_2)
the primary greenhouse gas that is contributing to recent global climate change; anthropogenic sources include the burning of fossil fuels, deforestation, burning of forests, changes in land use, cement manufacturing, agriculture, and land-clearing

carbon taxes
charges for burning fossil fuels

clathrates
frozen chunks of ice and methane found at the bottom of the ocean

climate-forcing
the process of greenhouse gases being released into the atmosphere

climate
long-term, predictable atmospheric conditions present in a specific area

climate change
the complete set of climate characteristics—temperature; precipitation; pressure systems; wind patterns; and oceanic currents—that are changing locally, regionally, and globally due to human influences

climate model
simulate the complex movements of energy and mass in the global circulation of the atmosphere; also examine the interactions of these processes with physical variables that are important aspects of climate, such as temperature and precipitation

climatologist
scientist who studies climate

coextinction
extinctions arising from the decoupling of mutualistic relationships

Conference of the Parties (COP)
a yearly gathering of signatories to the UNFCCC to renegotiate the terms and discuss climate change

confidence (climate)
grounded in an evaluation of underlying evidence and agreement

desalination
taking the salt out of seawater to make it potable

driver (climate)
cause of climate change

F-gas
a group of highly potent and long-lived greenhouse gases; used in coolants, foaming agents, fire extinguishers, solvents, pesticides, and aerosol propellants

fossil fuel
coal, oil, or natural gas; nonrenewable energy sources

fuel charge
part of the Canadian federal carbon pricing system; a regulatory charge on fossil fuels like gasoline and natural gas

global climate change
altered global weather patterns, including a worldwide increase in temperature, due largely to rising levels of atmospheric carbon dioxide

global warming
describes the general trend of increasing global temperatures seen under climate change

greenhouse effect
warming of Earth due to carbon dioxide and other greenhouse gases in the atmosphere

greenhouse gases
atmospheric gases such as carbon dioxide and methane that absorb and emit radiation, thus trapping heat in Earth's atmosphere

ground-level ozone (O_3)
potent greenhouse gas and air pollutant; anthropogenic sources include automobiles, power plants, and other industrial and commercial sources in the presence of sunlight

haze-effect cooling
effect of the gases and solids from a volcanic eruption on global climate

ice core
samples of polar ice obtained by means of drills that reach thousands of meters into ice sheets or high mountain glaciers; provide evidence of historical climate

Industrial Revolution
began in 1750 has improved the quality of life for many humans; powered by fossil fuels it has also disrupted the climate and biodiversity across the planet

Intergovernmental Panel on Climate Change (IPCC)
established in 1988; responsible for reviewing the scientific literature on climate change and issuing periodic reports on several topics, including the scientific basis for understanding climate change, humanity's vulnerability to observed and predicted climate changes, and what society can do to limit climate change and minimize its impacts

Kyoto Protocol
a non-binding agreement set in 1997 between signing and ratifying nations to reduce their GHG emissions

Little Ice Age
a slight cooling of a little less than 1°C was observed in North America, Europe, and possibly other areas of the Earth

Medieval Climate Anomaly
during this time period, slightly warmer weather conditions prevailed in many parts of the world

methane (CH_4)
a greenhouse gas 28x as potent as carbon dioxide; produced when bacteria break down organic matter under anaerobic conditions; anthropogenic sources primarily include agriculture, fossil fuel extraction and transport, mining, landfill use, and the burning of forests

Milankovitch cycles

cyclic changes in the Earth's orbit that may affect climate

mitigation (climate)
reducing emissions, and stabilizing the levels, of heat-trapping greenhouse gases in the atmosphere

nitrous oxide
a greenhouse gas produced through natural and human activities; anthropogenic sources include agricultural activities, industry, and fuel-burning

ocean acidification
the process of ocean waters' decreasing pH

ocean deoxygenation
because warmer water absorbs less oxygen, scientists predict that some areas of the ocean will see a 3–6% drop in dissolved oxygen concentrations under climate change

Output-Based Pricing System
part of the Canadian federal carbon pricing system; a performance-based system for industries

phenological mismatch
disruption of timed aspects of a species' life cycle, such as migration and breeding

resilience (climate)
the capacity of social, economic, and ecosystems to cope with a hazardous event, trend, or disturbance, responding, or reorganizing in ways that maintain their essential function, identity, and structure

risk (climate)
a measure that provides a framework for understanding the increasingly severe, interconnected, and often irreversible impacts of climate change

sink
removes greenhouse gases from the atmosphere

solar intensity
amount of solar power energy the sun emits in a given amount of time

solubility
the ability of a substance to dissolve in water

source
supplies greenhouse gases to the atmosphere

UN Framework Convention on Climate Change (UNFCCC)
an international agreement to reduce emissions of GHGs put into place in 1992

weather
conditions of the atmosphere during a short period of time

Unit 5.4

anthropocentric ethic
using resources wisely so that future generations have access to them

biocentric ethic

using resources wisely to prevent ecological damage

Canadian Environmental Assessment Act (CEAA)
requires federal decision-makers, referred to as “responsible authorities,” to consider the predicted environmental effects of a proposed project before it is allowed to go ahead

Cumulative Environmental Effects EIA
a planning activity under the Canadian Environmental Assessment Act that includes the need to evaluate cumulative environmental impacts, or those resulting from the effects of a proposed undertaking within some defined area, in addition to those caused by any past, existing, and imminent developments and activities

ecological integrity
if maintained or enhanced, then a protected area is doing its job of maintaining biodiversity and ecological functions

Environment and Climate Change Canada
plays a central role in preserving and enhancing environmental quality in Canada

environmental ethic
places limits on human activities (e.g., uncontrolled resource use), that may adversely affect the natural world

environmental equity
a society and culture in which no single group or community faces disadvantages in dealing with environmental hazards, disasters, or pollution

environmental impact assessment (EIA)
a planning process that is used to help prevent environmental problems

environmental justice
the fair treatment and meaningful involvement of all people regardless of race, color, ability, national origin, or income with respect to the development, implementation, andenforcement of environmental laws, regulations, and policies

environmental literacy
a well-informed understanding of environmental issues

environmental non-governmental organizations (ENGOs)
role is to lobby government and industry about issues, to raise public awareness, and increasingly (because of shortages of governmental capability), to raise funds that can be used to prevent and repair environmental damage

environmental quality
related to the concentrations of potentially toxic chemicals and other stressors in the environment, to the frequency and intensity of disturbances, and to the effects of these on humans, other species, ecosystems, and economies

environmental racism
the institutional racism that exists for marginalized communities, including Indigenous peoples in many developed countries regarding landfills, incinerators, waste sites, and industry in neighborhoods

ethics
standards of conduct that determine right from wrong

frontier ethic
assumes that the Earth has an unlimited supply of resources

land ethic
a type of moral extensionism; 'enlarges the boundary of the community to include soils, waters, plants and animals'

moral extensionism

defines how far a person's values extend outside of themselves

precautionary principle

proceed cautiously in the face of incomplete knowledge about something’s potential harm

Species at Risk Act (SARA)

toughened the legal provisions in support of the protection of species listed by COSEWIC

strong sustainability

tradeoffs among natural, human, and social capital are not allowed or are very restricted

sustainability

maintaining human existence by meeting the needs of the present without compromising the ability of future generations to meet their needs

sustainable development

progress made toward an economic system that is ultimately based on the wise use of renewable resources

sustainable ethic

assumes that the Earth’s resources are not unlimited and that humans must use and conserve resources in a manner that allows their continued use in the future

sustainable living

a lifestyle that attempts to reduce/eliminate an individual's (or society's) use of resources so as to be as close as possible to "net zero living"

United Nations Environment Programme (UNEP)

principal international organization that deals with environmental matters

valued ecosystem components (VECs)

society perceives them to be important for one or more of the following reasons: they are an economically important resource, such as an agricultural crop, a commercial forest, or a stock of fish, mammals, or birds; they are a rare or endangered species or ecological community; they are of cultural or aesthetic importance

weak sustainability

tradeoffs are unrestricted or have few limits

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5.S: Unit 5 - Summary

Unit 5.2

Biodiversity exists at multiple levels of organization and is measured in different ways depending on the goals of those taking the measurements. These measurements include numbers of species, genetic diversity, and ecosystem diversity. Ecosystems provide ecosystem services that support human agriculture: pollination, nutrient cycling, pest control, and soil development and maintenance. Loss of biodiversity threatens these ecosystem services. Estimates of contemporary extinction rates vary, but some rates are as high as 1000 times the background rate, as determined from the fossil record, and are predicted to rise. Loss of biodiversity will impact the number of pharmaceuticals available to humans, loss of crop diversity and ecosystem services, as well as psychological benefits to humans. Additionally, there are moral arguments for the maintenance of biodiversity.

The core threats to biodiversity are human population growth and unsustainable resource use. To date, the most significant causes of extinctions are habitat loss, invasive species, pollution, population (human), predator losses, overharvesting, and climate change (HIPPPOC). New technological methods such as DNA barcoding and information processing and accessibility are facilitating the cataloging of the planet's biodiversity. There is also a legislative framework for biodiversity protection, including international treaties. Conservation preserves are a major tool in biodiversity protection. Presently, 11 percent of Earth's land surface is protected in some way, however, preserves have limitations imposed by political and economic forces. In addition, climate change will limit the effectiveness of preserves in the future. Habitat restoration has the potential to restore ecosystems to previous biodiversity levels before species become extinct. Zoos have attempted to take a more active role in conservation and can have a limited role in captive breeding programs.

Unit 5.3

Natural drivers of climate change include Milankovitch cycles, changes in solar activity, and volcanic eruptions. None of these factors, however, leads to rapid increases in global temperature or sustained increases in carbon dioxide. The burning of fossil fuels is an important source of greenhouse gases, which plays a major role in the greenhouse effect. Long ago, climate change resulted in the Permian extinction: a large-scale extinction event that is documented in the fossil record. Currently, modern-day climate change is associated with the increased melting of glaciers and polar ice sheets, resulting in a gradual increase in sea level. Plants and animals can also be affected by global climate change when the timing of seasonal events, such as flowering or pollination, is affected by global warming and other associated factors.

Unit 5.4

Sustainability refers to three simple concerns: the need to arrest environmental degradation and ecological imbalance, the need not to impoverish future generations, and the need for quality of life and equity between current generations. Added up, these core concerns are an unmistakable call for transformation. Many problems face indigenous people, including lack of human rights, exploitation of their traditional lands and themselves, and degradation of their culture. Despite the lofty U.N. goals, the rights and feelings of indigenous people are often ignored or minimized, even by supposedly culturally-sensitive, developed countries. Business-as-usual is no longer an option.

The concept of ethics involves standards of conduct. These standards help to distinguish between behavior that is considered right and that which is considered wrong. The ways in which humans interact with the land and its natural resources are determined by ethical attitudes and behaviors. Environmental justice is achieved when everyone enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment.

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